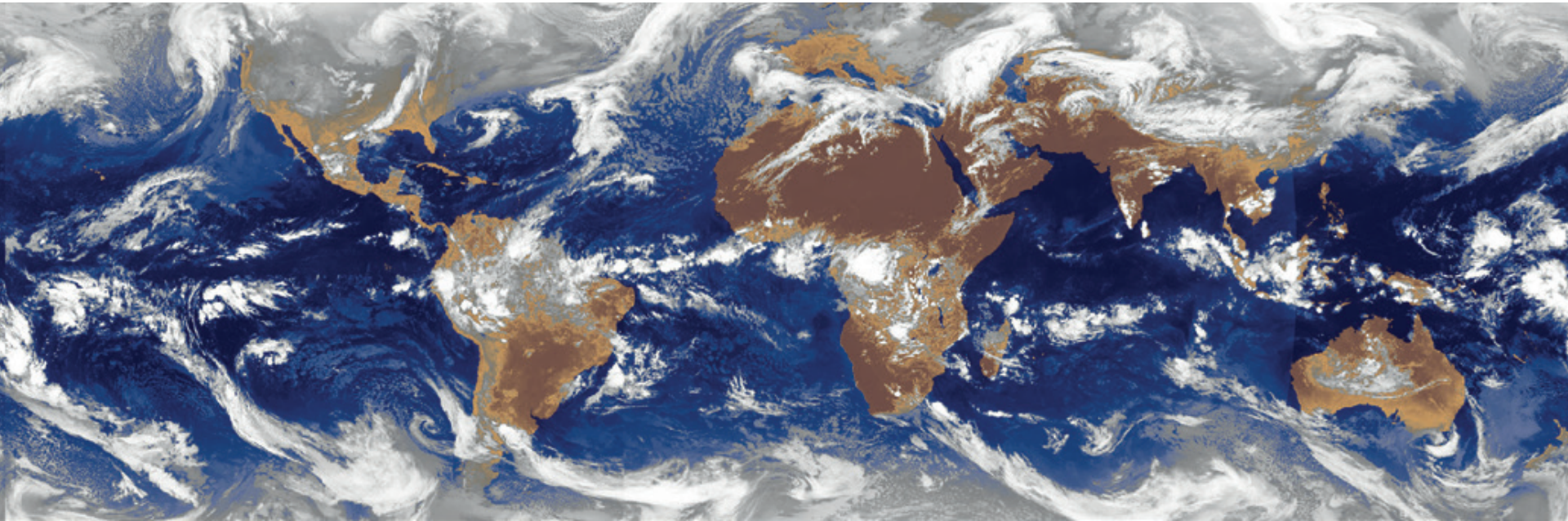


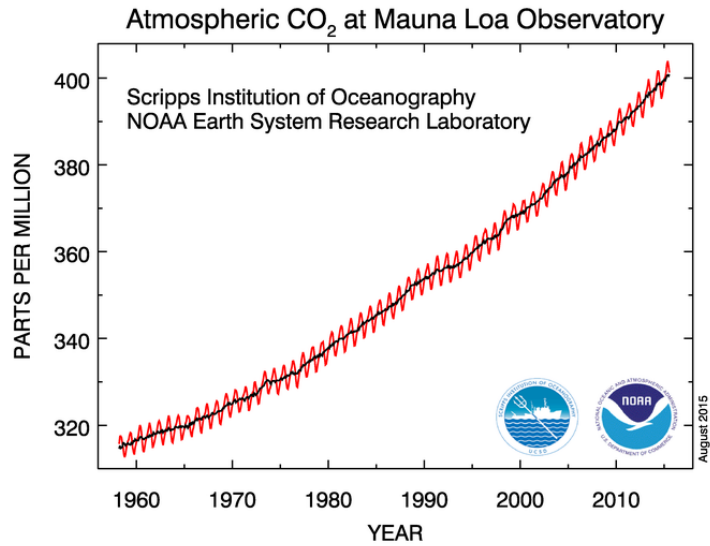
# (Un)certainities in our knowledge of Climate Sensitivity

A. Pier Siebesma  
siebesma@knmi.nl  
KNMI & TU Delft



Courtesy: Bony et al. Nature GeoScience 2015

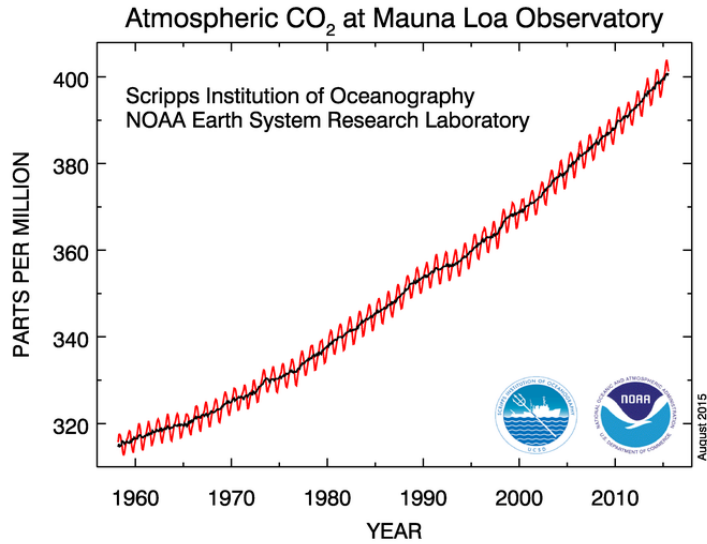
# Waarnemingen liegen niet



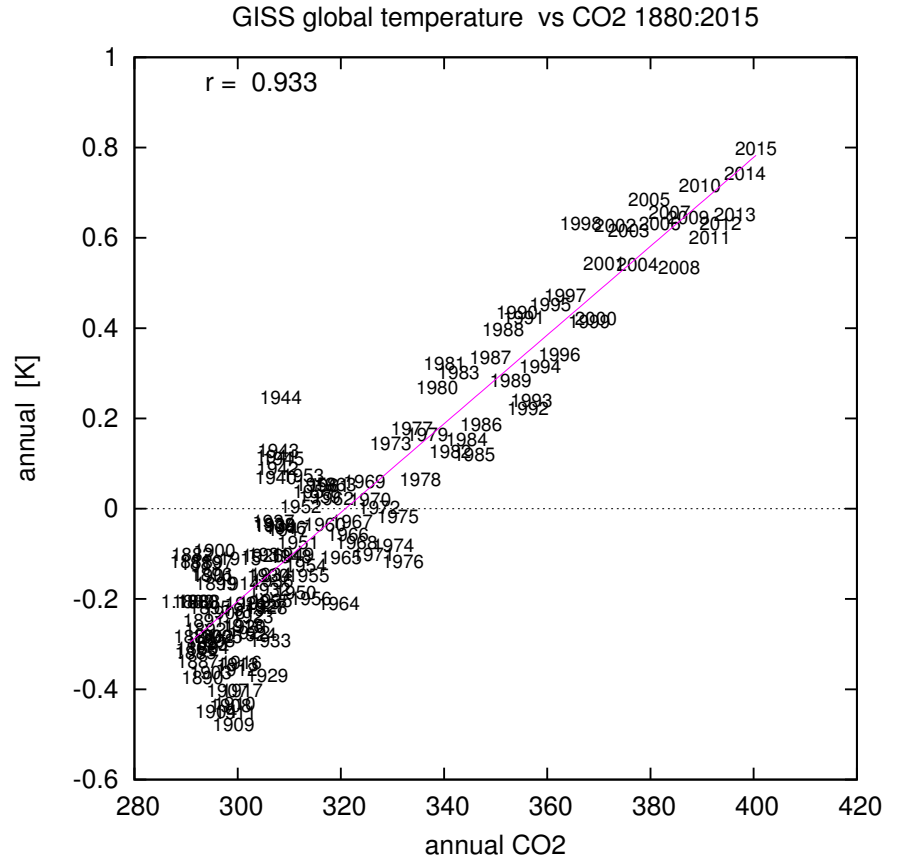
In-situ waarnemingen van CO<sub>2</sub>-trends in op Mauna Loa Observatory.



