Pourquoi l’incertitude sur l’estimation de la sensibilité climatique a été réduite dans le dernier rapport du GIEC

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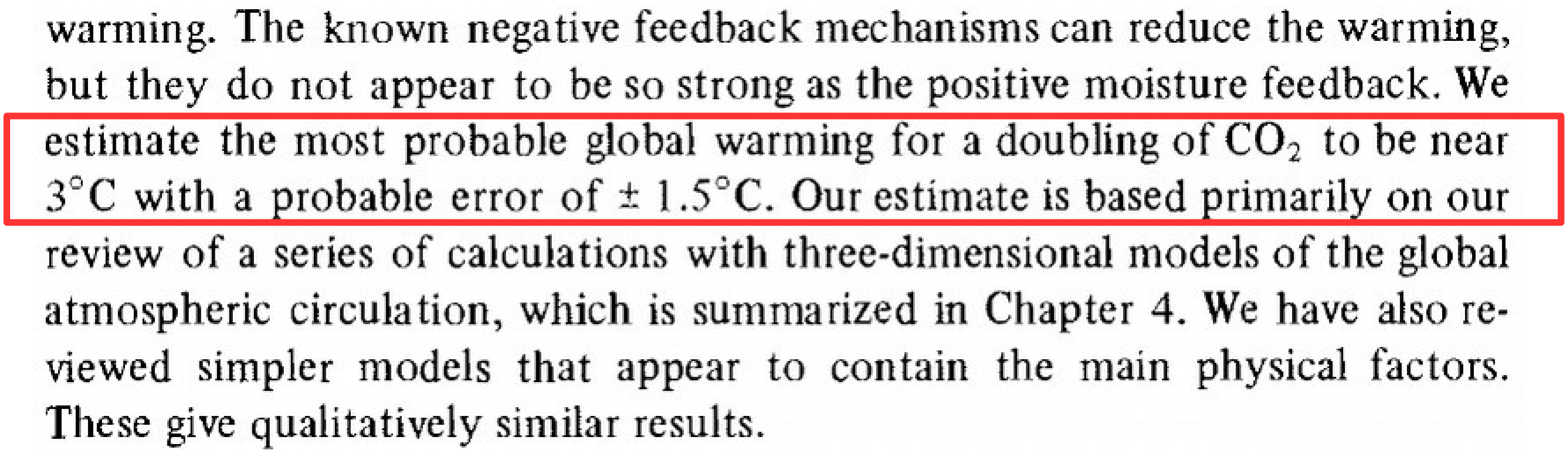
Outline

- Definition and interest of climate sensitivity
- The main physical mechanisms involved
  - Forcings
  - Feedbacks
- Different ways to determine climate sensitivity
- How to combine them?
- Conclusion

Carbon dioxide and climate: a scientific assessment.

Charney JG, A. Arakawa, DJ Baker, B. Bolin, R.E. Dickinson, R.M. Goody, C.E. Leith, H.M. Stommel, C.I Wunsh, (1979)

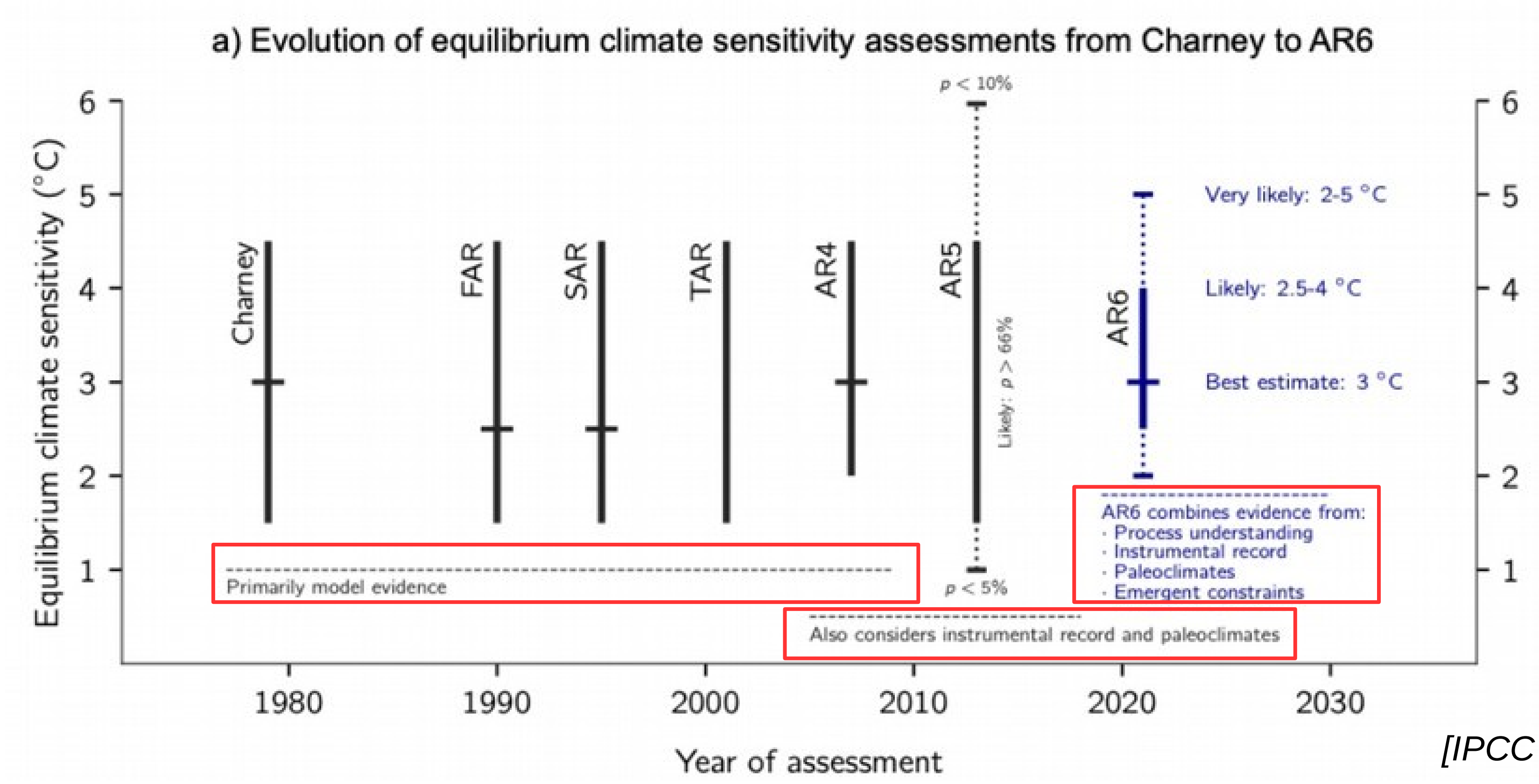
National Academy of Science, Washington, DC,



warming. The known negative feedback mechanisms can reduce the warming, but they do not appear to be so strong as the positive moisture feedback. We estimate the most probable global warming for a doubling of CO_2 to be near 3°C with a probable error of ± 1.5°C. Our estimate is based primarily on our review of a series of calculations with three-dimensional models of the global atmospheric circulation, which is summarized in Chapter 4. We have also reviewed simpler models that appear to contain the main physical factors. These give qualitatively similar results.

Estimating climate sensitivity

Equilibrium climate sensitivity (ECS) is the change in equilibrium temperature in response to a doubling of atmospheric CO_2 concentration relative to pre-industrial levels.

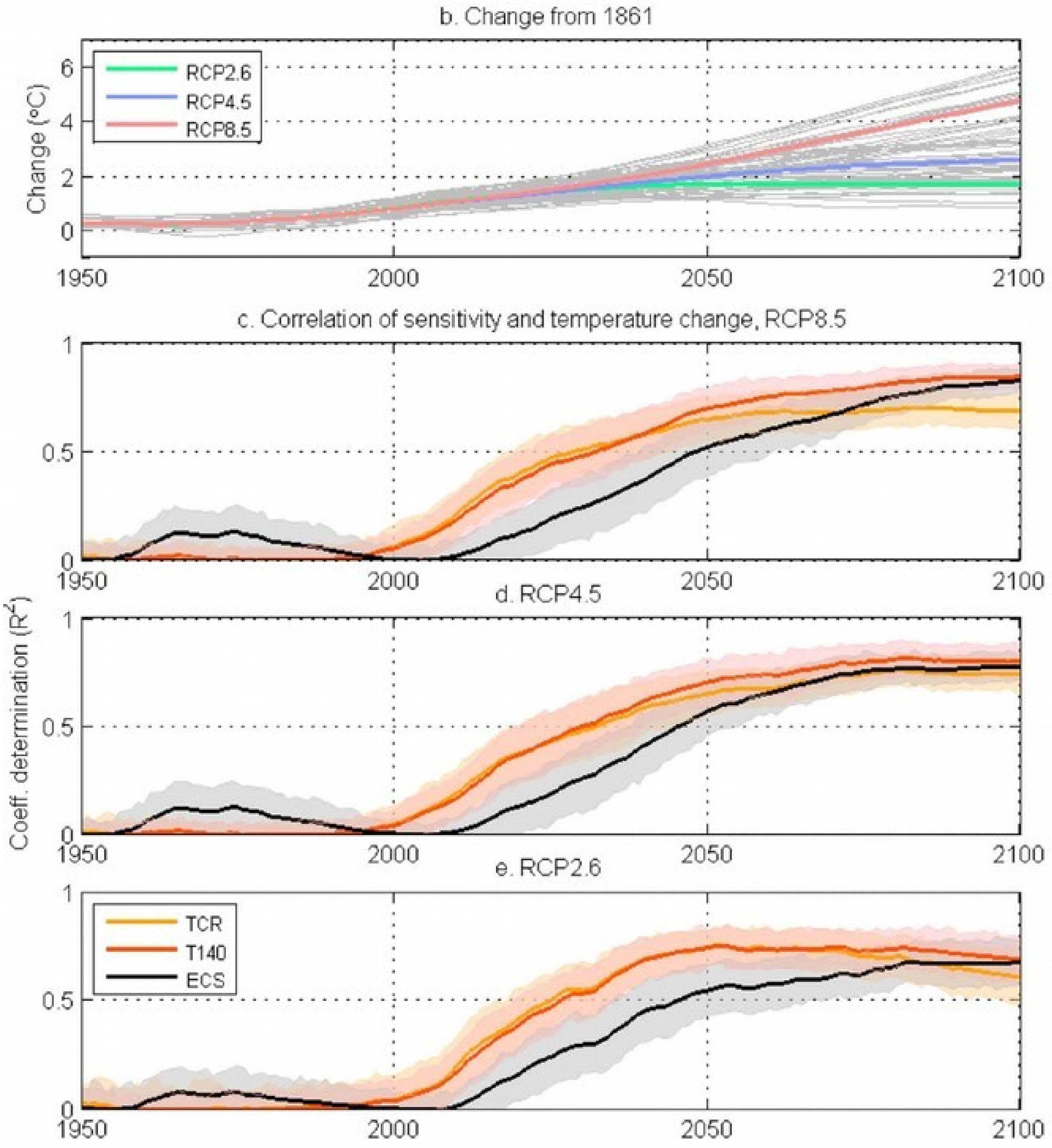


[IPCC AR6-WG1, TS]

ECS is a theoretical concept, useful because many changes in climate variables depend on the amplitude of warming.

Why do we care about climate sensitivity?

Correlation between ECS and the response for different scenarios (CMIP5 models ensemble):



RCP8.5

RCP4.5

RCP2.6

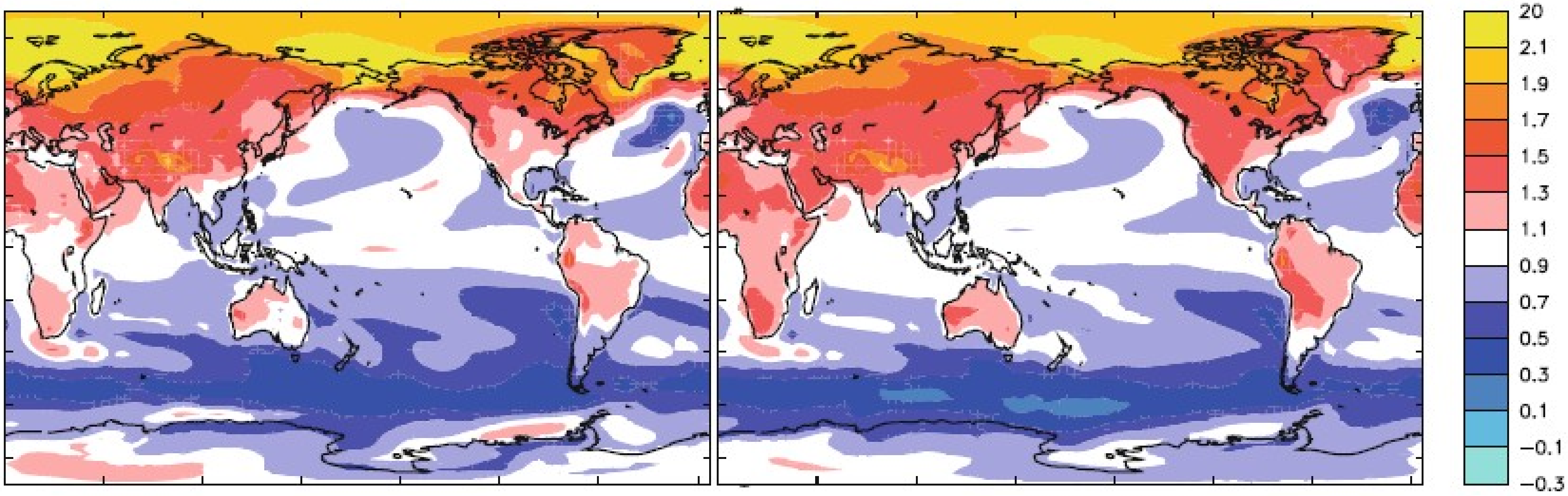
[Grose et al., 2018]

Why do we care about climate sensitivity?

- For many models, as a first approximation (pattern scaling):

  $\Delta X(\text{space,time}) = \text{global } \Delta T(\text{time}) \text{ x } \text{pattern}(\text{space})$

- **Global ΔT : a scaling factor for many global and regional climate responses**



Change in temperature normalized by global ΔT (K/K)

RCP 2.6 (ΔT = 2K)
low GHG scenario

RCP 8.5 (ΔT = 6K)
high GHG scenario

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Radiative forcing and feedback framework

In response to an external forcing (a driver of climate change), the response ΔR of the net flux at the TOA, may be expressed, at the first order, as:

$$\boxed{\Delta R = \Delta Q + \lambda \, \Delta T_s}$$

Change in global mean **surface** temperature

Change in net flux at the TOA

radiative forcing

“climate feedback parameter”

The ***radiative forcing ΔQ*** is the **change in the net radiative flux R** (W.m^{-2}) at the top of atmosphere due to the external forcing **without the surface temperature T_s adjusting** to this perturbation. The radiative forcing aims to compare the magnitude of different perturbations that impact climate.

