Climate of the Ocean

Lecture 7: The Monash Simple Climate Model

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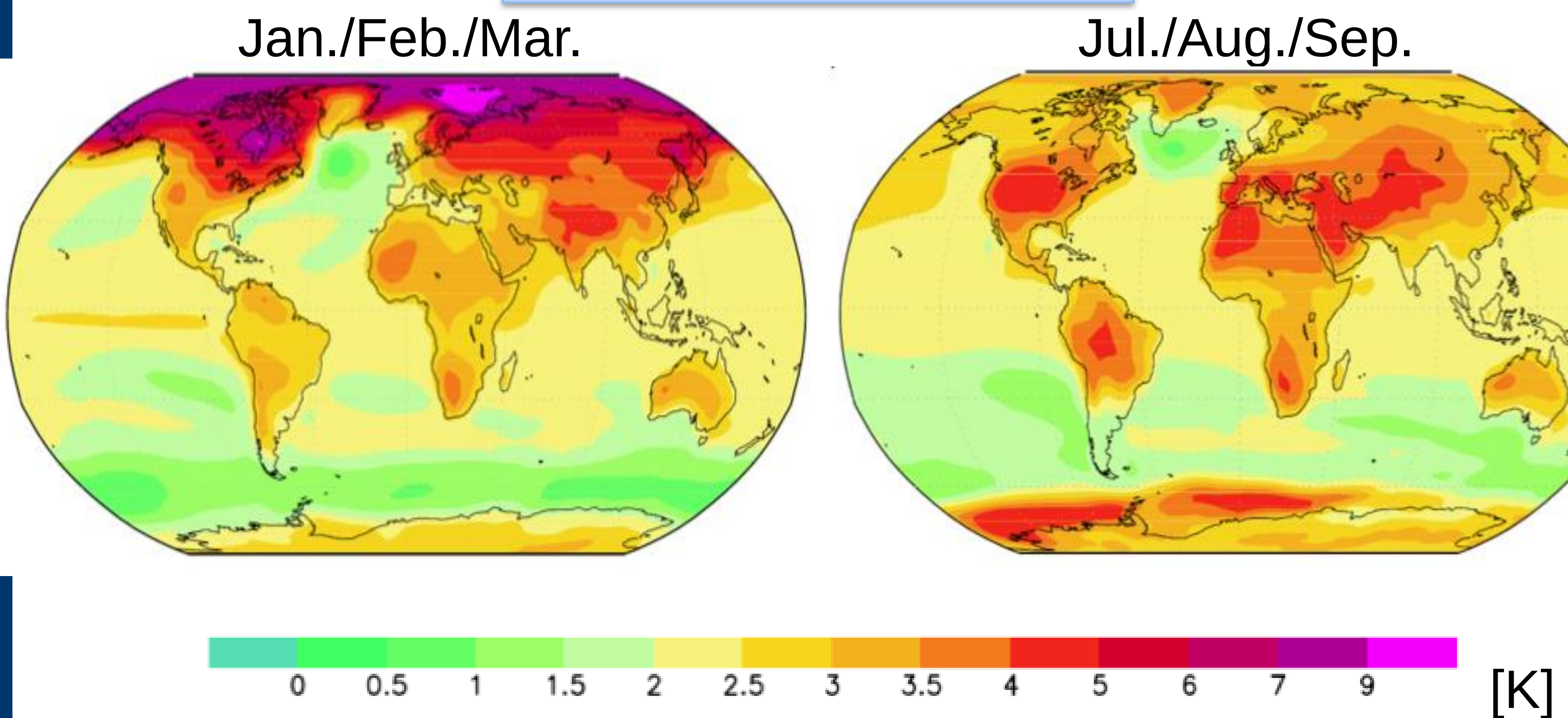
Outline:

- Motivation
- The GREB model
  - Processes:
    - Solar Radiation
    - Thermal Radiation
    - Hydrological Cycle
    - Sensible Heat
    - Subsurface Ocean
    - Sea Ice
  - Model boundary conditions / limitations
  - Model climate change prediction ‘skill’

MOTIVATION

Climate response to IPCC scenario A1B CO_2 forcing

Mean of 24 IPCC models



Difference in global mean temperature [2070-2100]-[1970-2000]

Climate response to IPCC scenario A1B CO_2 forcing

- Main features of the global response to CO_2 forcing:
  - Global mean warming by the end of 21th century is about 2.6^{o}K.
  - There are strong regional differences, although CO_2 forcing is the same everywhere.
  - Land warms more than the ocean.
  - The Arctic has the strongest warming.
  - The Northern Hemisphere warms more than the Southern.
  - The winter (cold) season warms more than the summer (warm) season.

GCM vs. simple model

- **GCMs are very complex**:
  - ~100,000 lines of source code
  - Not easily possible to “switch off” single processes to study their influence on the climate system
- **GCMs are very computing intensive**:
  - Need for super computers
  - 100 year global warming simulation takes weeks

➢ **Need for simple model to understand the main features of global warming!**

THE GREB MODEL

Difference between global mean vs. regionally resolved model:

Global:

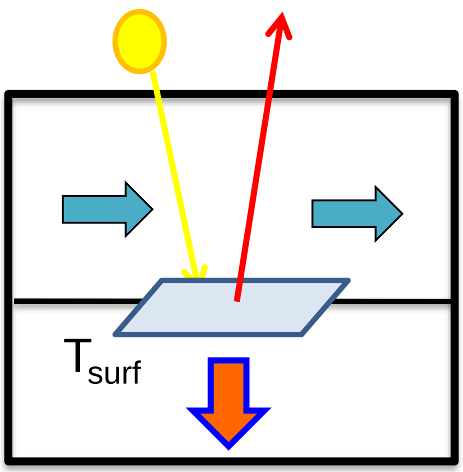
$$g_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal}$$

Only radiation exchange to space (no heat or mass transport)

Regional:

We can exchange heat with other regions

$$g_{surf}\frac{dT_{surf}}{dt} = \underbrace{F_{solar} + F_{thermal}}_{\text{radiation heat fluxes}} \underbrace{+ F_{sense} + F_{latent} + F_{ocean}}_{\text{turbulent heat fluxes}}$$

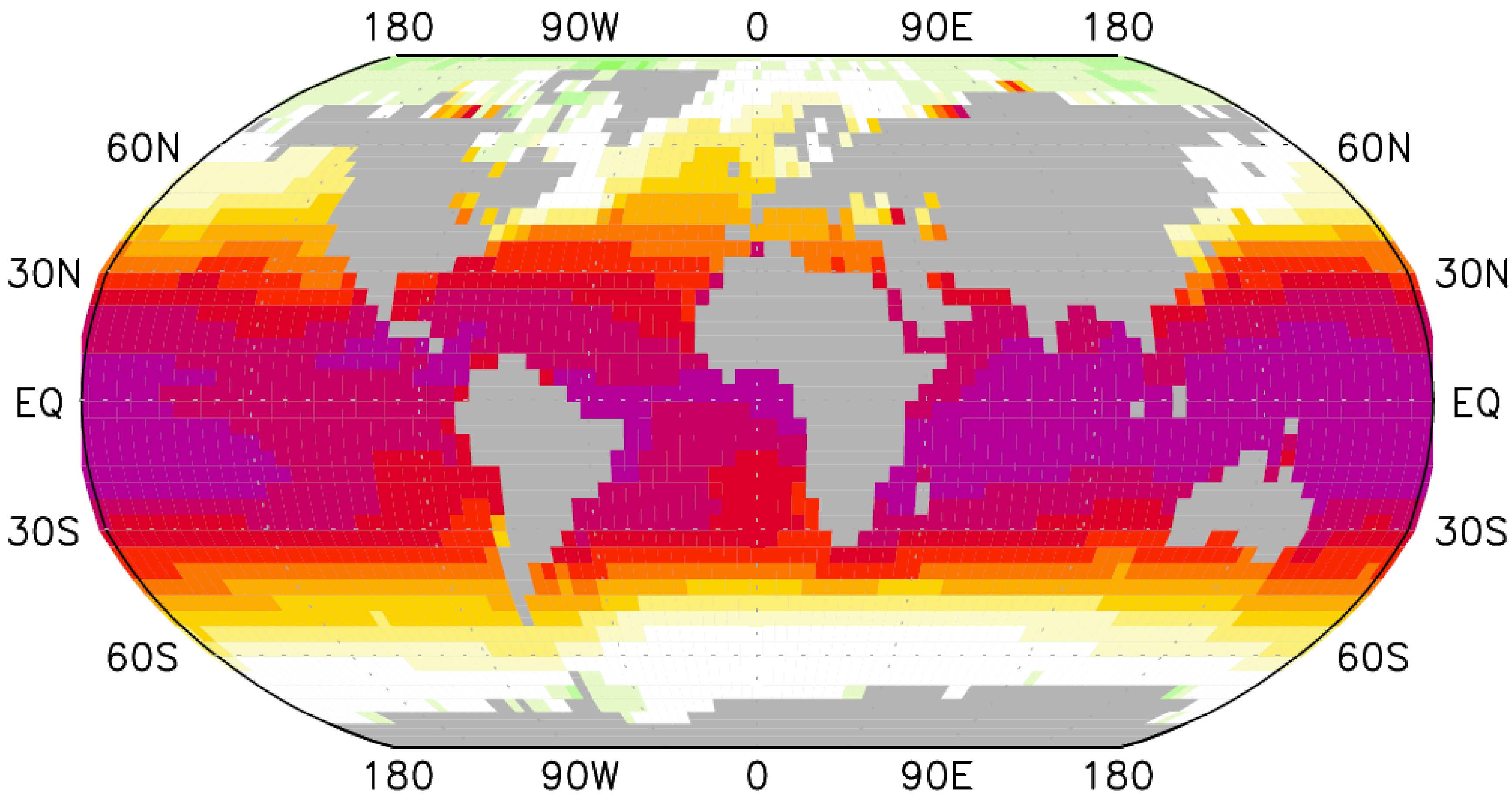


F_{sense} = turbulent heat exchange with atmosphere

F_{latent} = heat exchange by H_2O phase transitions (e.g. evaporation or condensation)

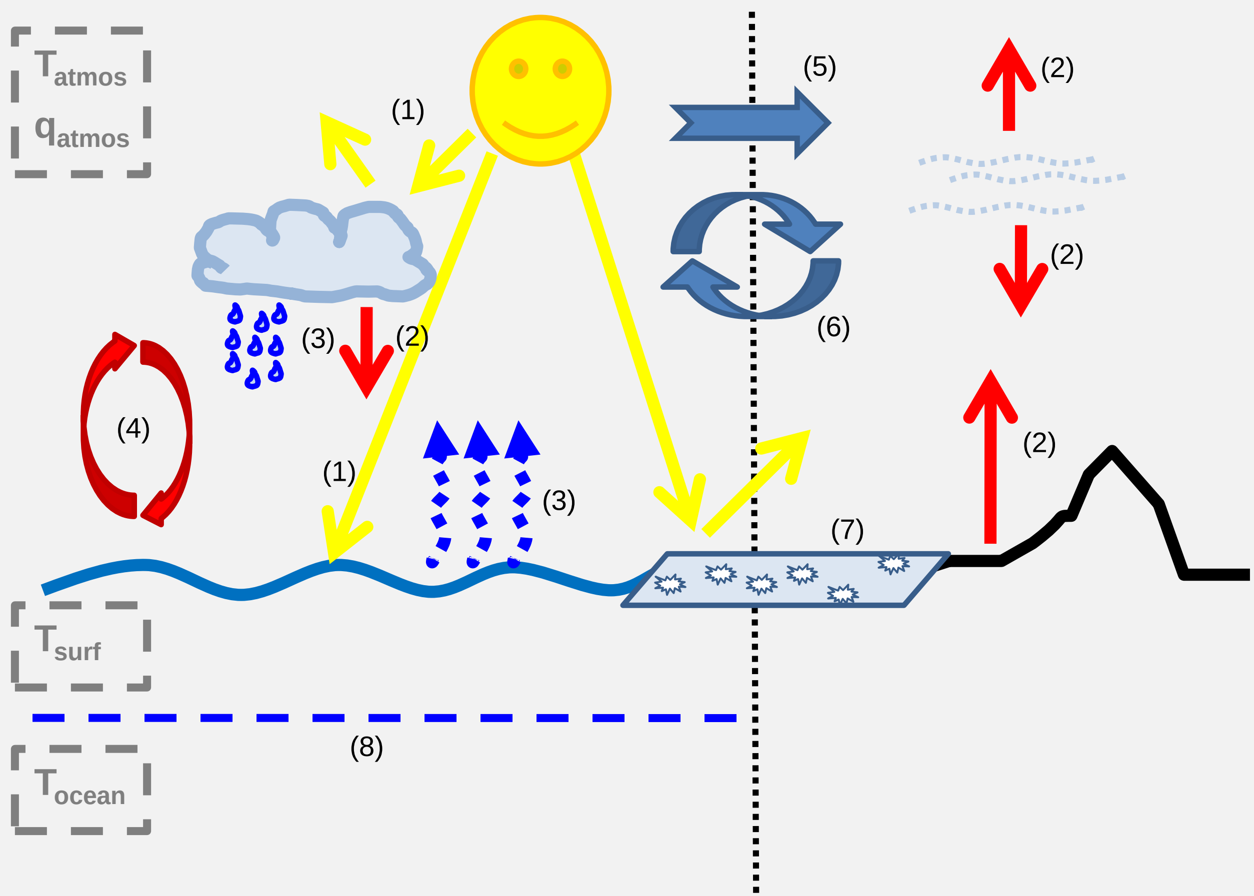
F_{ocean} = turbulent heat exchange with oceans