# Waarnemingen liegen niet



Global annual mean temperature  
vs CO<sub>2</sub>-concentrations



Source: Climate Explorer  
G.J. van Oldenborgh

## Maar we willen (nog) meer dan correlaties....

- Causaliteit (Attributie)
- Realistische toekomst scenario's
- Gebruik makend van fysische principes
- En door het opstellen en het testen van kritische hypotheses  
(de wetenschappelijke methode)



## Gelukkig hebben we fysische behoudswetten.....

$$\frac{d\vec{v}}{dt} = -\frac{1}{\rho}\vec{\nabla}p - \vec{g} + \vec{F}_{fric} - 2\vec{\Omega} \times \vec{v}$$

Behoudswet van momentum

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{v})$$

Behoudswet van massa

$$Q = C_p \frac{dT}{dt} - \frac{1}{\rho} \frac{dp}{dt}$$

Behouds wet van energie

$$\frac{\partial \rho q}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{v} q) + \rho(E - C)$$

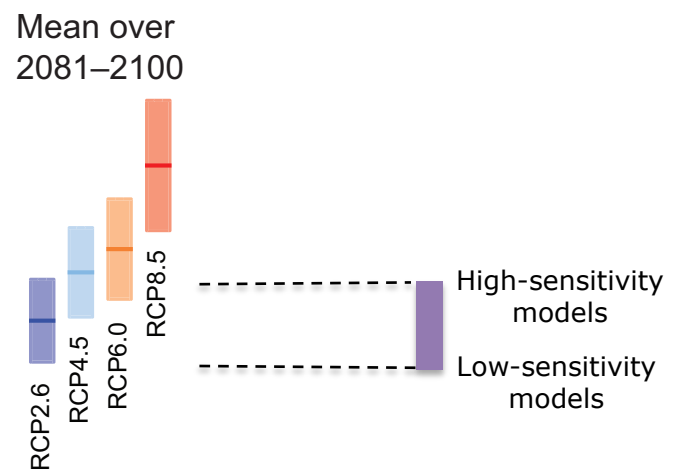
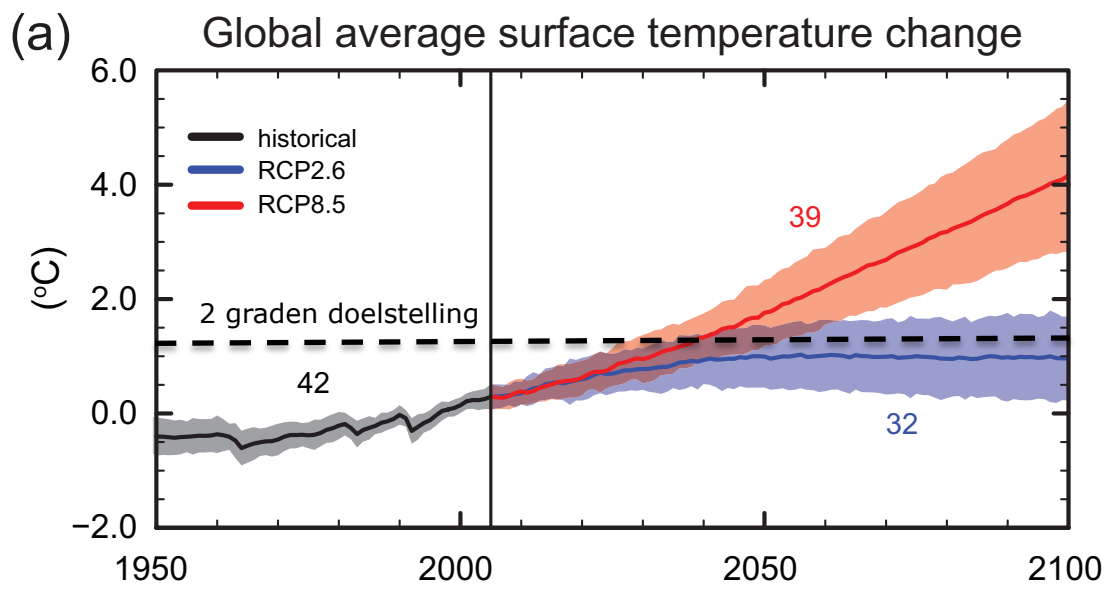
Behouds wet van vocht

$$p = \rho R_g T$$

Gas wet

Sir John Mason (1976) "You can thank your lucky stars that you are not economists. Those poor souls don't even know their equations!"

# klimaatmodellen introduceren (grote) onzekerheden in de toekomst scenario's

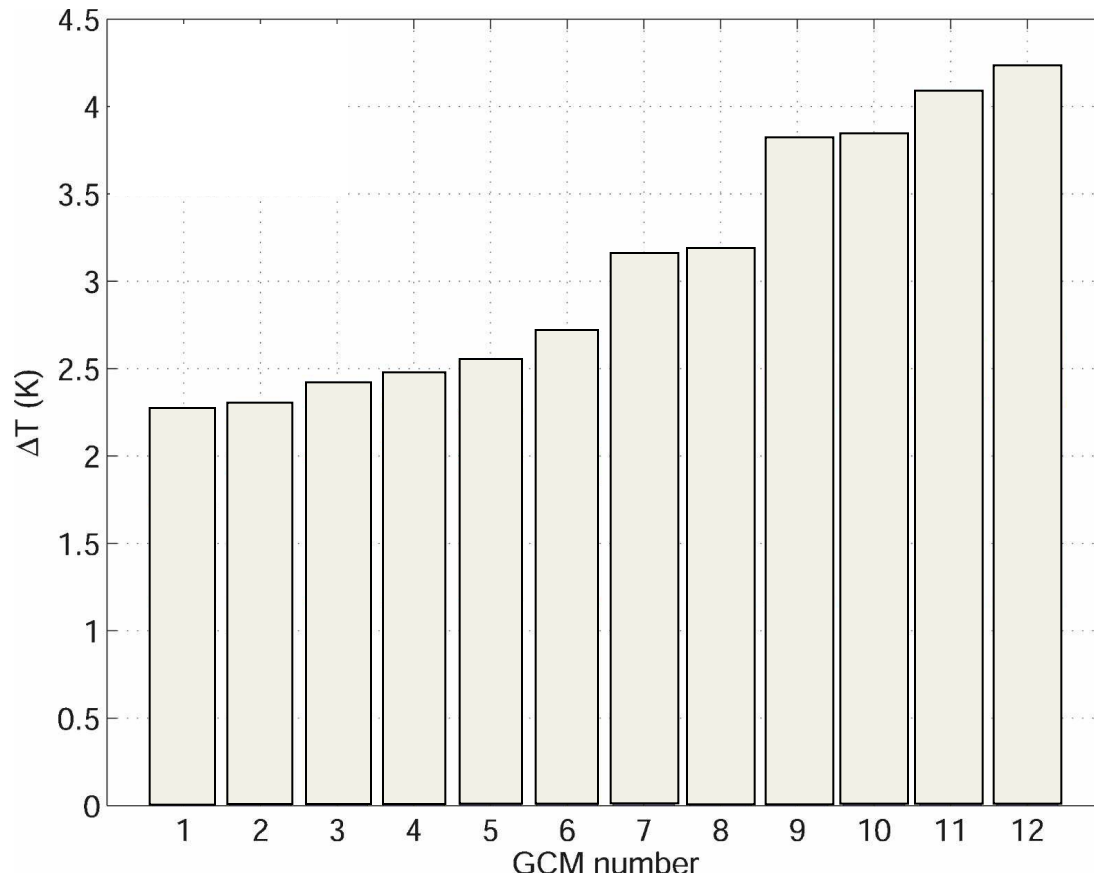


# Klimaat Gevoeligheid.

## Evenwichts Klimaat Gevoeligheid (Equilibrium Climate Sensitivity (ECS))

De globale temperatuursverandering in een nieuwe evenwichtssituatie  
tgv een verdubbeling van CO<sub>2</sub> (2XCO<sub>2</sub>)