The ***climate feedback parameter λ*** (W m^{-2} K^{-1}) is the **sensitivity of the net radiative flux R** at the top of atmosphere due to a change in the **surface temperature T_s**

$$\boxed{\lambda = -\frac{dR}{dT_s}}$$

Radiative forcing and feedback framework

In response to an external forcing (a driver of climate change), the response ΔR of the net flux at the TOA, may be expressed, at the first order, as:

$$\boxed{\Delta R = \Delta Q + \lambda \Delta T_s}$$

Change in global mean **surface** temperature

Change in net flux at the TOA

radiative forcing

“climate feedback parameter”

When ***a new equilibrium*** is reached, $\Delta R=0$

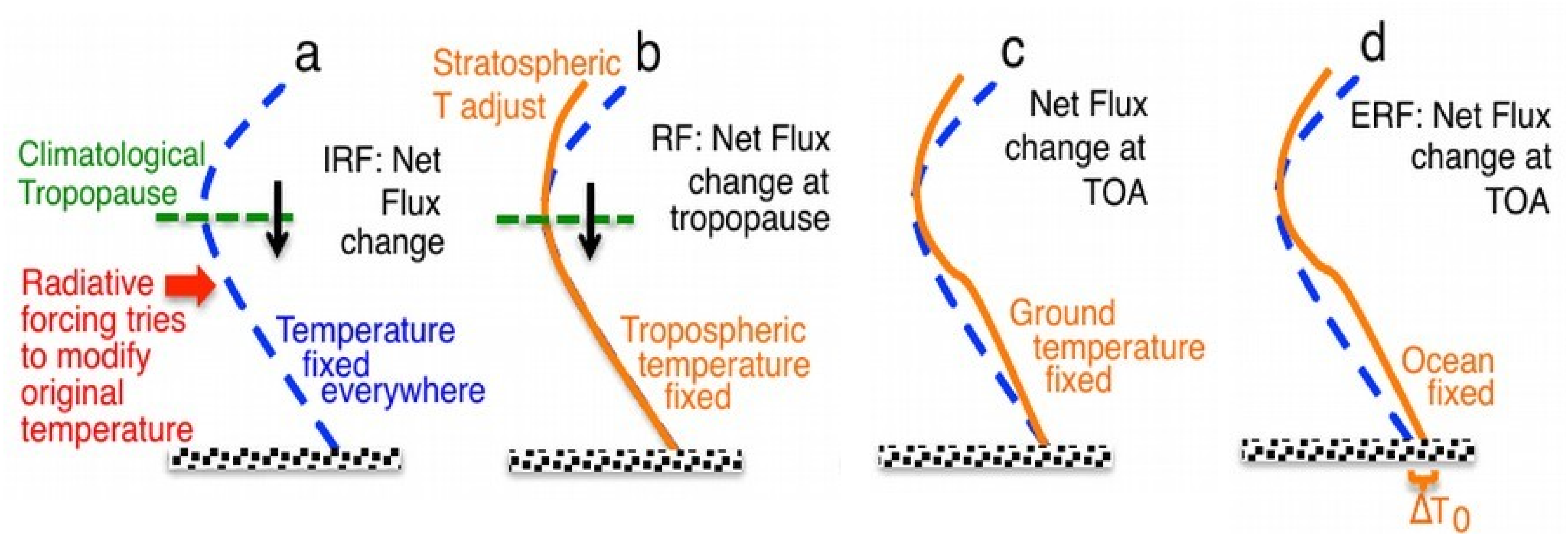
$$\boxed{\Delta T_s^e = \frac{-\Delta Q}{\lambda}}$$

The ***equilibrium temperature change*** $\boldsymbol{\Delta T_s^e}$ is the temperature change due to a forcing after a new equilibrium has been reached.

If λ is constant, ΔT^e is proportional to the radiative forcing

The ***Equilibrium climate sensitivity*** **(ECS)** is the equilibrium temperature change in response to a ***doubling*** of the atmospheric ***CO_2 concentration*** relative to pre-industrial levels.

Radiative forcing



[IPCC AR5]

Climate feedbacks

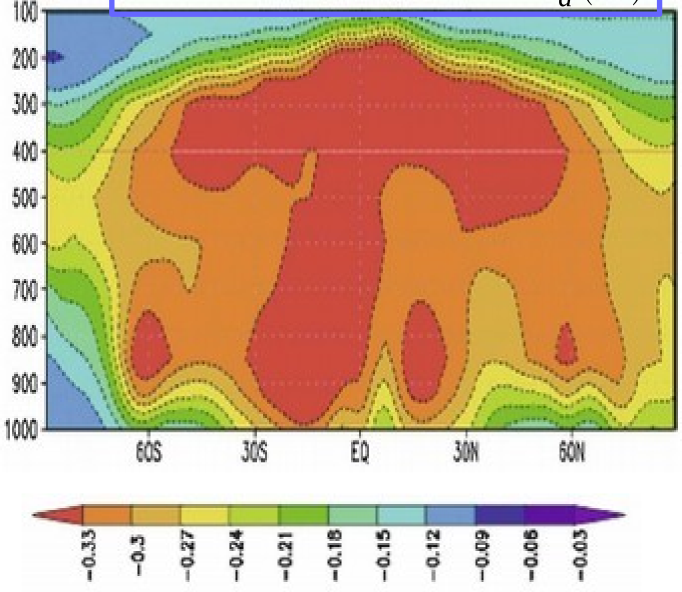
$$\Delta R = \Delta Q + \lambda \, \Delta T_s \qquad \lambda = \frac{dR}{dT_s} \qquad \lambda \approx \sum_x \boxed{\frac{\partial R}{\partial x}} \boxed{\frac{dx}{dT_s}}$$

sensitivity of radiative flux *R* to change in variable *x*

response of variable *x* to surface temperature change

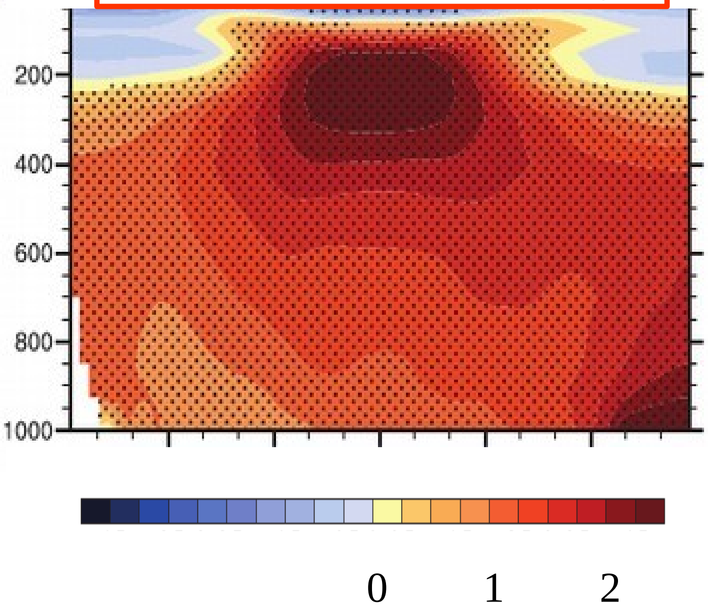
e.g. for *x* = *T_a* :

Temperature kernel $\frac{\partial R}{\partial T_a(P)}$



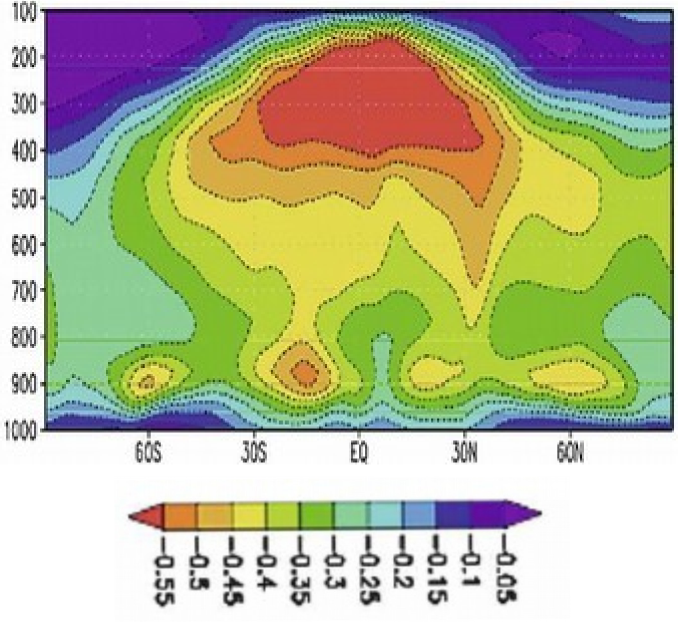
W/m^2/K/(100hPa)

Temperature change $\frac{\partial T_a(P)}{\partial T_s}$



K/K (approximate)

$\frac{\partial R}{\partial T_a(P)} \frac{dT_a(P)}{dT_s}$



W/m^2/K/(100hPa)

Soden et al., J. Climate, 2008

Climate feedbacks

$$\Delta R = \Delta Q + \lambda \, \Delta T_s$$

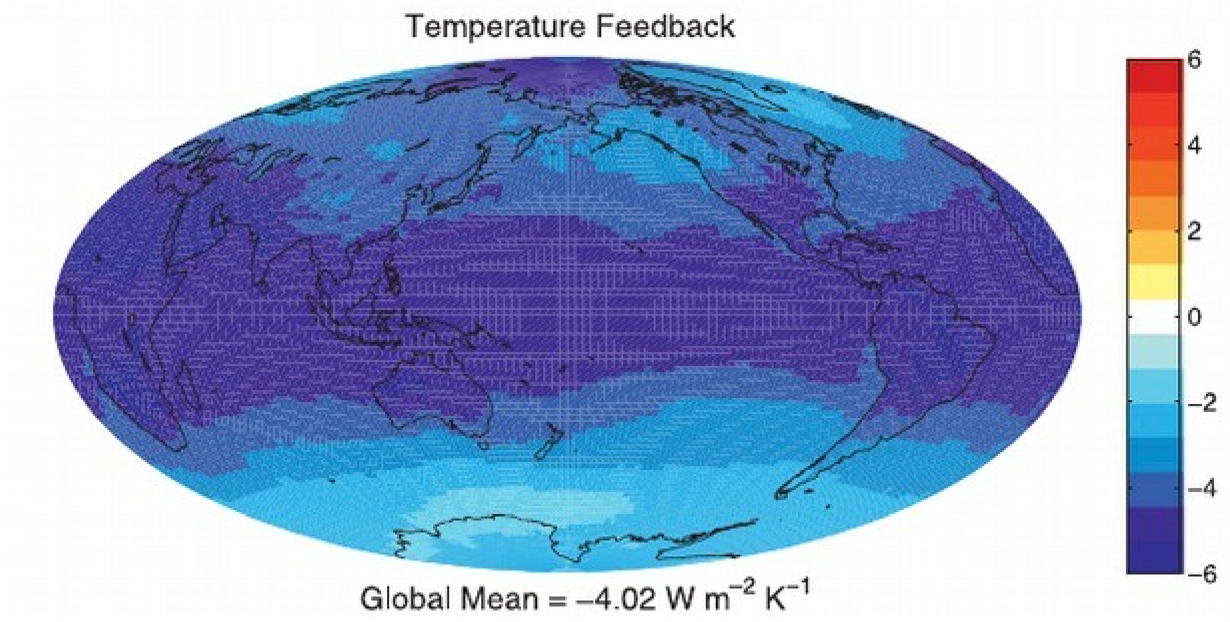
$$\lambda = \frac{dR}{dT_s}$$

$$\lambda \approx \sum_x \boxed{\frac{\partial R}{\partial x}}\boxed{\frac{dx}{dT_s}}$$

sensitivity of radiative flux *R* to change in variable *x*

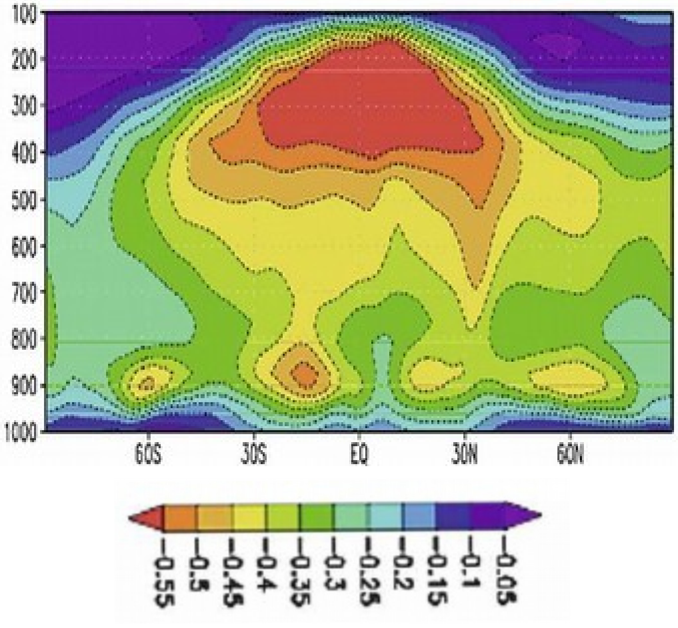
response of variable *x* to surface temperature change

Temperature feedback parameter $\lambda_{T_a} = \int_P \frac{\partial R}{\partial T_a(P)} \frac{dT_a(P)}{dT_s} dP$



[Zelinka et al., 2012]

$$\frac{\partial R}{\partial T_a(P)} \frac{dT_a(P)}{dT_s}$$



W/m^2/K/(100hPa)

Soden et al., J. Climate, 2008

Climate feedbacks

The ***temperature** feedback parameter* λ_T is further decomposed in two terms

- the ***Planck** feedback parameter* λ_P where the temperature change is vertically uniform and equal to the surface temperature change

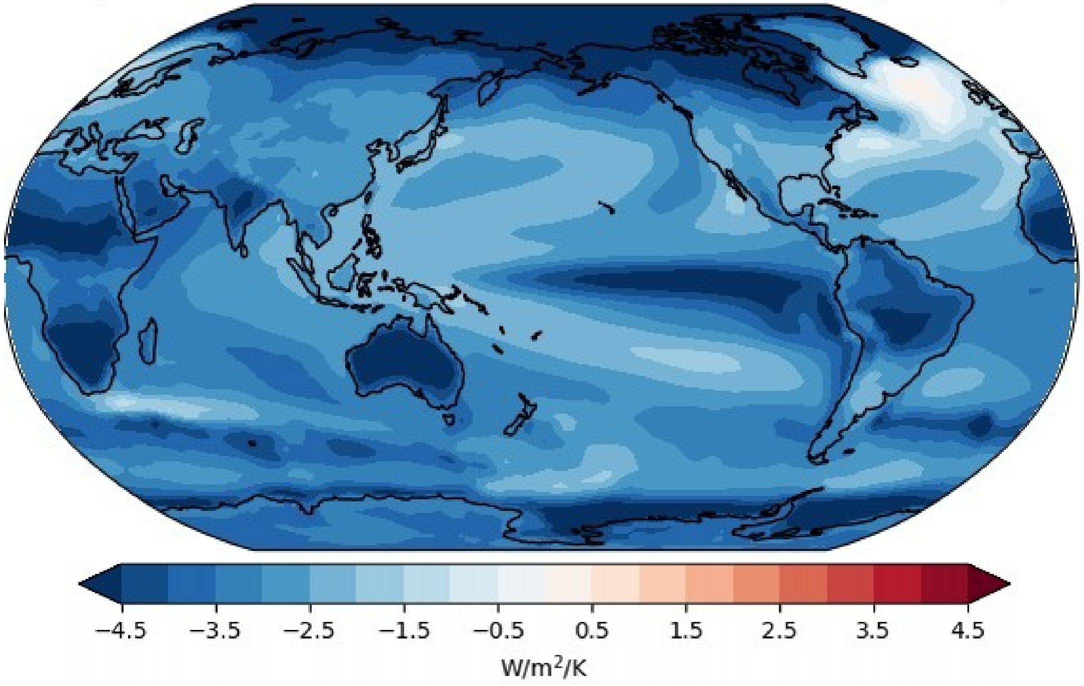
- the ***lapse rate** feedback parameter* λ_L where the temperature change is the difference between the actual temperature change and the vertically uniform one.

