Climate Sensitivity and the Earth Energy Budget

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Climate sensitivity

Charney et al. definition: Global surface temperature rise after a doubling of preindustrial CO2 concentrations

$$\Delta T_{eq} = f\left(2xC_{CO_2,t=1860}\right)$$

ECS tells how much warming we can expect (both in the near-term and the long-term) for a given increase in CO2:

[2.5 - 4] K (66%CL) IPCC AR6

Or ECS tells how much CO2 we can emit to stay below 2K in 2100 (66%CL):

Emit less than 2900 Gt of CO2 before 2100 IPCC AR6

Climate sensitivity

The climate sensitivity is extremely relevant socialy as it characterises the relation between CO2 emissions and impacts

$$\Delta T_{eq} = f\left(2xC_{CO_2,t=1860}\right)$$

impacts

emissions



$= f\Big($  $\Big)$

Adaptation cost **vs** Mitigation cost

Climate sensitivity

The climate sensitivity has a fuzzy physical sense: the average change in global mean surface temperature in response to a radiative forcing

$$\Delta T_{eq} = f(R)$$

The climate sensitivity has a clear physical sense when we precise

- the climate system (components and initial state) (e.g. Atm+ Ocean+ Cont since 1860)
- the time scales of interest (e.g. month to millenia)
- the type of forcing F (e.g. radiative forcing due to a doubling of atm CO_2 concentrations)

⇨ It is then the average change in global mean surface temperature at steady state of the tangent linear climate system in response to the radiative forcing F

⇨ It is tightly link to a fundamental constant of the climate system : the climate feedback parameter of the tangent linear climate system λ

$$\Delta T_{eq} = -\frac{F}{\lambda}$$

The climate feedback parameter and the energy budget

The climate feedback parameter is the most fundamental constant of the climate system energy budget dynamics

- With the heat capacity of the climate system C, λ defines the linear tangent climate system energy budget dynamics (i.e. C, λ are the most simple description possible of the climate system)

- λ fixes the level of feedback (in the dynamical sense) in the linear tangent climate system (LTCS) energy budget dynamics

- λ fixes the amplitude of the LTCS energy budget response to forcing at steady state

- λ/C is the primary characteristic time scale of the LTCS energy budget dynamics

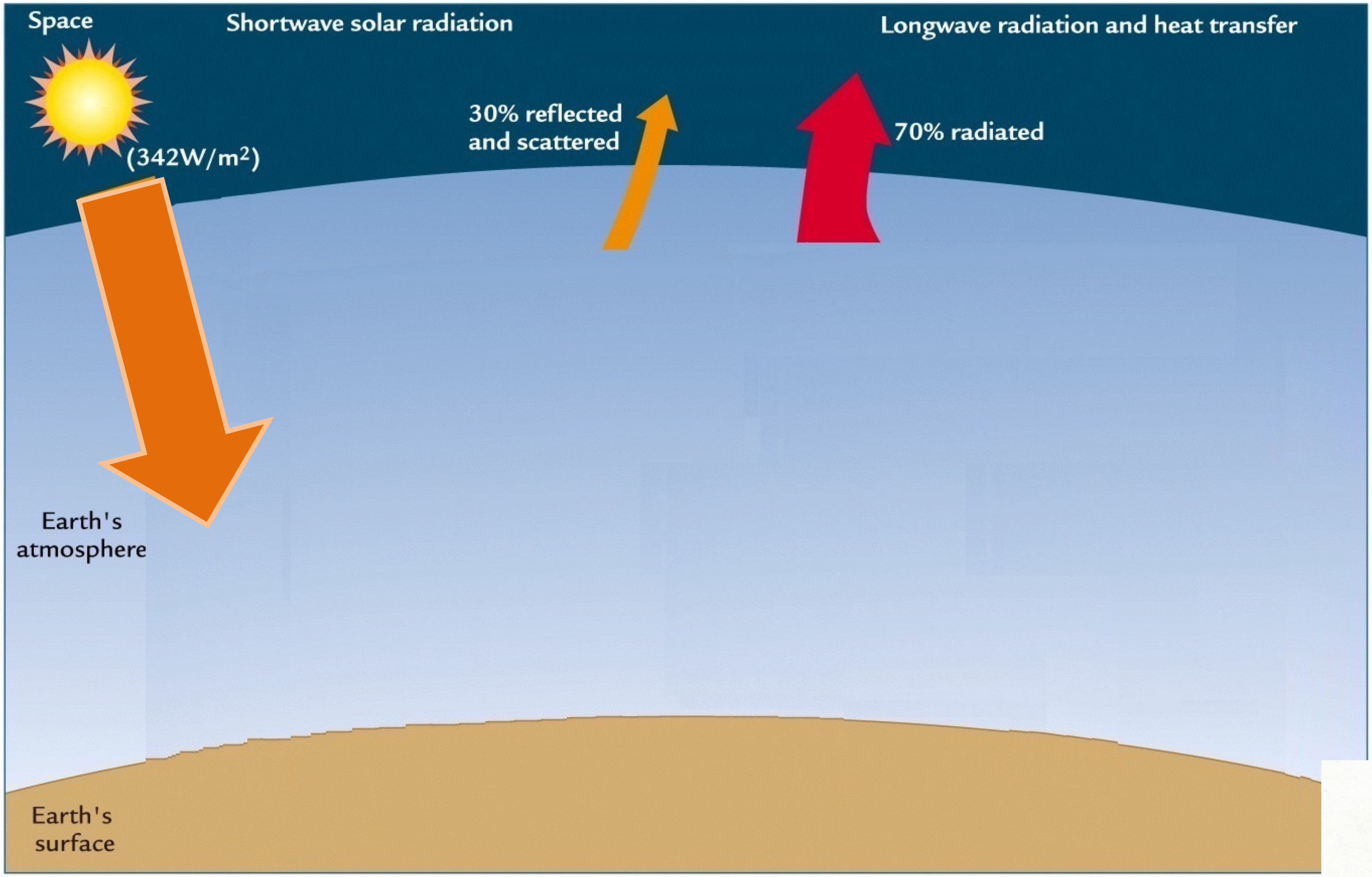
Overview

Here I propose to

- describe the water-energy cycle of the climate system
- derive the LTCS energy budget from the water-energy cycle and simple assumptions
- Explain the link betwen the climate sensitivity and λ in the LTCS energy budget. Explain the importance of λ in the LTCS energy budget
- show how λ (and thus the climate sensitivity) can be estimated from observations of the global energy budget and the associated issues
- Show the current reponse to these issues and the current directions of research