GREB model resolution



- 96 x 48 grid points = 3.75° x 3.75°

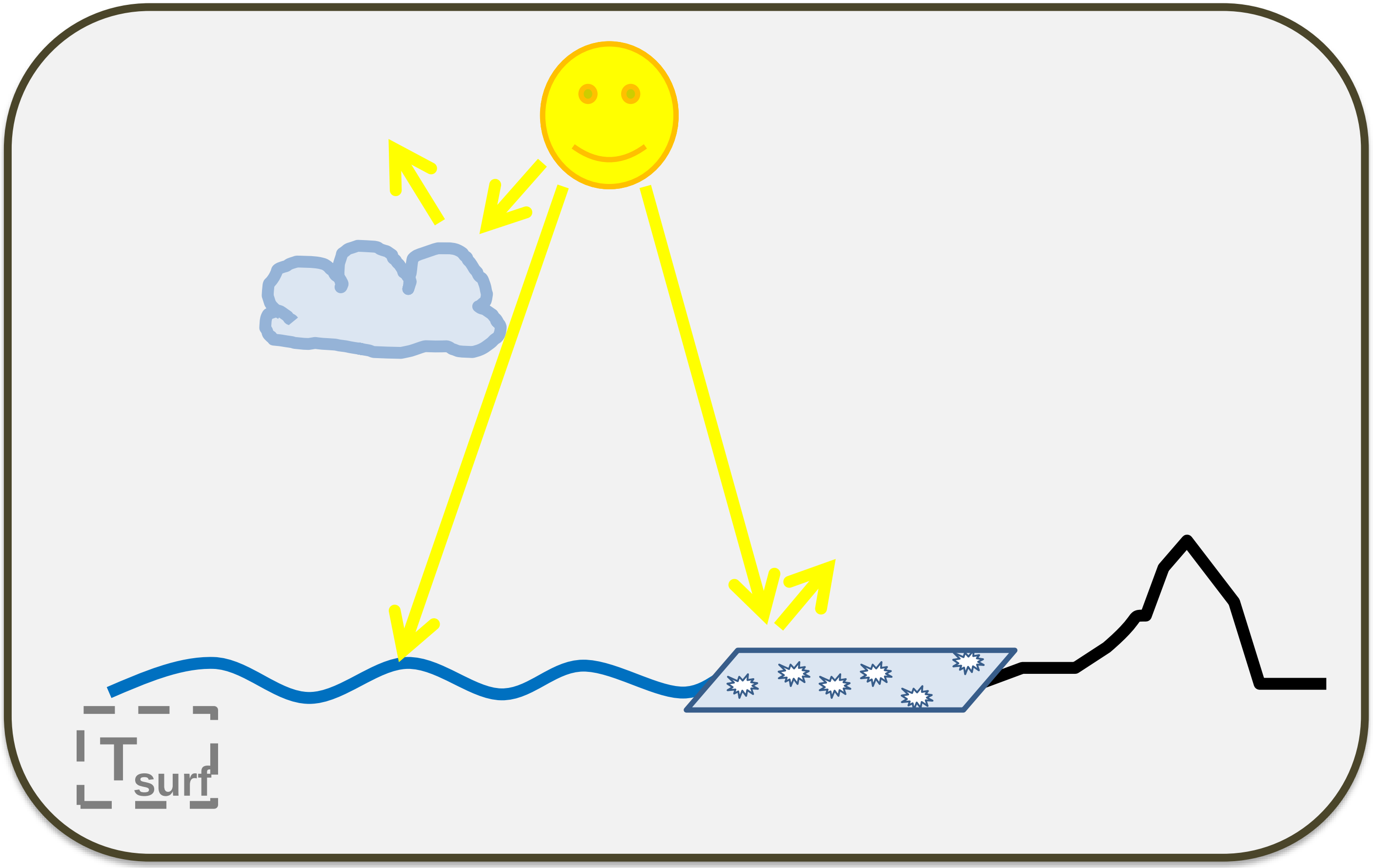
Greb model sketch



Processes:
(1) Solar radiation
(2) Thermal radiation
(3) Hydrological cycle
(4) Sensible heat
(5) Advection
(6) Diffusion
(7) Sea ice
(8) Deep ocean

THE GREB MODEL: PROCESSES

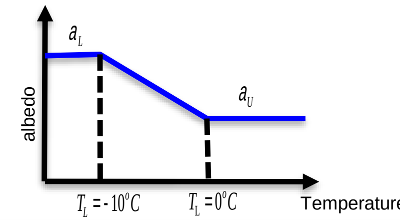
Solar radiation



Solar radiation

Global:
(Budyko)

$$F_{solar} = \tfrac{1}{4}(1 - a_P(T_{surf}))S_0$$



Regional:
(GREB)

$$\boxed{F_{solar} = (1 - a_{clouds})(1 - a_{surf})S_0 \times r(j, t_{julian})}$$