The classical feedback decomposition is then :

$$\boxed{\underbrace{\lambda = \lambda_P}_{\text{Planck}} + \underbrace{\lambda_L}_{\text{lapse rate}} + \underbrace{\lambda_W}_{\text{water vapor}} + \underbrace{\lambda_C}_{\text{clouds}} + \underbrace{\lambda_a}_{\text{surface albedo}}}$$

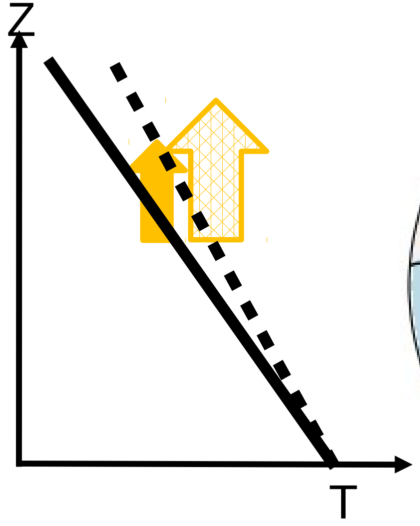
Planck feedback

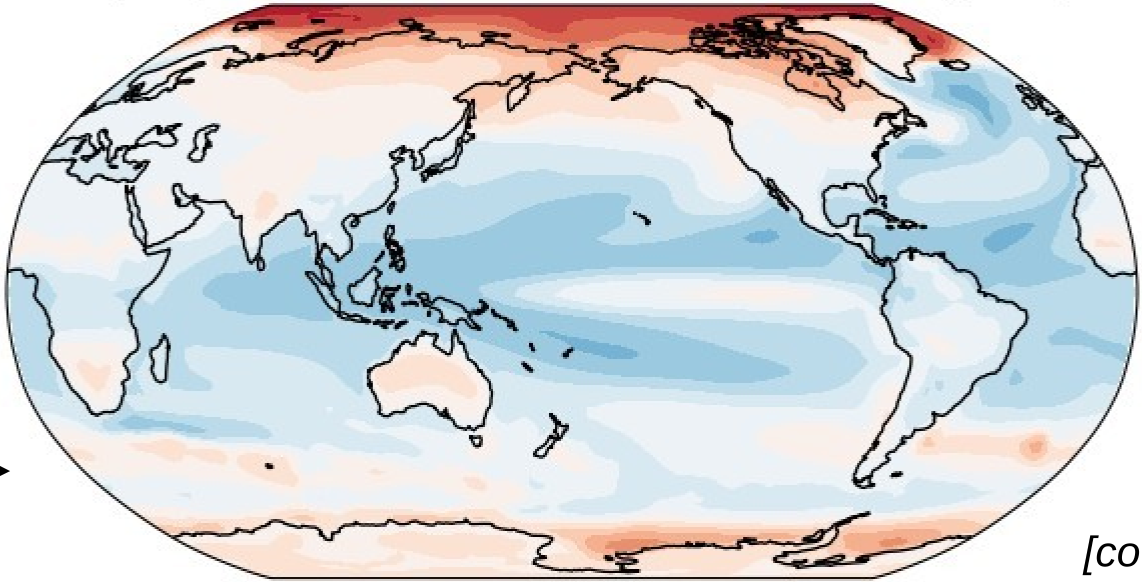
[-3.28]



Lapse-rate feedback

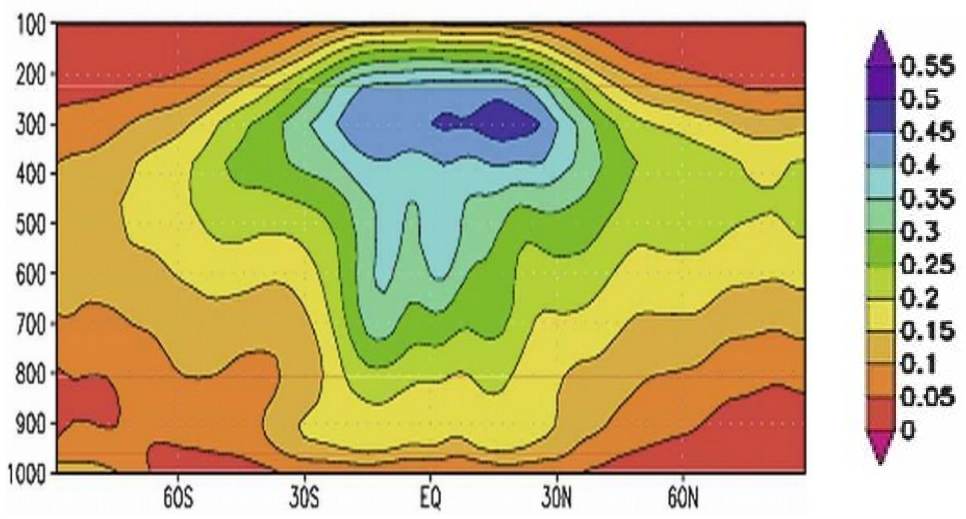
[-0.5]





[courtesy of M. Zelinka 2021]
(https://doi.org/10.5281/zenodo.5206851)

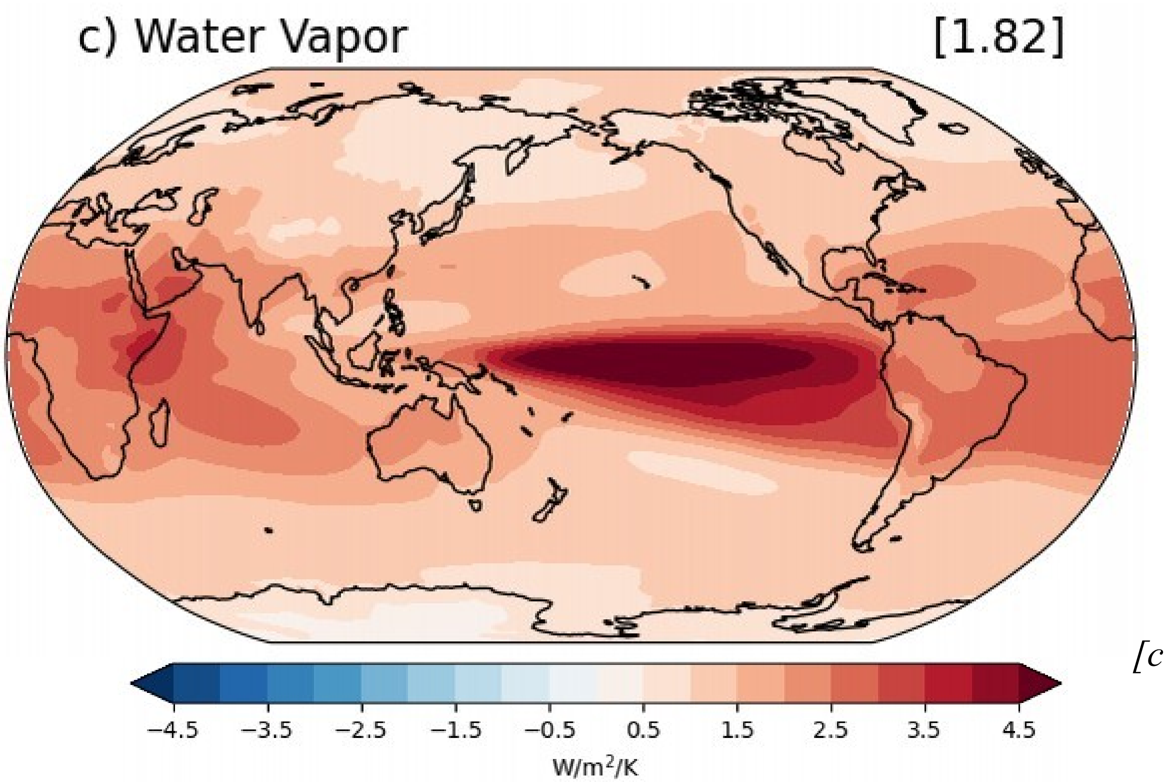
Water vapour feedback



$$\frac{\partial R}{\partial Q_a(P)}\frac{d\,Q_a(P)}{d\,T_s}$$

W/m^2/K/(100hPa)

Soden et al., J. Climate, 2008



[courtesy of M. Zelinka 2021]

Water vapor

increase of WV

decrease of OLR

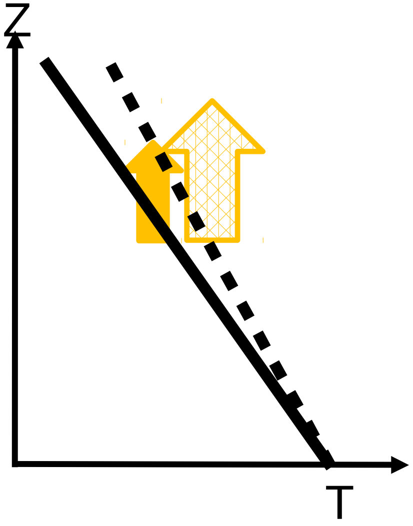
positive feedback

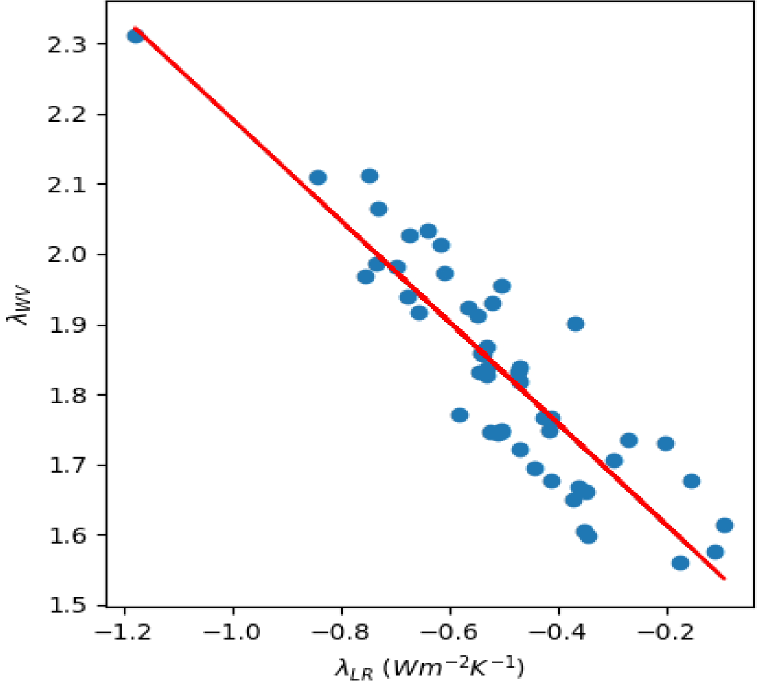
lapse rate feedbacks

decrease of lapse rate

increase of OLR

negative feedback



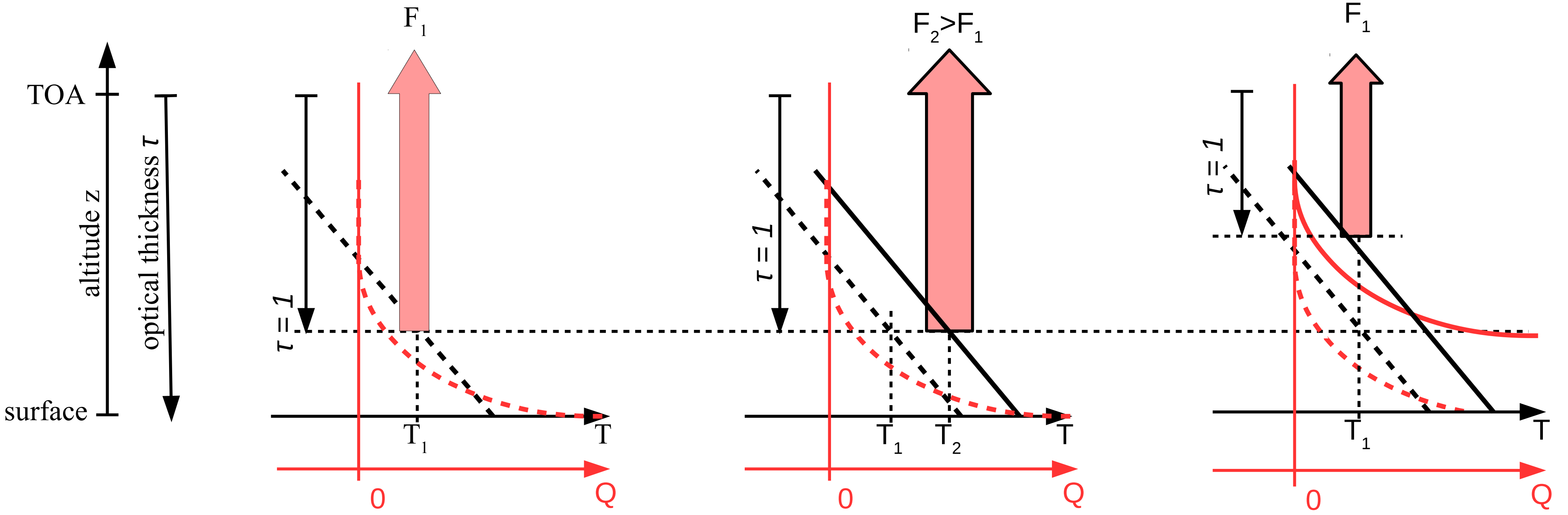


Strong anti-correlation

Water vapor + lapse rate feedbacks

Simpson's law

In spectral regions where gases are highly absorbent of an atmosphere whose properties vary continuously and smoothly with altitude and pressure...



Emission height

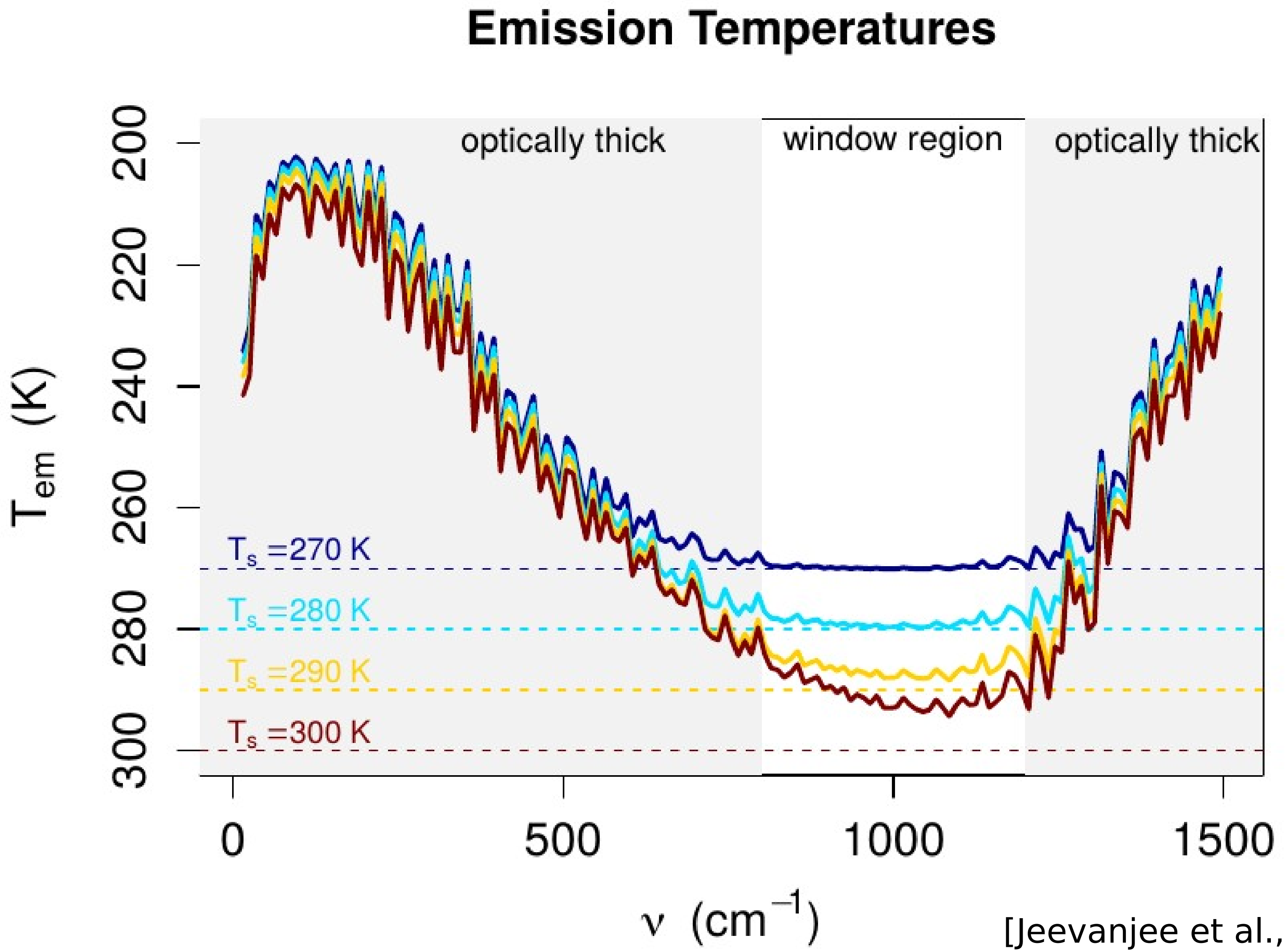
A warmer atmosphere with fixed GHG profile

A warmer atmosphere with fixed relative humidity profile

Hypothesis:

- Spectral domain with H_2O strong absorption, no other GHGs, no clouds
- Relative humidity is constant, as is the vertical temperature gradient
- The absorption properties do not depend on temperature and pressure => the emission altitude can be considered independent of the temperature profile and dependent only on the GHGs concentration profile.