The global water-energy cycle response to greenhouse gases emissions

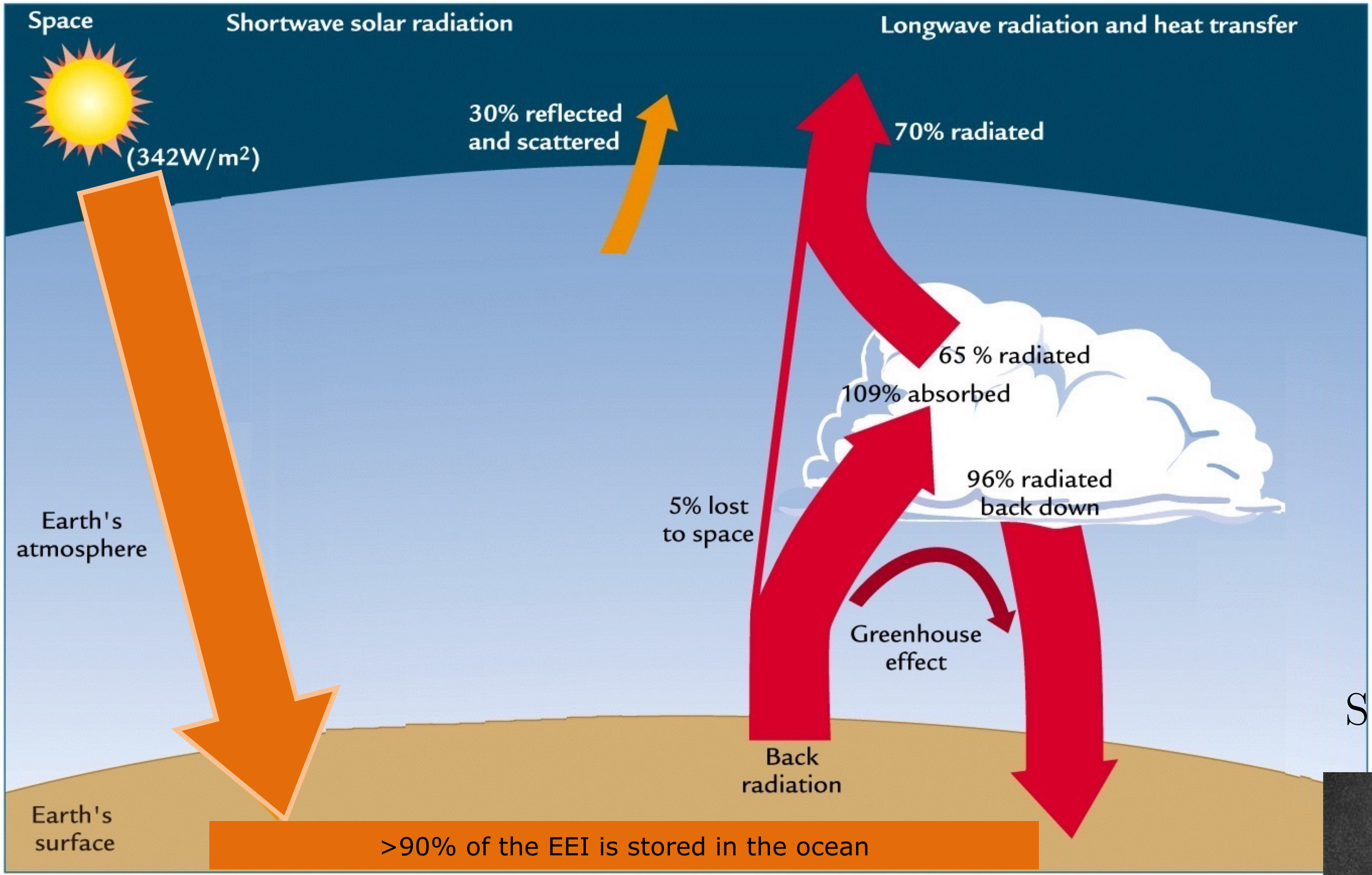
The global water-energy cycle



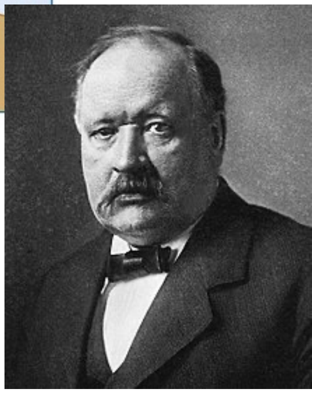
J.Fourier

$$0 = F - R(T_s)$$

The global water-energy cycle

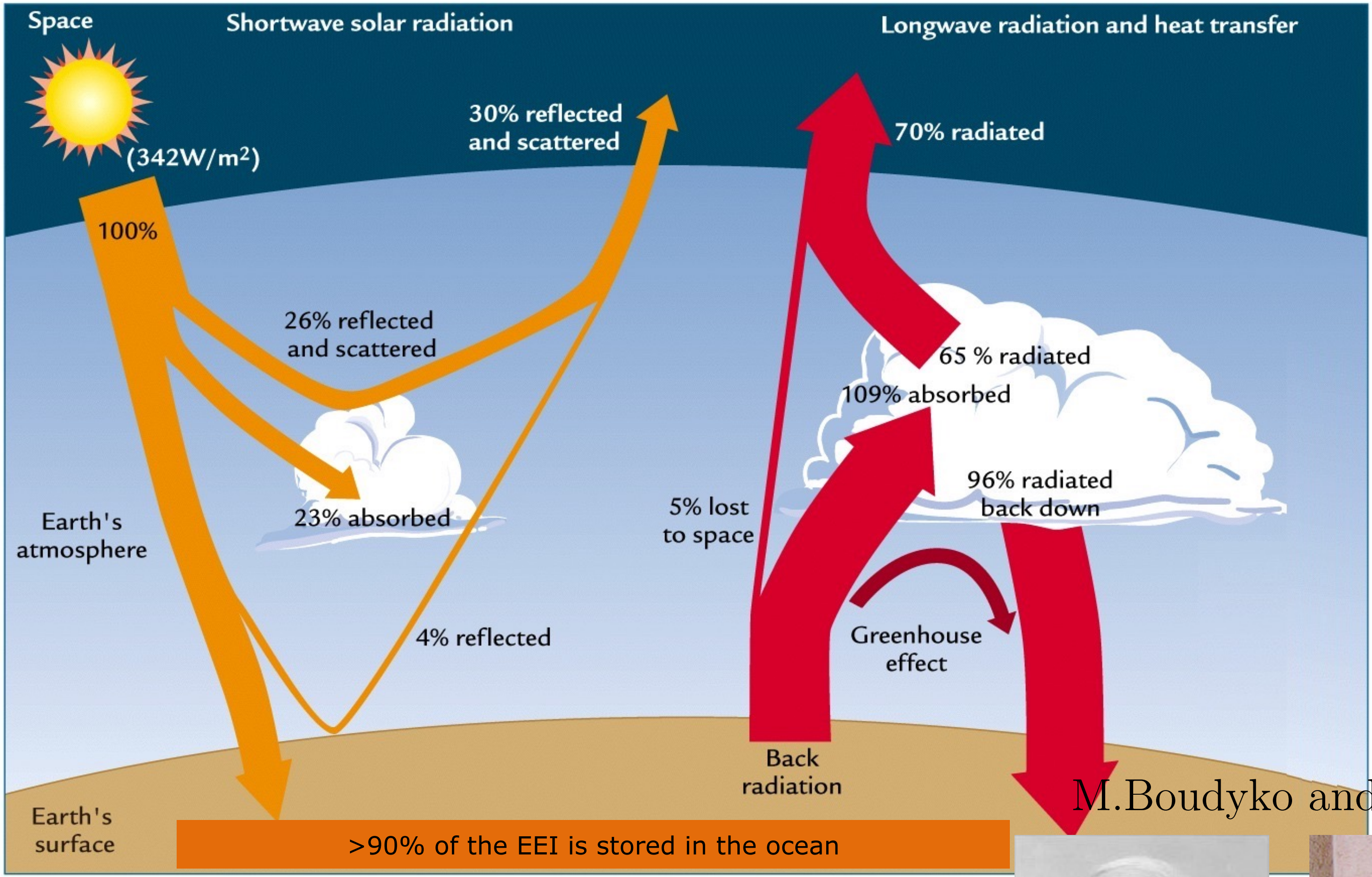


S.Arrhenius



$$EEI = F - R\left(T_S, P_{CO_2}, P_{H_2O}\right)$$

The global water-energy cycle

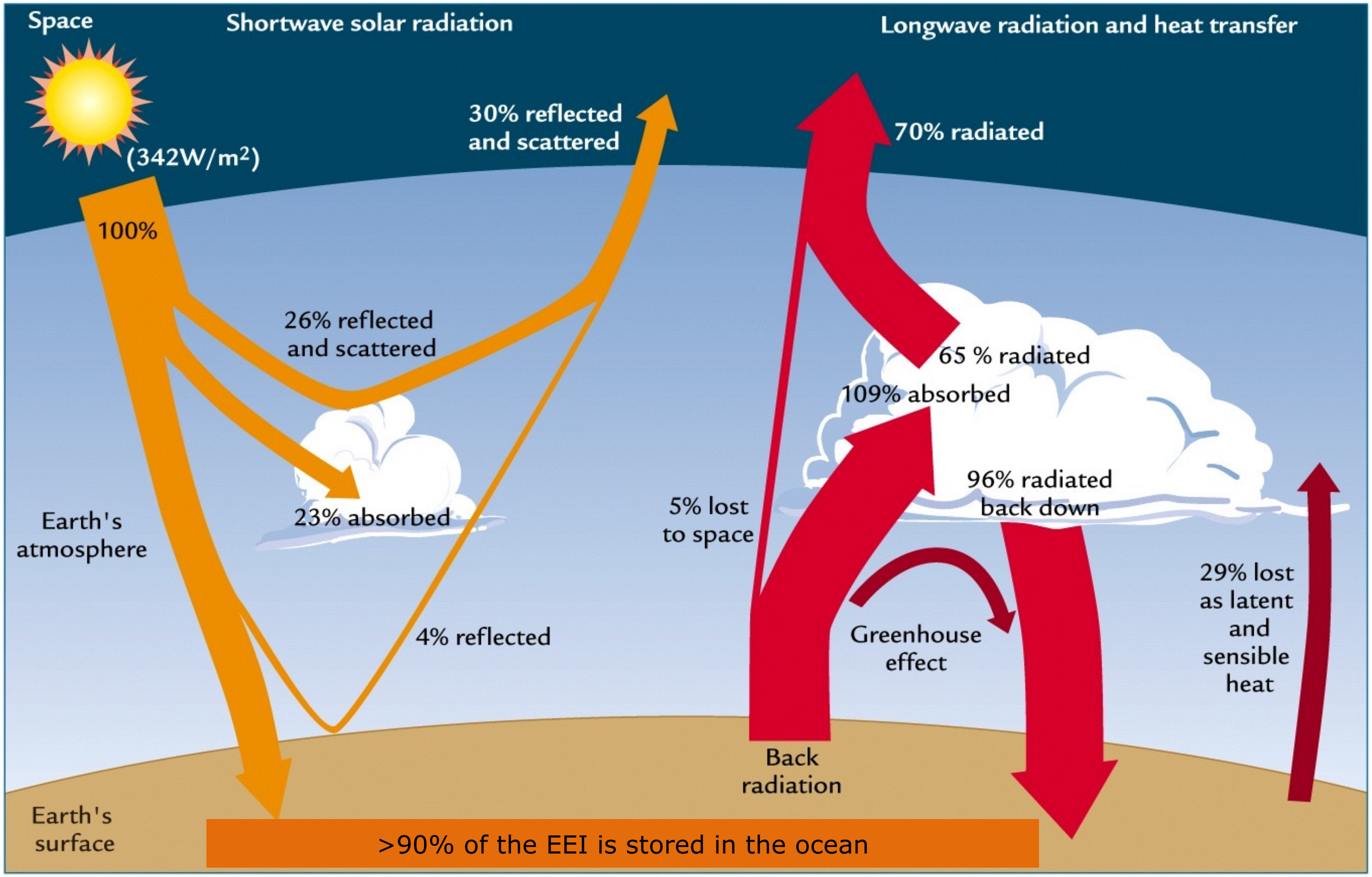


M.Boudyko and W.Sellers

$$EEI = F - R\left(T_S, P_{CO_2}, P_{H_2O}, A_I\right) \approx F - \lambda T_s$$

For Ts small.

The global water-energy cycle

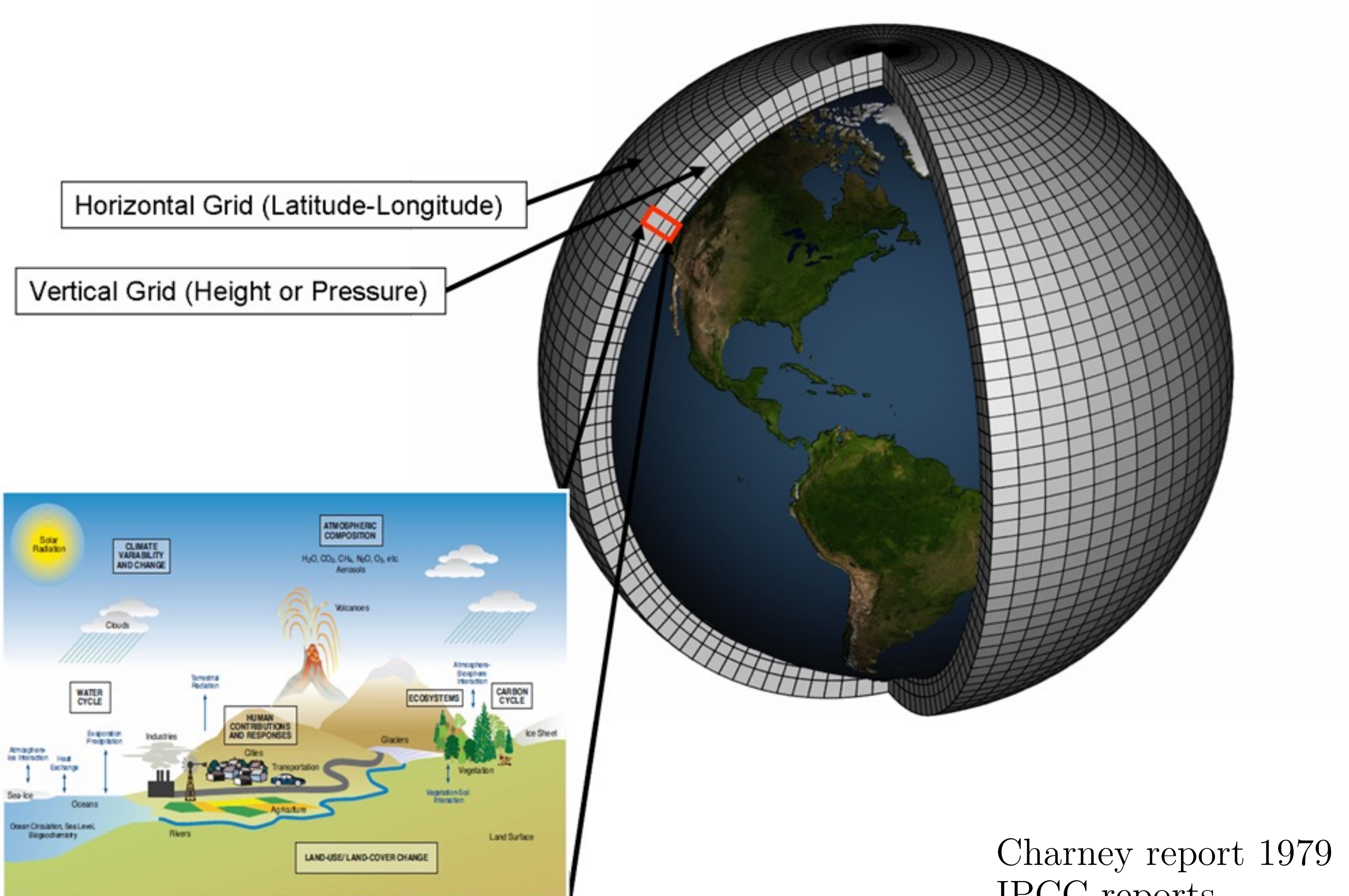


S.Manabe

$$EEI = F - R(T_s, P_{CO_2}, P_{H_2O}, A_I, C) \approx F - \lambda T_s$$

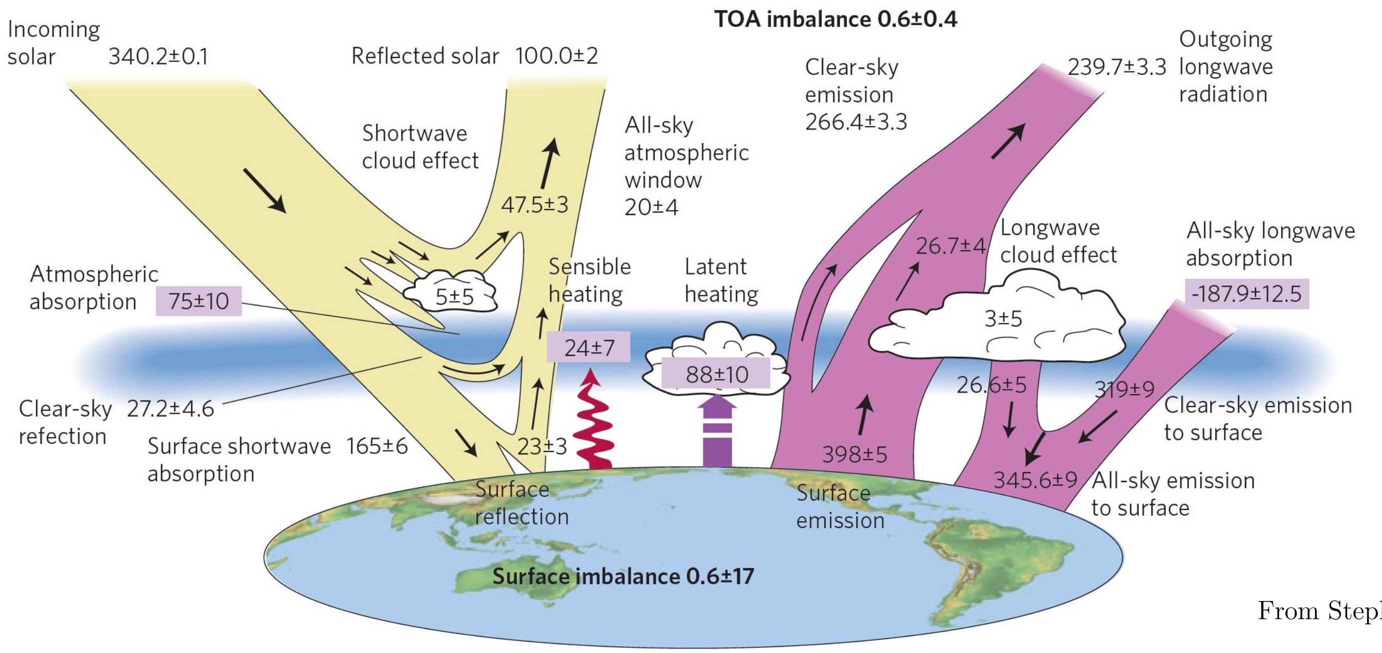
For Ts small, at global scale and under radiative-convective equilibrium