$r(j, t_{julian}) =$ 24hrs mean incoming fraction

$j =$ latitude

$t_{julian} =$ day of year

$a_{clouds} = 0.35 \times a_{cloud}$

a_{clouds} = albedo caused by clouds

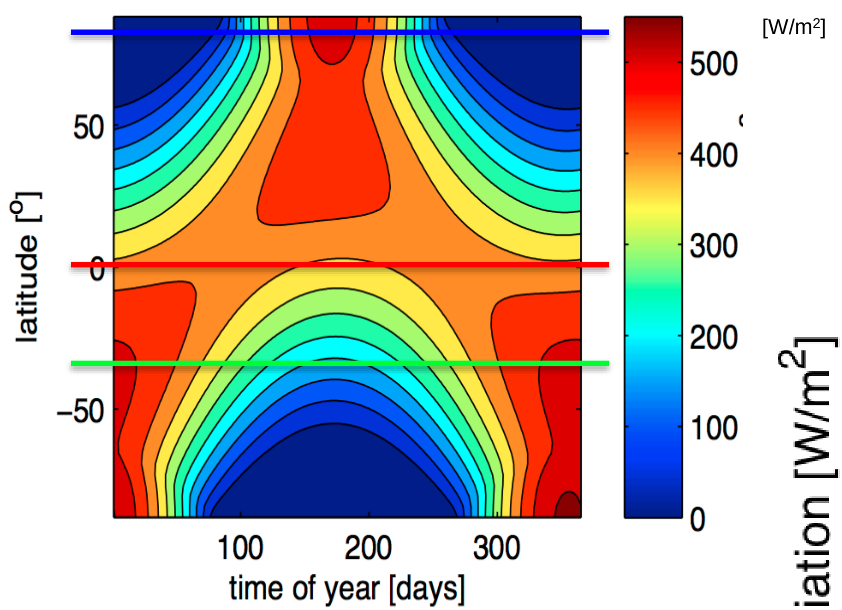
a_{cloud} = cloud cover

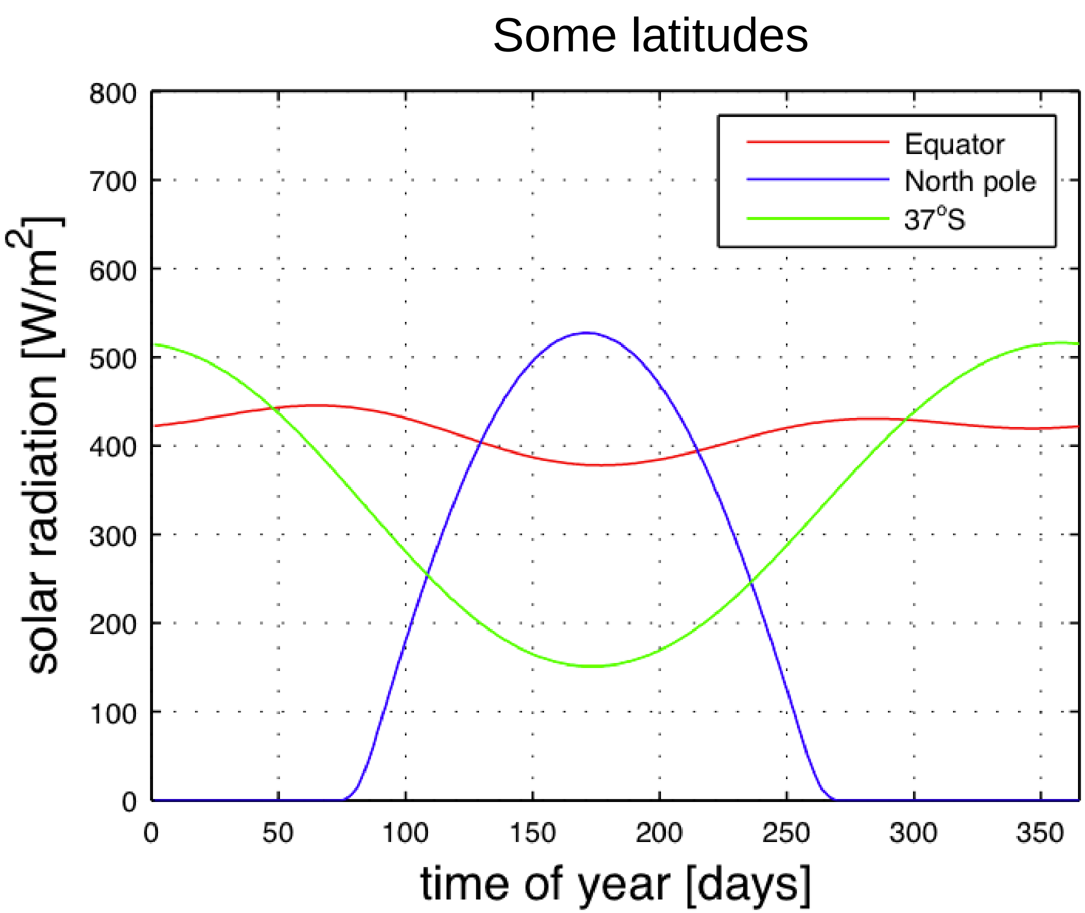
a_{cloud} = 0 $\rightarrow$ no clouds

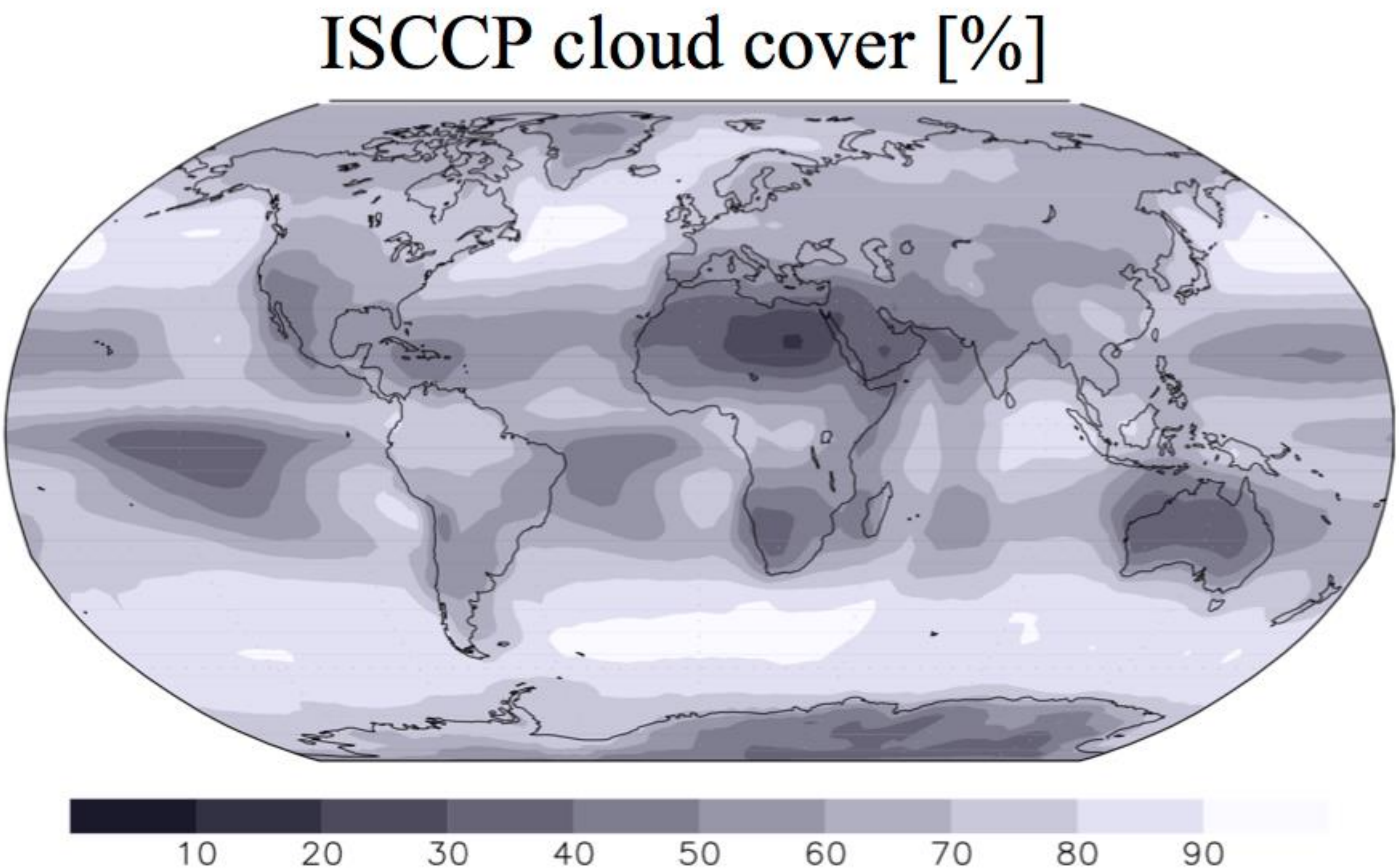
a_{cloud} = 1 $\rightarrow$ complete cloud cover

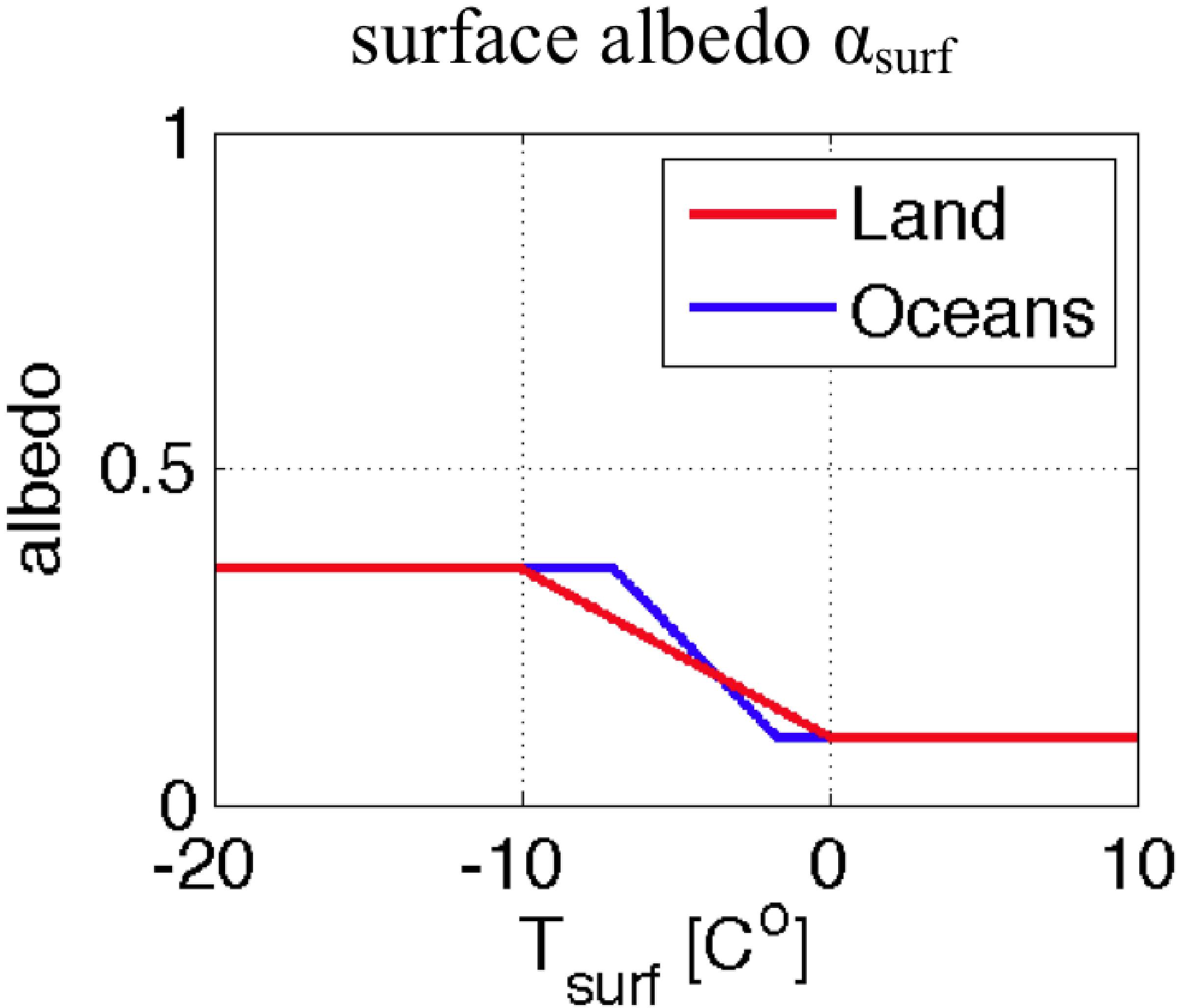
Incoming solar radiation

$S_0 \times r(j, t_{julian})$

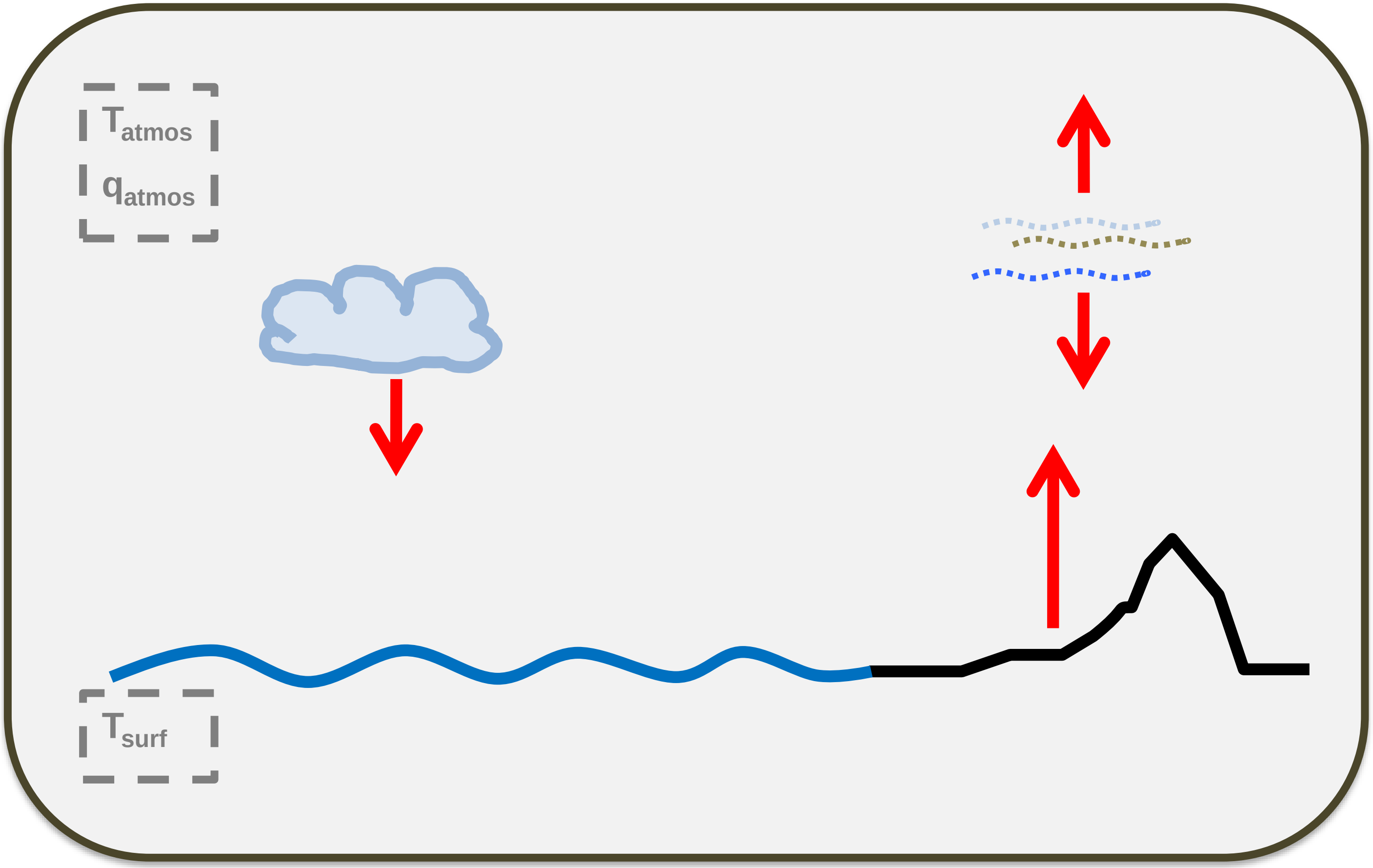





ISCCP cloud cover [%]
10
20
30
40
50
60
70
80
90


surface albedo α_{surf}
1
0.5
0
albedo
-20
-10
0
10
T_{surf} [C°]
Land
Oceans

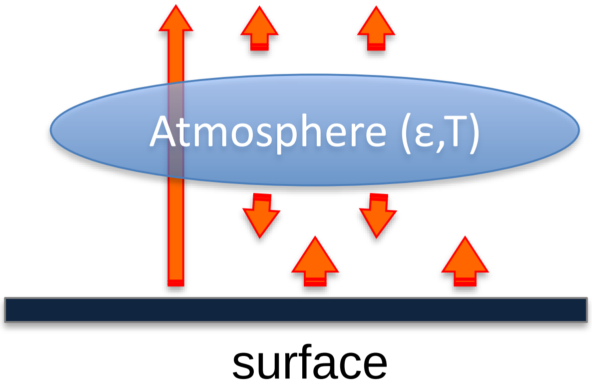
Thermal radiation



Global:
(greenhouse shield)

Surface: $-\sigma T_{surf}^4 + \varepsilon\sigma T_{atmos}^4$

atmosphere: $-2\varepsilon\sigma T_{atmos}^4 + \varepsilon\sigma T_{surf}^4$



A more detailed model of the thermal radiation balance in the atmosphere

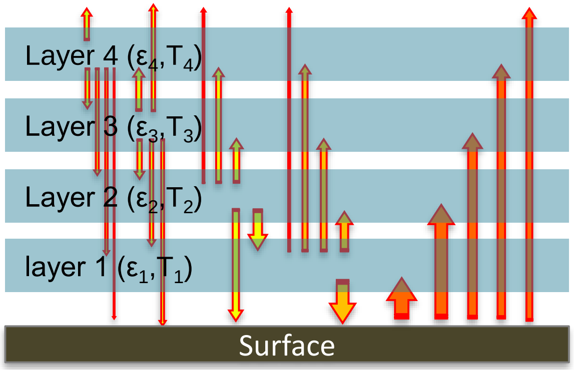
✧Thermal radiation emitted from each layer is a function of emissivity ε and T.

