Measuring the Earth energy imbalance by space geodesy to constrain the Earth energy budget and estimate the climate sensitivity

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Equilibrium climate sensitivity

Energy budget equation

$$\left[\begin{array}{rcl} N & = & F + R \quad (W \cdot m^{-2}) \\ \text{incoming rad.} - \text{outgoing rad.} & = & \text{rad. forcing} + \text{rad. response} \end{array}\right]_{\text{TOA}}$$

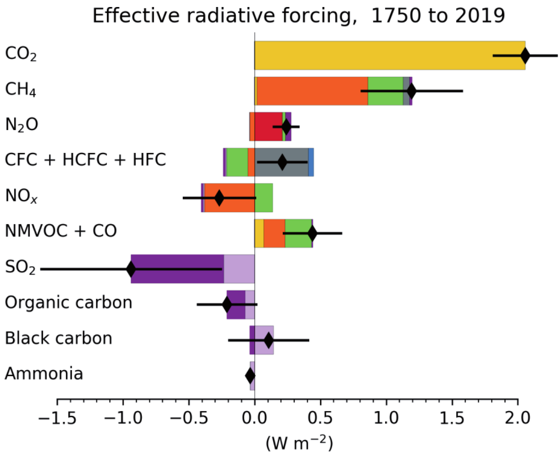
[Charney *et al.*, 1979 ; Ramanathan, 1987]

TOA : *Top of atmosphere*

- N : energy imbalance
- F : radiative forcing
- R : radiative response of the Earth

All three equation terms detailed in the next slides...

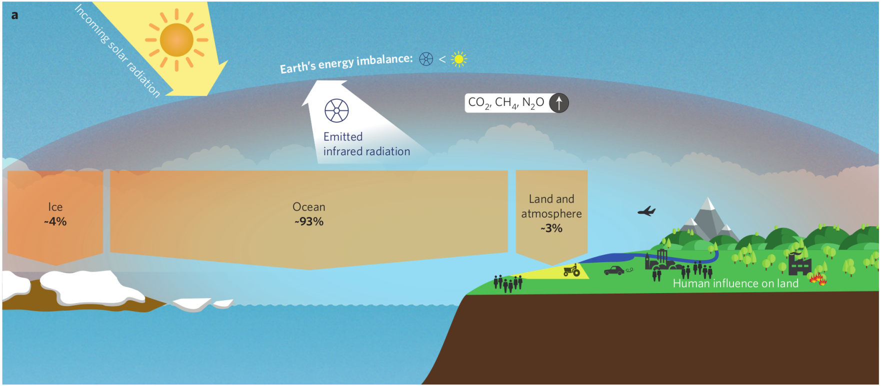
Radiative forcing F : greenhouse gases and aerosols



[ARIAS *et al.*, 2021] (IPCC AR6 TS)

Total (2019 vs 1750) : 2.72 [1.96 ; 3.48] $W{\cdot}m^{-2}$ (5 ;95%)

Earth energy imbalance : $N < 10^{-2}$ visible solar flux !



[von Schuckmann *et al.*, 2016]

$\sim$ 91% absorbed in the ocean

$\sim$ 4% absorbed in glaciers and ice sheet

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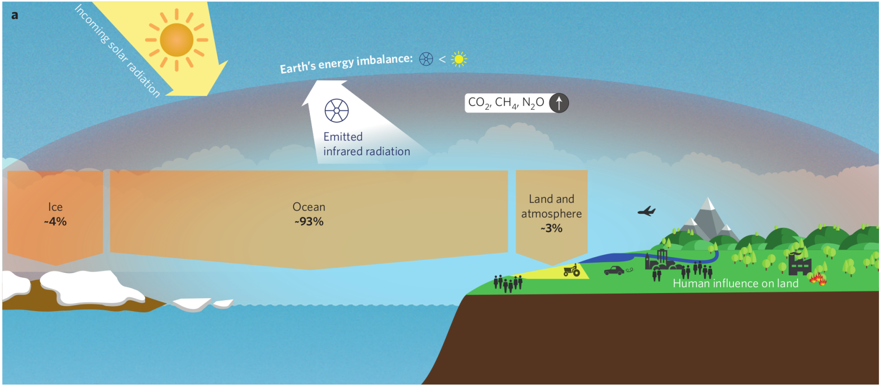