Global circulation



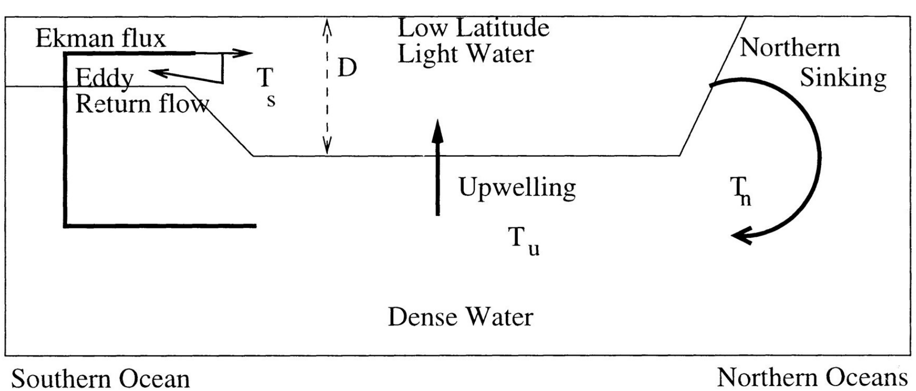
Charney report 1979
IPCC reports

Current representation of the global water-energy cycle



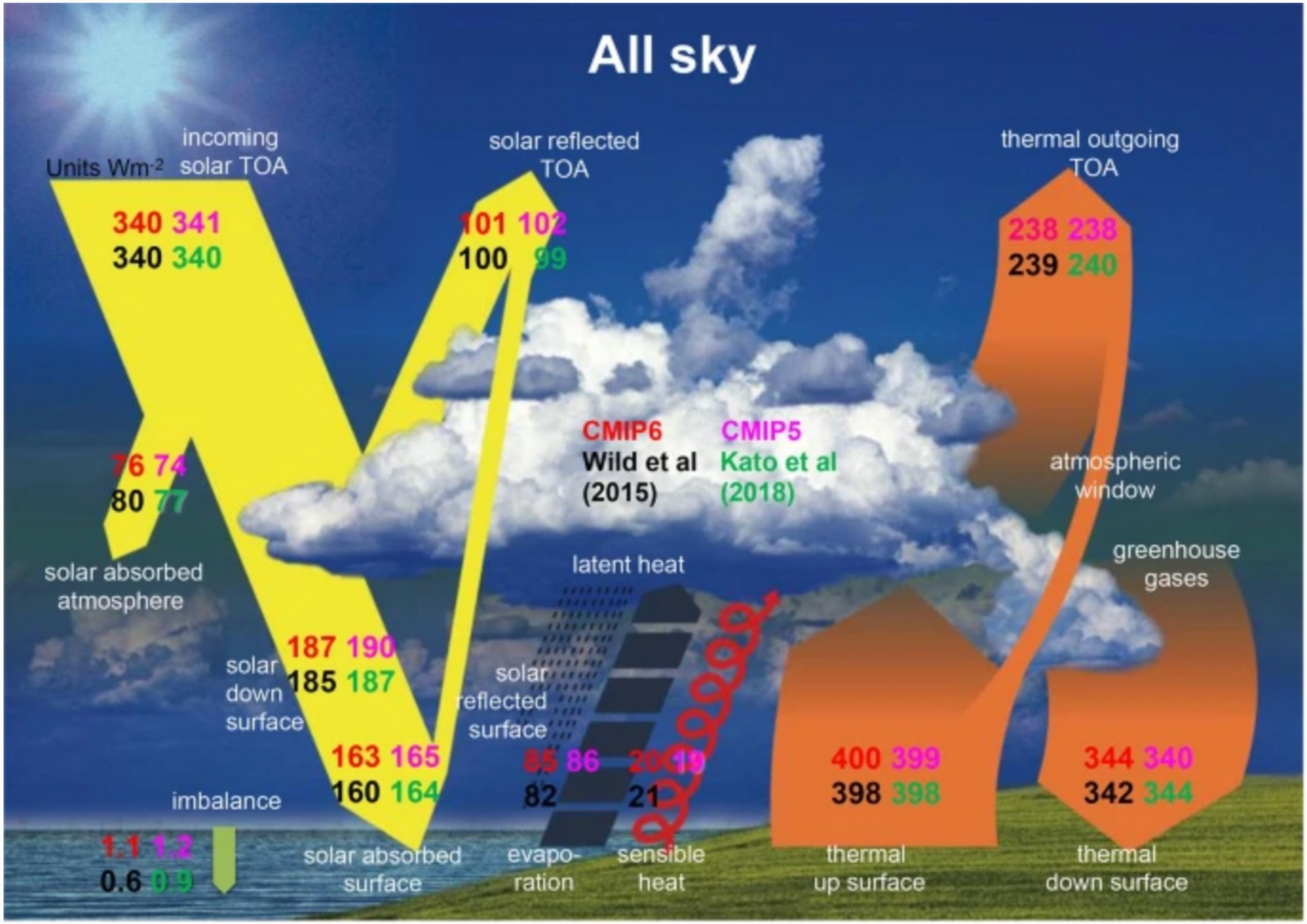
From Stephens et al. 2012

Vertical heat distribution in the ocean



From Gnanadesikan 1999

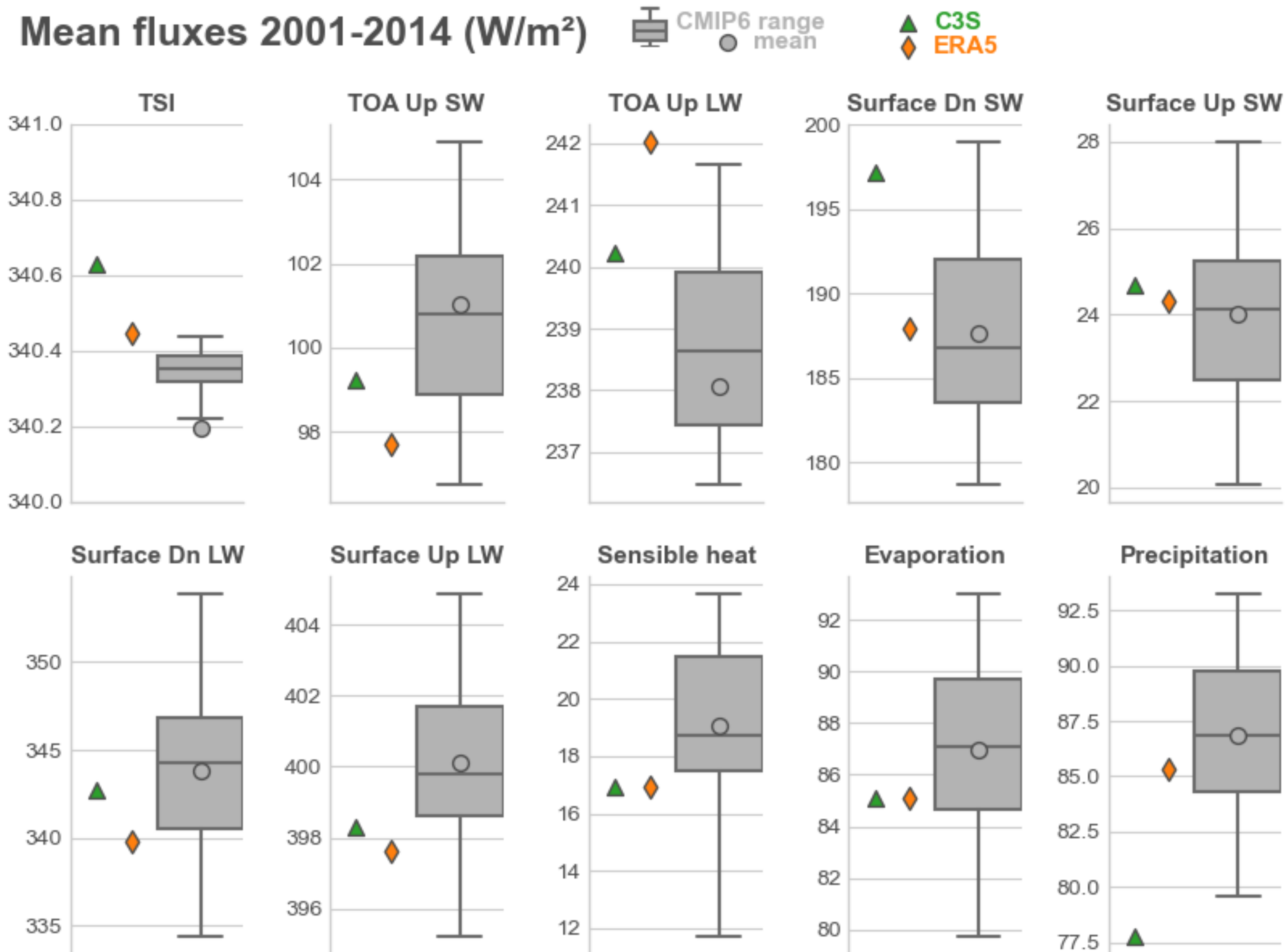
Current representation of the global water-energy cycle



2000-2004 CMIP5 and Wild et al. 2015

2000-2014 CMIP6 and Kato et al. 2018

Current representation of the global water-energy cycle

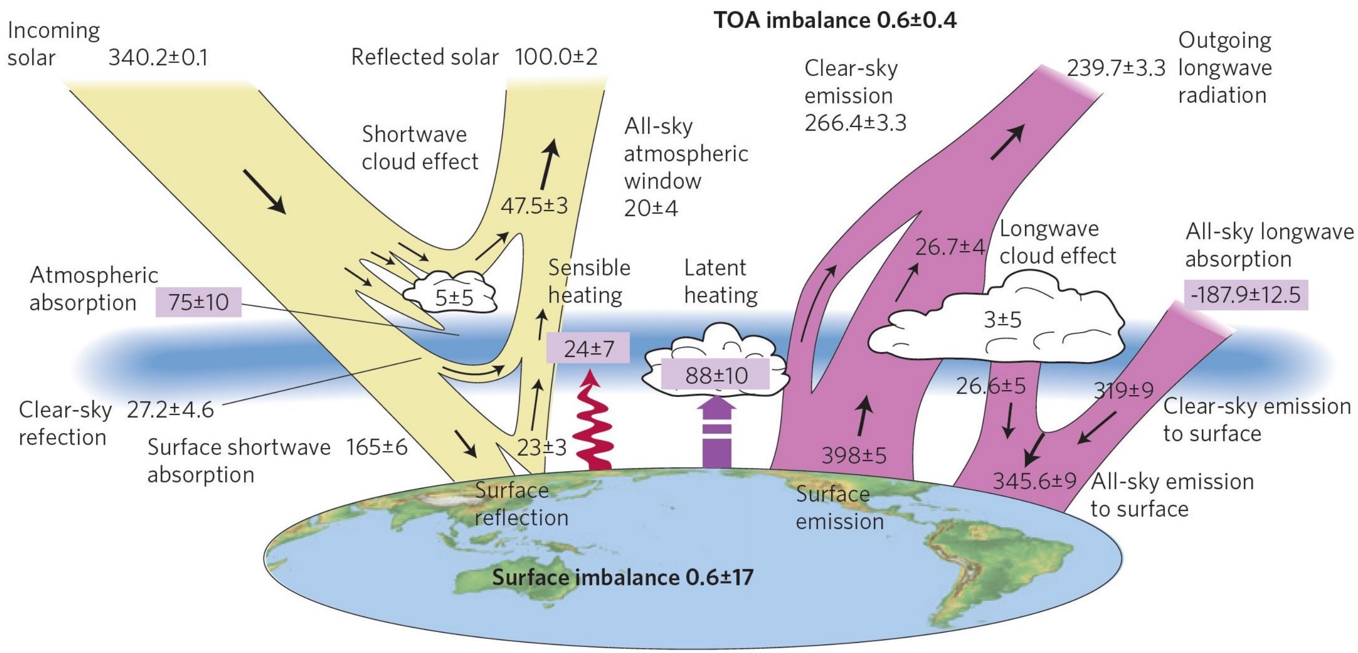


2000-2014 CMIP6

The Linear Tangent Climate System Theory

(called Energy Balance Model –EBM- in the litterature)