12 Climate Models (CMIP3) ; 2X CO<sub>2</sub> scenario  
onzekerheids marge [2, 4.5] °C

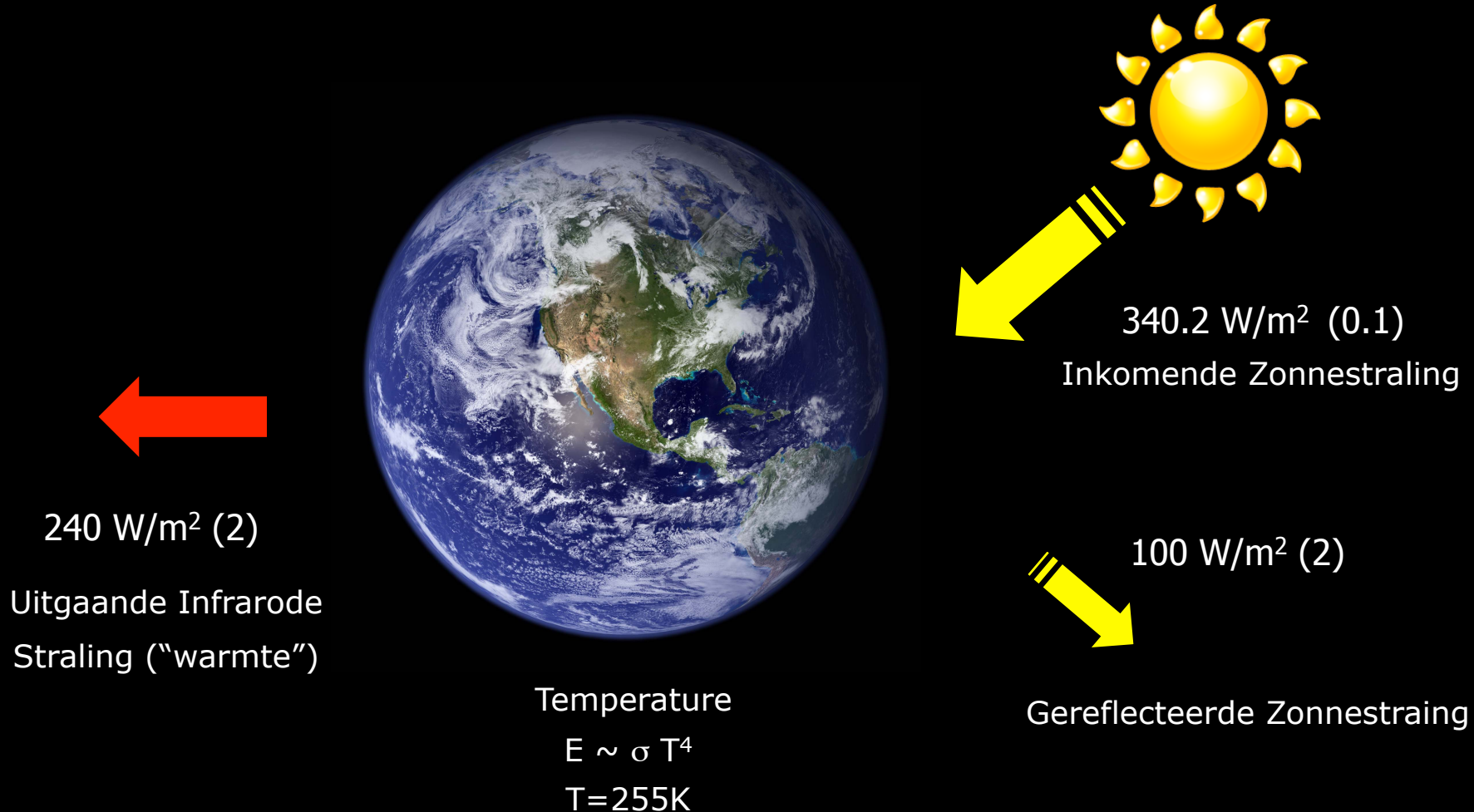


- Alle relevante klimaatveranderingen (zee-spiegelstijging, neerslag, regionale patronen) schalen met ECS
- Alle onzekerheden in klimaatverandering zijn dus terug te voeren op onzekerheid in klimaatgevoeligheid
- Dit maakt ECS een ge-idealiseerde maar fundamentele maat voor klimaatgevoeligheid.