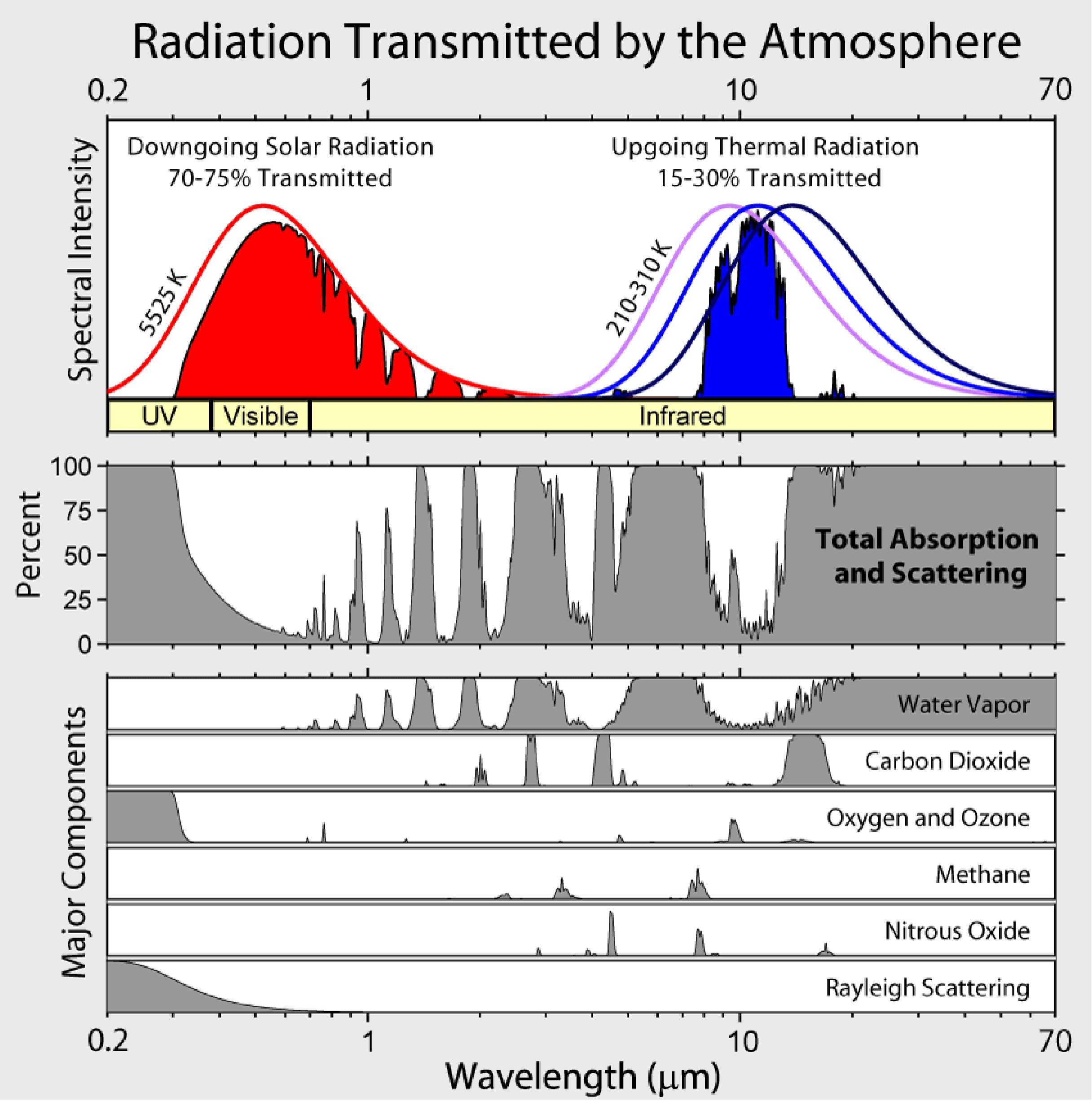
✧Thermal radiation absorbed from each layer is a function of the layers emissivity and all other layers ε and T.

✧ε at each layer is a function of pressure, chemical composition (H_2O, CO_2) and cloud droplet density.

✧Emissivity of chemical components is a function of wave length

✧Overall: … its complicated!

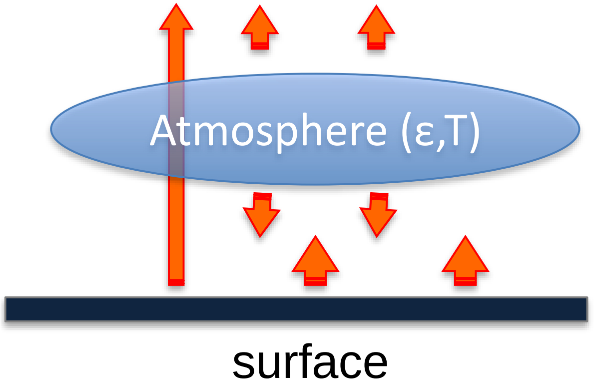



Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (µm)

GREB-model
(greenhouse shield/ slab atmosphere model)

Surface: $-\sigma T_{surf}^4 + \varepsilon\sigma T_{atmos}^4$

Atmosphere: $-2\varepsilon\sigma T_{atmos}^4 + \varepsilon\sigma T_{surf}^4$



GREB emissivity function:

$$\varepsilon_{atmos} = F(CO_2, H_2O_{vapor}, \text{cloud cover})$$

Approach:

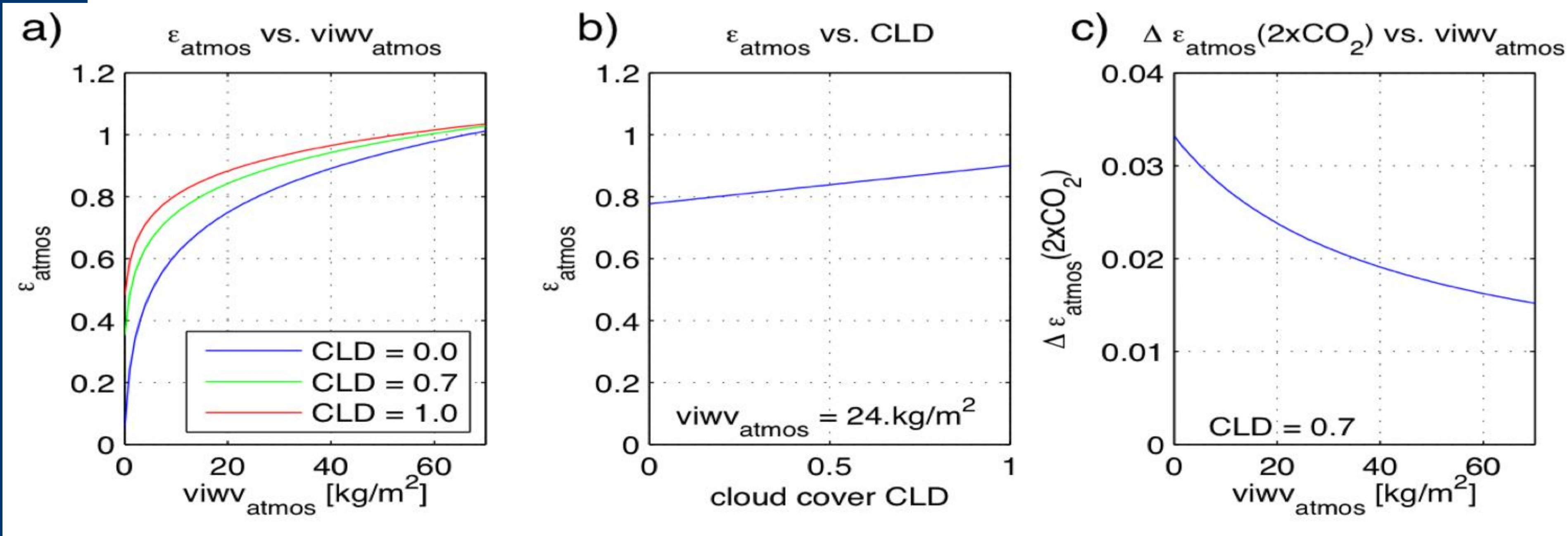
✧Assume saturation effect (a doubling of greenhouse gases does not double the greenhouse effect; see multi-layer greenhouse shield)

✧log-function approximation (to simulate saturation effect; note, there is no fundamental physical law behind this log-function)

✧3 spectral bands (to simulate the overlap of absorption bands in H_2O and CO_2)

✧Fit function to data (from more sophisticated radiation models; IPCC-type models)

GREB emissivity function



✧Water vapor has a strong effect on ε

✧The effect of water vapor is non-linear

✧The sensitivity to change in water vapor (slope) is bigger for small amounts of water vapor

✧Clouds increase ε

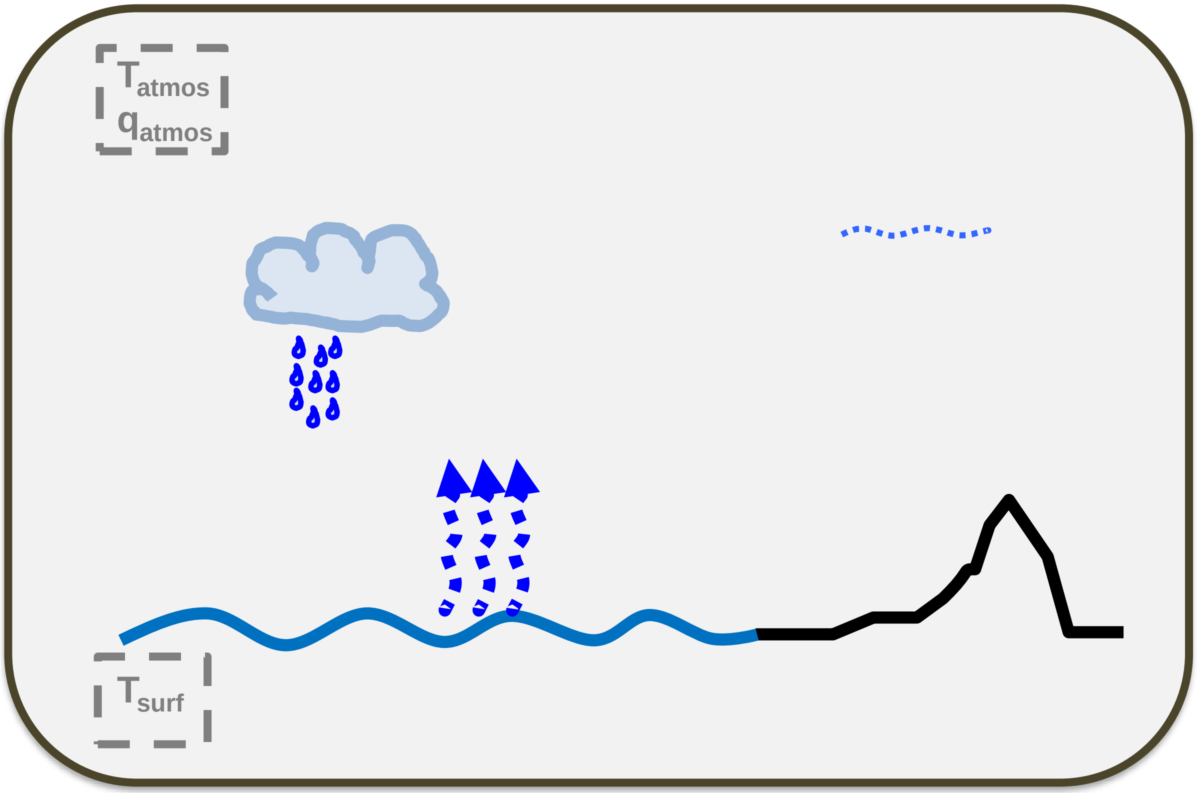
✧Clouds dilute the effect of greenhouse gases

✧The sensitivity to CO_2 is bigger if water vapor is less

Characteristics of the emissivity function:

1. Global mean emissivity $\varepsilon \approx 0.8$
2. $\Delta\varepsilon$(water-vapor -> 0) ≈ 0.5. The largest part of emissivity is due to water vapor
3. $\Delta\varepsilon(CO_2 \rightarrow 0) \approx 0.18$
4. $\Delta\varepsilon$(cloud cover -> 0) ≈ 0.16
5. $\varepsilon(CO_2 = H_2O =$ cloud cover $= 0) \approx 0$ No greenhouse gases and no clouds -> no emissivity.
6. $\varepsilon(H_2O = 70kg/m^2$, cloud cover $= 1) \approx 1$ a very humid and fully cloud cover atmosphere has emissivity of about 1.
7. ¾ of the H_2O absorption is non-overlapping with CO_2 absorption bands
8. H_2O and CO_2have about equal strength in spectral bands where they both absorb
9. CO_2 absorbs about equally strong in the two absorption bands
10. Clear sky sensitivity to greenhouse gases is about twice as strong as for completely cloud covered sky
11. $\Delta\varepsilon(2xCO_2) \approx 0.02$. The change in emissivity due to doubling of CO_2, which follows from the IPCC models 3.8W/m2 additional thermal downward radiation.
12. $\Delta\varepsilon(\Delta$water-vapor$) \approx 0.02$. It follows from the IPCC models

Hydrological cycle



Water Vapor Cycle

Latent Heating

Result of thermal radiation model:

1. We need a prognostic equation for T_{atmos} $$g_{atmos}\frac{dT_{atmos}}{dt} = F_{thermal} + \ldots$$

2. We need a prognostic equation for q_{atmos} $$\frac{dq_{atmos}}{dt} = \ldots$$

Hydrological cycle:

Lifetime of CO_2 in atmosphere: 10yrs – 10,000yrs -> is globally well mixed

Lifetime of H_2O in atmosphere: 10days (rain, weather) -> is not well mixed

$$\frac{dq_{surf}}{dt} = \Delta q_{eva} + \Delta q_{precip} + \ldots$$

q_{surf} = surface humidity

Dq_{eva} = evaporation of water into the atmosphere

Dq_{precip} = condensation and precipitation of water out of the atmosphere

Precipitation: It rains if water vapor in the atmosphere condensates and the droplets get big enough to fall to ground. Therefore the air must saturate with water vapor.