LTCS Theory: the energy budget at global scale



The Earth radiative response to GHG emissions

$$R_i = R_i(Q_0)$$

$$R_o = R_o(G_k, T_z, F_{ve}(T_z), F_{GT}(T_z), F_n(T_z), F_c(T_z))$$

The Earth energy budget (1st law of thermodynamics)

$$dE = N = R_i - R_o$$

LTCS Theory: The energy budget at global scale

The Earth energy budget (1st law of thermodynamics)

$$dE = N = R_i - R_o$$

At global scale, on monthly and longer time scales there is radiative convective equilibrium thus:

$$R_o(G_k, T_z, F_{ve}(T_z), F_{GT}(T_z), F_n(T_z), F_c(T_z)) = R_o(G_k, T, F_{ve}(T), F_{GT}(T), F_n(T), F_c(T))$$

At annual and longer time scales, the ocean mixed layer is in equilibrium with the atmosphere. The energy budget of the atm + ocean ML reads:

$$C\frac{dT}{dt} + \phi(k, w) = dE = N = R_i - R_o(G_k, T, F_{ve}(T), F_{GT}(T), F_n(T), F_c(T))$$

At global scale: First order Taylor development of R_o in T (Budyko 1969, Sellers 1969)

$$R_i - R_o(G_k, T + \delta T, F_{ve}(T + \delta T), F_{GT}(T + \delta T), F_n(T + \delta T), F_c(T + \delta T))$$
$$= RF_k - \lambda \delta T$$

LTCS Theory: The energy budget at global scale

The Earth energy budget (1st law of thermodynamics)

$$dE = N = R_i - R_o$$

At global scale, on monthly and longer time scales there is radiative convective equilibrium thus:

$$R_o(G_k, T_z, F_{ve}(T_z), F_{GT}(T_z), F_n(T_z), F_c(T_z)) = R_o(G_k, T, F_{ve}(T), F_{GT}(T), F_n(T), F_c(T))$$

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At global scale: First order Taylor development of R_o in T (Budyko 1969, Sellers 1969)

$$R_i - R_o\ (G_k, T + \delta T, F_{ve}(T + \delta T), F_{GT}(T + \delta T), F_n(T + \delta T), F_c(T + \delta T))$$
$$= RF_k - \lambda\delta T = RF_k - \lambda_p\delta T + \lambda_{ve}\delta T + \lambda_{GT}\delta T + \lambda_n\delta T + \lambda_c\delta T$$

LTCS Theory: The energy budget at global scale

Now the energy budget of the atm + ocean ML reads

$$C\frac{d(\delta T)}{dt} + \phi(k,w) = RF_k - \lambda\delta T$$

If we add the vertical diffusion of heat in the deep ocean

$$\phi(k,w) = k\left(\delta T - \delta T_p\right)$$

LTCS Theory (EBM)

$$C\frac{d(\delta T)}{dt} + k\left(\delta T - \delta T_p\right) = RF_k - \lambda\delta T$$

$$C_p\frac{d\left(\delta T_p\right)}{dt} - k\left(\delta T - \delta T_p\right) = 0$$

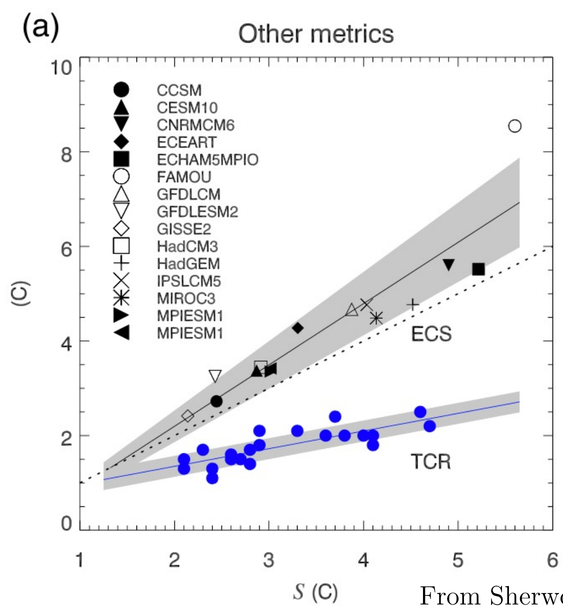
LTCS Theory: asymptotic response and climate sensitivity

At steady state, heat fluxes in the atmosphere and in the ocean are balanced and ocean heat storage stops

$$\cancel{C\frac{d(\delta T)}{dt}} + \cancel{k(\delta T - \delta T_p)} = RF_k - \lambda\delta T \Longrightarrow \delta T_{eq} = \frac{RF_k}{\lambda}$$

Climate sensitivity is defined as the warming at steady state after an abrupt doubling of atmospheric CO_2 concentrations (wrt 1850)

$$ECS = \frac{RF_{2xCO_2}}{\lambda}$$



From Sherwood et al. 2020

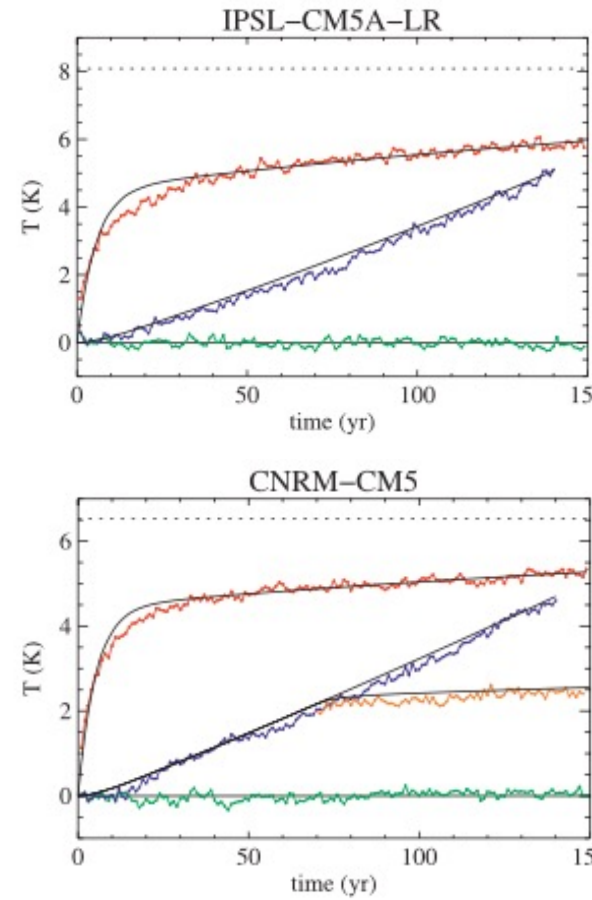
LTCS Theory : transient response and heat absorption by the ocean

We can solve the 2-layer differential equation system (e.g. for a step forcing) simulate the transient response and test it in general circulation models

$$\begin{cases} \delta T(t) = \dfrac{RF}{\lambda}\left[a_f\left(1-e^{-t/\tau_f}\right) + a_s\left(1-e^{-t/\tau_s}\right)\right] \\ \delta T_p(t) = \dfrac{RF}{\lambda}\left[\phi_f a_f\left(1-e^{-t/\tau_f}\right) + \phi_s a_s\left(1-e^{-t/\tau_s}\right)\right] \end{cases}$$

$$\tau_f = \frac{CC_p}{2\lambda k}\left(b-\sqrt{\delta}\right) \qquad b = \left(\frac{\lambda+k}{C}+\frac{k}{C_p}\right)$$

$$\tau_s = \frac{CC_p}{2\lambda k}\left(b+\sqrt{\delta}\right) \qquad \delta = b^2 - 4\frac{\lambda k}{CC_p}$$



The ocean adds a slow time scale essential to reproduce the transient response

From Geoffroy et al. 2013

Estimating the ECS from observations of the global energy budget

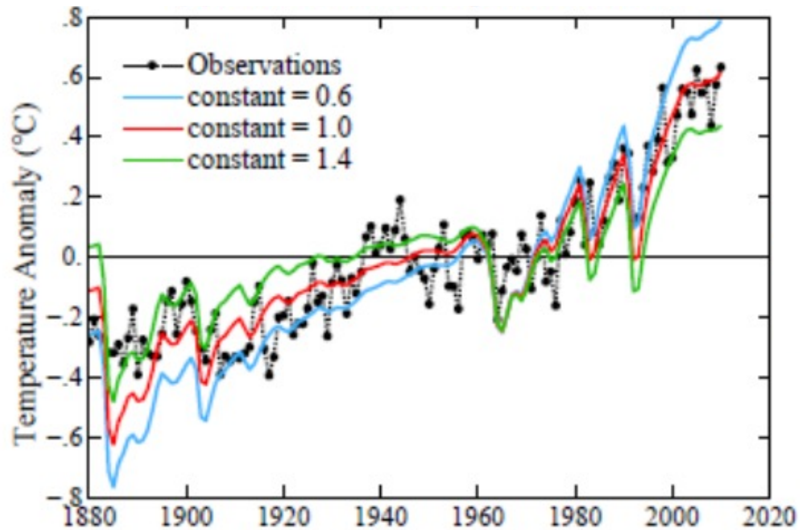
Estimating λ from observations

Now that we have a reasonable order 0 model of the energy budget dynamics (EBM)

$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = RF_k - \lambda \delta T$$

$$C_p\frac{d(\delta T_p)}{dt} - k(\delta T - \delta T_p) = 0$$

Can we find λ such that the EBM reproduces the current temperature rise?



From Hansen et al. 2011

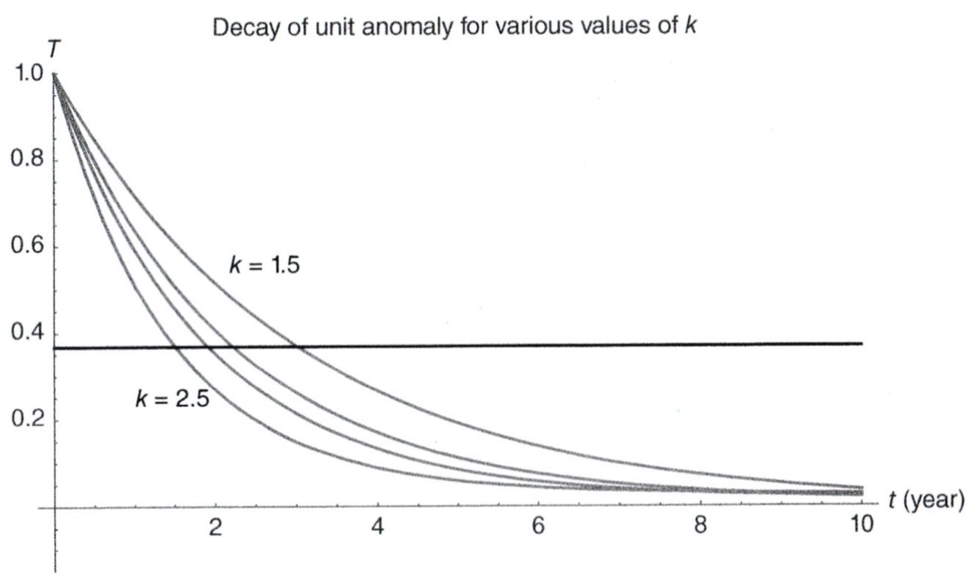
This is a classical problem (cf Gauss 1801, Legendre 1805) but it turns out to be difficult!!!