For idealized clear sky tropical atmospheres with constant relative humidity



[Jeevanjee et al., GRL, 2021]

Climate feedbacks

Two decompositions for the temperature + water vapor feedback:

the (classical) **absolute humidity** feedback decomposition :

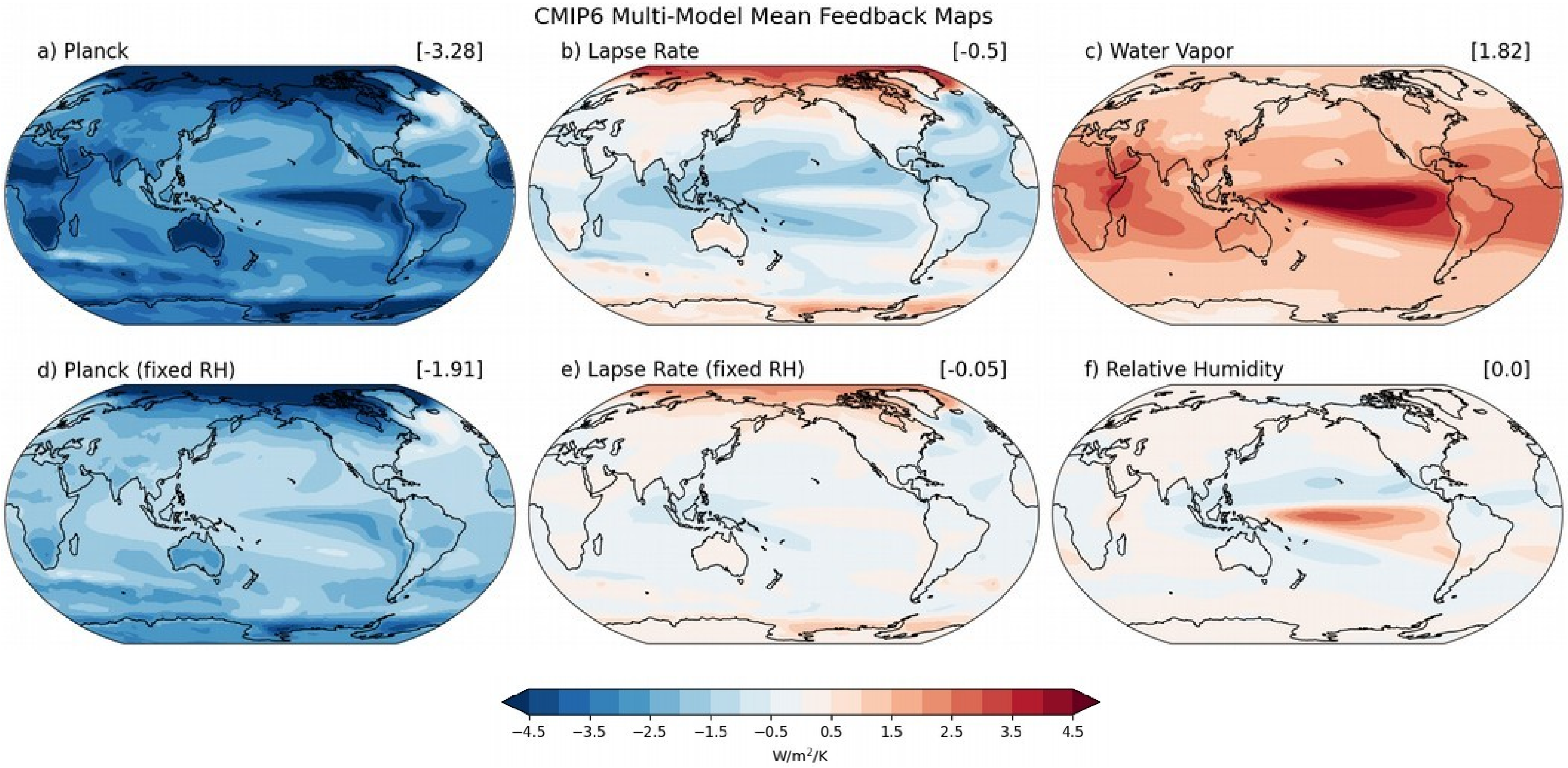
$$\boxed{\lambda = \underset{\text{Planck}}{\lambda_{P|Q}} + \underset{\substack{\text{lapse}\\ \text{rate}}}{\lambda_{L|Q}} + \underset{\substack{\text{water}\\ \text{vapor}}}{\lambda_{Q}} + \underset{\text{clouds}}{\lambda_{C}} + \underset{\substack{\text{surface}\\ \text{albedo}}}{\lambda_{a}}}$$

the **relative humidity** feedback decomposition :

$$\boxed{\lambda = \underset{\substack{\text{Planck at}\\ \text{fixed RH}}}{\lambda_{P|R}} + \underset{\substack{\text{lapse rate}\\ \text{at fixed RH}}}{\lambda_{L|R}} + \underset{\text{RH}}{\lambda_{R}} + \underset{\text{clouds}}{\lambda_{C}} + \underset{\substack{\text{surface}\\ \text{albedo}}}{\lambda_{a}}}$$

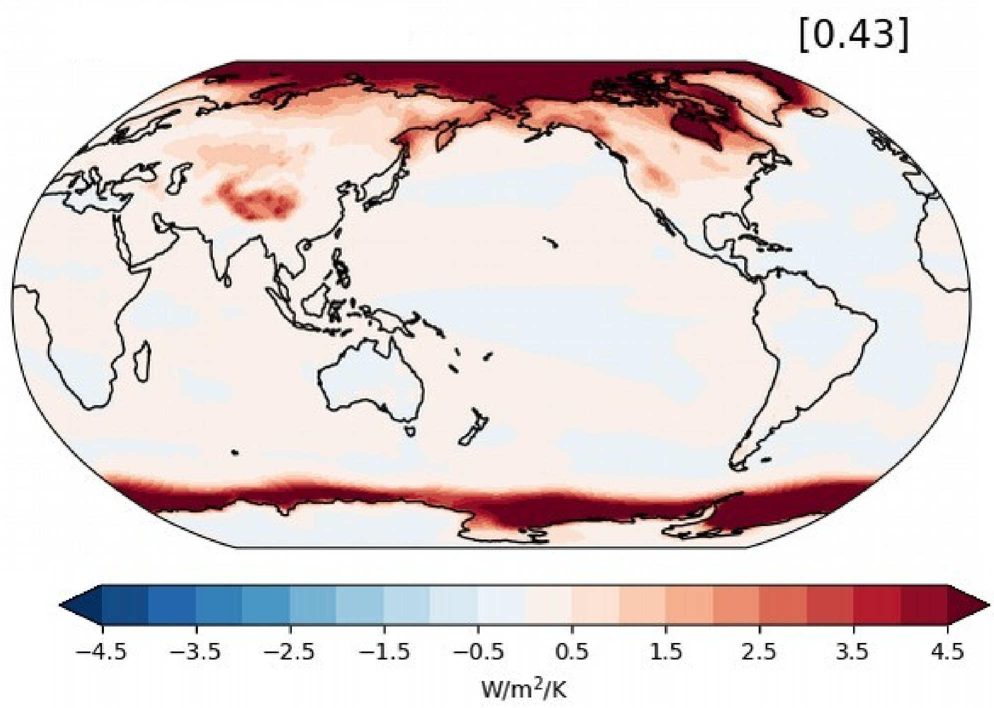
[Held & Shell, J. Clim, 2012]

Climate feedbacks with the absolute and relative humidity decompositions

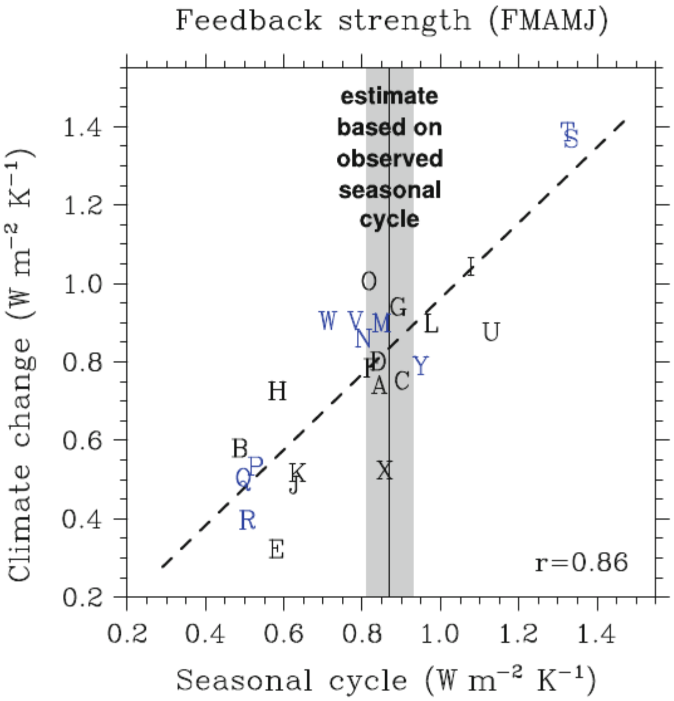


[courtesy of M. Zelinka 2021]
(https://doi.org/10.5281/zenodo.5206851)

Surface albedo feedback



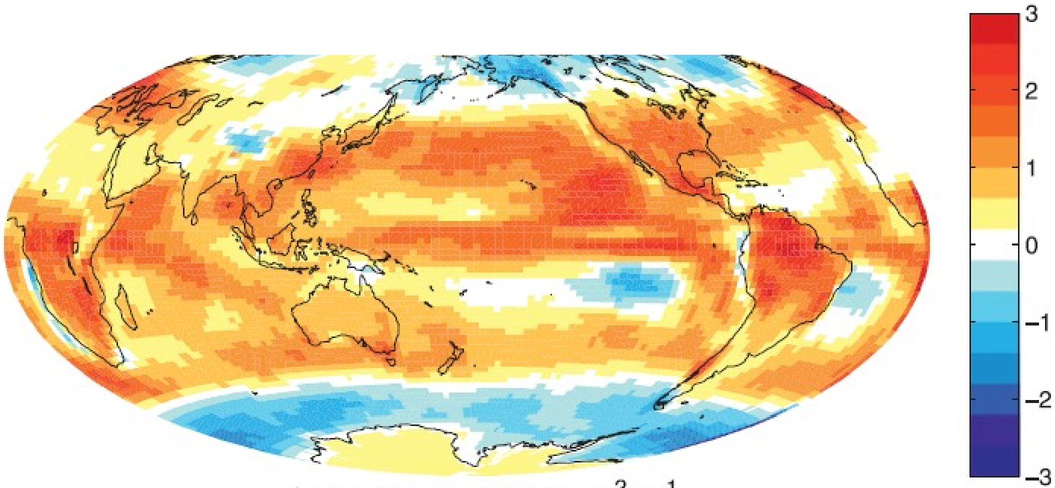
Relationship between snow-albedo feedback for climate change and for seasonal cycle



[Qu & Hall., Clim Dyn., 2014]

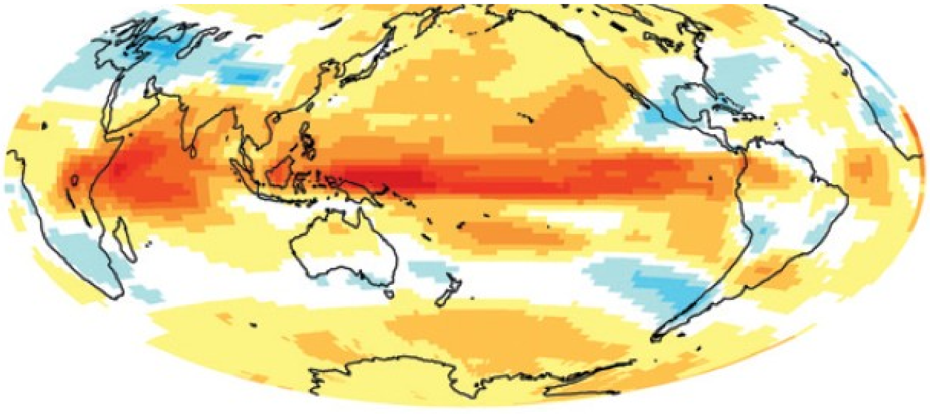
Cloud feedbacks

total



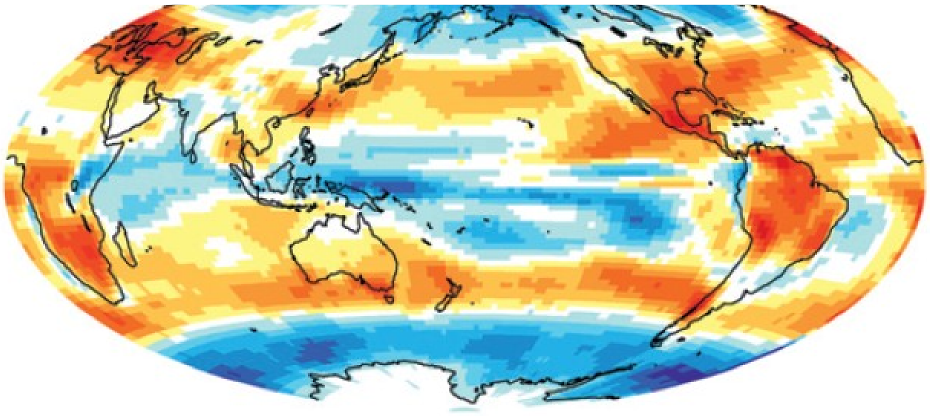
Global Mean = 0.61 W m^{-2} K^{-1}

LW (infrared)



Global Mean = 0.56 W m^{-2} K^{-1}

SW (solar)

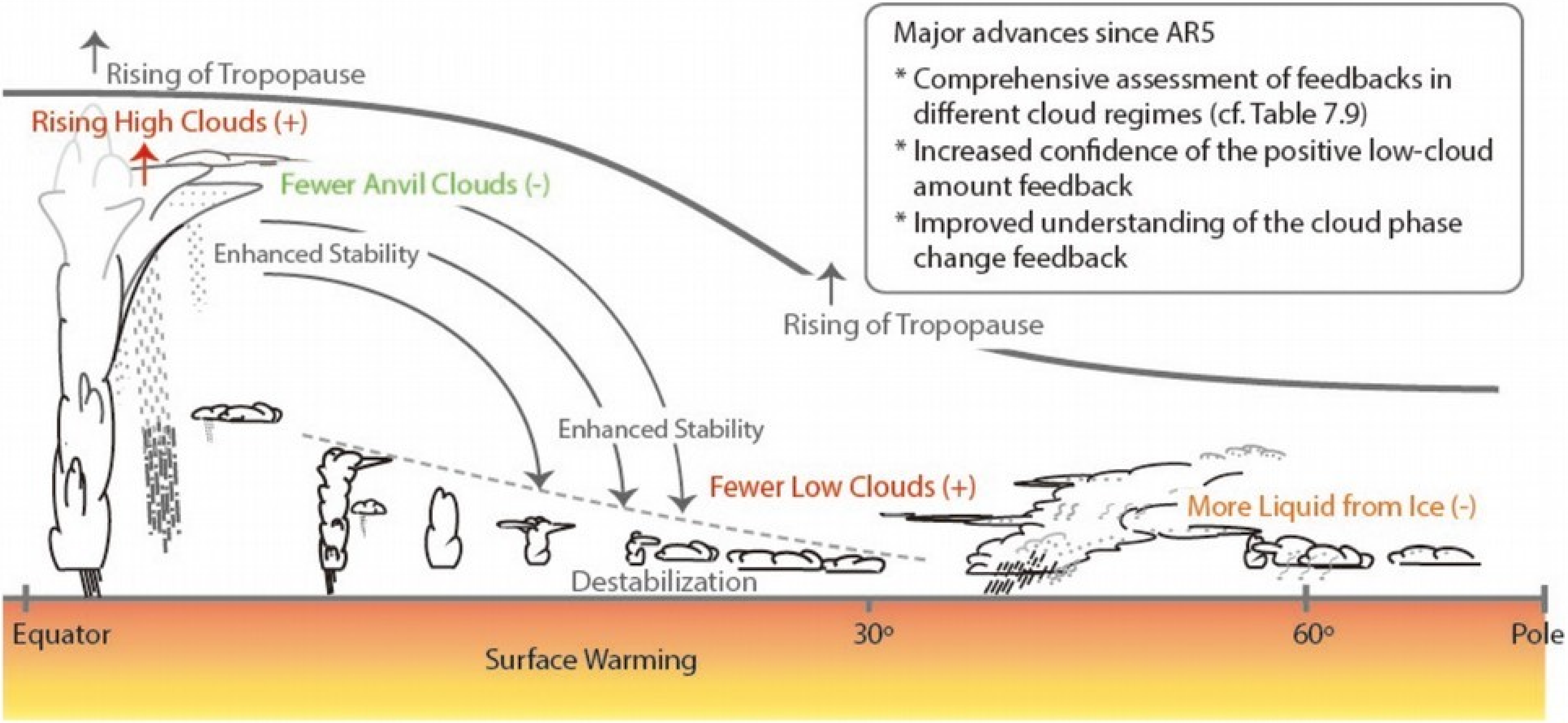


Global Mean = 0.05 W m^{-2} K^{-1}

[Zelinka et al., 2012]

Cloud feedbacks

- Very large inter-model spread of cloud feedbacks in climate models
- Clouds feedbacks are assessed separately for ***different cloud regimes*** and then summed
- Each cloud regimes is assessed using different lines of evidence (theory, observation, HR models...)