Saturation: Air typically saturates with water vapor if air is lifted (vertical motion) and therefore adiabatically (by reducing pressure) cooled

-> Processes of the hydrological cycle are complex and are strongly controlled by weather fluctuations. They can not be '*simulated*' in the simple GREB model. But we have to find a simple approximation.

Precipitation

How to estimate rain in GREB?

✧ Roughly: it rains if there is atmos. water vapor

✧ Atmospheric water vapor stays in the atmosphere about 10 days

$$\Rightarrow \Delta q_{precip} = 0.1\frac{1}{day} q_{atmos}$$

10% of the current atmos. water vapor will rain every day

Evaporation

Empirical bulk formula:

$$\Delta q_{eva} = \frac{1}{r_{H2O}} \cdot \rho_{air} \cdot C_w \cdot \left|\vec{u}_*\right| \cdot \upsilon_{soil} \cdot (q_{sat} - q_{atmos})$$

Saturated water vapor :
(following from Clausius-Clapeyron equation)

$$q_{sat} = \boxed{e^{\frac{-z_{topo}}{h_{atmos}}}} \times 3.75 \times 10^{-3} \times e^{\left(17.1 \frac{T_{surf} - 273.15}{T_{surf} - 38.98}\right)}$$

Consider surface
pressure decrease
with altitude

r_{H2O} = regression parameter
r_{air} = density of air at sea level
C_w = empirical transfer coefficient over oceans
$\left|\vec{u}_*\right|$ = effective wind speed
u_{soil} = surface moisture [%]
q_{sat} = saturated humidity [kg/kg]
q_{atmos} = densithumidity [kg/kg]

Evaporation is strong if:

- ✧Winds are strong
- ✧Air is dry and warm
- ✧Surface is wet

Latent heat

$$F_{latent} = -L \cdot r_{H2O} \cdot \Delta q_{eva}$$

$$L = 2300000 \cdot J/kg = \text{ latent heat of condensation}$$

$$c_{h2o} \approx 4000 \cdot J/kg/K = \text{ specific heat of water}$$

Note: this is a lot of heat if compared to the specific heat of water. Condensing water vapor to water (raining) releases more heat than is required to heat water by 500K!!

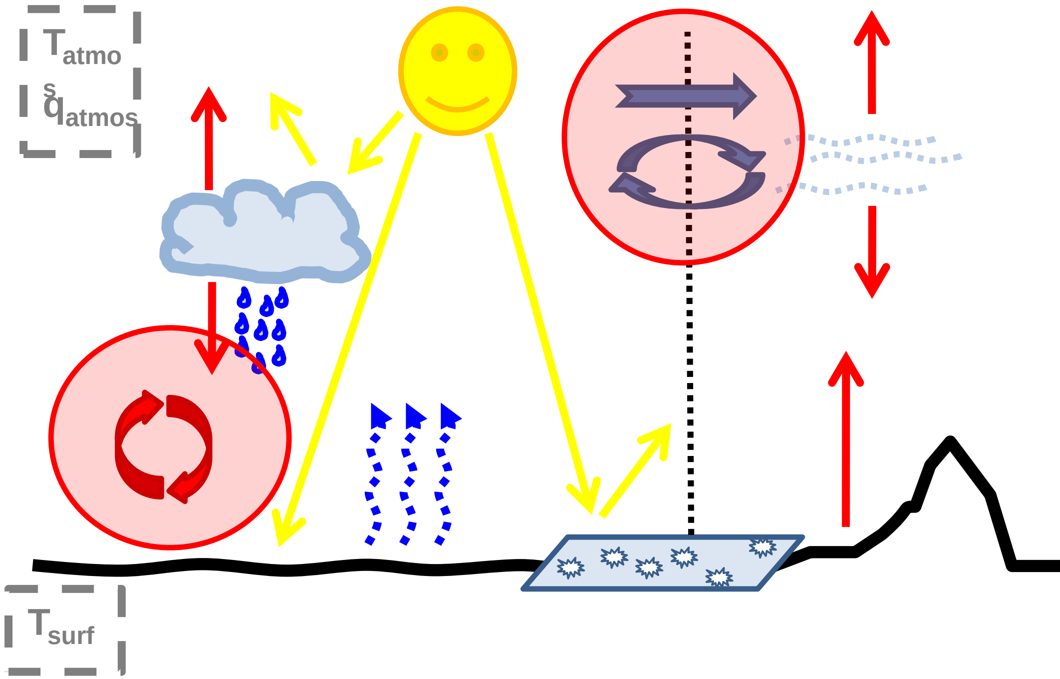
Latent heat atmosphere

$$F_{atmos-latent} = -L \cdot r_{H2O} \cdot \Delta q_{precip}$$

$$\Rightarrow F_{latent} \neq -F_{atmos-latent}$$

The heat lost at the surface by evaporation is not the same as the one gained in the atmosphere by condensation, as there may be some transport of water vapor to or from other regions

Sensible heat



Processes:
(1) Solar radiation
(2) Thermal radiation
(3) Hydrological cycle
(4) Sensible heat
(5) Advection
(6) Diffusion

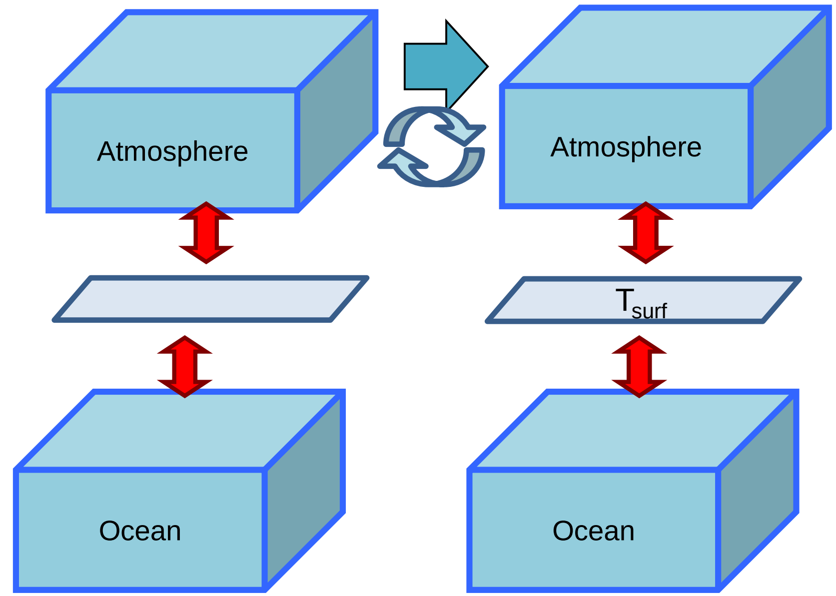
$$g_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal} + F_{latent} + \ldots.$$

$$g_{atmos}\frac{dT_{atmos}}{dt} = F_{thermal} + F_{atmos-latent} + \ldots$$

$$\frac{dq_{surf}}{dt} = \Delta q_{eva} + \Delta q_{precip} + \ldots$$

Sensible heat and circulation

Simplification:
Assume heat transport only in atmosphere
(not in ocean, not in surface layer)



Sensible heat flux from atmosphere:

$$F_{sense} = C_{A-S} \cdot (T_{atmos} - T_{surf}) \qquad C_{A-S} = 22.5 \frac{W}{m^2} \cdot \frac{1}{K}$$

The turbulent heat exchange between surface and atmosphere is estimated by a ***Newtonian damping***. The stronger the temperature difference the stronger the heat exchange

Sensible heat flux from deeper ocean:

$$Fo_{sense} = C_{O-S} \cdot (T_{ocean} - T_{surf}) \qquad C_{O-S} = 5 \frac{W}{m^2} \cdot \frac{1}{K}$$

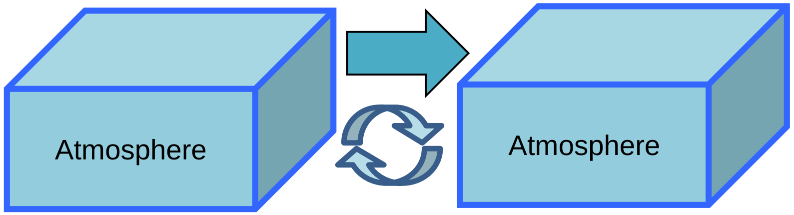
The turbulent heat exchange with deeper ocean is much weaker due to the much weaker turbulence in the deeper ocean.

Atmospheric heat transport

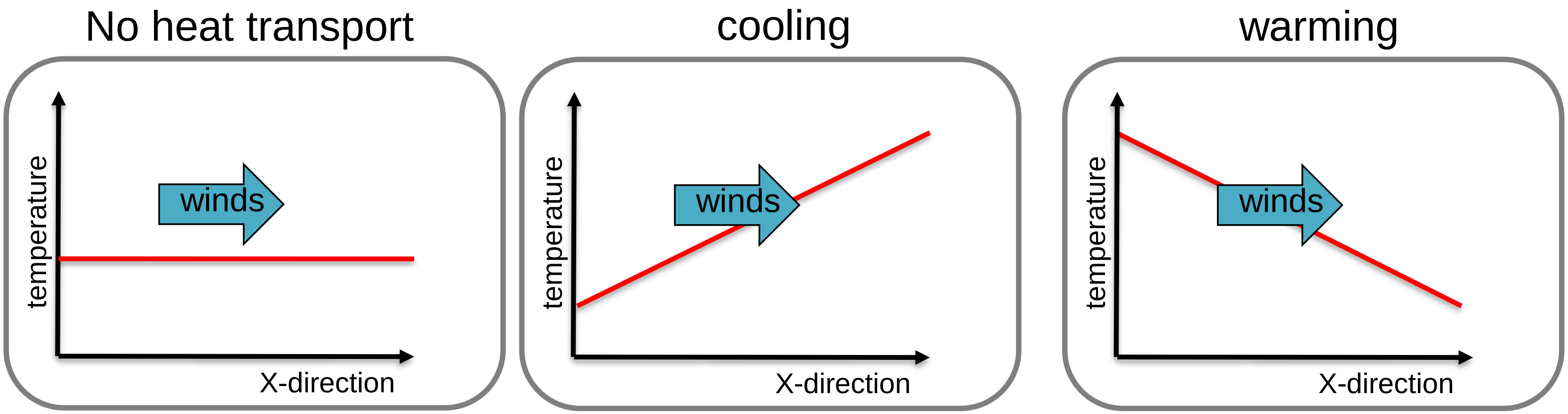
Simplification of transport:

✧Assume a mean transport (advection)

✧Assume a turbulent isotropic diffusion



advection



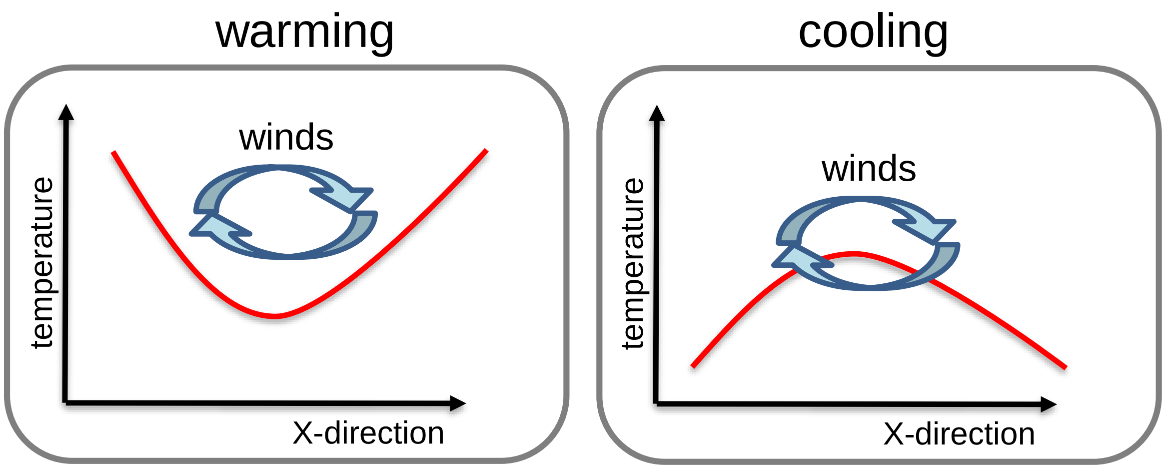
$$F_{adv} \propto -\vec{u} \cdot \vec{\nabla} T$$