Estimating λ from observations: issues

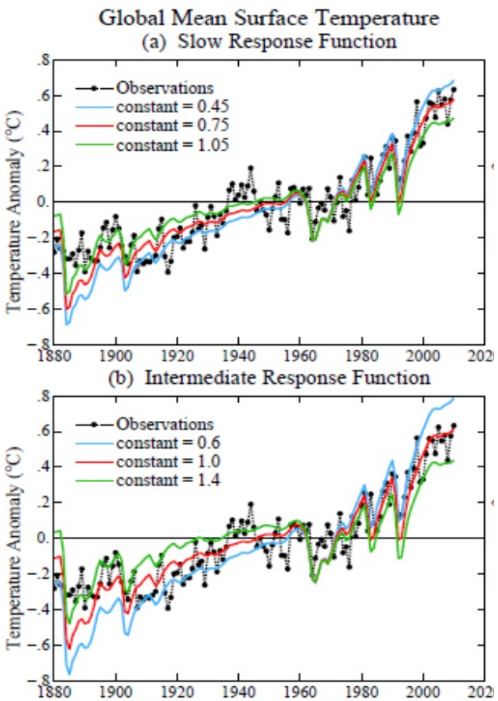
1. A problem that is not observable

$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = RF - \lambda\delta T$$

The characteristic response time of Ts depends on the coupling between λ and k



From North and Kim 2017



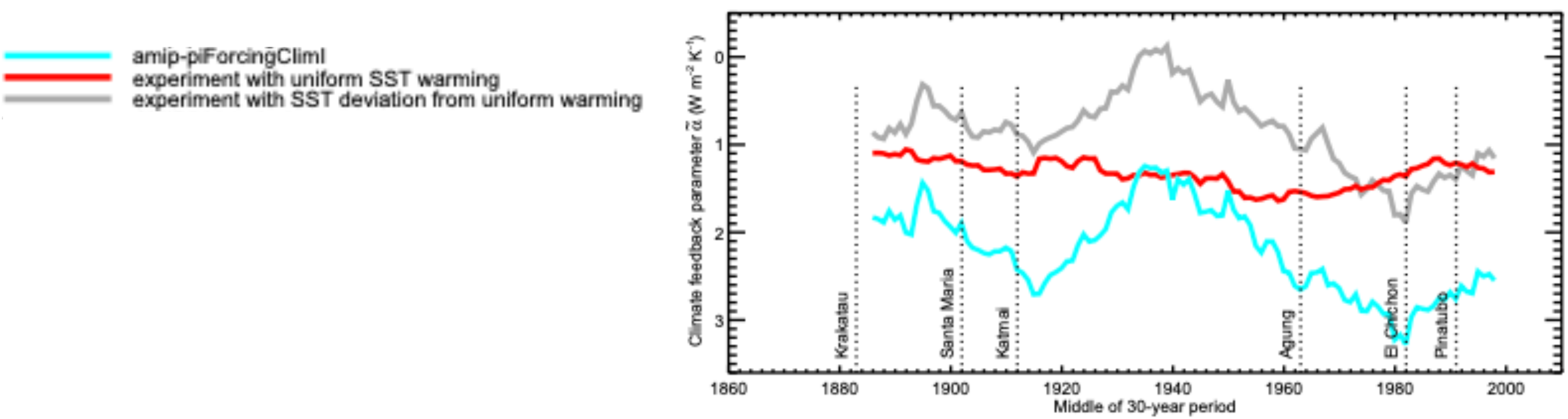
From Hansen et al. 2011

Estimating λ from observations: issues

2. An energy budget that is approximative

$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) \overset{?}{=} RF - \lambda\delta T$$

- The radiative response of the Earth depends on the regional distribution of surface temperature (the “SST pattern effect”)



From Gregory et al. 2020

Estimating λ from observations: issues

2. An energy budget that is approximative

$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) \overset{?}{=} RF - \lambda \delta T$$

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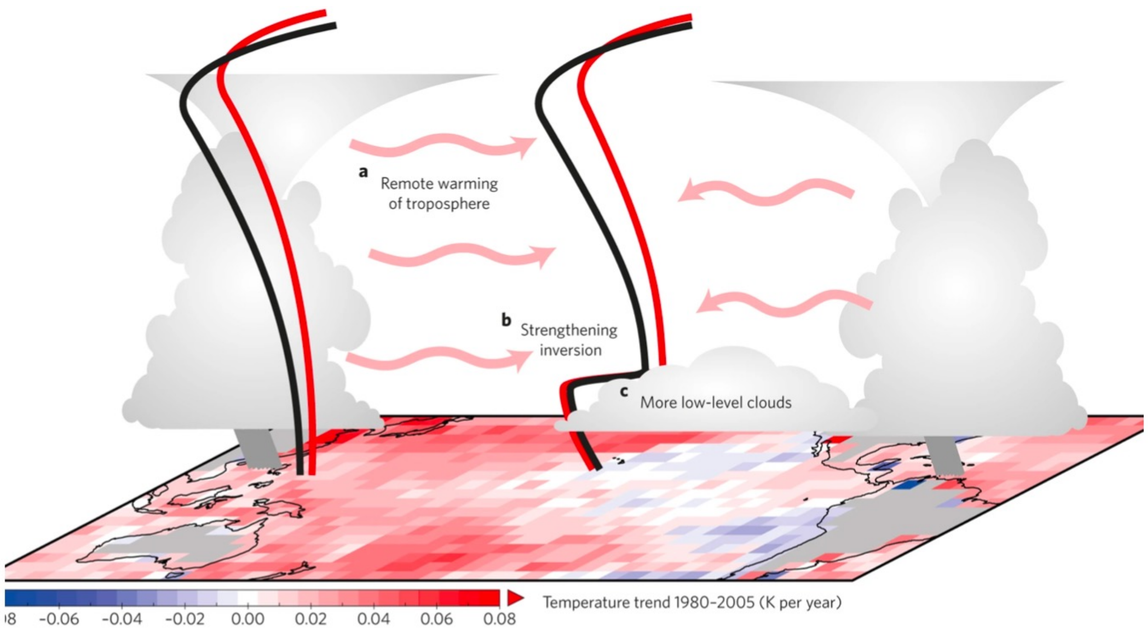


From Mauritsen 2016

Estimating λ from observations: issues

3. A stochastic problem

$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = RF - \lambda \delta T \overset{?}{+ VI}$$

- Surface temperature follows a Langevin stochastic differential equation

$$Cd(\delta T) + k(\delta T - \delta T_p)dt = (RF + \lambda \delta T)dt + wdt$$

- The solution is a gaussian distribution around the deterministic solution with the following standard deviation

$$\frac{\sigma_V}{\sqrt{2\lambda C}}\sqrt{\left(1 - e^{\frac{2\lambda}{C}t}\right)}$$

- To be explored with a multiplicative noise (instead of an additive noise)

Current approaches to cope with these issues

- Decoupling the issue associated with the vertical diffusion of heat in the ocean k from the issue associated with the climate feedback parameter λ

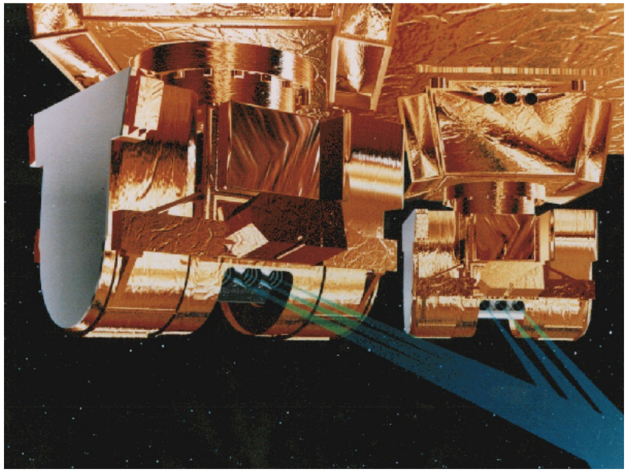
$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = RF - \lambda \delta T \quad \Rightarrow \quad \begin{cases} \delta N(t) = RF - \lambda \delta T \\ C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = \delta N(t) \end{cases}$$

$$\Rightarrow \quad -\lambda = \frac{\delta N - RF}{\delta T}$$

- Use observations of N(t) from CERES.

Seven CERES instruments on five satellites (TRMM, Terra, Aqua, S-NPP, NOAA-20)

Measurements since 03/2000
Accuracy: $\pm 2.5 W.m^{-2}$,
Stability: $\pm 0.1 W.m^{-2}$ per decade



Current approaches to cope with these issues

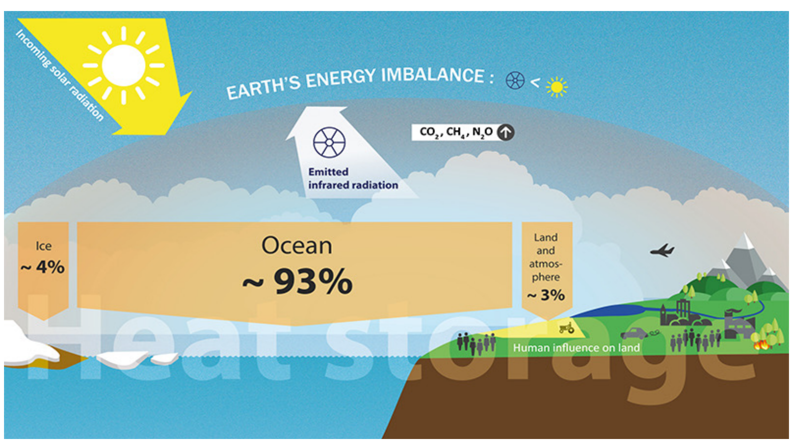
- Decoupling the issue associated with the vertical diffusion of heat in the ocean k from the issue associated with the climate feedback parameter λ

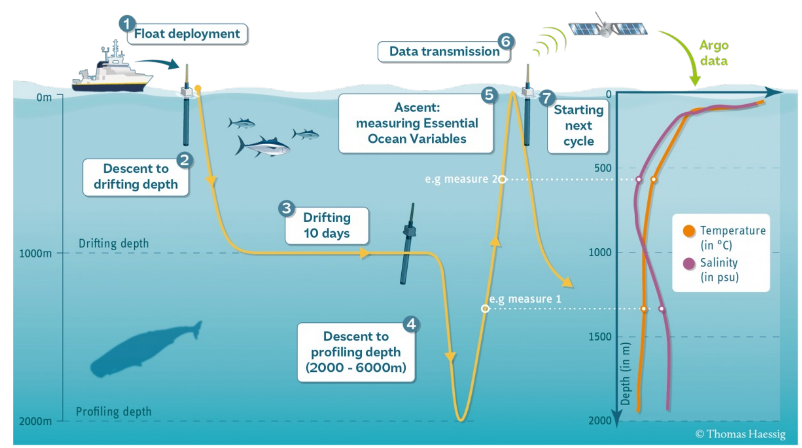
$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = RF - \lambda \delta T \quad \longrightarrow \quad \begin{cases} \delta N(t) = RF - \lambda \delta T \\ C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = \delta N(t) \end{cases}$$

$$\longrightarrow \quad -\lambda = \frac{\delta N - RF}{\delta T}$$

- Use observations of N from in-situ ocean temperature (e.g. Argo)

Accuracy: ±0.1W.m^{-2} (without sampling uncertainty) global since 2005





Current approaches to cope with these issues

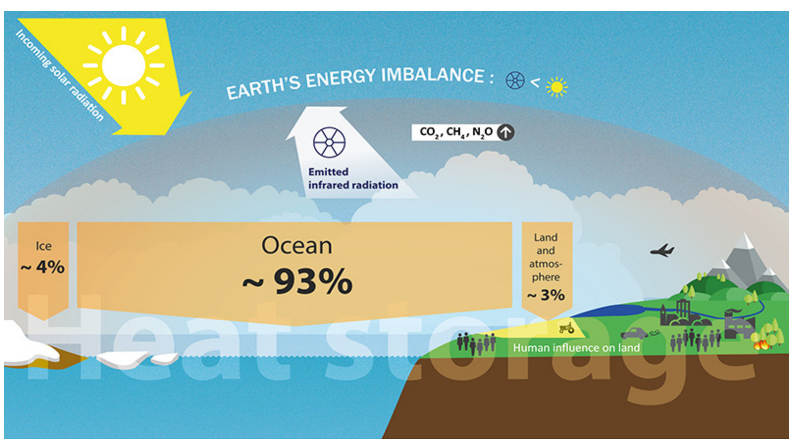
- Decoupling the issue associated with the vertical diffusion of heat in the ocean k from the issue associated with the climate feedback parameter λ

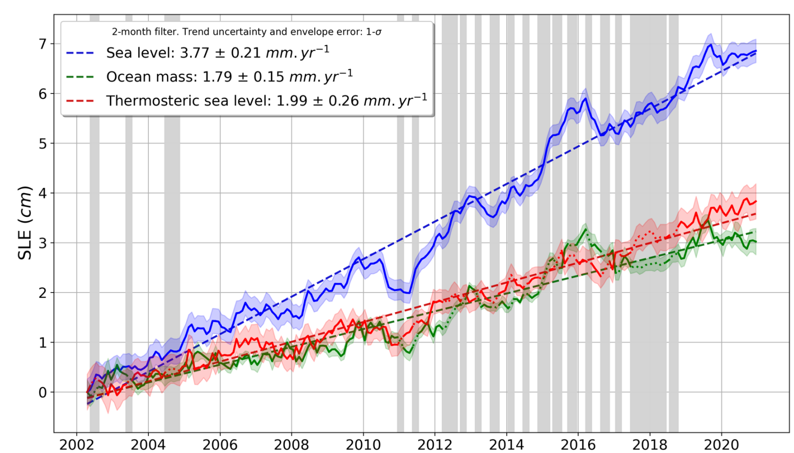
$$C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = RF - \lambda \delta T \;\Longrightarrow\; \begin{cases} \delta N(t) = RF - \lambda \delta T \\ C\frac{d(\delta T)}{dt} + k(\delta T - \delta T_p) = \delta N(t) \end{cases}$$

$$\Longrightarrow\; -\lambda = \frac{\delta N - RF}{\delta T}$$

- Use geodetic observations of sea level and the earth gravity field to determine the thermal expansion of the ocean.