Major advances since AR5

- * Comprehensive assessment of feedbacks in different cloud regimes (cf. Table 7.9)
- * Increased confidence of the positive low-cloud amount feedback
- * Improved understanding of the cloud phase change feedback

Thin grey text and arrows represent robust responses. Text and arrows in red, orange and green show the major cloud responses assessed with high, medium and low confidence, respectively, with the sign of their feedbacks in parenthesis.

[IPCC AR6 WG1, ch 7]

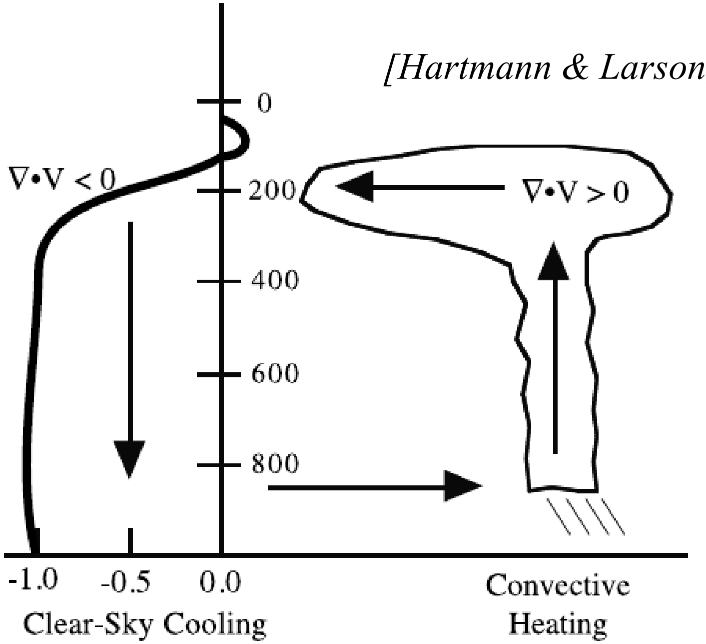
High cloud feedbacks

The detainment of anvil clouds is driven by clear sky radiative cooling.

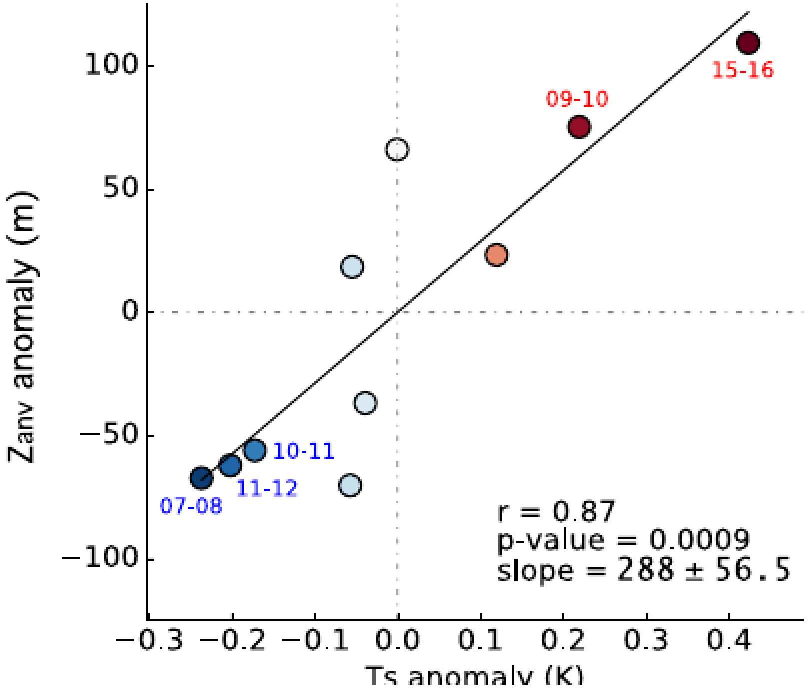
FAT (fixed anvil temperature) (Hartmann & Larson 2002, Zelinka & Hartmann (2010)

Stability Iris effect (Bony et al., 2016)

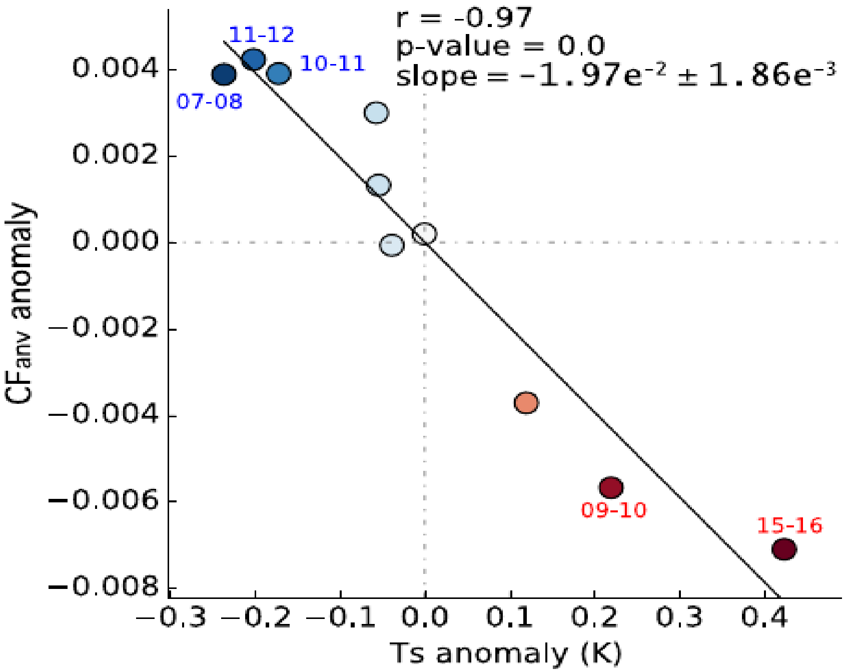
Evidence using observations (Saint-Lu et al., 2020)



[Hartmann & Larson, 2002]

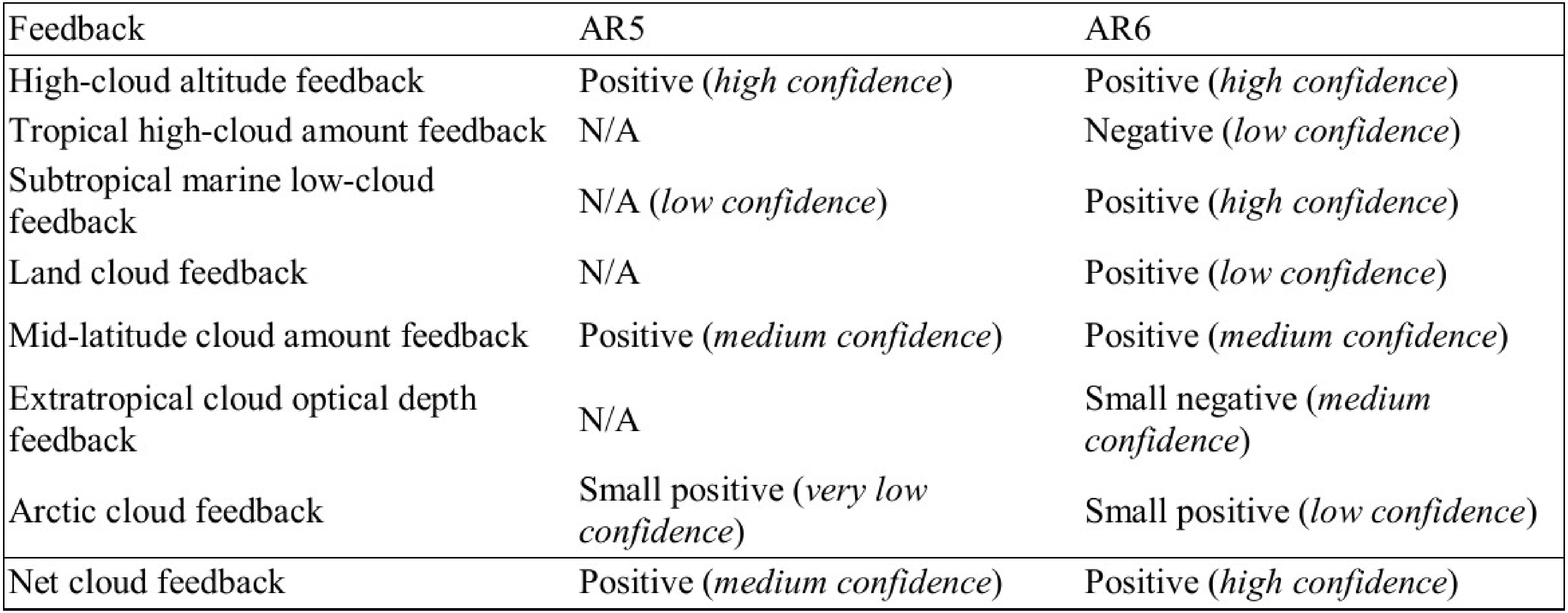


(a) Zanv against Ts



(a) CFanv against Ts

Cloud feedbacks



Feedback	AR5	AR6
High-cloud altitude feedback	Positive (*high confidence*)	Positive (*high confidence*)
Tropical high-cloud amount feedback	N/A	Negative (*low confidence*)
Subtropical marine low-cloud feedback	N/A (*low confidence*)	Positive (*high confidence*)
Land cloud feedback	N/A	Positive (*low confidence*)
Mid-latitude cloud amount feedback	Positive (*medium confidence*)	Positive (*medium confidence*)
Extratropical cloud optical depth feedback	N/A	Small negative (*medium confidence*)
Arctic cloud feedback	Small positive (*very low confidence*)	Small positive (*low confidence*)
Net cloud feedback	Positive (*medium confidence*)	Positive (*high confidence*)

[IPCC AR6 WG1, ch 7]

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1) Estimating climate sensitivity by **understanding the processes**

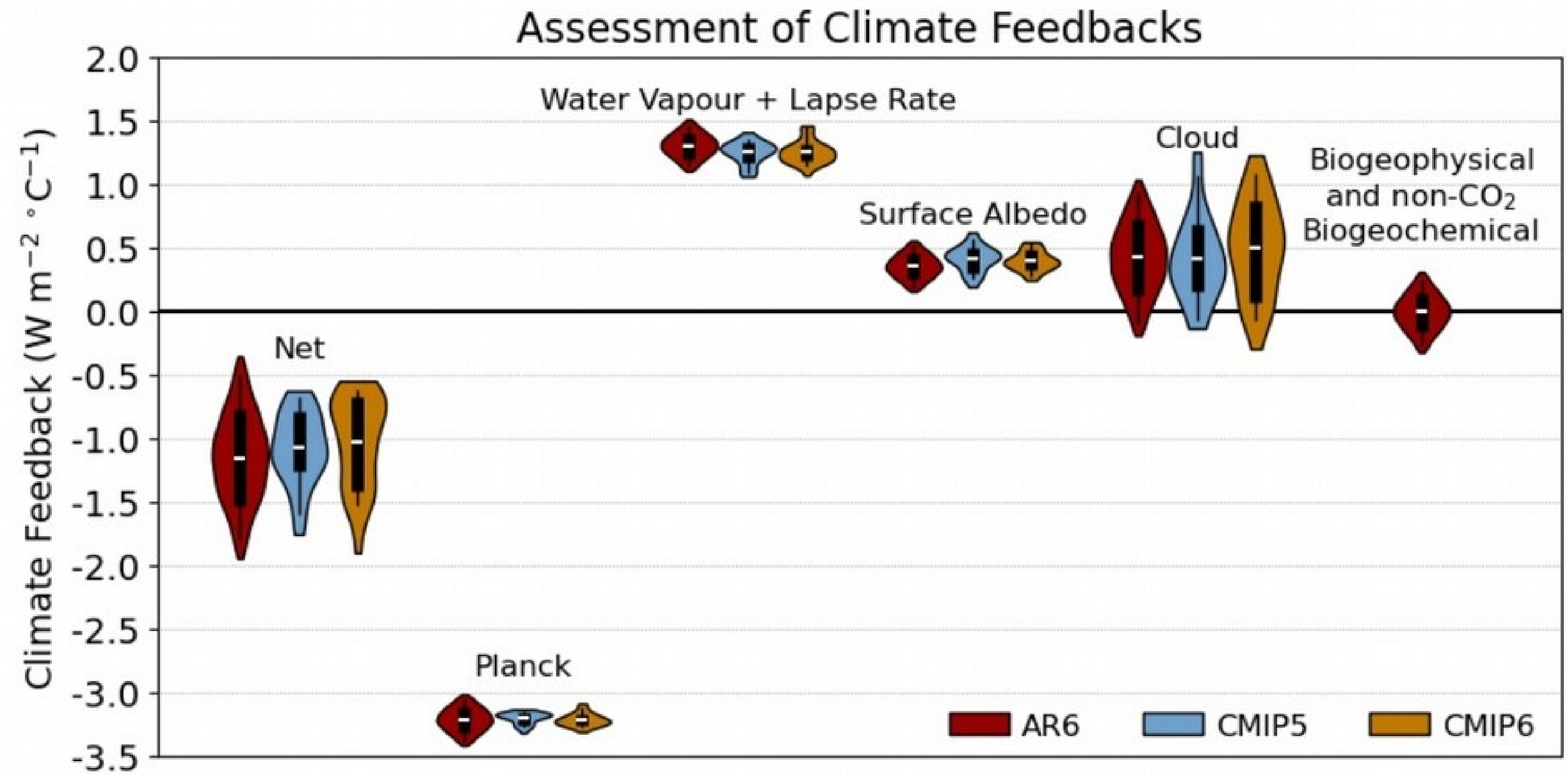
$$\boxed{ECS = \frac{\Delta Q(2\times CO_2)}{-\lambda}}$$

← Radiative forcing for a doubling of the CO_2 concentration

← Climate feedback parameter

Separate estimate of $\Delta Q(2xCO_2)$ and λ

λ is estimated using different approaches, models and observations



[IPCC AR6 WG1, ch 7]