[von Schuckmann *et al.*, 2016]

∼ 91% absorbed in the ocean
∼ 4% absorbed in glaciers and ice sheet

95% of the ENERGY IMBALANCE
⇕
SEA LEVEL RISE

[Church *et al.*, 2011 ; Levitus *et al.*, 2012 ; Meyssignac *et al.*, 2019 ; von Schuckmann *et al.*, 2020 ; Arias *et al.*, 2021]

Radiative response of the Earth R : transformation of Earth surface to restore equilibrium

Main hypothesis : linearity with global mean surface temperature T
[Budyko, 1968 ; Dickinson *et al.*, 1982 ; Ramanathan, 1988]

$$R = \lambda T$$

λ : climate feedback parameter

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Classical model of the energy budget

$$N = F + \lambda T$$

Equilibrium climate sensitivity (ECS)

[ARRHENIUS, 1896 ; MANABE & WETHERALD, 1967 ; CHARNEY *et al.*, 1979]

$$ECS = -\frac{F_{2x}}{\lambda}$$

Fundamental metric of climate change amplitude and projections

Equilibrium climate sensitivity (ECS)

[Arrhenius, 1896 ; Manabe & Wetherald, 1967 ; Charney *et al.*, 1979]

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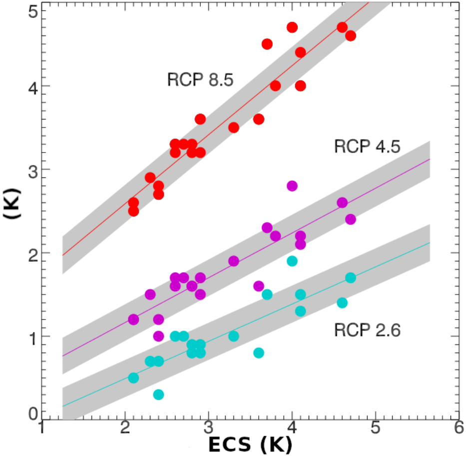
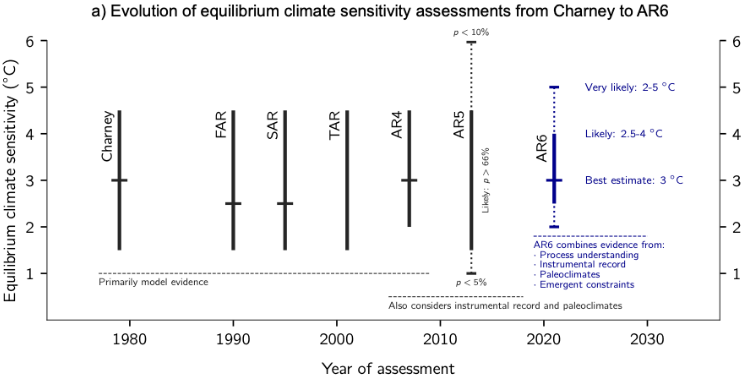


$T(2100) \propto ECS$ for three IPCC socio-economic scenarios
Adapted from [Sherwood *et al.*, 2020]

Problem : ECS is still very uncertain !



1979-2013 :
$1.5 \leq ECS \leq 4.5$ K (likely)
[Charney *et al.*, 1979 ; IPCC, 2013]

Recently :
$2.3 \leq ECS \leq 4.5$ K (likely) [Sherwood *et al.*, 2020]
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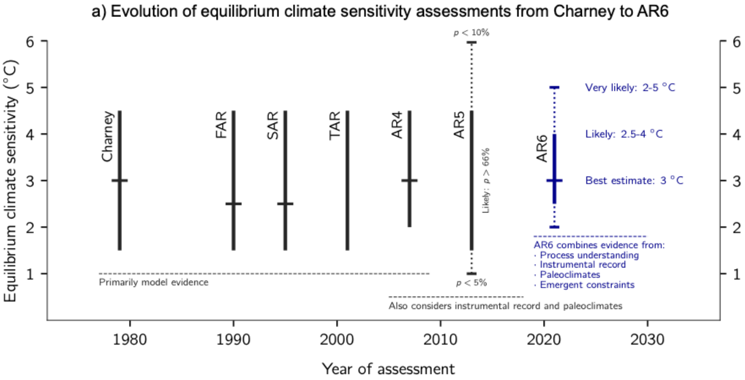