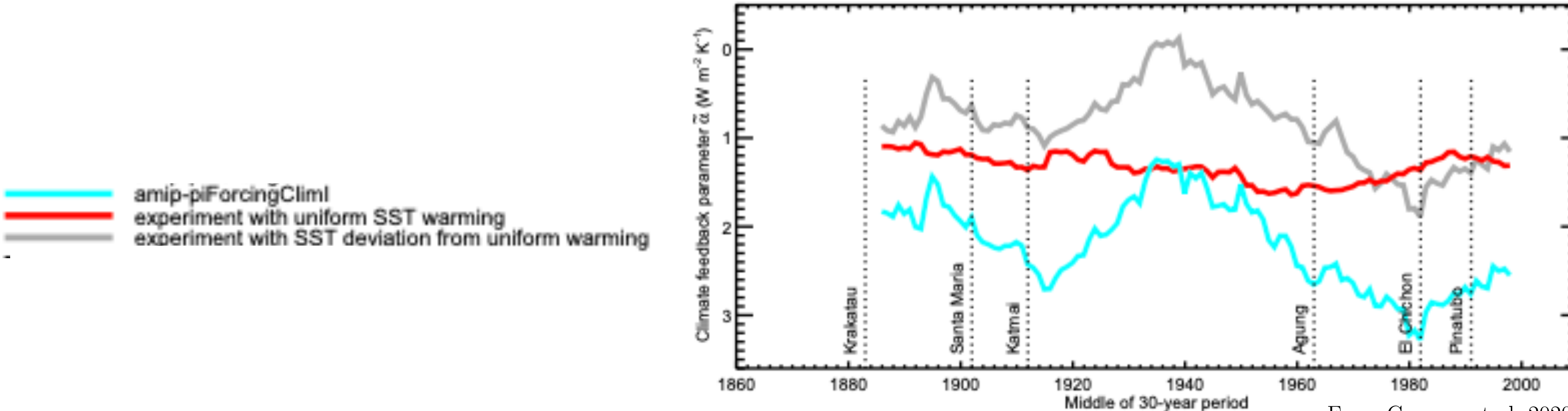
Accuracy: $\pm 0.2 \mathrm{W.m^{-2}}$ since 2002





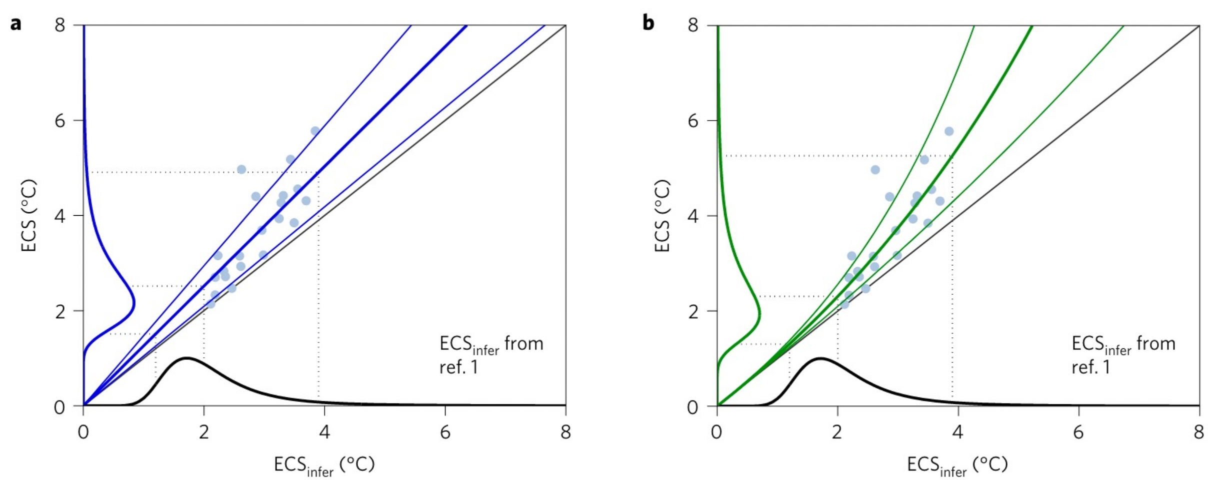
Current approaches to cope with these issues

- Pattern effect and time dependence of λ



From Gregory et al. 2020

- Use climate models to evaluate the time variability in the climate feedback parameter λ: 26% underestimate of the ECS. Larger discrepancy for high ECS



From Armour 2017

Current approaches to cope with these issues

- Internal variability

$$\delta \mathrm{N} = RF - \lambda \delta T + VI$$

- Use long periods to minimise the role of the internal vvariability WRT to the forcing

$$-\lambda = \frac{\delta N - RF - \delta VI}{\delta T}$$

For a time period ΔT long enough RF is large enough so that $RF \gg VI$

$$-\lambda = \frac{\Delta N - RF}{\Delta T}$$

$$\boxed{ECS = -\frac{RF_{2xCO_2}}{\lambda} = -RF_{2xCO_2}\frac{\Delta T}{\Delta N - RF}}$$

- Use Detection and attribution studies (see next course)

Current estimates of the ECS from observations of the global energy budget

Current estimates of the climate sensitivity from observations of the energy budget

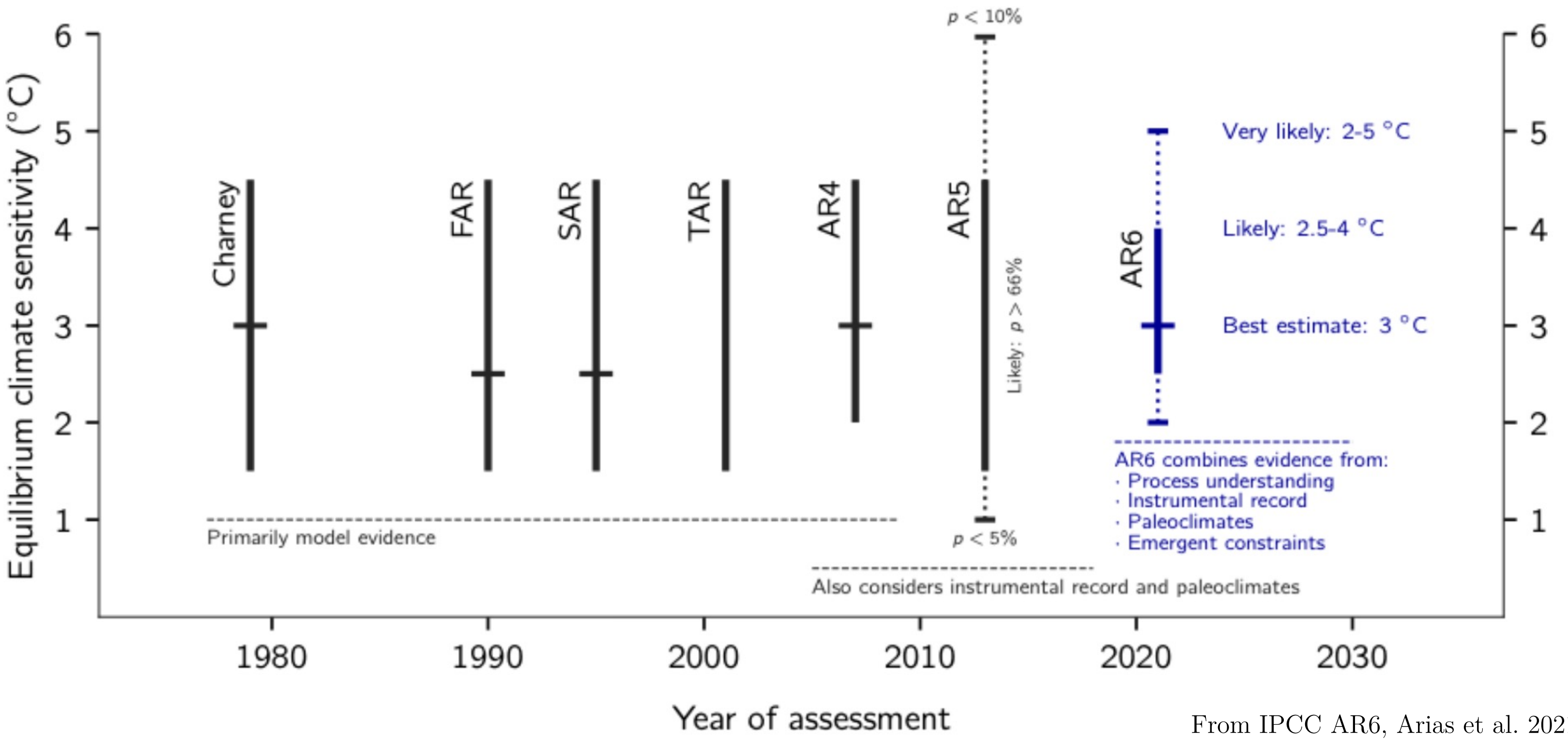
- Difference Method between the preindustrial period (1860-1880) assumed to be in quasi steady state and current epoch (Argo period: 2005-present)

$$-\lambda = \frac{\Delta N - RF}{\Delta T}$$

$$ECS = -\frac{RF_{2xCO_2}}{\lambda}$$

- Data
  - T from Hadcrut, GISS, NOAA essentially. In situ and satellite estimate of the surface temperature. Corrections for historical gaps in the poles and bias in satellite estimates of the SST
  - N current state: from TOA radiative budget (CERES) and in-situ ocean temperature profiles (essentially Argo), Earth energy inventory
    preindustrial state: model estimate +0.2W.m^{-2}
  - RF times series deduced from radiative transfer codes , GCM and historical concentrations
    regular updates of the aerosol forcing (large uncertainty in particular in the interaction between aerosols and clouds)
  - Uncertainty: structural long tail for the inverse relation between ECS and λ

Current estimates of the climate sensitivity from observations of the energy budget

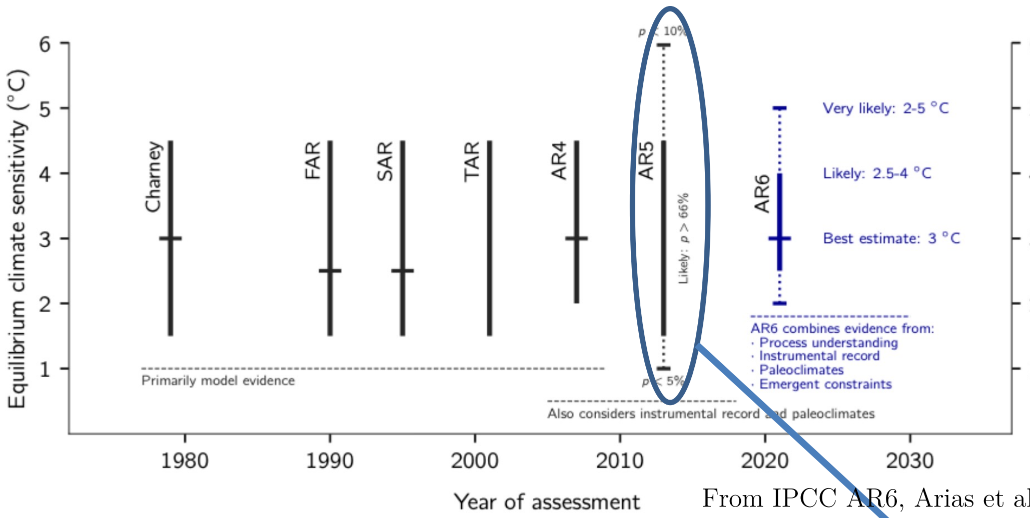


From IPCC AR6, Arias et al. 2021

- 1979-2013: ECS from models (Charney et al. 1979, IPCC 2013)

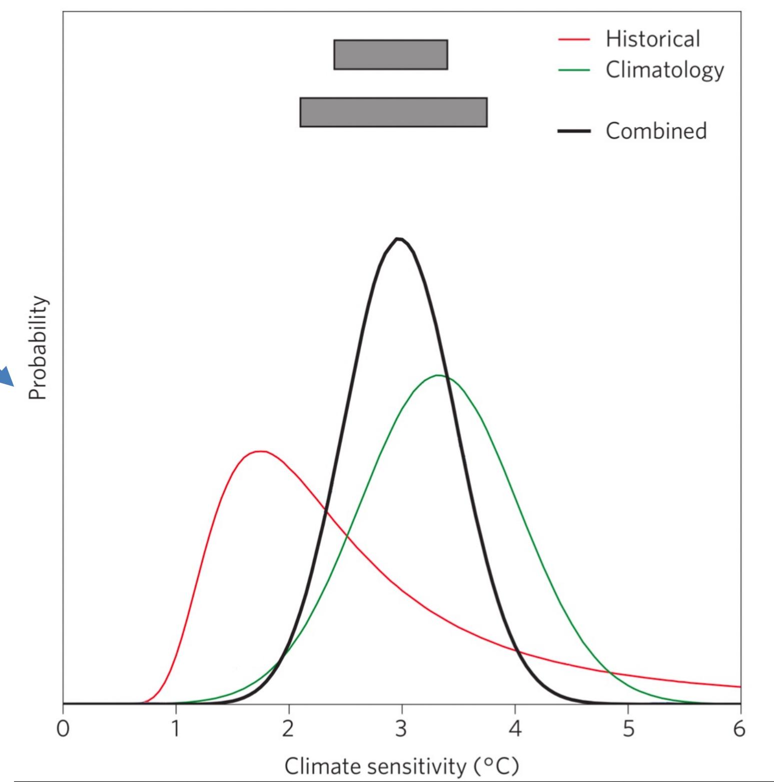
  1.5K<ECS<4.5K (66% CL)