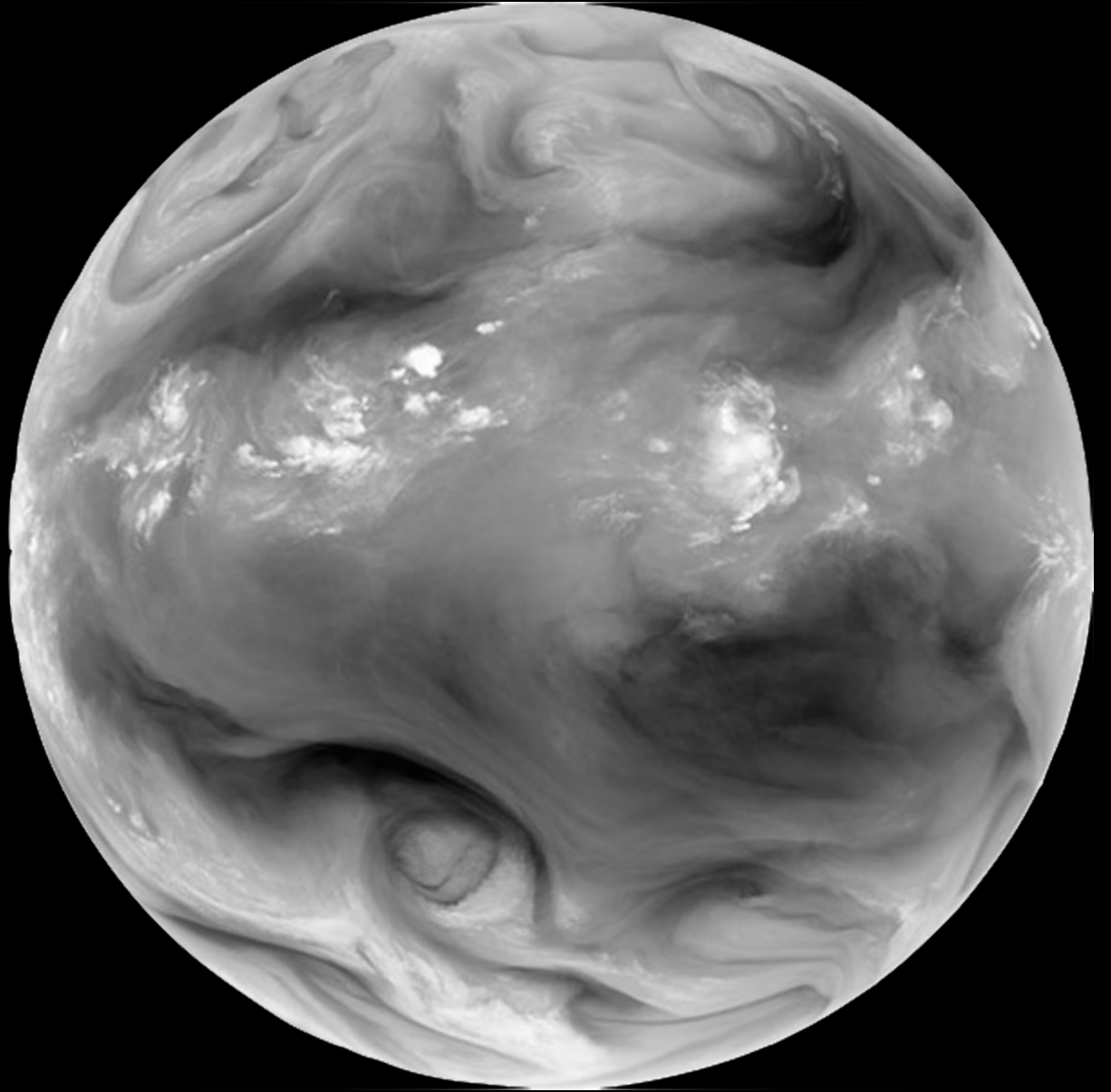


# Energie Balans aan de top van de atmosfeer

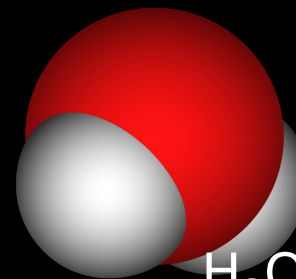
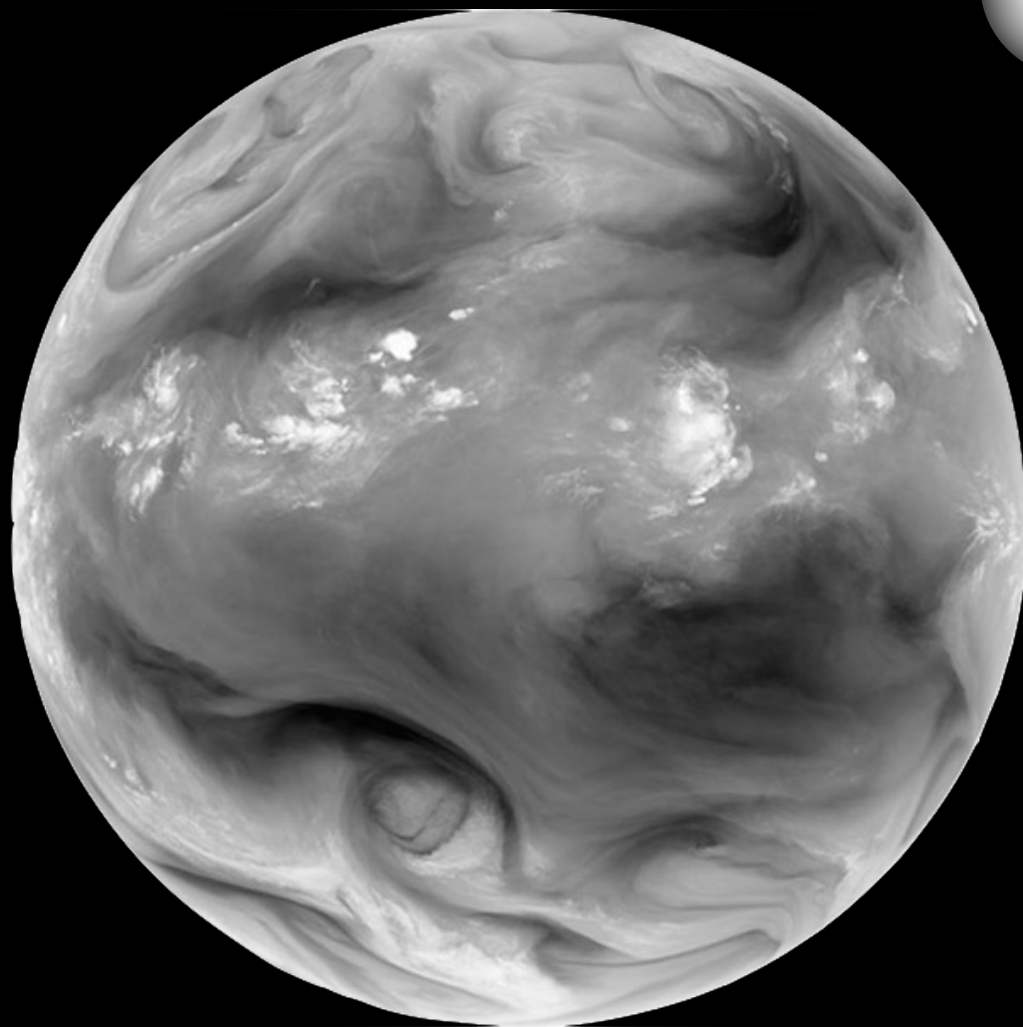
Stephens et al. Nature (2013) ; Wild et al Climate Dyn (2013) Period 2010



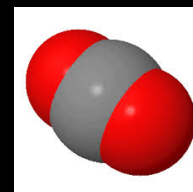








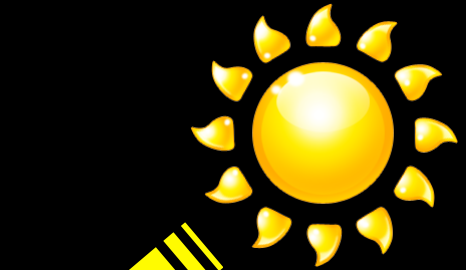
H<sub>2</sub>O



CO<sub>2</sub>

# Toename Broeikasgassen.....

Bijv: verdubbeling CO2



340 W/m<sup>2</sup>

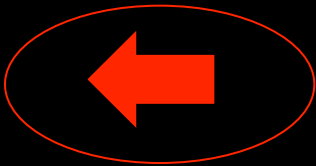
Inkomende Zonnestraling

100 W/m<sup>2</sup>

Gereflecteerde Zonnestraling

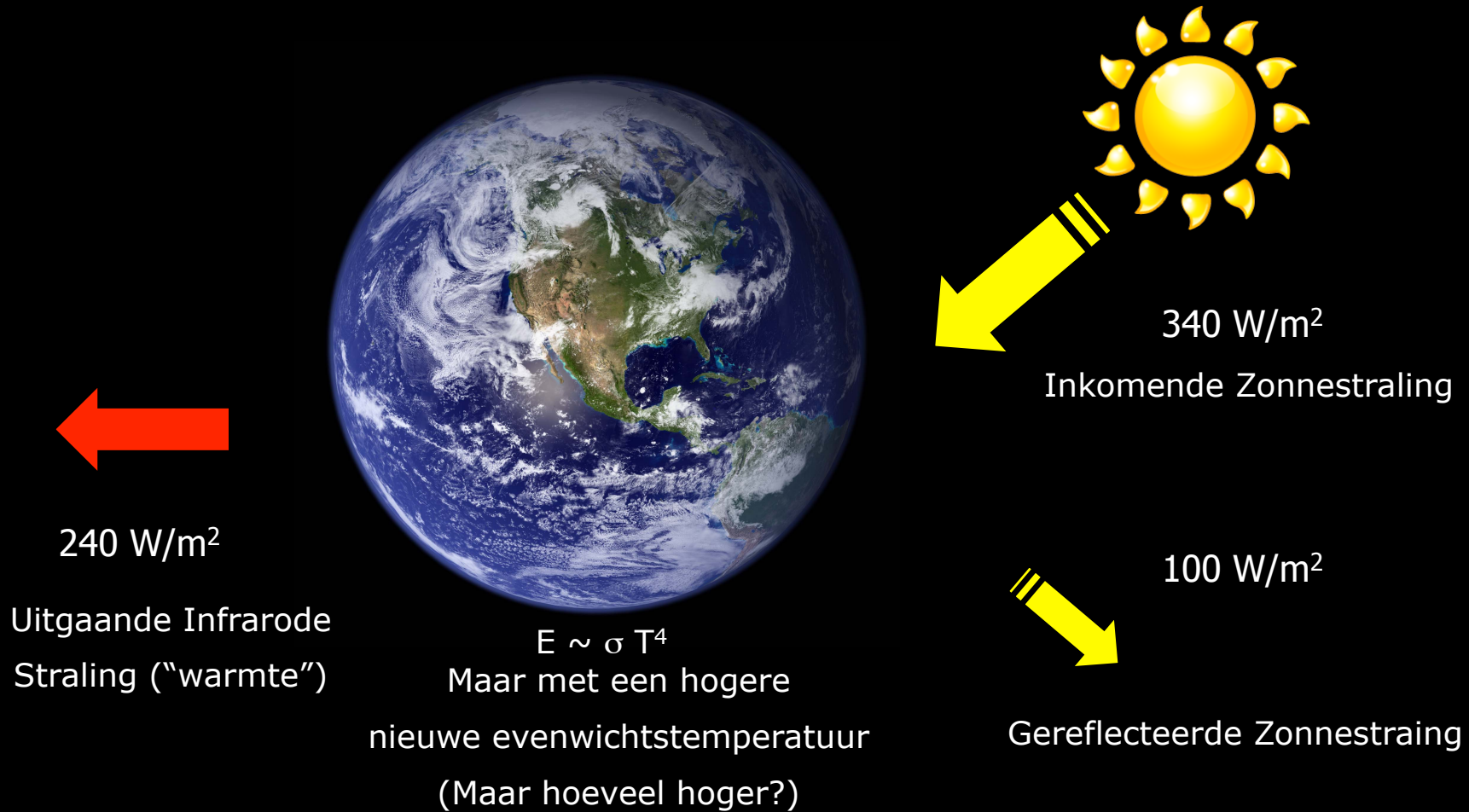
$$E \sim \sigma T^4$$

Hoe zal de atmosfeer reageren?



Afname uitgaande  
infrarood straling  
(3,7 Wm<sup>2</sup> afname  
Stralingsforcering)

Totdat een nieuw evenwicht ontstaat



# Concepten van Forcing en Feedback

Stralingsbalans top atmosfeer:  $R = ASR - OLR \simeq 0$

$d\Phi$ : externe factor (zonne-constante, or anthropogene toename CO2, anthropogene toename aerosolen,.....)