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Inconsistencies between methods despite recent attempts of reconciliation between methods
[Andrews *et al.*, 2018 ; Sherwood *et al.*, 2020]

- Observational estimates : low values
- Climate models estimates : high values

Key : $\lambda(t)$ not constant ! [Senior & Mitchell, 2000 ; Armour *et al.*, 2013 ; Gregory & Andrews, 2016]

- depends on global mean surface temperature itself
- depends on the intrinsic internal climate variability
- depends on forcing agents and their time variations

$\Rightarrow$ effects of warming pattern on marine low clouds : **« pattern effect »**

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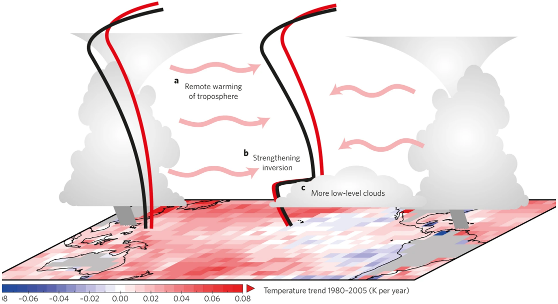

[Mauritsen, 2016]

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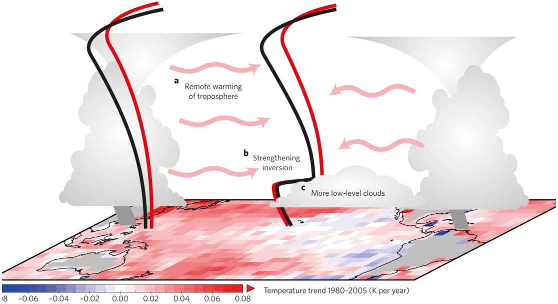

[Mauritsen, 2016]

Observational climate sensitivity is necessarly uncertain
and only reflects
a time-mean sensitivity calculated in a transient regime with many forcing agents
observational effective climate sensitivity (obseffCS)
≠ « canonical » equilibrium climate sensitivity (CO_2effCS)

⇒ **Need to model the bias obseffCS→CO_2effCS**

Methods, data, results

- radiative forcing F : GHG [Sherwood *et al.*, 2020], aerosols [Bellouin *et al.*, 2020]
  $F_{2\times}$ from [Smith *et al.*, 2020]
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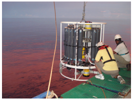
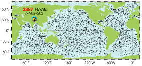
  - **space geodesy ocean heat content estimate** [Hakuba *et al.*, 2021 ; Marti *et al.*, 2022]

$$OHC = \frac{1}{\varepsilon}(\Delta SL_{Alti} - \Delta SL_{Grace})$$

$\varepsilon \approx 0.145$ m·J^{-1} : *expansion efficiency of heat*





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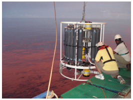

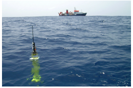

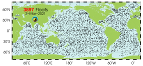

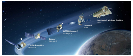

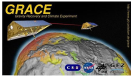

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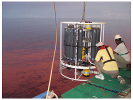
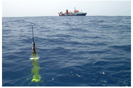
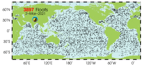
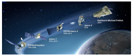
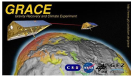










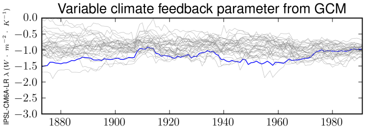
Earth energy imbalance at top of atmosphere ($\mathrm{W \cdot m^{-2}}$)

$$N = \frac{1}{\beta}\frac{1}{S_{TOA}}\frac{dOHC}{dt}$$

$\beta \approx 0,93$: fraction of EEI absorbed in the ocean
$S_{TOA} = 4\pi r_{TOA}^2$: sphere surface at TOA