Current estimates of the climate sensitivity from observations of the energy budget



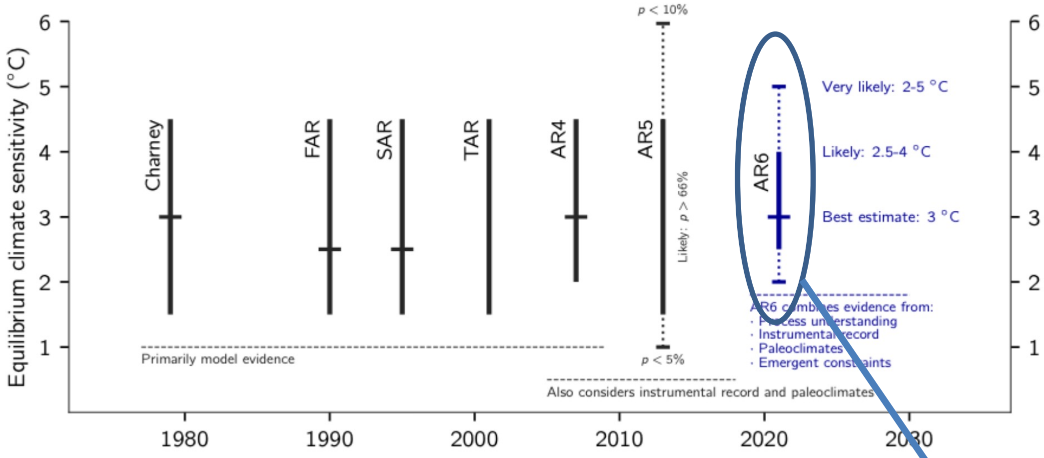
From IPCC AR6, Arias et al. 2021

- 2013: AR5 inclusion of observation estimates
  1.5K<ECS<4.5K (66% CL)
- Observations constrain the lower end of the uncertainty range in ECS, Otto et al. 2013 confirmed by Lewis and Curry 2015
- Structural long tail in observation estimates for the inverse relation between ECS and λ. No constraint on the upper end
- Disagreement obs vs model



Froùm Knutti et al. 2017

Current estimates of the climate sensitivity from observations of the energy budget



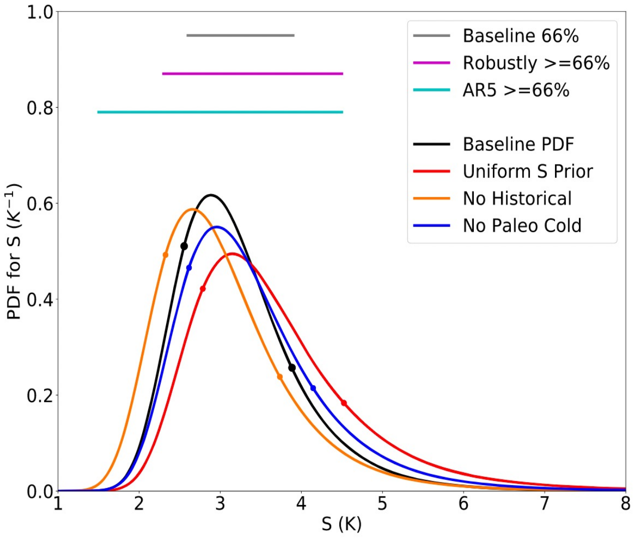
From IPCC AR6, Arias et al. 2021

- 2021: AR6 inclusion of observation estimates, pattern effect and new aerosols
  2.5K<ECS<4.0K (66% CL)

- Observations constrain the lower end of the uncertainty range in ECS, No constraint in the upper end Sherwood et al. 2020.

- Shift in the lower end: pattern effect + RF aerosols

- Agreement obs vs models



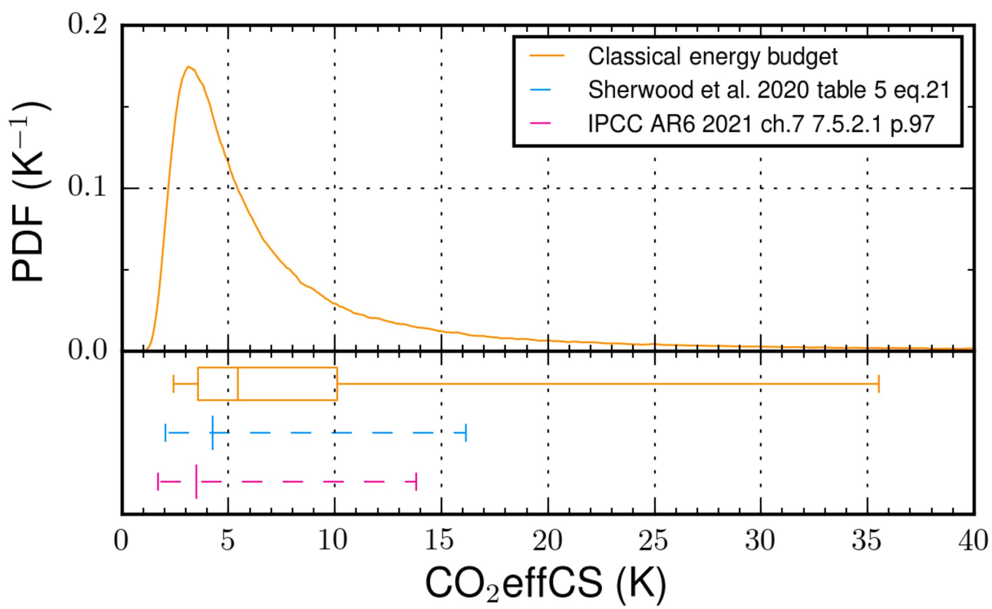
From Sherwood et al. 2022

Current estimates of the climate sensitivity from observations of the energy budget

- 2022: post AR6: Chenal et al. 2022. observation estimates with pattern effect , new aerosols + regression method.

$$-\lambda = \frac{\delta N - RF}{\delta T}$$

- No preindutrial reference. No estimate of preindustrial N. Use of in-situ ocean temperature data and sea level reconstruction since 1971

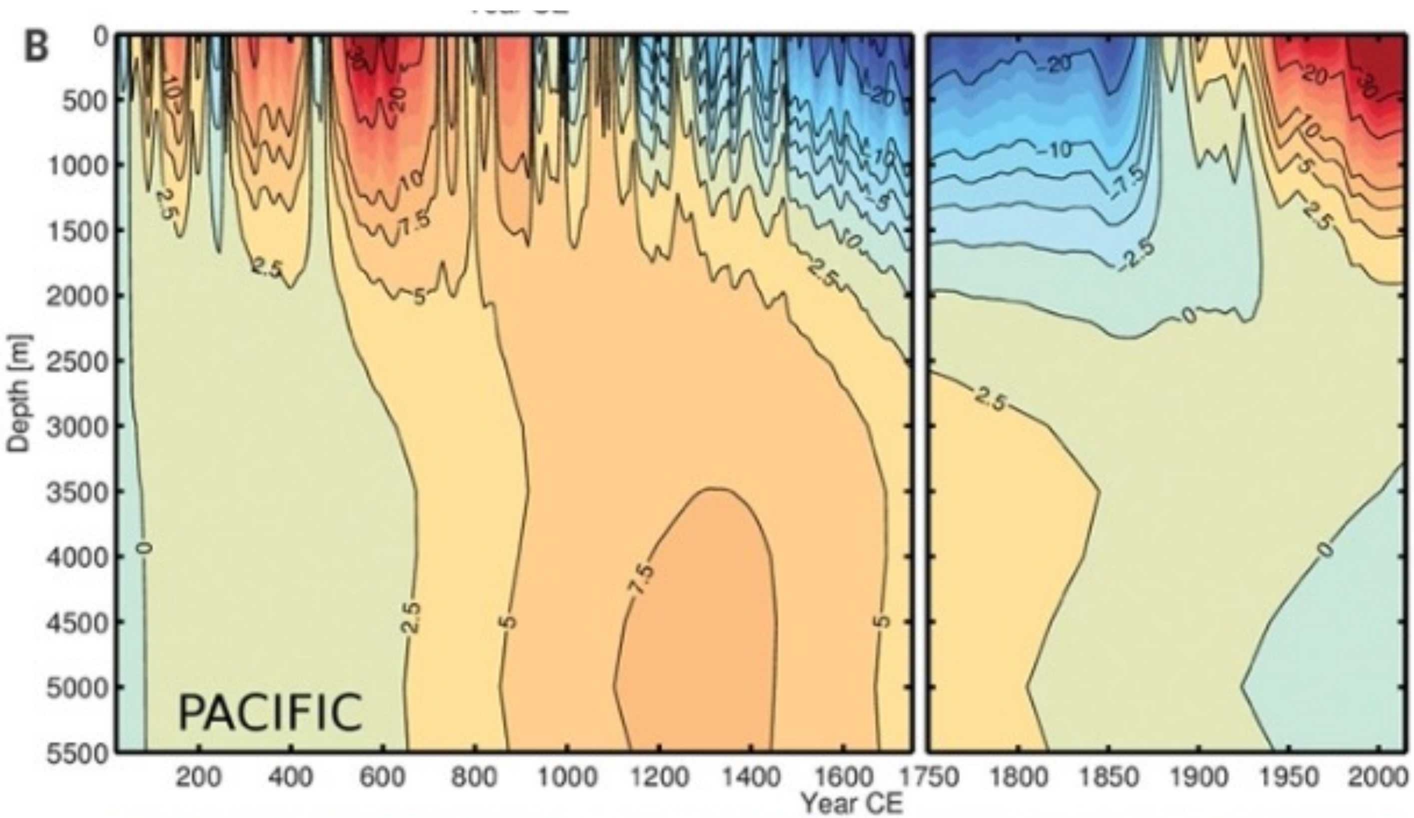


- Resulting ECS 3.6K<ECS<23K (66% CL). Low end 1.3K (0.5K) above AR6 and Sherwood et al. (2020) at the 66%CL (90%CL)

Current estimates of the climate sensitivity from observations of the energy budget

- Low end 1.3K (0.5K) above AR6 and Sherwood et al. (2020) at the 66%CL (90%CL) due to the reference state in AR6 Npi =+0.2W.m^{-2}