Heat transport by advection is proportional to scalar product between wind-vector and the direction of the temperature gradient

$$\Rightarrow \frac{F_{adv}}{\gamma_{atmos}} = -\vec{u} \cdot \vec{\nabla} T$$

The temperature tendencies by advection do not depend on the heat capacity, but the heat flux does

Isotropic diffusion



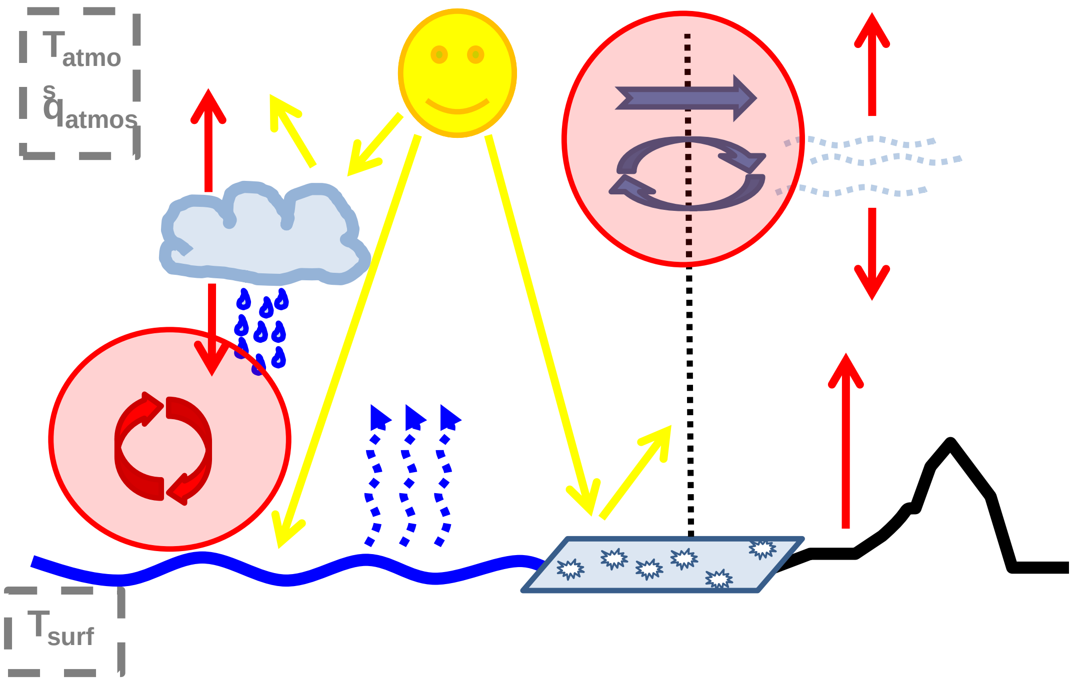
$$\frac{F_{diffuse}}{\gamma_{atmos}} = \kappa \cdot \nabla^2 T$$

Heat transport by isotropic diffusion is strong if the 2. derivative of the temperature field is strong and the turbulence of the winds (kappa) is strong

$$k = 2 \times 10^5 \frac{m^2}{s}$$

This defines the strength of turbulent winds (weather). It should erase any temperature maxima/minima in the atmosphere within days

Sensible heat and circulation



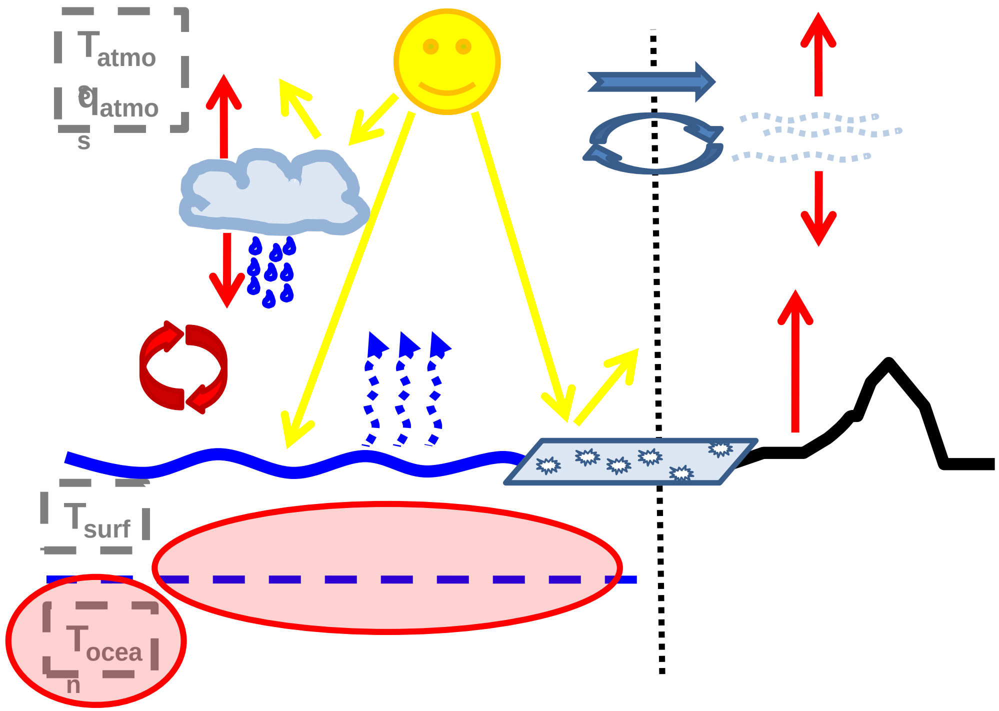
Processes:
(1) Solar radiation
(2) Thermal radiation
(3) Hydrological cycle
(4) Sensible heat
(5) Advection
(6) Diffusion

$$g_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal} + F_{latent} \boxed{+F_{sense}} + \ldots$$

$$\gamma_{atmos}\frac{dT_{atmos}}{dt} = F_{thermal} + F_{atmos-latent} \boxed{-F_{sense} + \gamma_{atmos}\left(\kappa \cdot \nabla^2 T - \vec{u} \cdot \vec{\nabla} T\right)}$$

$$\frac{dq_{surf}}{dt} = \Delta q_{eva} + \Delta q_{precip} \boxed{+\left(\kappa \cdot \nabla^2 q_{surf} - \vec{u} \cdot \vec{\nabla} q_{surf}\right)}$$

Subsurface ocean



Processes:
(1) Solar radiation
(2) Thermal radiation
(3) Hydrological cycle
(4) Sensible heat
(5) Advection
(6) Diffusion
(7) Deep ocean

$$\gamma_{atmos}\frac{dT_{atmos}}{dt} = F_{thermal} + F_{atmos-latent} - F_{sense} + \gamma_{atmos}\left(\kappa\cdot\nabla^2 T - \vec{u}\cdot\vec{\nabla}T\right)$$

$$\frac{dq_{surf}}{dt} = \Delta q_{eva} + \Delta q_{precip} + \left(\kappa\cdot\nabla^2 q_{surf} - \vec{u}\cdot\vec{\nabla}q_{surf}\right)$$

$$g_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal} + F_{latent} + F_{sense} + \ldots.$$

$$g_{ocean}\frac{dT_{ocean}}{dt} = \ldots.$$

Ocean heat uptake

Simplification:

✧ No lateral heat transport in ocean

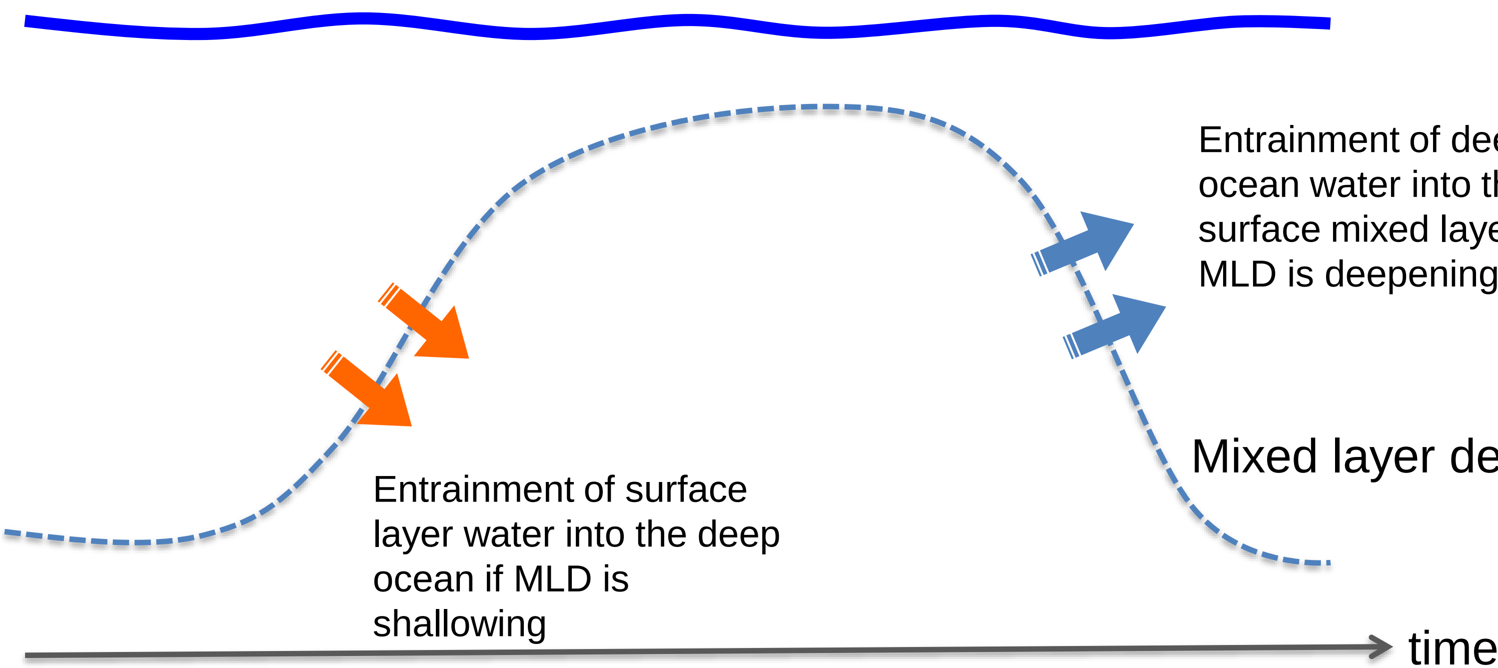
✧ Sensible heat flux (Newtonian damping)

✧ Entrainment by changes in mixed layer depth (MLD)

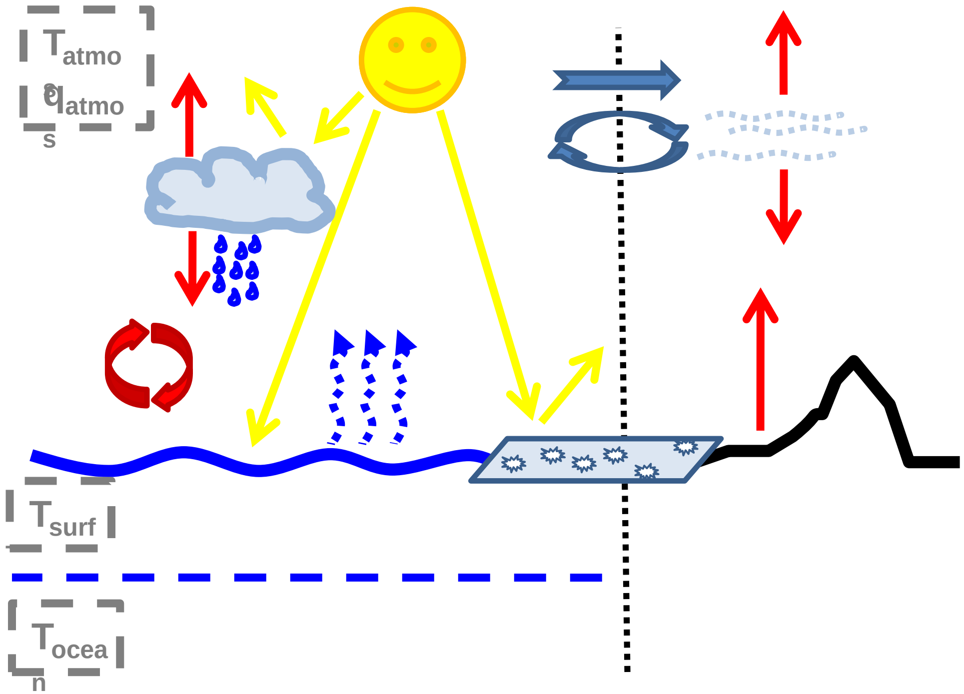
✧ effective ocean heat capacity is proportional to MLD