1) Estimating climate sensitivity by **understanding the processes**

$$\boxed{ECS = \frac{\Delta Q(2\times CO_2)}{-\lambda}}$$

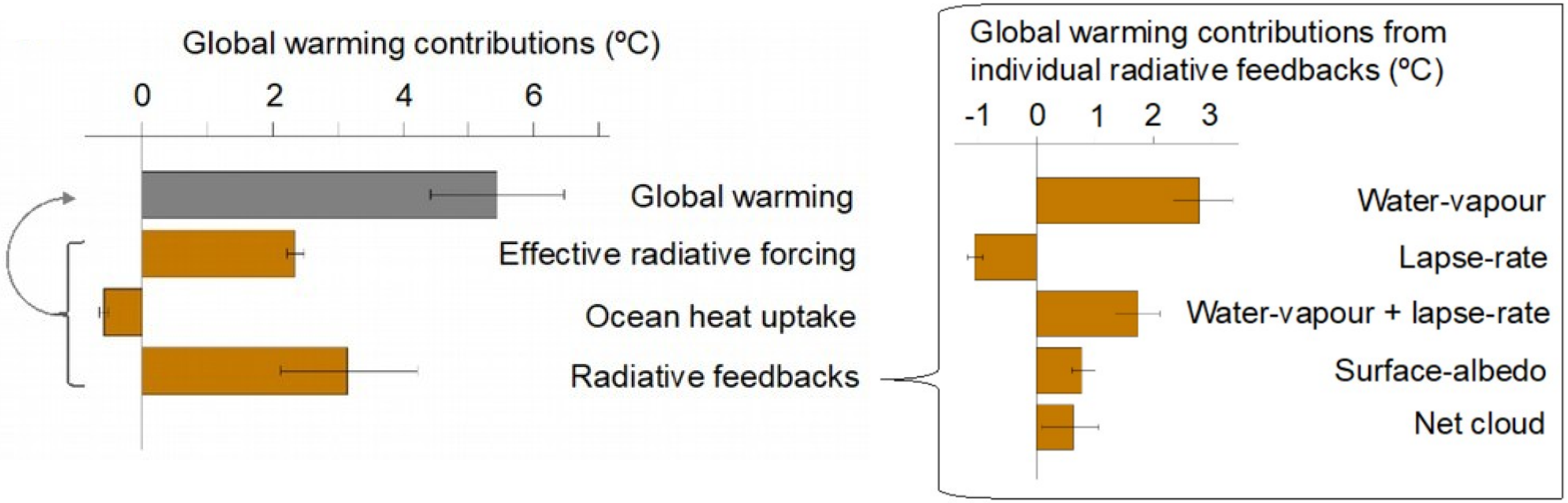
Radiative forcing for a doubling of the CO_2 concentration

Climate feedback parameter

Separate estimate of $\Delta Q(2xCO_2)$ and λ

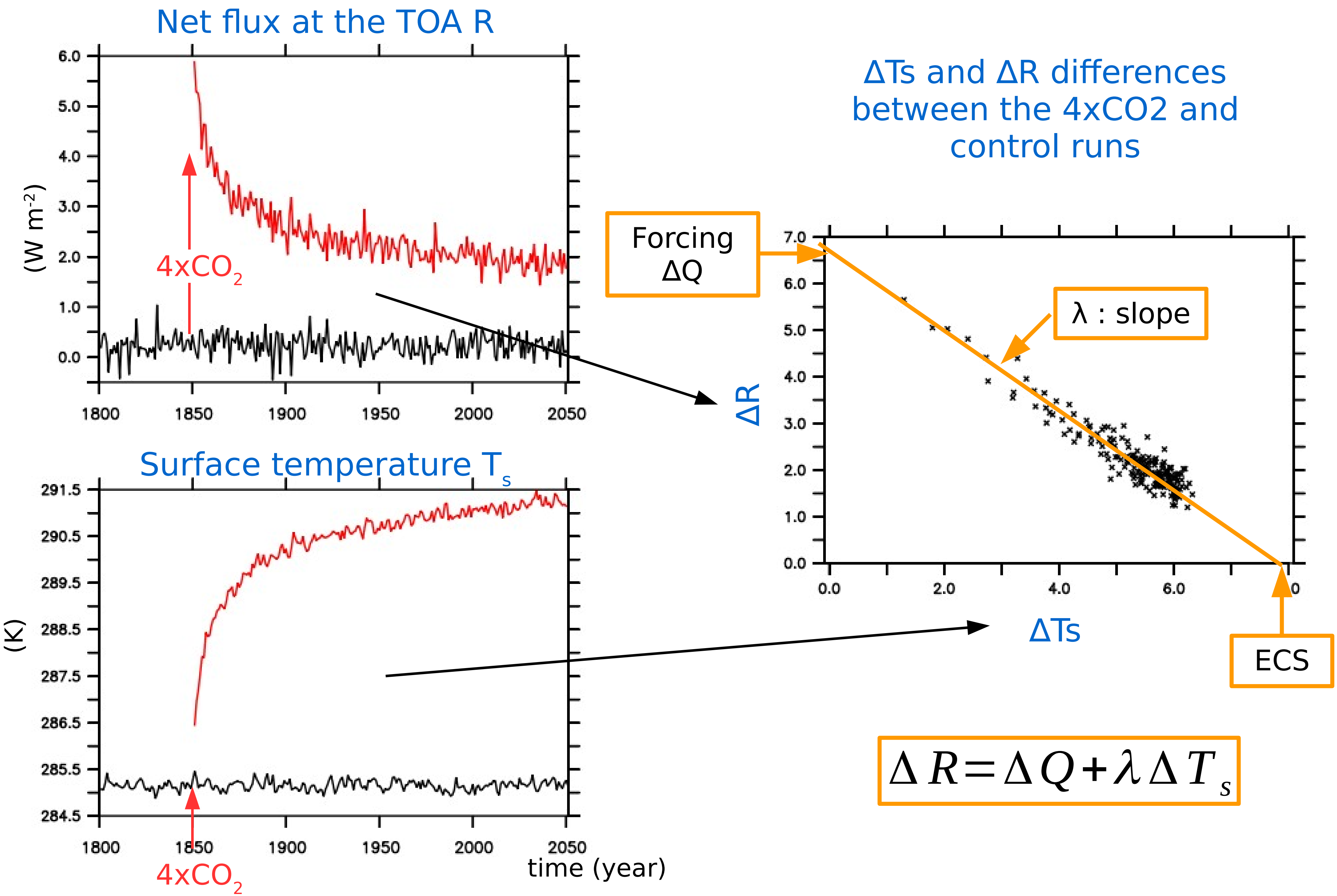
λ is decomposed into a « basic » (Planck) response + climate feedbacks

Response for 4xCO2



[IPCC AR6 WG1, ch 7]

2) Estimating climate sensitivity by **direct** use of **climate models results**



Net flux at the TOA R

Surface temperature T_s

ΔTs and ΔR differences between the 4xCO2 and control runs

Forcing ΔQ

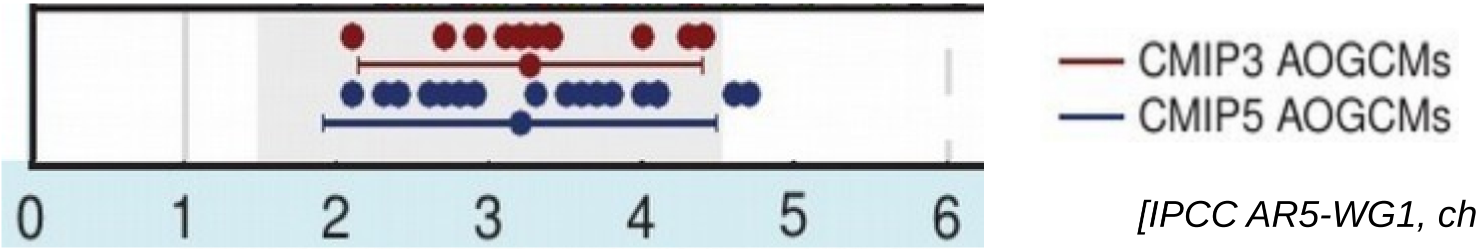
λ : slope

ECS

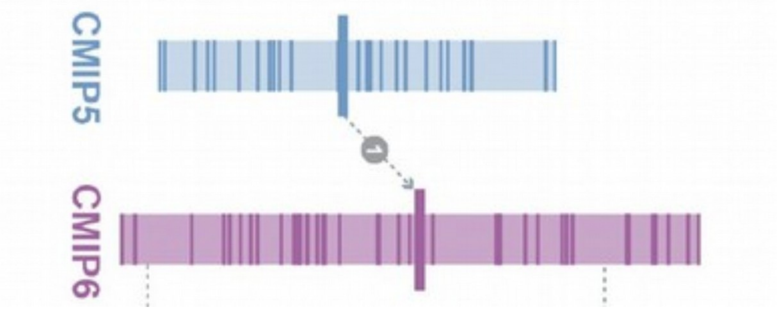
$$\boxed{\Delta R = \Delta Q + \lambda \Delta T_s}$$

2) Estimating climate sensitivity by **direct** use of **climate models results**

ΔT simulated by climate models in response to 2xCO2, extrapolated for an equilibrium ocean



[IPCC AR5-WG1, ch 12]



[IPCC AR6-WG1, ch 7]

Small panic during AR6: a large number of models have a very high climate sensitivity.

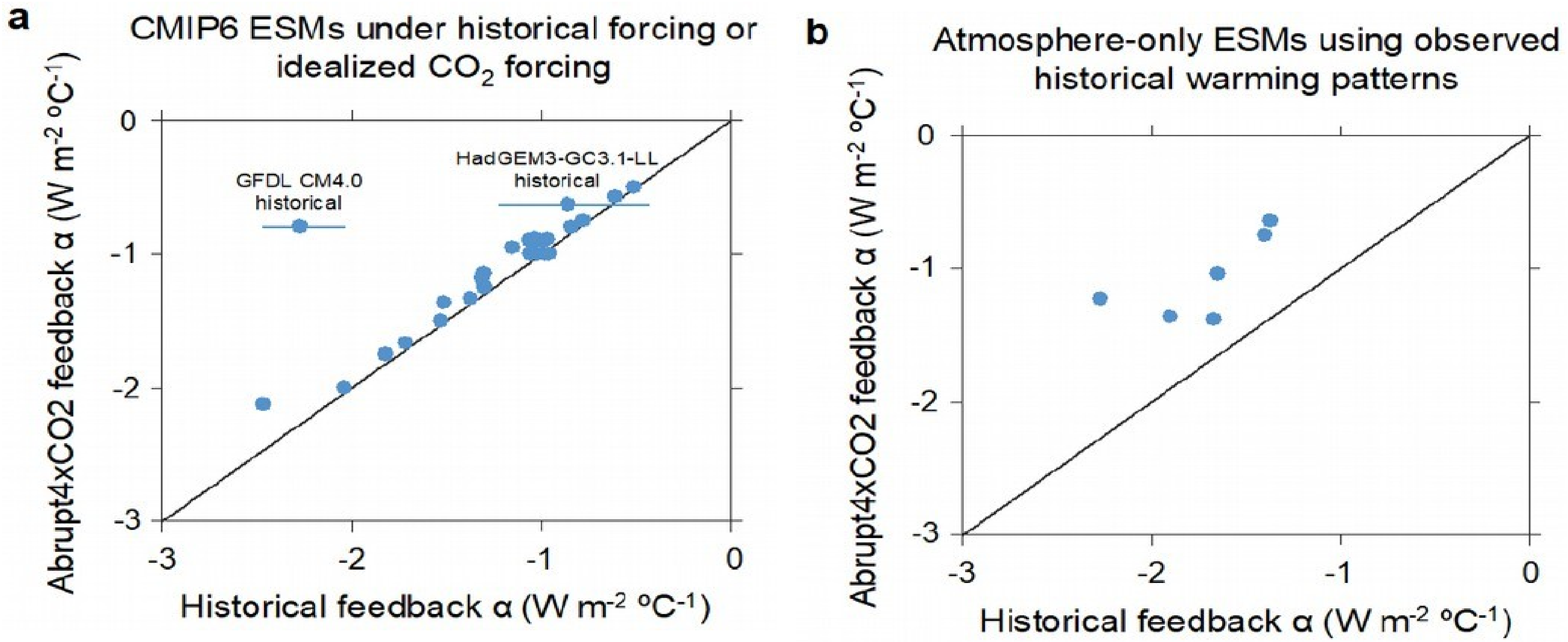
3) Estimating climate sensitivity based on the **instrumental record**

The ECS can be estimated using recent trends if the changes in temperature ΔT_p and heat budget ΔR in response to a forcing ΔQ_p are known

$$\Delta R = \Delta Q_p + \lambda\, \Delta T_p \qquad ECS = \frac{-\Delta Q(2xCO_2)}{\lambda} \quad \Rightarrow \quad \boxed{ECS = \Delta T_p \frac{\Delta Q(2\times CO_2)}{[\Delta Q_p - \Delta R]}}$$

In the AR5, estimates based on the instrumental record **were consistently lower** than those based on climate models.

In this approach, an implicit assumption is that **feedback parameters are constant**

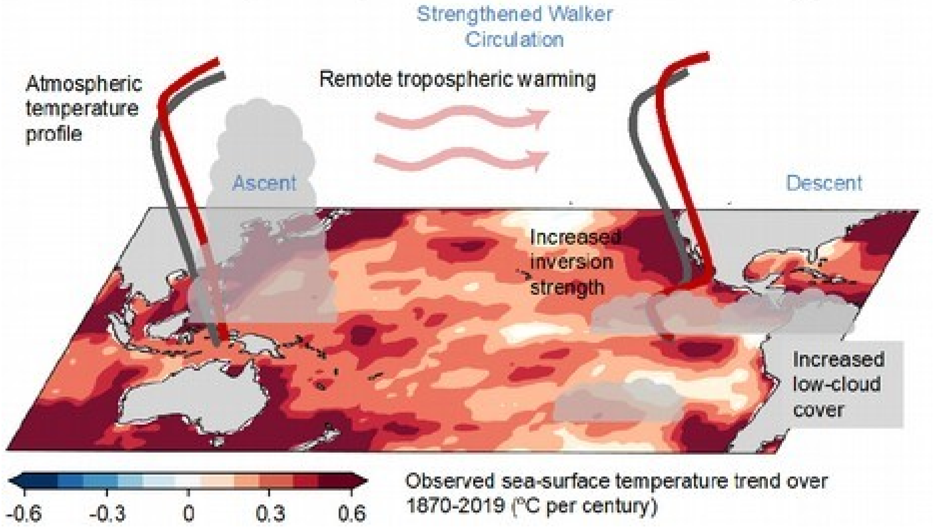


[IPCC AR6 WG1, ch 7]

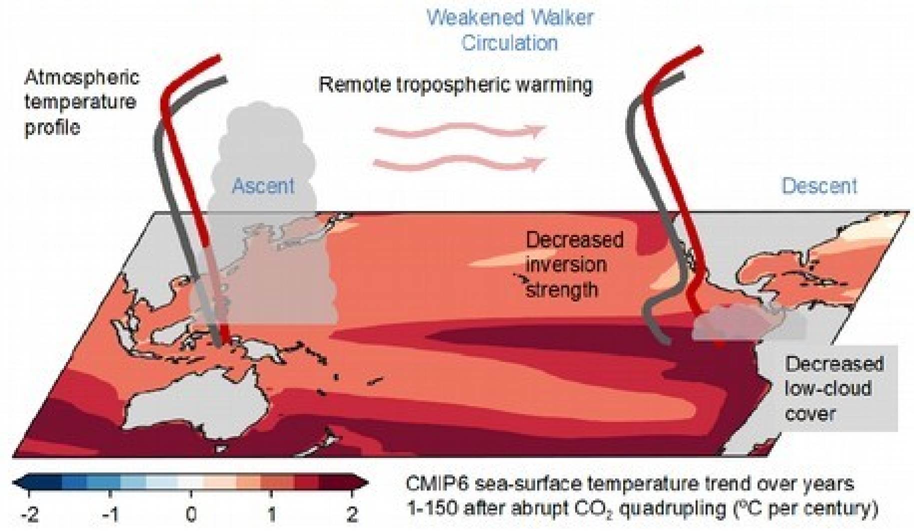
The « pattern effect »