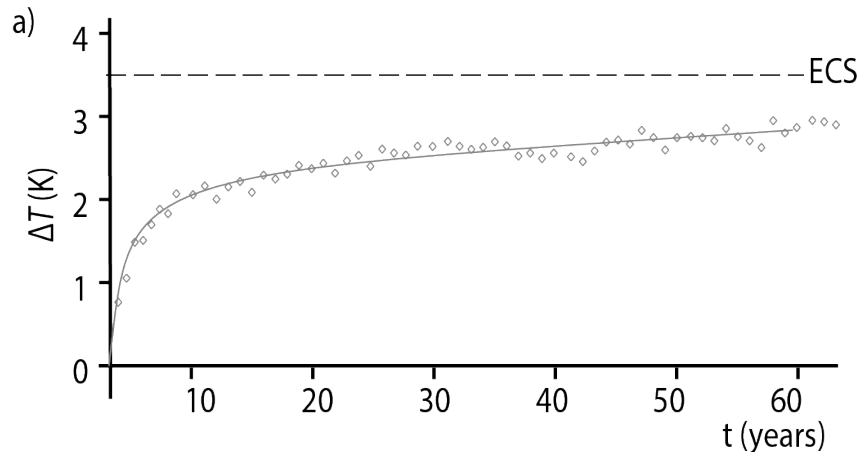
$$\delta R = \left( \frac{\partial R}{\partial \phi} \right)_{T_s} d\phi + \left( \frac{\partial R}{\partial T_s} \right)_{\phi} dT_s$$

In analogie met electronics

$$\delta R = F + \lambda dT_s \quad \left\{ \begin{array}{l} F \equiv \left( \frac{\partial R}{\partial \phi} \right)_{T_s} d\phi \quad : \text{Forcing} \\ \lambda \equiv \left( \frac{\partial R}{\partial T_s} \right)_{\phi} \quad : \text{Feedback Factor} \end{array} \right.$$

Wanneer een forcing (i.e. doubling CO2:  $3,75 \text{ Wm}^{-2}$ ) wordt ingeschakeld, zal  $T_s$  zich aanpassen tot dat stralingsevenwicht is hersteld.

$$\Delta T_s = -\frac{F}{\lambda} = \text{ECS}$$



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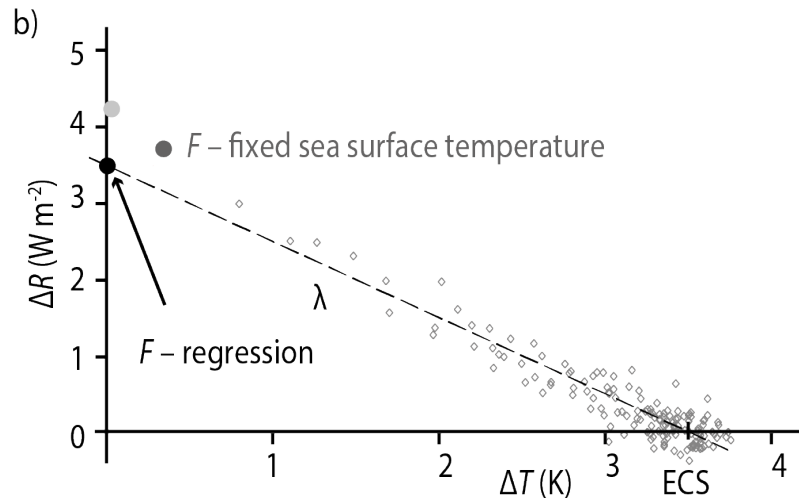
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# Concepten van Forcing en Feedback

Toy Energy Balance Model:

$$R = ASR - OLR$$

$$= \frac{S_0}{4} (1 - \alpha) - \gamma \sigma T_s^4$$

$S_0$  solar constant : 1360 Wm<sup>-2</sup>  
 $\alpha$  planetary albedo: 0,29  
 $\sigma$  SB. cst: 5,8 10<sup>-8</sup> Wm<sup>-2</sup> K<sup>-4</sup>  
 $\gamma$  : atmosph. emissivity 0.61  
(GHG, vv clouds etc)

Als alleen de opp temperature kan reageren

$$\lambda_P = \left( \frac{\partial R}{\partial T_s} \right)_\phi = -4 \gamma \sigma T_s^3 = -3.3 \text{ Wm}^{-2} \text{ K}^{-1}$$

$$\Delta T_{s,P} = -F / \lambda_p = 1.1 \text{ K}$$

Planck Response



# Concepten van Forcing en Feedback

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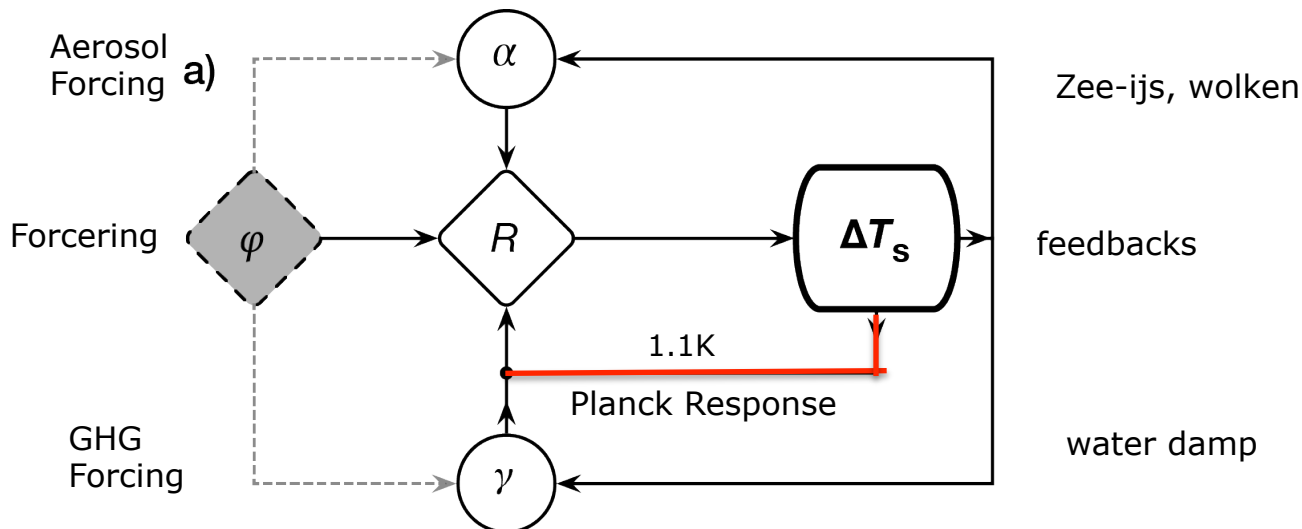
Simpel: Alleen temperatuur kan reageren

$$\lambda_P = \left( \frac{\partial R}{\partial T_s} \right)_\phi = -4 \gamma \sigma T_s^3 = -3.3 W m^{-2} K^{-1}$$

$$\Delta T_{s,P} = -F / \lambda_p = 1.1 K$$

Planck Response

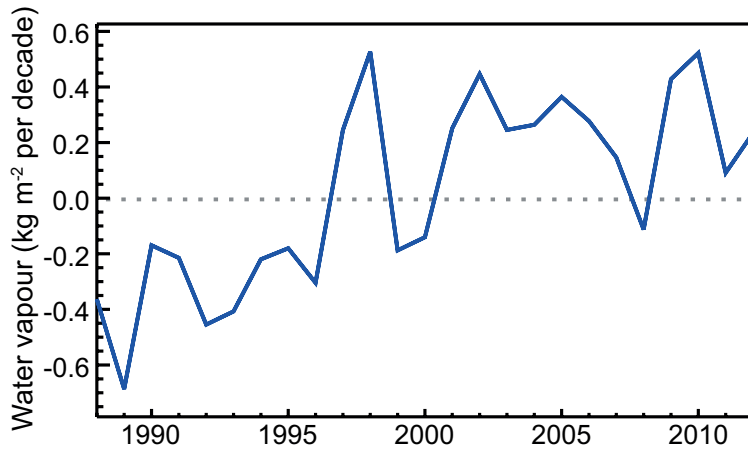
Maar als de opp temperature toeneemt zullen andere atmosferische variabelen (x) ook reageren (waterdamp, zee-ijs, wolken ), zg feedbacks:



# Water Damp Feedback

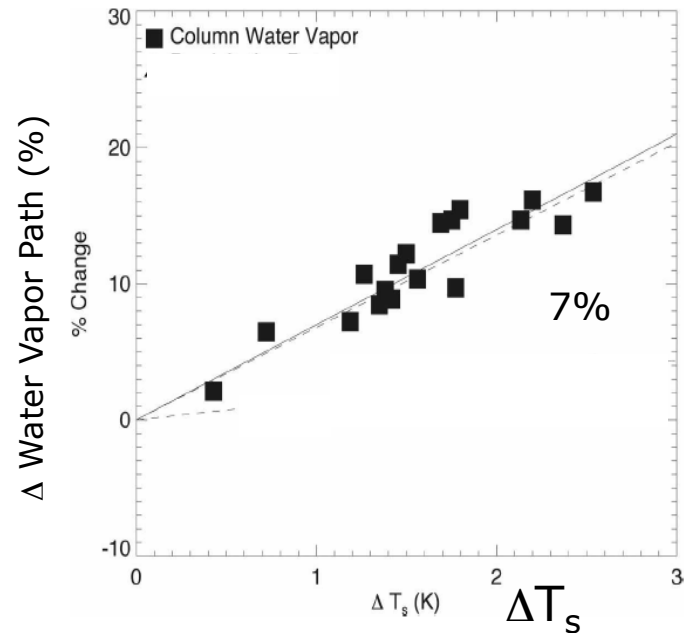
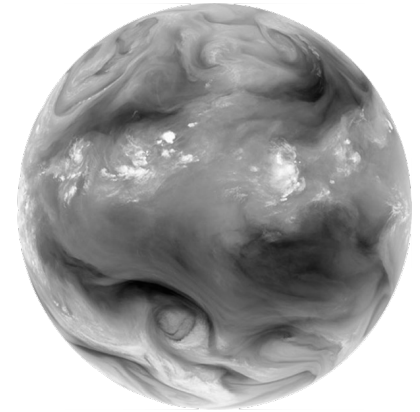
Clausius-Clayperon:  $\frac{de_s}{dT} = \frac{L}{T\alpha}$  De verzadigings dampspanning neemt exponentieel met temperatuur toe.

Een warmere atmosfeer kan (en zal) meer waterdamp bevatten (plus/min 7% /K)



CMIP3 Climate Models  
Stephens&Ellis (2008)

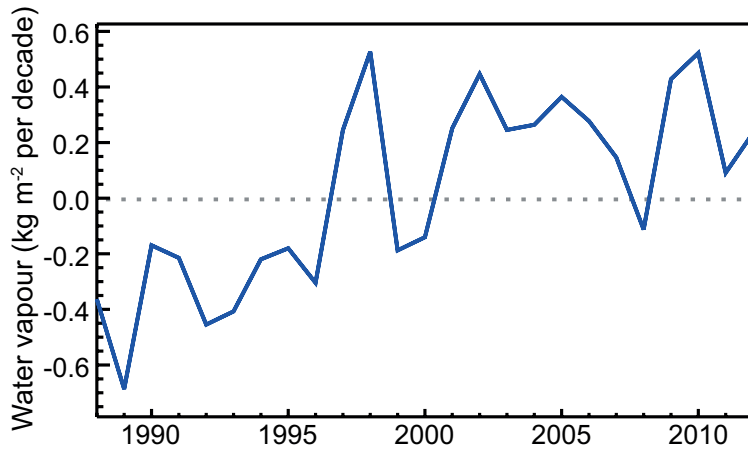
Satellite  
SSMI Wentz et al. 2007)



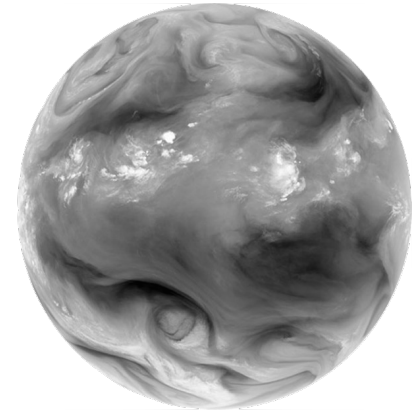
# Waterdamp Feedback

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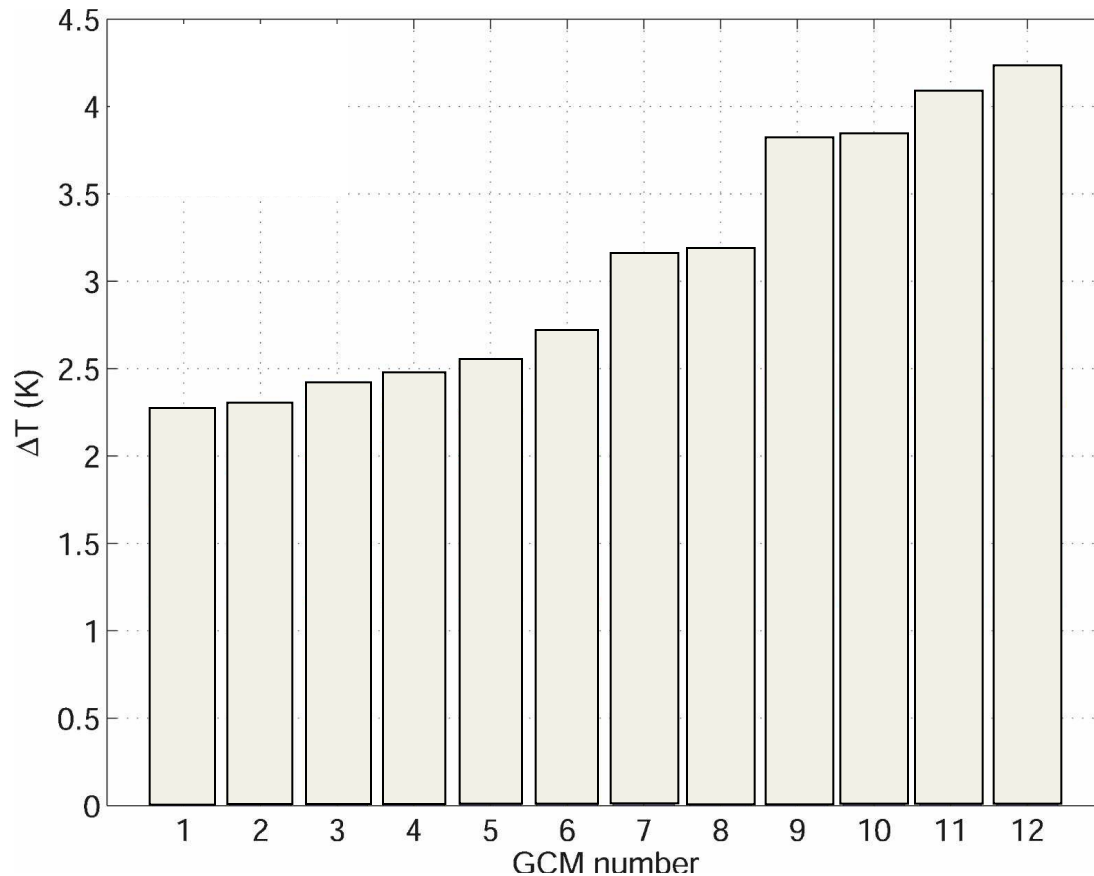
Waterdamp : Robuste en sterke feedback die de Planck response ongeveer verdubbelt:

$\Delta T_s$

# Fysische Argumenten in overeenstemming met klimaatmodellen (CMIP3) ?

12 Climate Models (CMIP3) ; 2X CO2 scenario

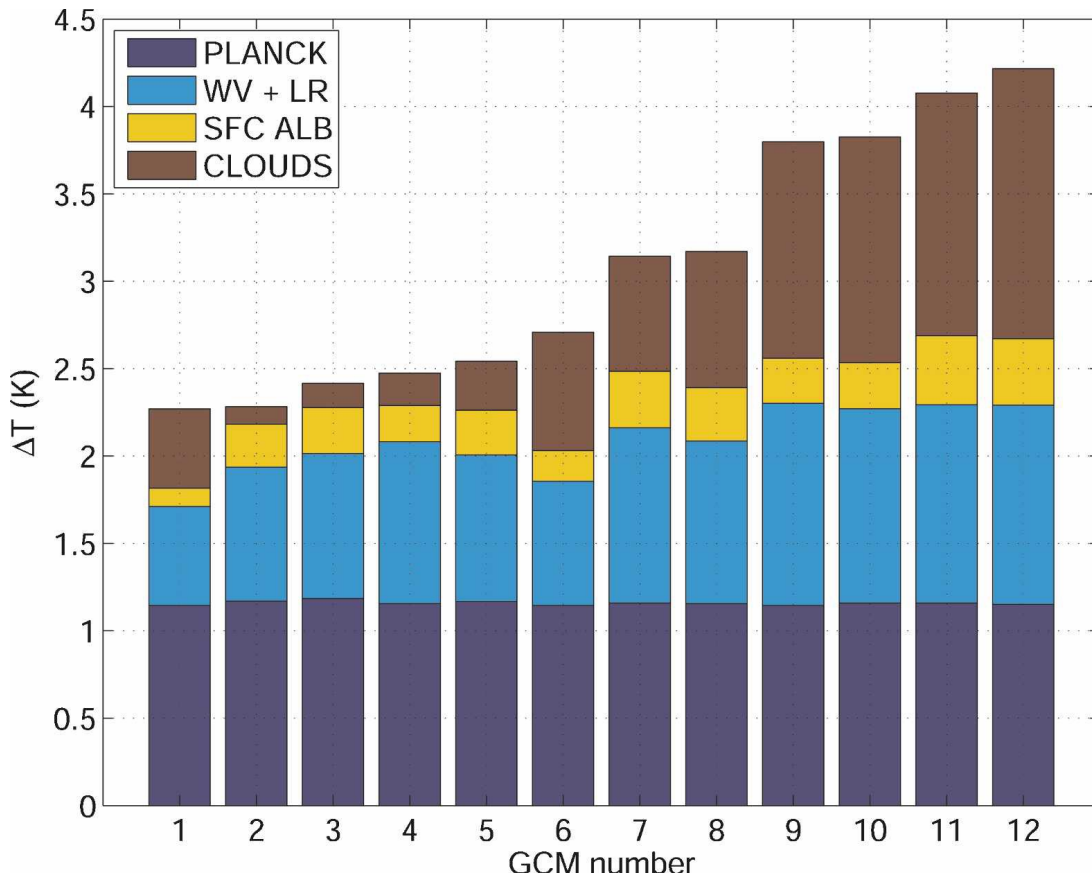
onzekerheids marge [2, 4.5] °C



Bony & Dufresne J of Climate 2008

*Cloud effects "remain the largest source of uncertainty" in model based estimates of climate sensitivity IPCC 2013*

## 2x CO<sub>2</sub> scenario



Wolken feedback



Opp. albedo feedback



Waterdamp feedback

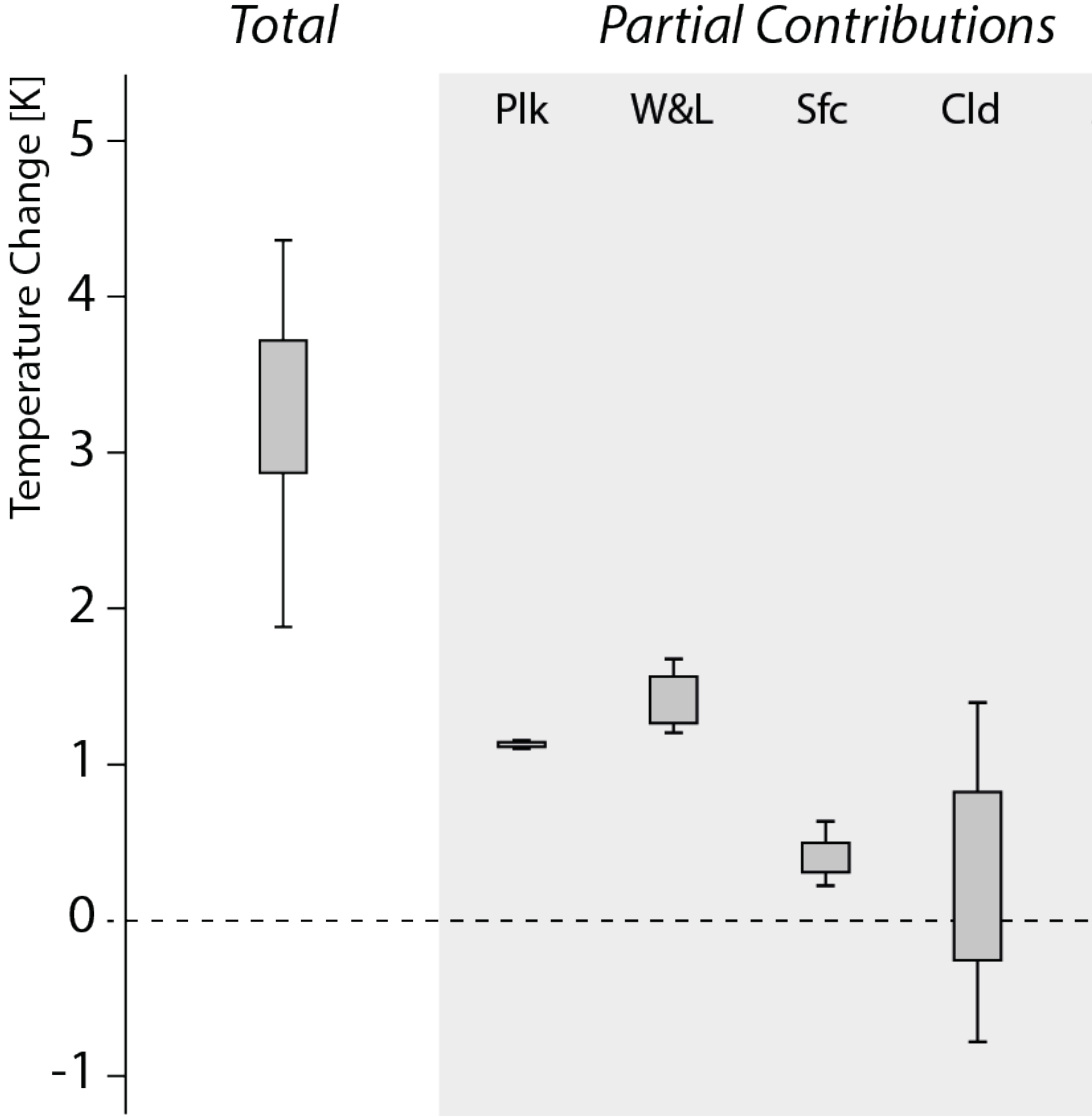


Direct Stralings effect

Bony & Dufresne J Of Climate 2008

# CMIP5 Estimates of Equilibrium Climate Sensitivity

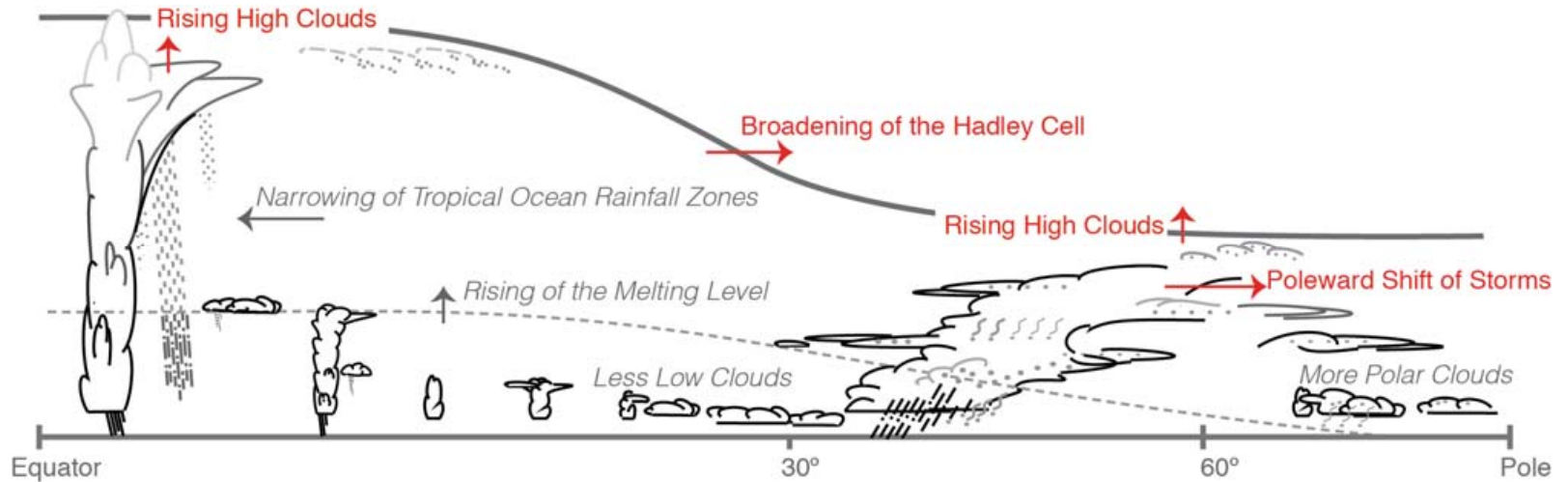
After Vial et al. Clim. Dyn (2013)