Sensible heat flux from deeper ocean:

$$Fo_{sense} = C_{O-S} \cdot (T_{ocean} - T_{surf}) \qquad C_{A-S} = 5 \frac{W}{m^2} \times \frac{1}{K}$$



Sea Ice



Processes:
(1) Solar radiation
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(7) Deep ocean
(8) Sea ice

$$\gamma_{atmos}\frac{dT_{atmos}}{dt} = F_{thermal} + F_{atmos-latent} - F_{sense} + \gamma_{atmos}\left(\kappa \cdot \nabla^2 T - \vec{u}\cdot\vec{\nabla}T\right)$$

$$g_{surf}\frac{dT_{surf}}{dt} = F_{solar} + F_{thermal} + F_{latent} + F_{sense} + F_{ocean}$$

$$\gamma_{ocean}\frac{dT_{ocean}}{dt} = \Delta To_{entrain} - Fo_{sense}$$

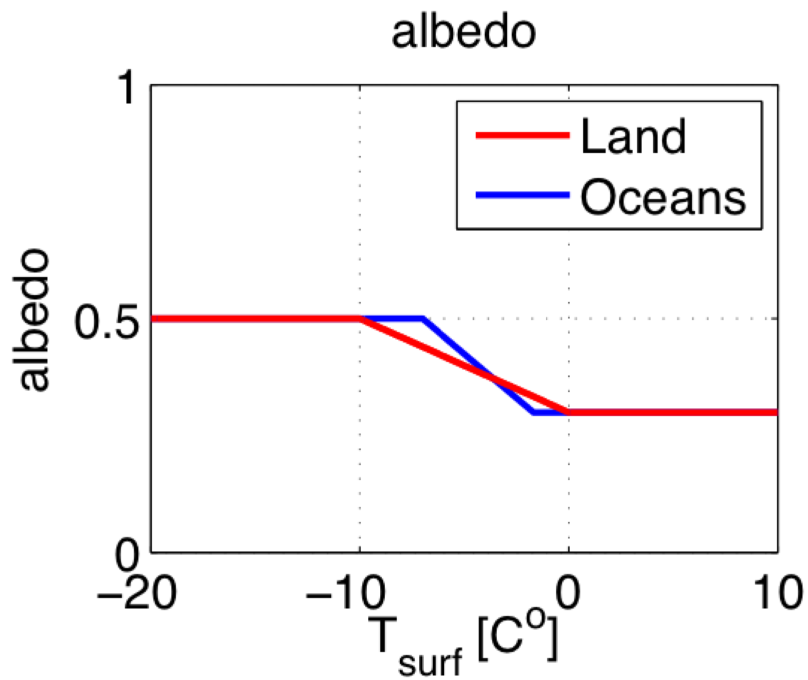
$$\frac{dq_{surf}}{dt} = \Delta q_{eva} + \Delta q_{precip} + \left(\kappa \cdot \nabla^2 q_{surf} - \vec{u}\cdot\vec{\nabla}q_{surf}\right)$$

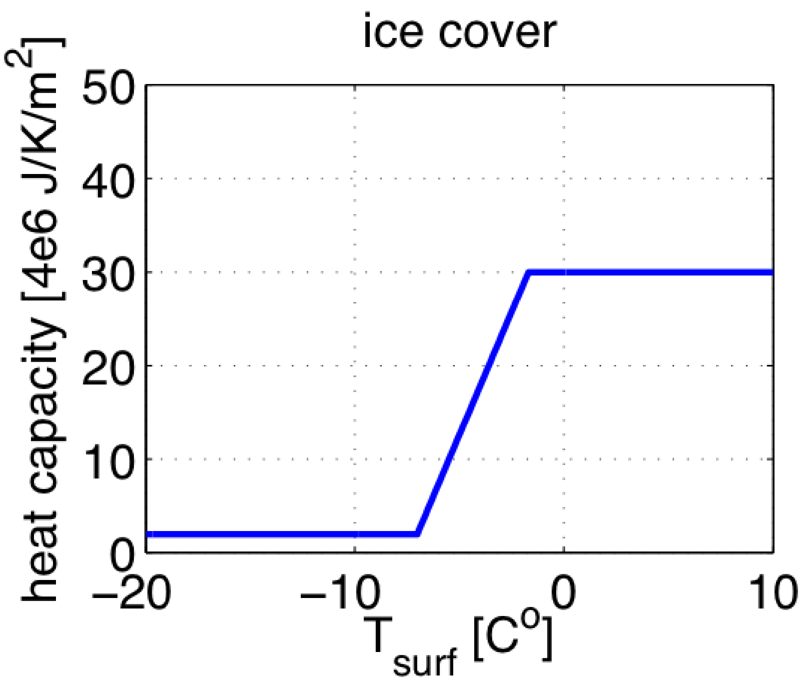
Heat capacity

Atmosphere	$g_{atmos} = 5 \times 10^6 \times J/m^2/K$	About 5000m air column
Land	$g_{surf} = 4 \times 10^6 \times J/m^2/K$	About 2m soil column
Ocean surface	$g_{surf} \approx 200 \times 10^6 \times J/m^2/K$	In average 50m water column; large regional and seasonal differences depending on mixed layer depth
Subsurface ocean	$g_{ocean} \approx 1000 \times 10^6 \times J/m^2/K$	About three times the max. mixed layer depth; strong regional differences. ***Not*** the whole ocean is mixed. Deep ocean is ignored!
Sea Ice	$g_{surf} = 4 \times 10^6 \times J/m^2/K$	As for ice-albedo feedback, same ocean points are sometimes ice covered. Sea ice insolates the ocean from the atmosphere very well. -> heat capacity over ocean is function of temperature for below freezing values.

Heat capacity

Sea ice has a special feedback on the climate by changing the effective heat capacity



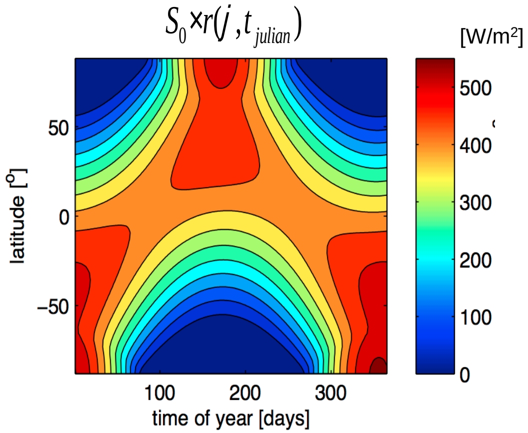


MODEL BOUNDARY CONDITIONS / LIMITATIONS

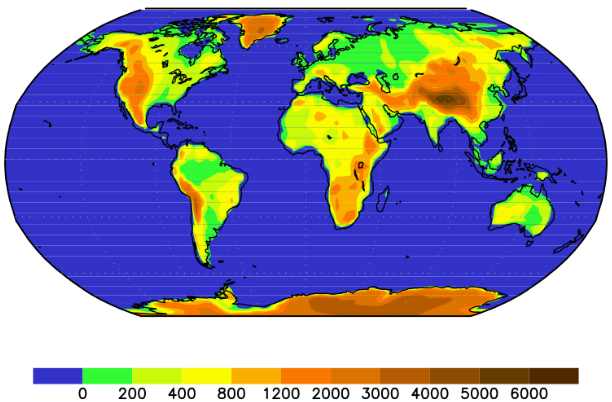
GREB boundary conditions: external

(IPCC models will have similar boundary conditions)

Incoming solar radiation



topography



Glacier mask

Large ice masses, as in Greenland will not melt completely within 100yrs, but take 1000yrs for melting. So we assume the albedo will not change over these glaciers.

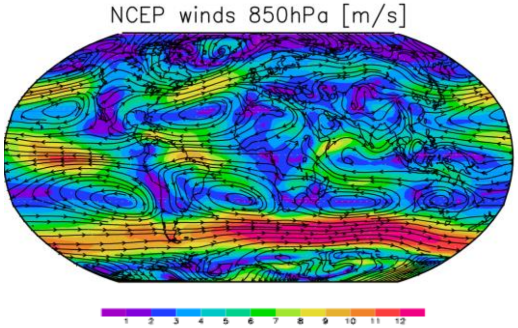
Additionally, there are some physical constants for the climate system: e.g. surface air pressure, CO_2 concentration, etc.

GREB boundary conditions: internal

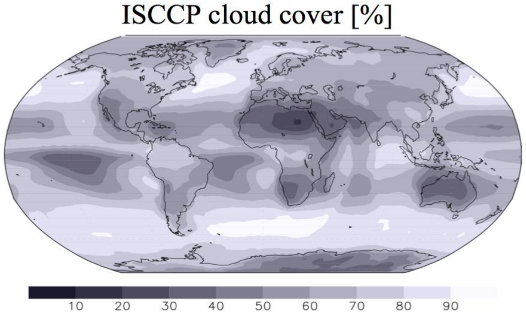
IPCC models will simulate these internal boundary conditions. Thus for an IPCC model these are not boundary conditions, but are computed by the state of the system with prognostic equations.