But the feedback parameters **depends on the pattern of SST warming**

Atmospheric response to **observed** warming



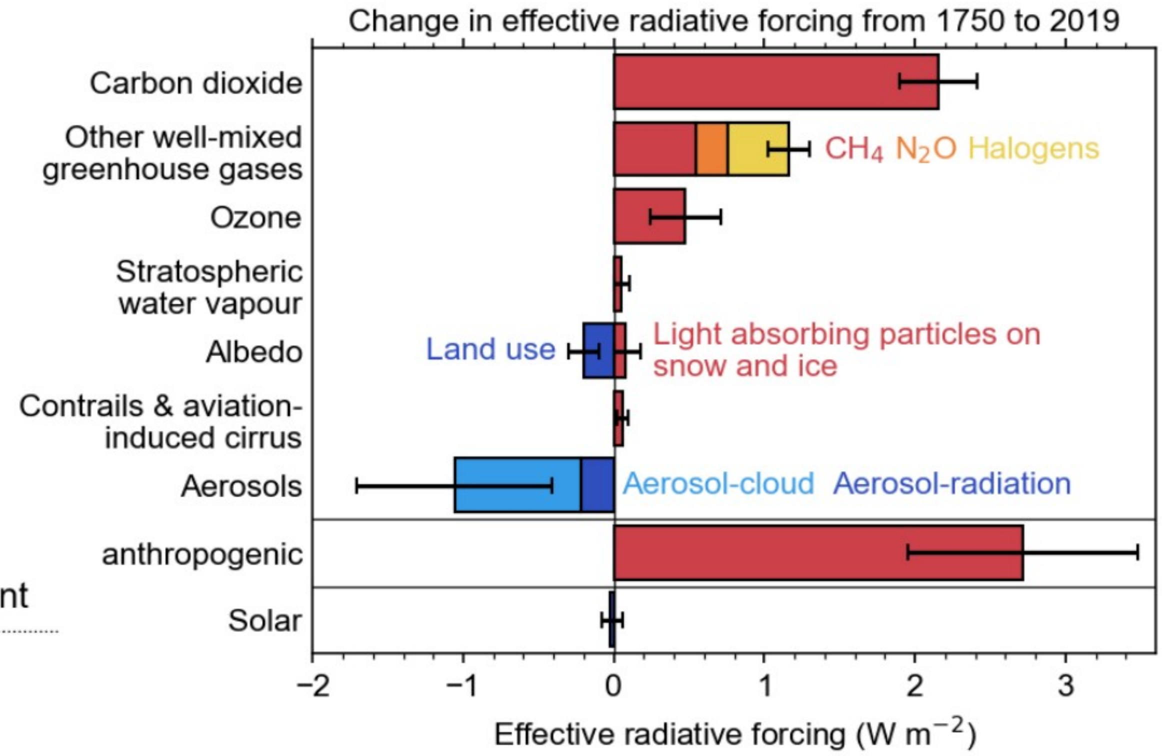
Atmospheric response to **projected** warming

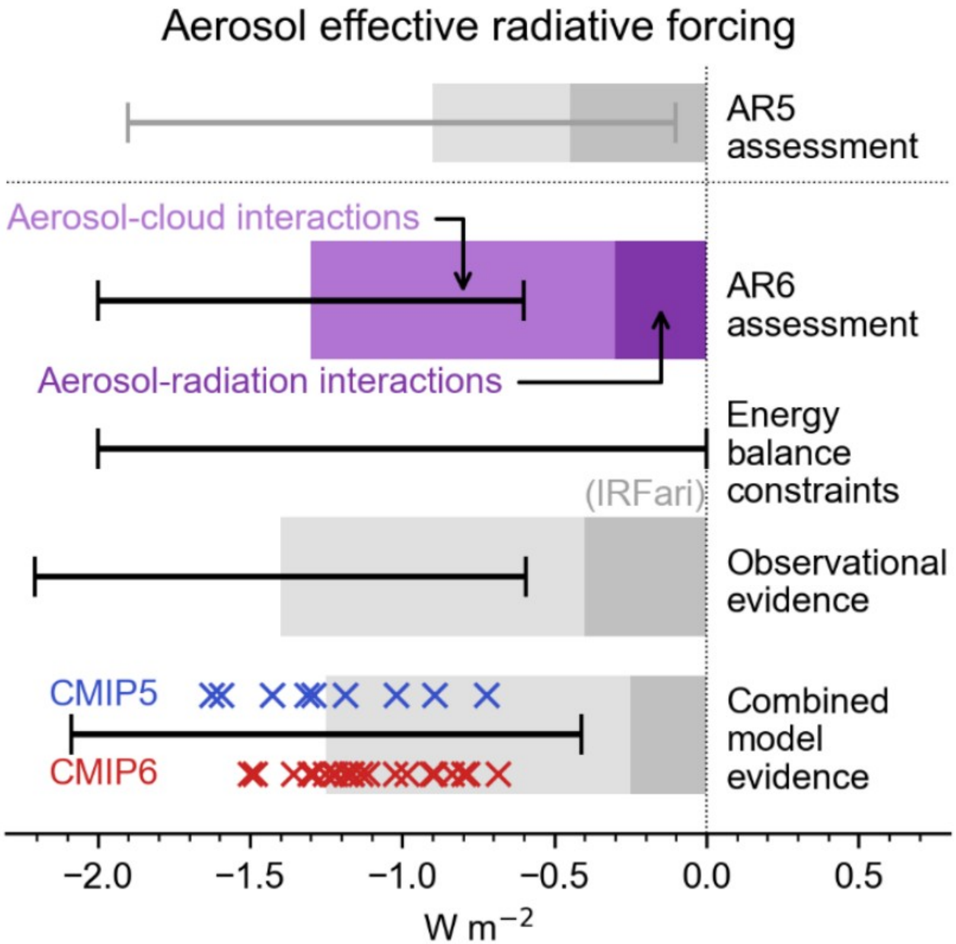


[IPCC AR6 WG1, ch 7]

The radiative forcings

$$ECS = \Delta T_p \frac{\Delta Q(2\times CO_2)}{[\Delta Q_p - \Delta N]}$$





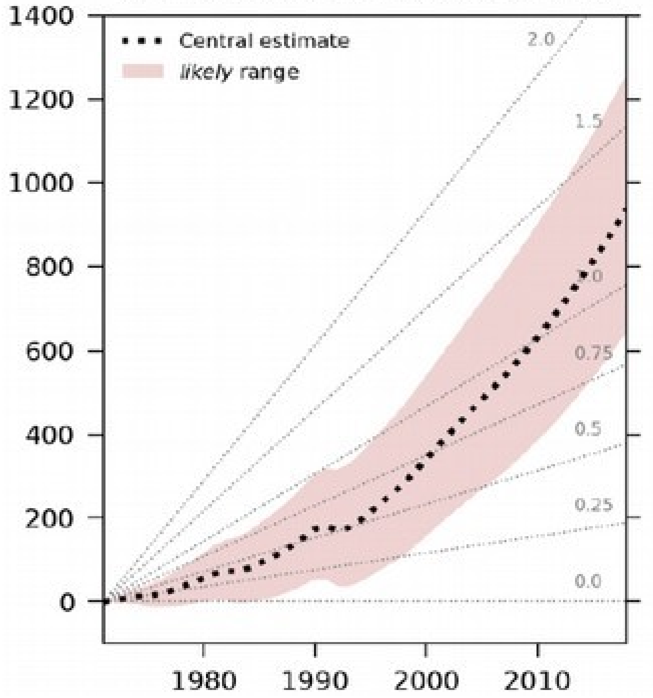
[IPCC AR6 WG1, ch 7]

3) Estimating climate sensitivity based on the **instrumental record**

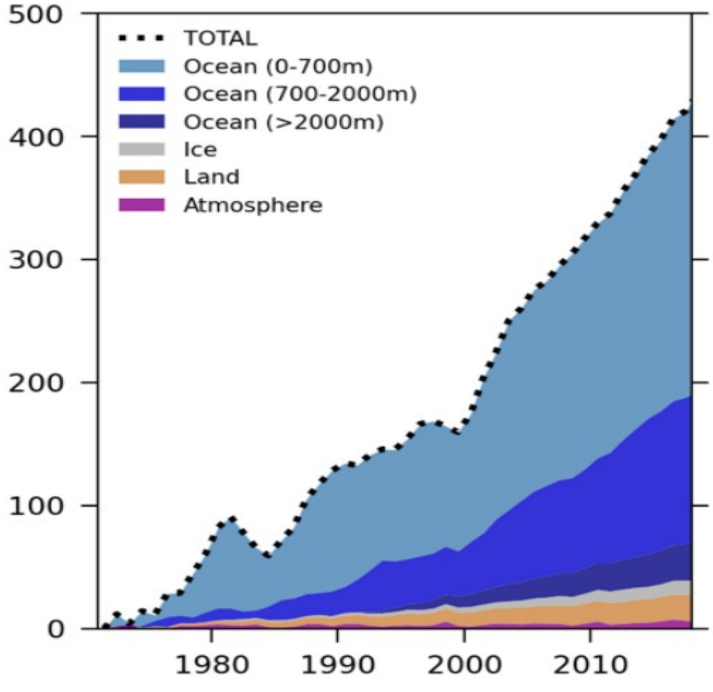
The ECS can be estimated using recent trends if the changes in temperature ΔT_p and heat budget ΔN in response to a forcing ΔQ_p are known

$$ECS = \Delta T_p \frac{\Delta Q(2\times CO_2)}{[\Delta Q_p - \Delta N]}$$

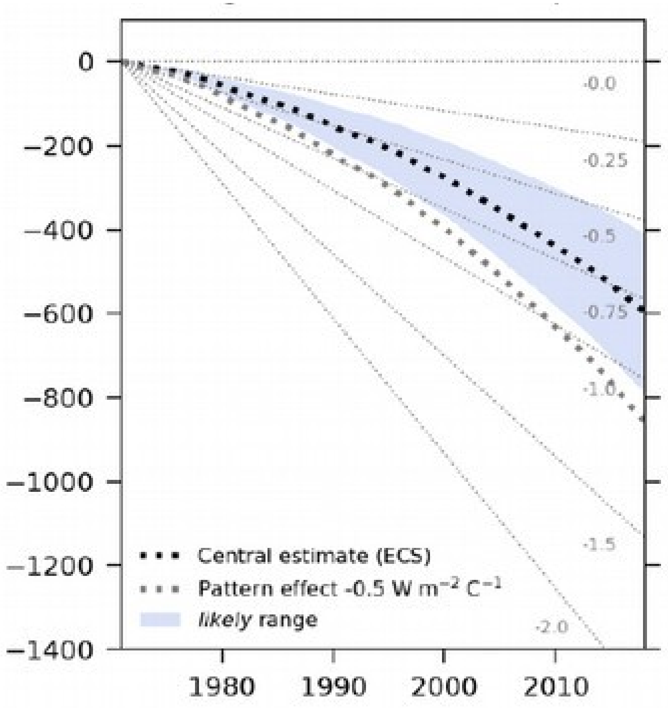
Integrated radiative forcing (ΔQ_p)



Heat budget (ΔN)



Integrated radiative response (λ ΔTs)

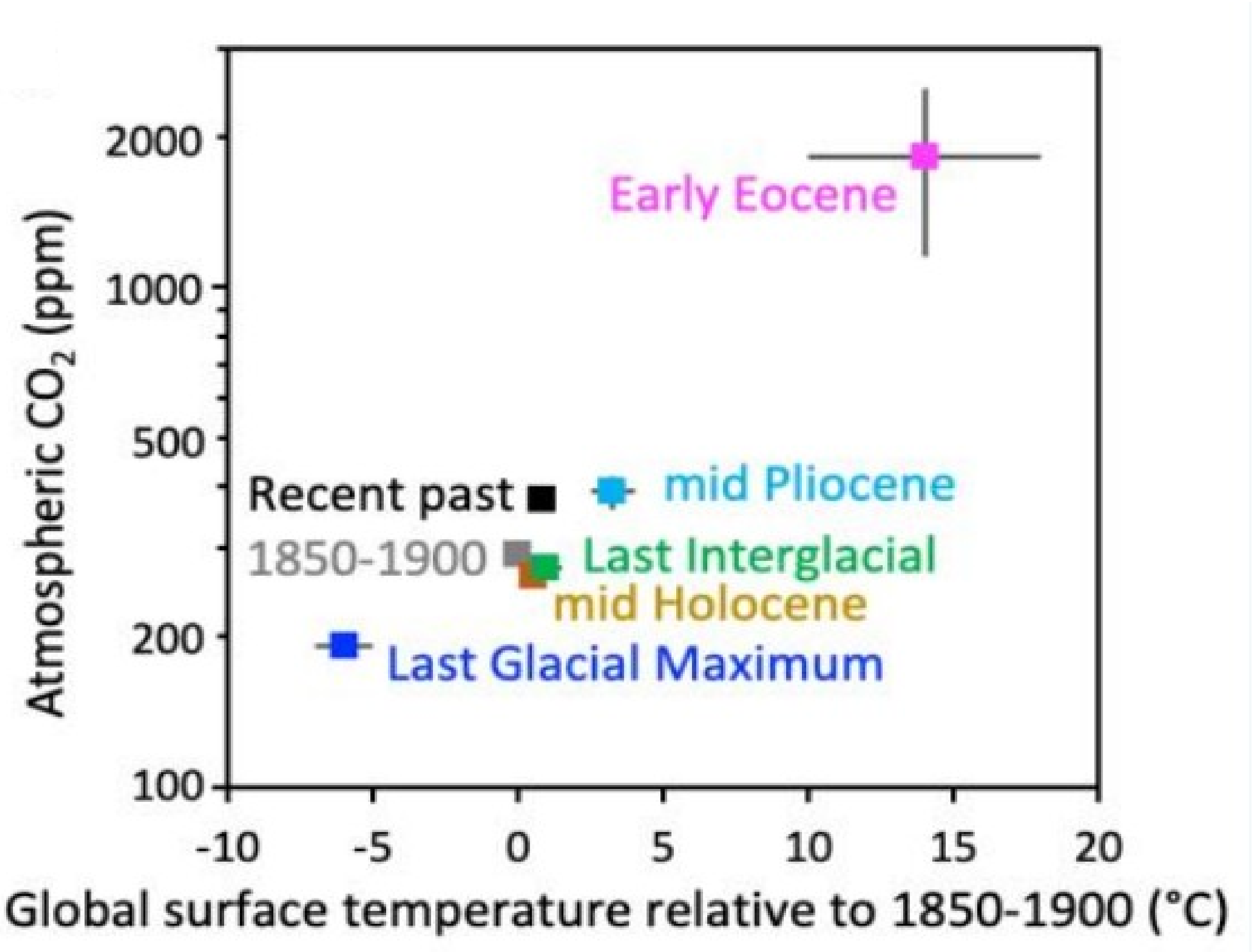


[IPCC AR6 WG1, ch 7]

4) Estimating climate sensitivity based on **paleoclimate data**

Périodes Paléo

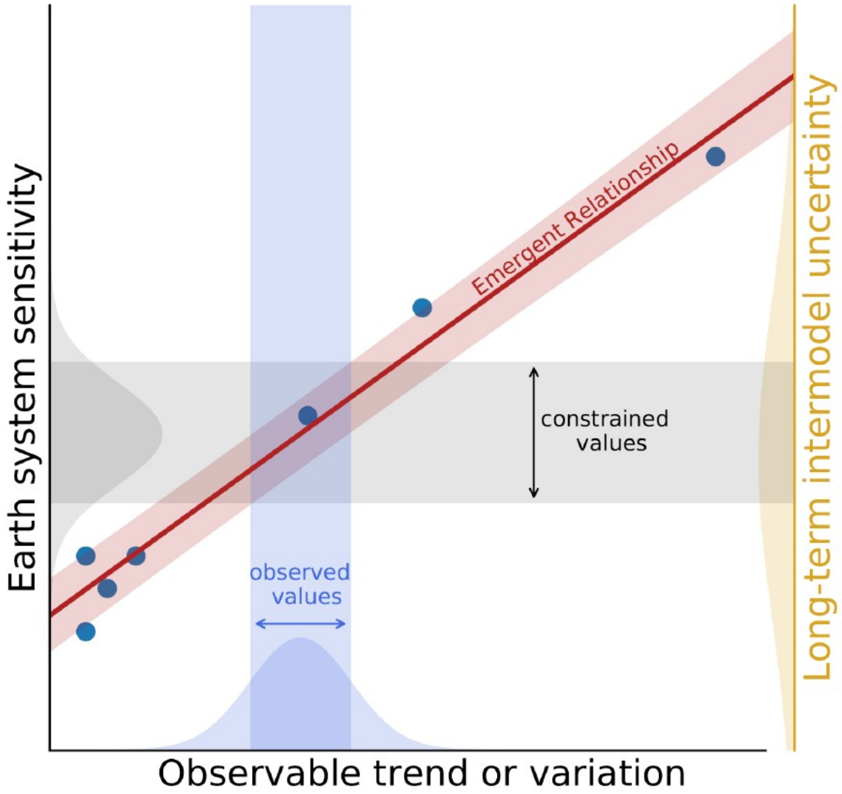
$$ECS = \Delta T_p \frac{\Delta Q(2 \times CO_2)}{[\Delta Q_p - \Delta N]}$$



[IPCC AR6-WG1, TS]

5) Estimating climate sensitivity based on **emergent constraints**

An emergent constraint is a physically interpretable relationship between an uncertain aspect of future climate change and an observable feature of the Earth system, identified in an ensemble of models.