Need for a transfer function from observationnal effective climate sensitivity to equilibrium climate sensitivity :
two separated **« pattern effects »** to take into acount modeled from $\lambda(t)$ behaviour in climate models :

- **internal variability** :
  the real climate trajectory is only one among an infinite number
  $\Longrightarrow$ **histeffCS :**
  historical effective climate sensitivity
- **forced variability** :
  λ is not the same between the historical climate evolution and the climate evolution corresponding to the canonical definition of the ECS
  $\Longrightarrow$ **CO_2effCS :**
  effective climate sensitivity to CO_2
  (good proxy to ECS [Gregory *et al.*, 2019])



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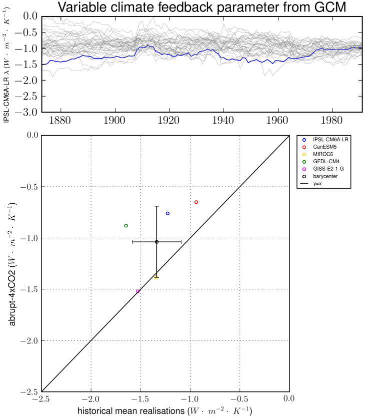

[Chenal *et al.*, 2022]

EEI solution

		CO_2effCS Median [5% ;95%] (K)
Argo [Loeb et al., 2021]	(2005-2018)	3.5 [1.6 ; 21.4]
Geodetic [Marti et al., 2022]	(2002-2016)	3.6 [1.6 ; 20.8]
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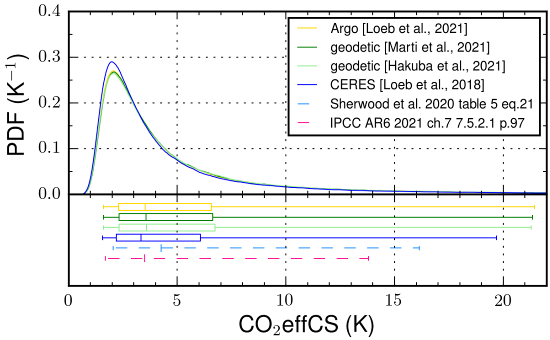

Geodetic, **Argo**, **CERES**, [Sherwood et al., 2020], IPCC AR6 : state base difference vs 1869-1882

- validation of the space geodesy approach (first ECS estimate)
- with longer time series : state difference vs time series regression
- contribution to the reconciliation between observational and models estimates

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In situ (without volcanic eruptions effect)* [Chenal *et al.*, 2022]	(1971-2017)	5.4 [**2.4** ; 35.6]
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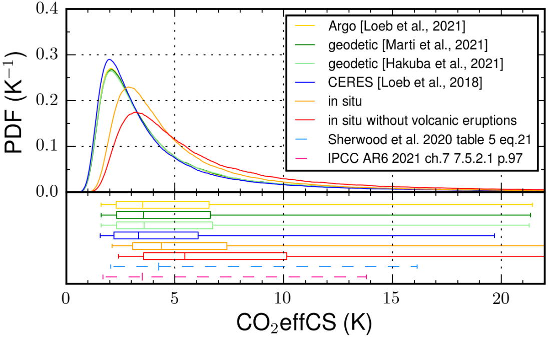

Geodetic, **Argo**, **CERES**, [Sherwood *et al.*, 2020], IPCC AR6 :
state base difference vs 1869-1882
In situ, **In situ (without volcanic eruptions effect)*** :
regression of $N - F$ over T

El Chichon (1982), Pinatubo (1991)