All given with seasonally changing climatology

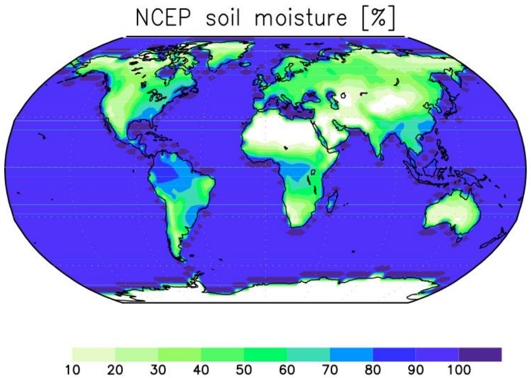
Wind field



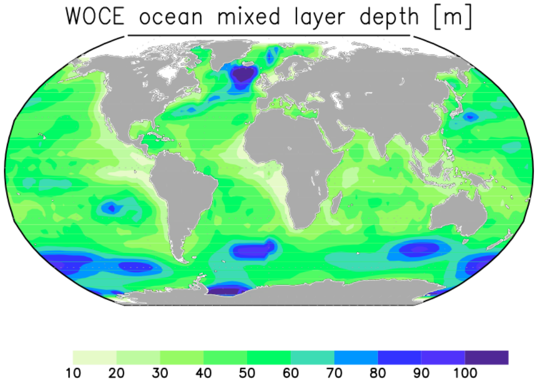
Cloud cover



Soil moisture



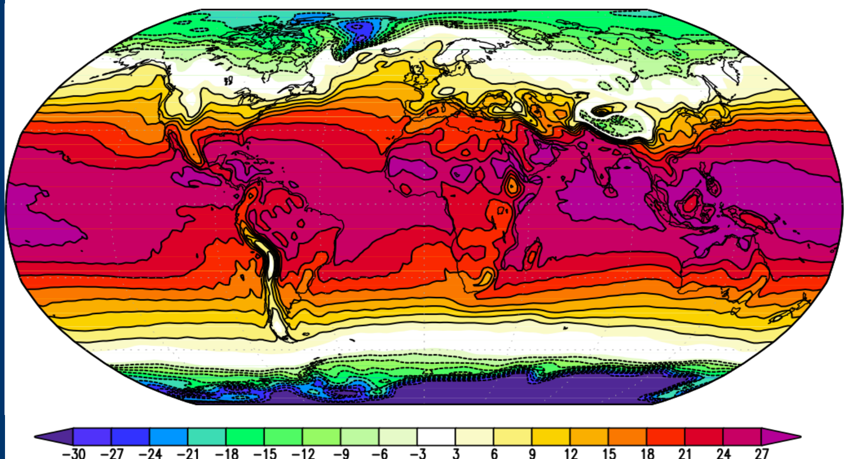
Ocean mixed layer depth



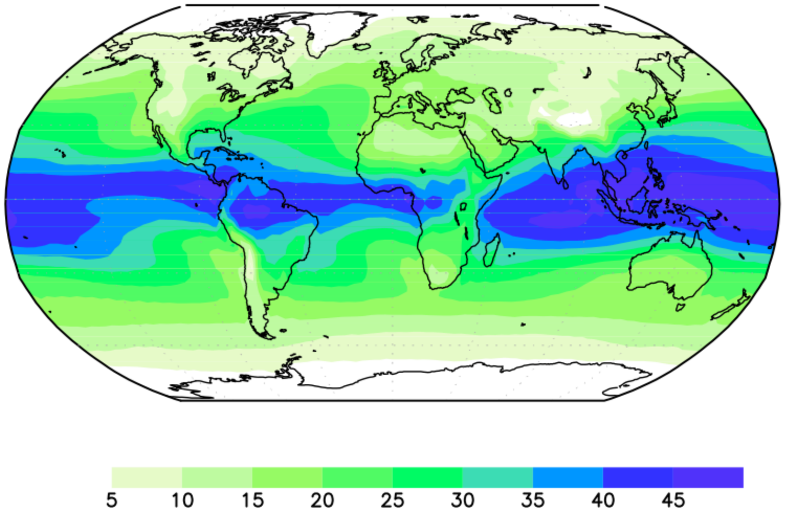
GREB constraints

IPCC models will simulate these variables without artificial constraints

Mean surface temperature



Atmospheric water vapor



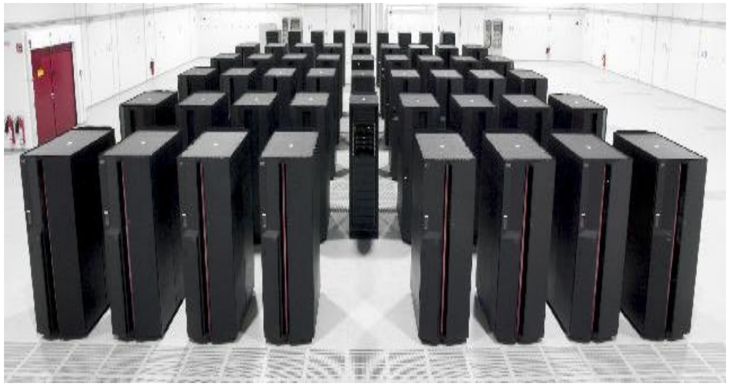
- The GREB model is too simple to produce a realistic climate state
- To keep GREB close to the observed climate state artificial heat fluxes are introduced to force the model to produce exactly the observed mean T_{surf} and mean q_{surf}

MODEL CLIMATE CHANGE PREDICTION ‘SKILL’

Model performance

IPCC-models

100,000 lines of code



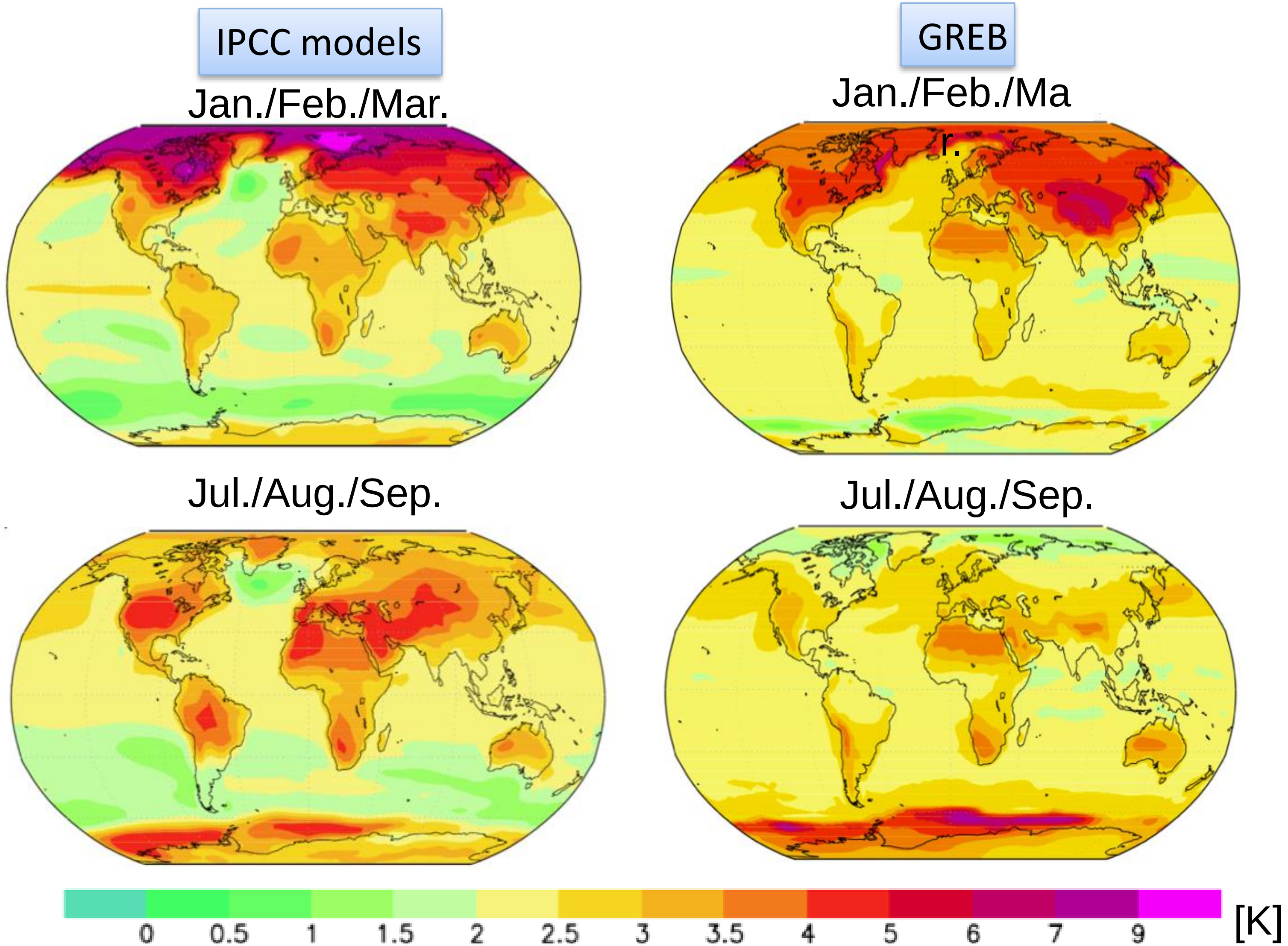
2 weeks of computation

GREB

700 lines of code

1 min. of computation

Climate response to IPCC scenario A1B CO_2 forcing



Difference in global mean temperature [2070-2100]-[1970-2000]

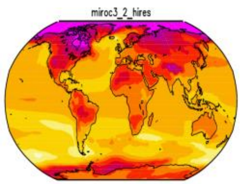
Climate response to IPCC scenario A1B CO_2 forcing

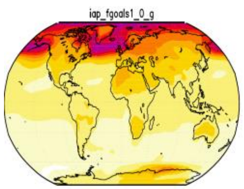
Main features of the global T_{surf} response to CO_2 forcing:

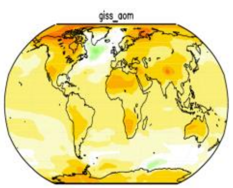
	IPCC	GREB	comment
Global mean	2.6°K	2.7°K	This is somewhat expected as we have fitted our emissivity function by the IPCC results
Land warms more than oceans	60% more	30% more	GREB is not warming enough over land
Polar amplification	By factor 2	By factor 1.3	GREB is not warming enough over Arctic sea
Northern Hemisphere warms more than the Southern	Yes	yes	GREB inter-hemispheric contrast is weaker
Cold season warms more	Yes	yes	-

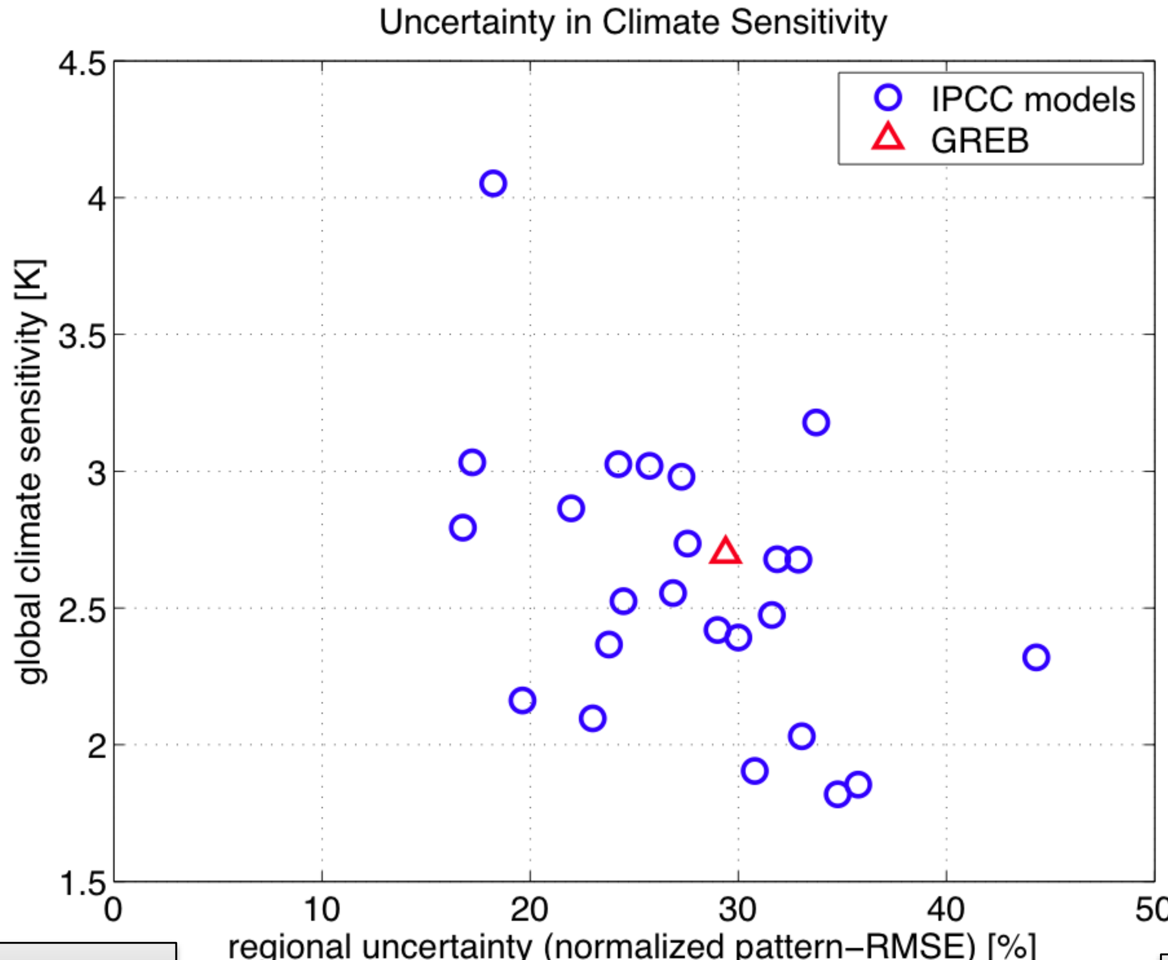
The GREB model is able to simulate the main IPCC T_{surf} response structures

GREB response 'skill'

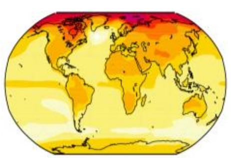


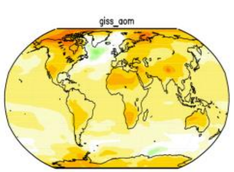


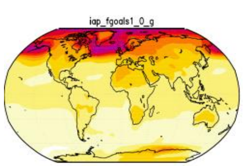




Similar pattern as ensemble mean







Pattern different to ensemble mean

GREB global warming response cautionary note

- **<u>This is only a model, not the real world</u>**:
  - The GREB is a very simple, uncertain and highly tuned (to IPCC models not observations) model.
  - IPCC models will in many regions or seasons have different responses for different reasons.
  - The GREB model cannot say anything about how the *circulation in the atmosphere or ocean* responds. And it is likely that such responses will exist on the small scale (turbulence) and large scale (mean).
  - GREB models cannot say anything about how *cloud cover* or *soil moisture* responds.

More information:

- Go to

  https://monash.edu/research/simple-climate-model/mscm/overview_i18n.html?locale=EN

- Scientific publication:

  Dommenget D. and J. Flöter (2011): Conceptual understanding of climate change with a globally resolved energy balance model, Clim. Dyn. 37: 2143. doi:10.1007/s00382-011-1026-0