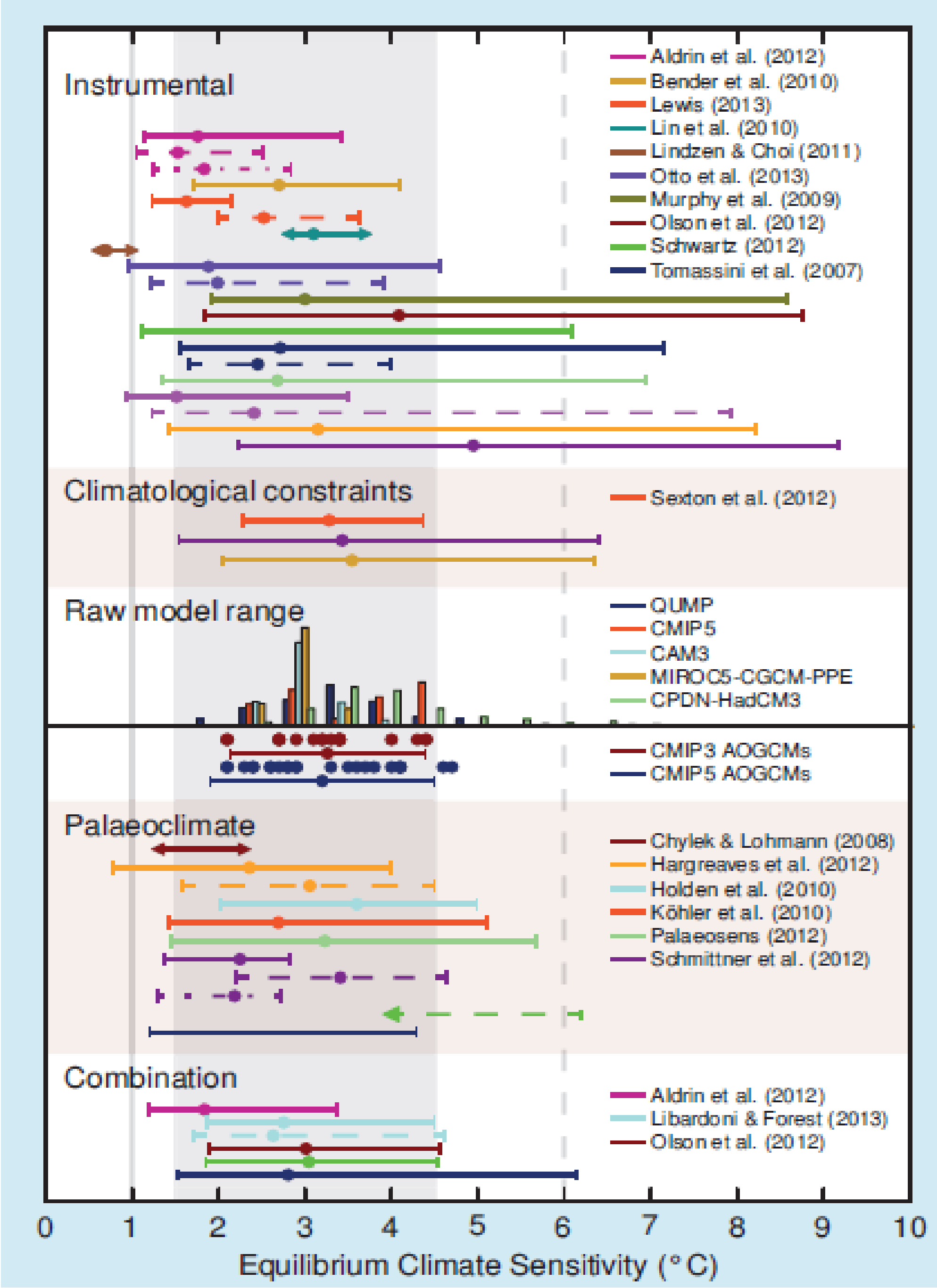
[IPCC AR6 WG1, ch 1]

- Paleoclimate (temperature)
- Recent past (temperature)
- Natural variability (temperature)
- Key uncertain process (i.e. low level cloud response)

Outline

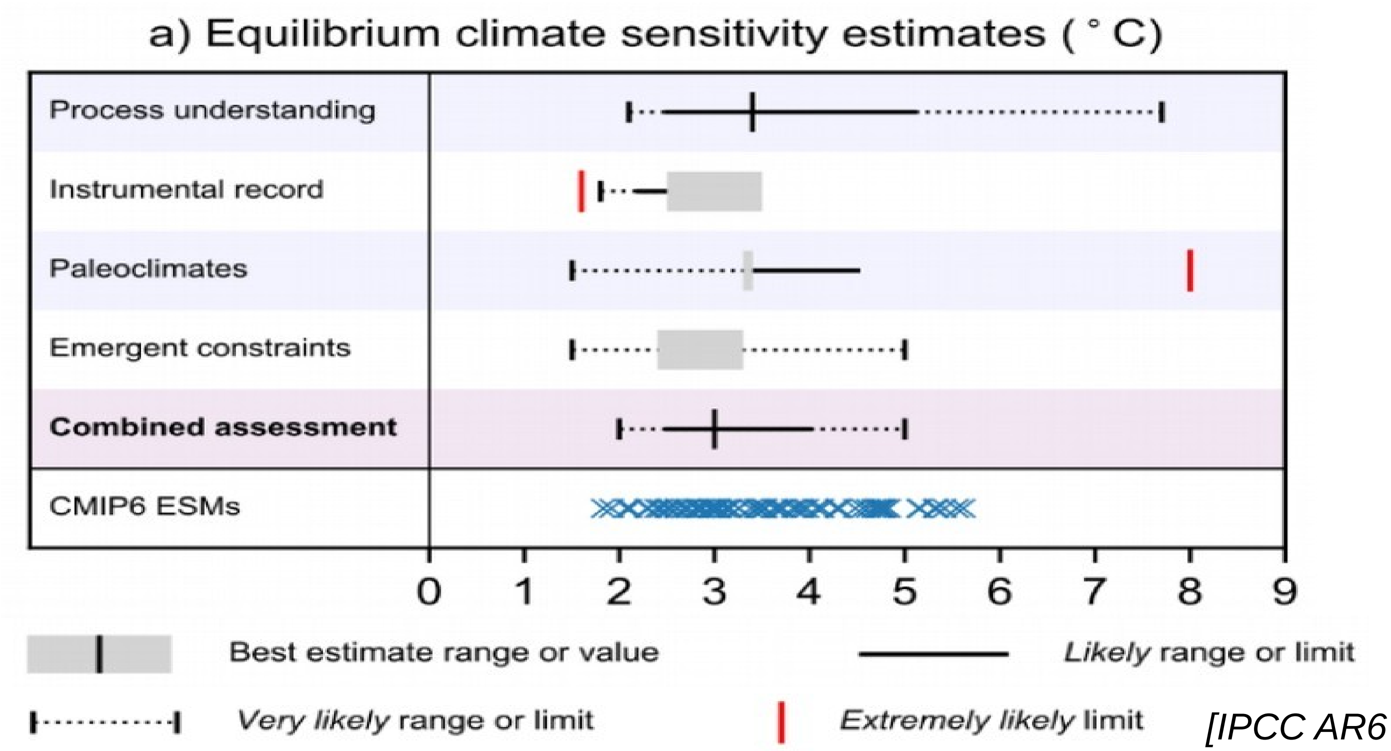
- Definition and interest of climate sensitivity
- The main physical mechanisms involved
  - Forcings
  - Feedbacks
- Different ways to determine climate sensitivity
- How to combine them?
- Conclusion

Estimates of equilibrium climate sensitivity in the AR5



[IPCC AR5-WG1, ch 12]

Combining the different estimates of climate sensitivity in the AR6



[IPCC AR6 WG1, ch 7]

The **central values** are consistent.

For the **limit values**, the estimates are based on:

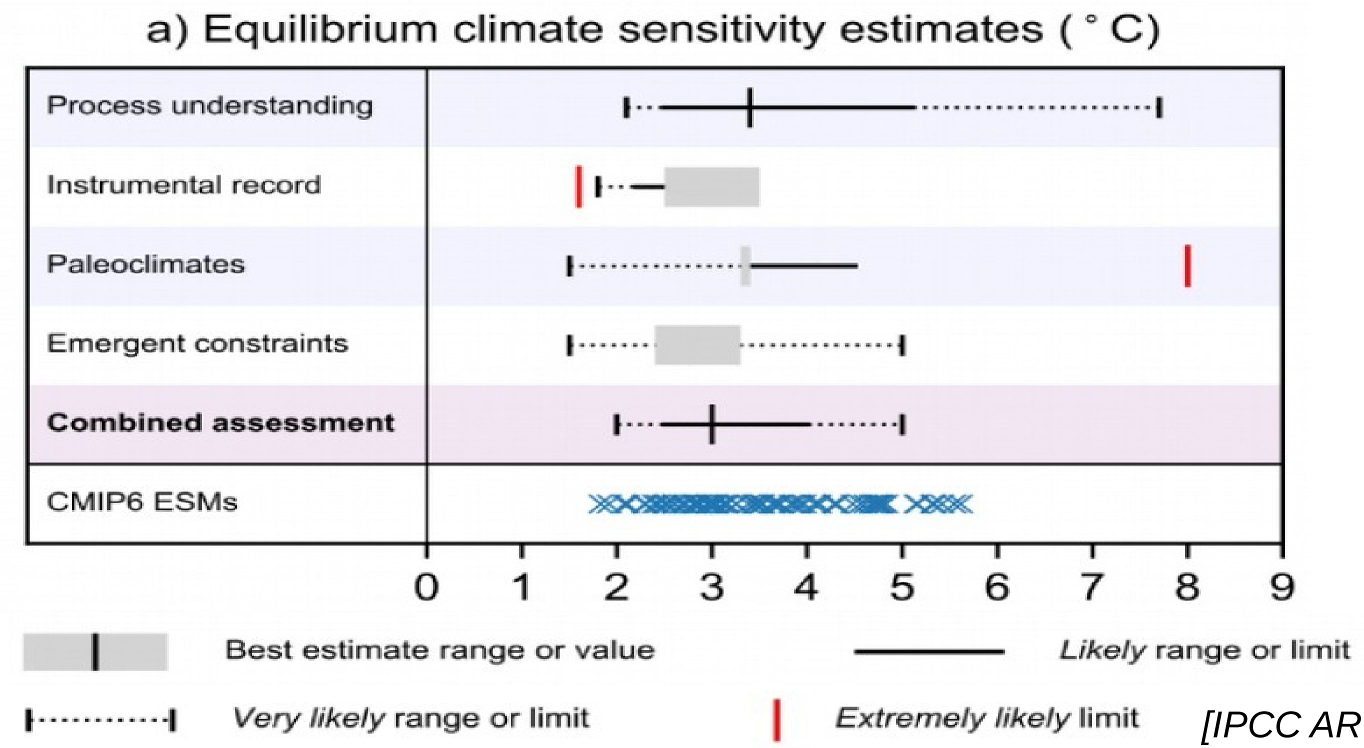
- **AR5** : the "majority" of studies
- **AR6** : the ***combination of probabilities***. If two "lines of evidence" are independent and give a low probability to a limit value, then the combined probability is even lower.

The “CMIP6 models ensemble” is not considered as a line of evidence

Outline

- Definition and interest of climate sensitivity
- The main physical mechanisms involved
    - Forcings
    - Feedbacks
- Different ways to determine climate sensitivity
- How to combine them?
- Conclusion

Role of models in estimating climate sensitivity



[IPCC AR6 WG1, ch 7]

Climate models inform each of the estimates

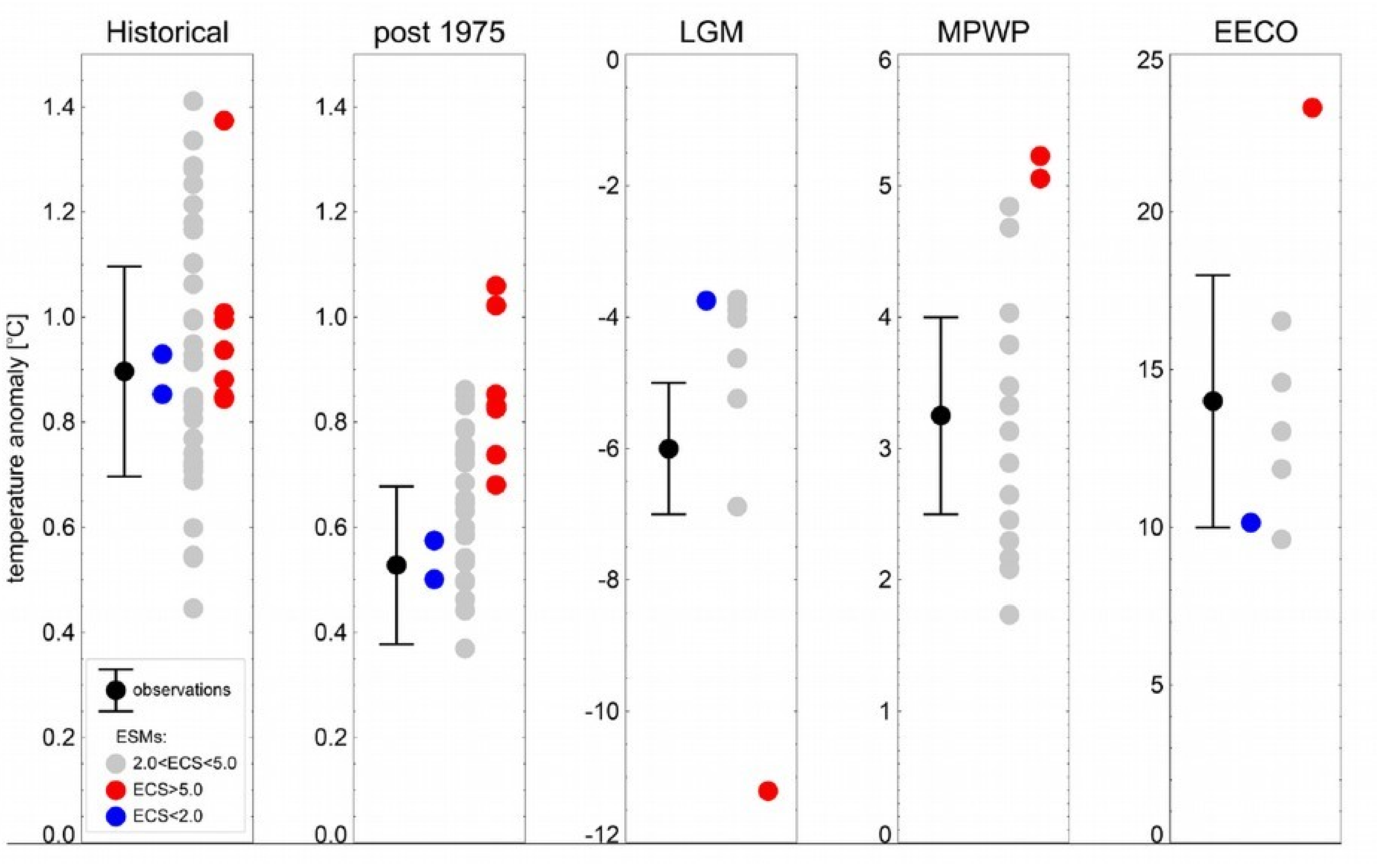
Climate models, taken as a whole, are not used in the estimation of the ECS.

The models are not weighted according to their "good performance".

Model mean and scatter are not relevant to the estimation of warming amplitude

Use (development) of emulators to replace some results previously established on a multi-model basis

Test of models with observational evidence



[IPCC AR6 WG1, ch 7]

climate sensitivity estimate

Reduction of uncertainty on ECS in AR6 results from

- Considering 'muliple lines of evidence' in order to estimate climate sensitivity
- Changing the way they are combined

An approach promoted by the WCRP, implemented by a group of about 20 scientists and which has produced a first assessment (Stevens et al. 2016, Sherwood et al., 2020)

=> Different ways to estimate climate sensitivity

Merci de votre attention