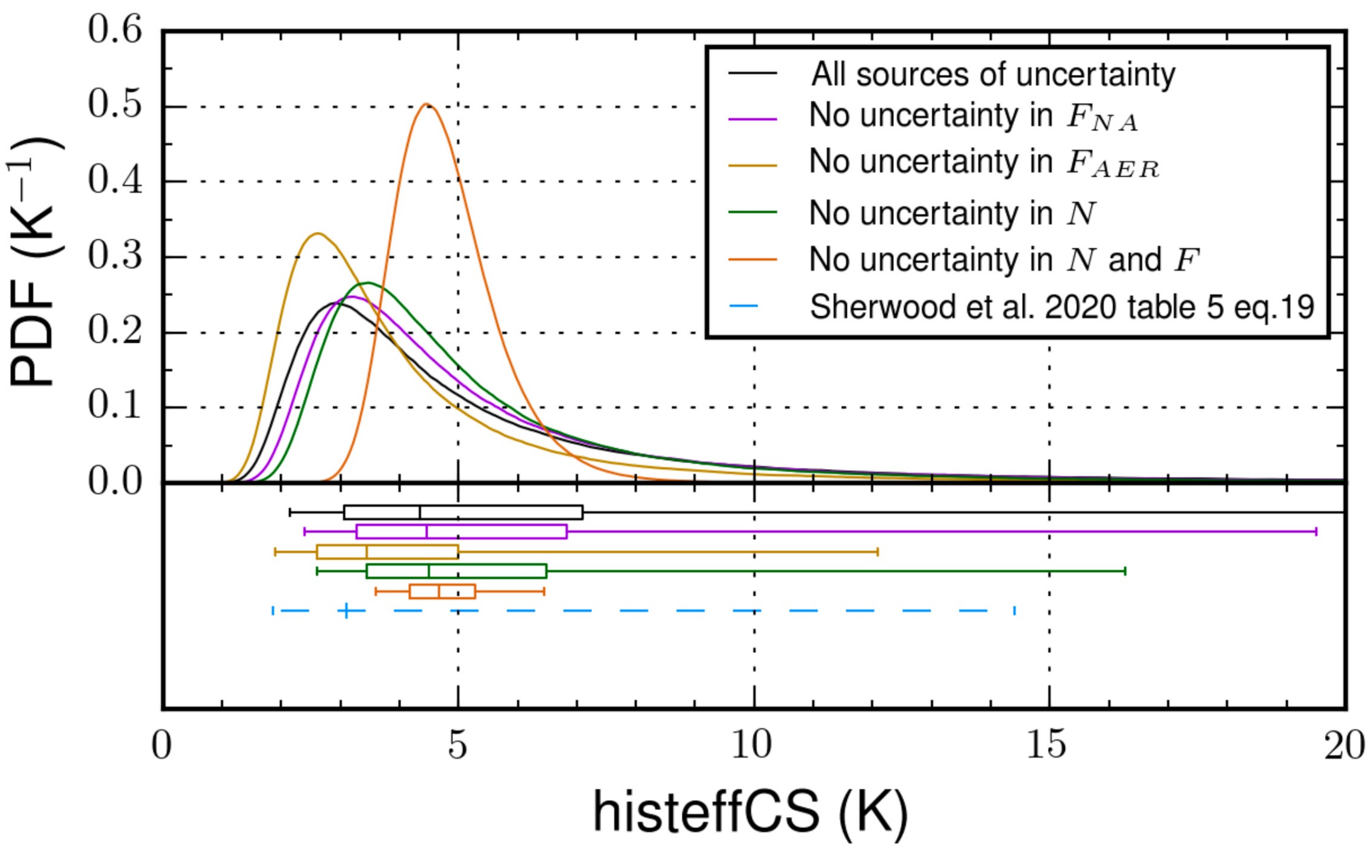
- Ocean reanalysis using HMS challenger data suggest Npi close to 0 or negative



From Gebbie and Huybers 2011

Current estimates of the climate sensitivity from observations of the energy budget

- Uncertainty essentially due to RF aerosols and Nenhanced by the pattern effect



Summary

- When the climate system is specified, the climate sensitivity has a fundamental physical sense that is central for the dynamics of the climate system energy budget.

- ECS is the average change in global mean surface temperature at steady state of the tangent linear climate system in response to the radiative forcing F

$$\Delta T_{eq} = -\frac{F}{\lambda}$$

- λ characterises the zero order energy budget

- It fixes the amplitude and the primary time scales of the energy budget change (and thus climate change) under the radiative anomaly F

Summary

- Determining λ (and thus ECS) from observations is difficult because of
  - A problem of observability (with k and λ)
  - An approximative representation of the energy budget (pattern effect not represented)
  - The role of internal variability

- Approaches to estimate ECS from observations
  - Use observations of N (since 2005 from Argo, since 2002 from staelllite altimetry and Grace)
  - Correct for the pattern effect with GCMs
  - Use long periods to minimize the internal variability

- Observations of the energy budget fix the lower end of ECS estimates :

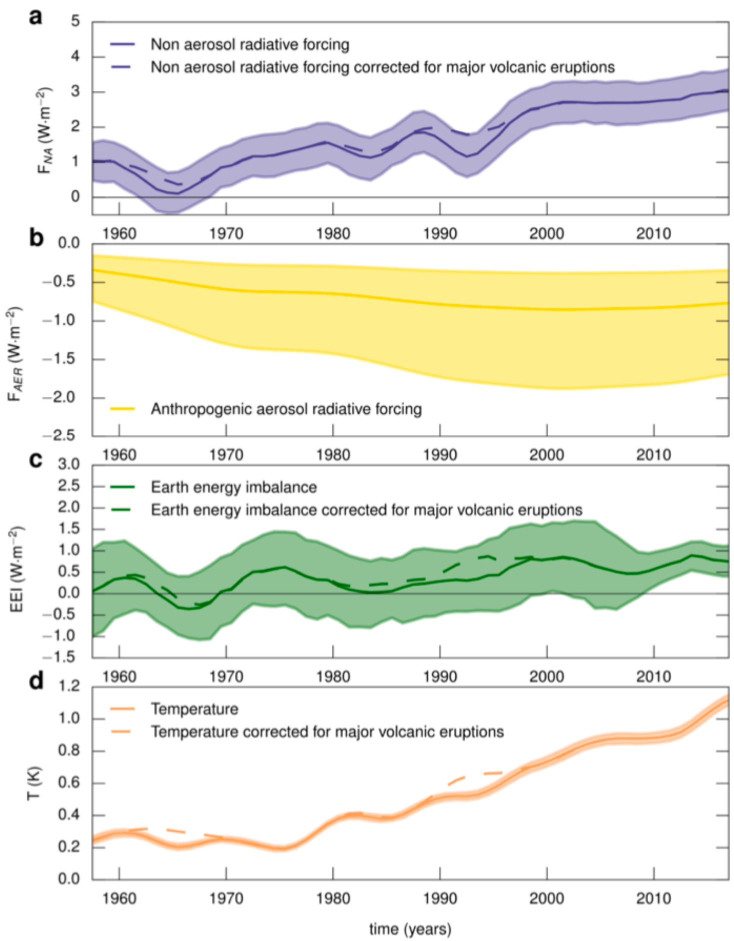
  ECS>2.0K (90%CL) (potentially biased by 0.5K due hypothesis on N in 1860)

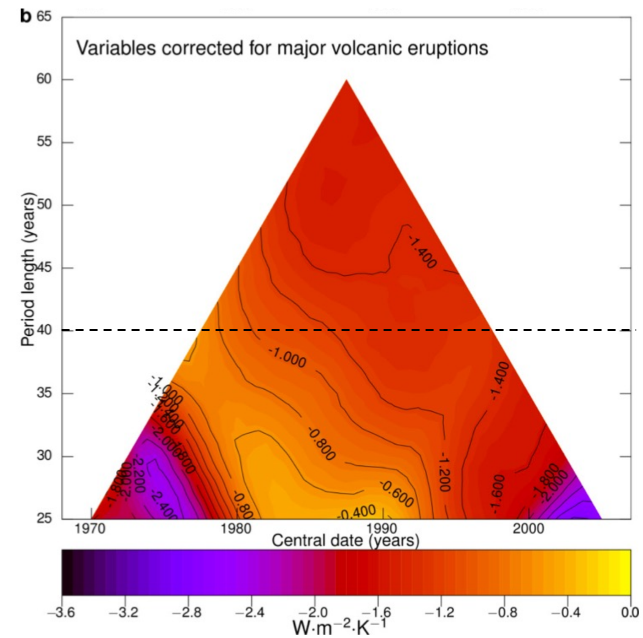
- No constraint on the upper end because of structural uncertainty + uncertainty in the aerosol forcing and N

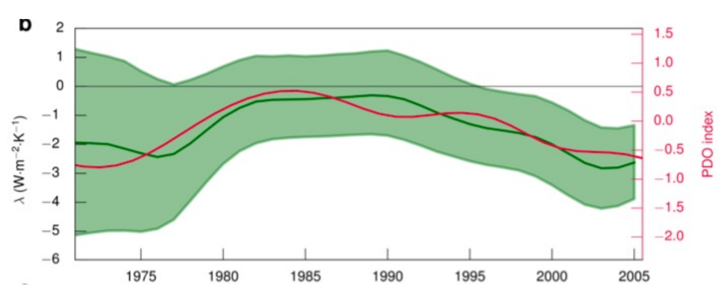
Perspective: Estimate of λ(t)

- Observations of T, RF and EEI

$$\lambda(t) = -\frac{\delta EEI(t) - RF(t)}{\delta T(t)}$$

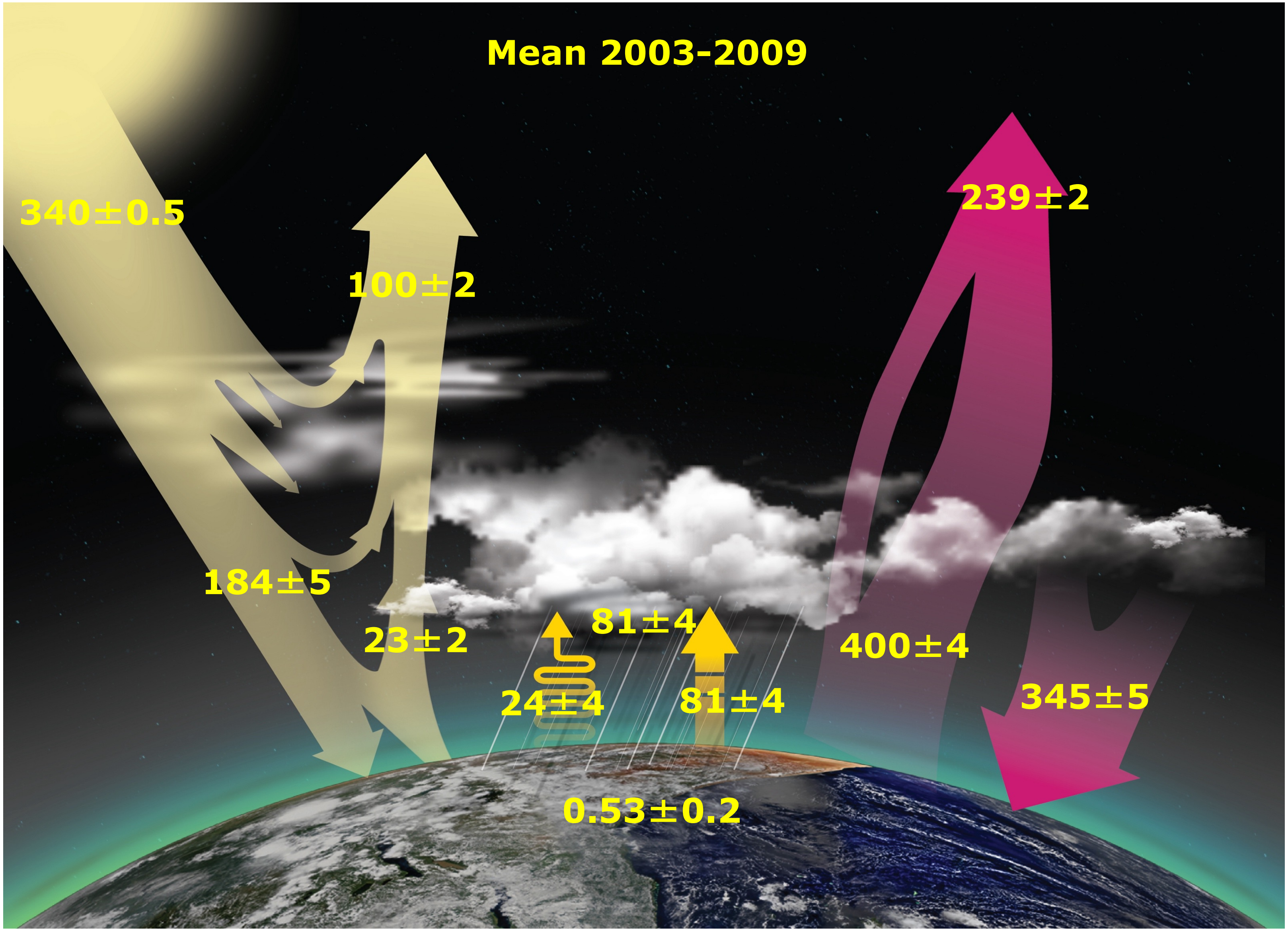






From Meyssignac et al. in revision

Perspective: Constraining the Earth energy budget time variations



From Stephens et al. in revision

Further reading (non exhaustive):

Essential Articles

- Budyko 1969 Tellus
- Sellers 1969
- Manabe and Wetherald 1967
- Hasselmann 1976
- Murphy et al. 1995
- Gnanadesikan 1999
- Marshall et al. 2014
- Winton et al. 2010
- Held et al. 2010
- Geoffroy et al. 2012a,b
- Armour et al. 2013
- Roe et al. 2009
- Forster 2016
- Fueglistaler et al. 2019
- Ceppi and Gregory 2019
- Sherwood et al. 2020
- Lewis and Curry 2018

Books

- North and Kim 2017
- Pierrumbert 2020 Principles of Planetary Climate.

HDR

- Mon HDR qui donne plus de details sur la relation ECS et bilan d'energie de la planète et qui fournit aussi une longue liste bibliographique sur le sujet : https://hal.archives-ouvertes.fr/tel-03700636/