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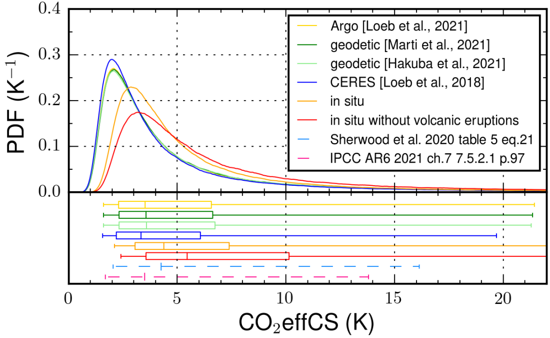

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Some results (2) : influence of the mean epoch and duration of observations on the estimate of parameter λ

We extend our *in situ* EEI solution on 1957-2017 from [Meyssignac *et al.*, subm.] :

- thermosteric component of [Frederikse *et al.*, 2020] sea level reconstruction by GMSL - GMBSL (low-pass filter, 15yr)
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Radiative forcing and temperature : low-pass filter, 10yr

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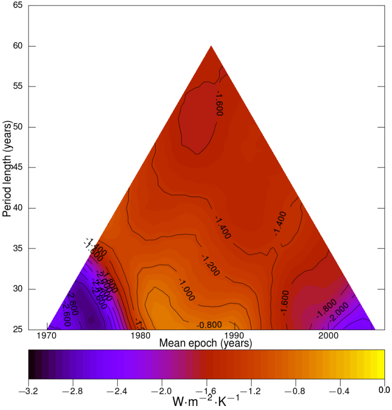
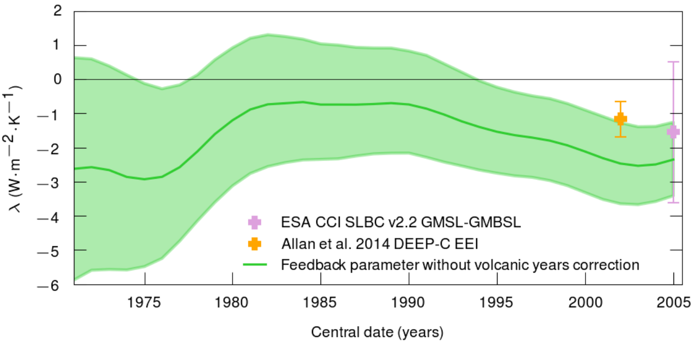


25-yr duration (median, 17%-83%)

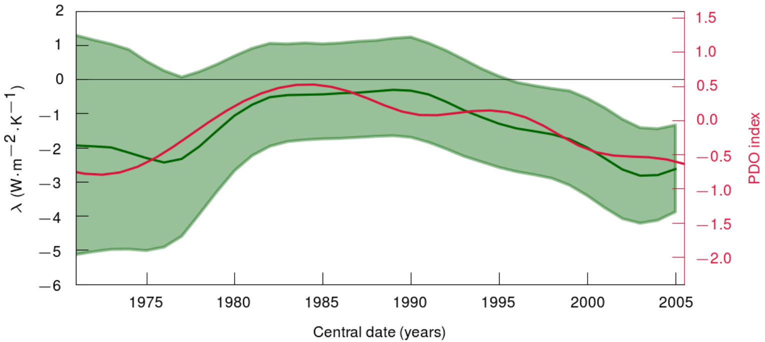
Variables non corrected from the effect of major volcanic eruptions
+ two regressions of short time series



- visible variations of parameter λ from long OHC time series (1957-2017) for $D \leqslant 35$ years
- recent λ observed by regression with other observation systems with short time series

25-yr duration (median, 17%-83%)

Variables corrected from the effect of major volcanic eruptions
+ PDO index (low-pass filter, 15 years cut) NOAA ERSST v5 [Boyin *et al.*, 2017 ; Huang *et al.*, 2017]



- variations of λ possibly due to the pattern effect from the Decadal Pacific Oscillation (see also [Zhou *et al.*, 2016 ; Ceppi & Gregory, 2017 ; Zhou *et al.*, 2017 ; Andrews & Webb, 2018 ; Dessler, 2020 ; Loeb *et al.*, 2021])

Conclusions

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    today $\pm$0.3 mm/yr on 20 years ($\pm$0.14 W·m^{-2} on EEI on 20 years)
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Thanks for your attention

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