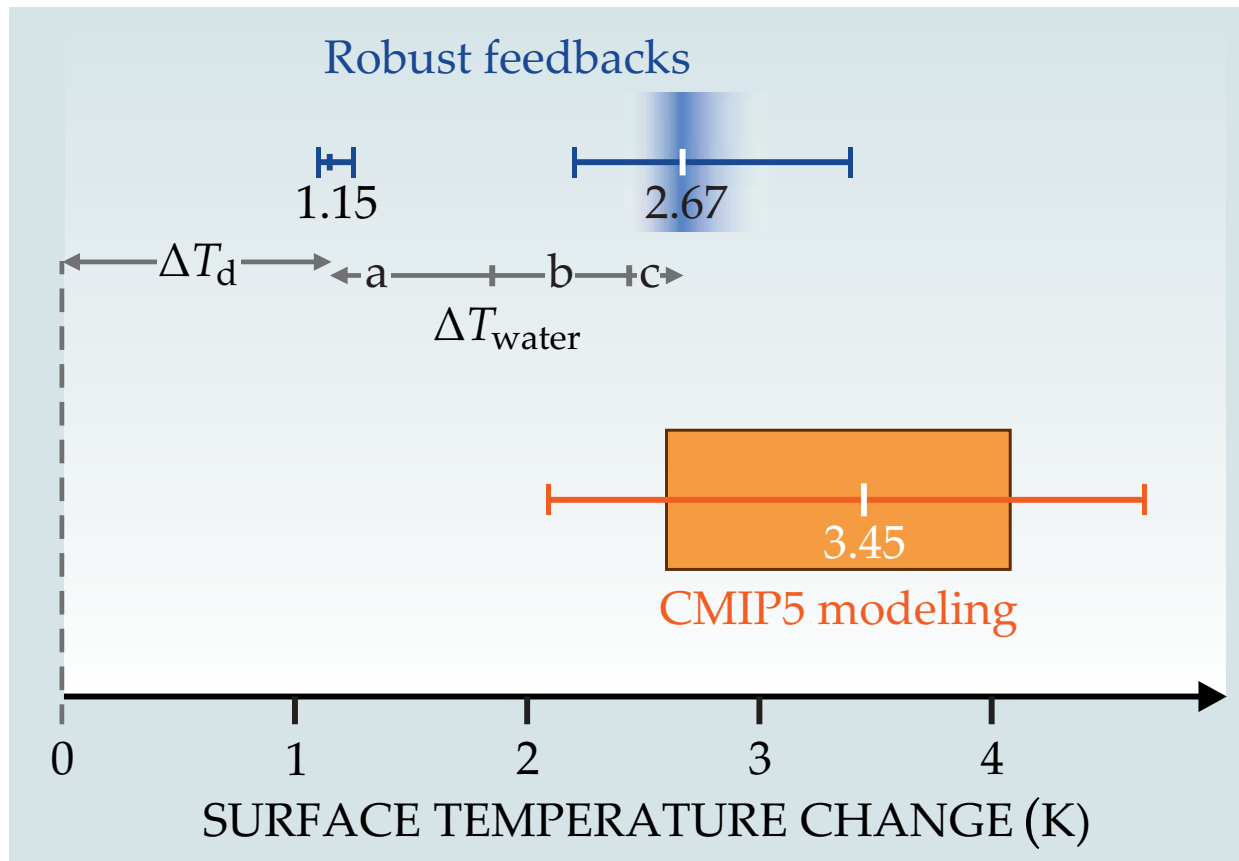
# Cloud Feedback Mechanisms

Source: FP7 EUCLIPSE final report  
IPCC AR5



- Cloud feedback likely positive
- Largest uncertainty from low clouds
- Robust positive feedback Signal from Fixed Anvil Theory (FAT)
- But missing processes can not be excluded

# CMIP5 Intermodel spreading vs Robuste Feedbacks



# Bepaling van Equilibrium Climate Sensitivity (ECS) uit observaties

Als de mondiale temperatuurstijging, de Forcering, en de Warmte Opname van het klimaatsysteem kan worden gemeten dan kan ECS worden bepaald uit:

$$ECS = \frac{F_{CO_2}}{F - \Delta R} \Delta T_s$$

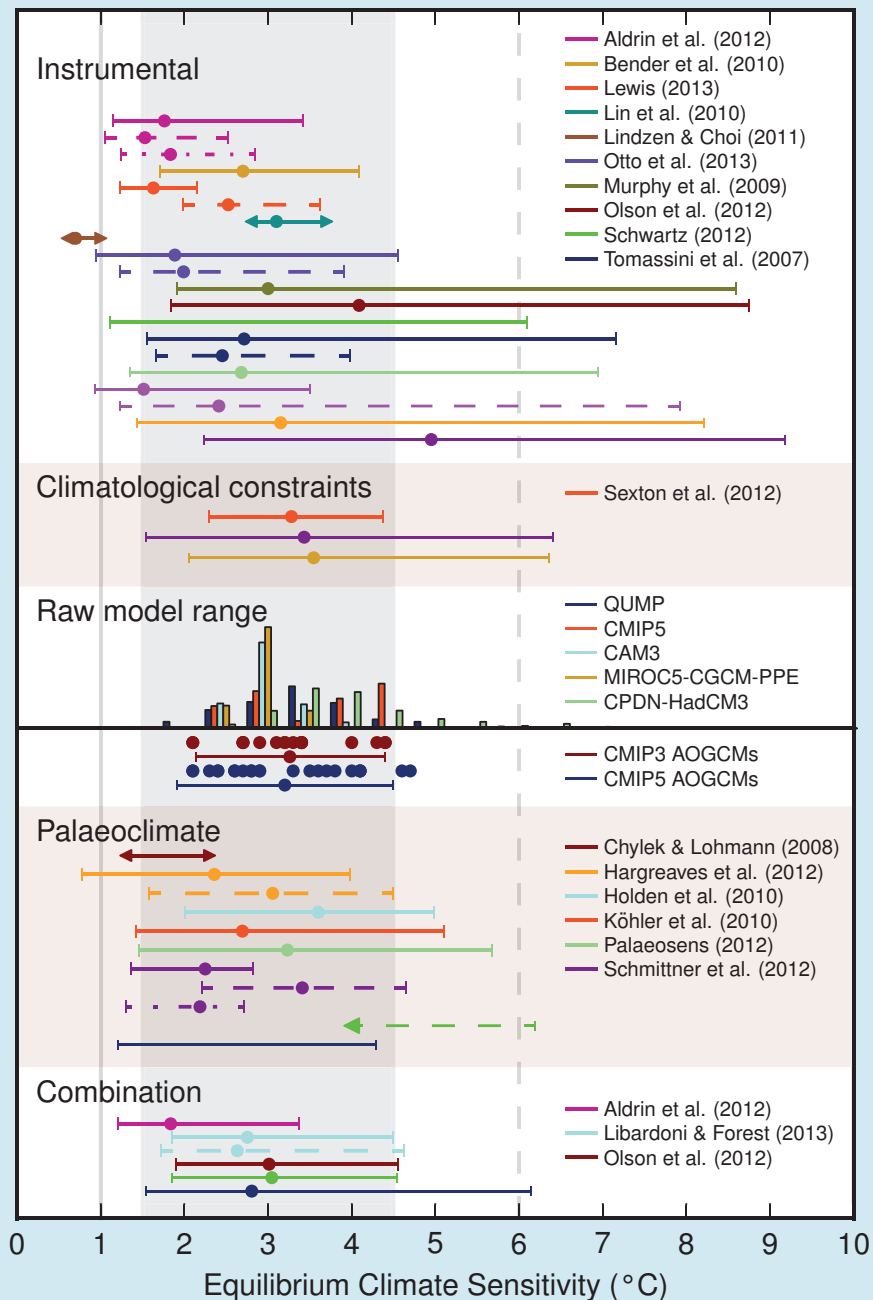
$F_{CO_2} = 3,45 \text{ Wm}^{-2}$  ("Effective" Radiative Forcing)

$\Delta R =$  Essentially the ocean heat uptake  $\sim 0.6 \text{ Wm}^{-2}$

$F =$  Radiative Forcing over the period where  $\Delta T_s$  is determined

Toegepast op 20e eeuw (maar ook op paleo-data)

Grote onzekerheid in aerosol forcing en in ocean heat uptake.



20e eeuw observaties

ECS: [1....9 K]

AR5

[1.5, 4.5 K]

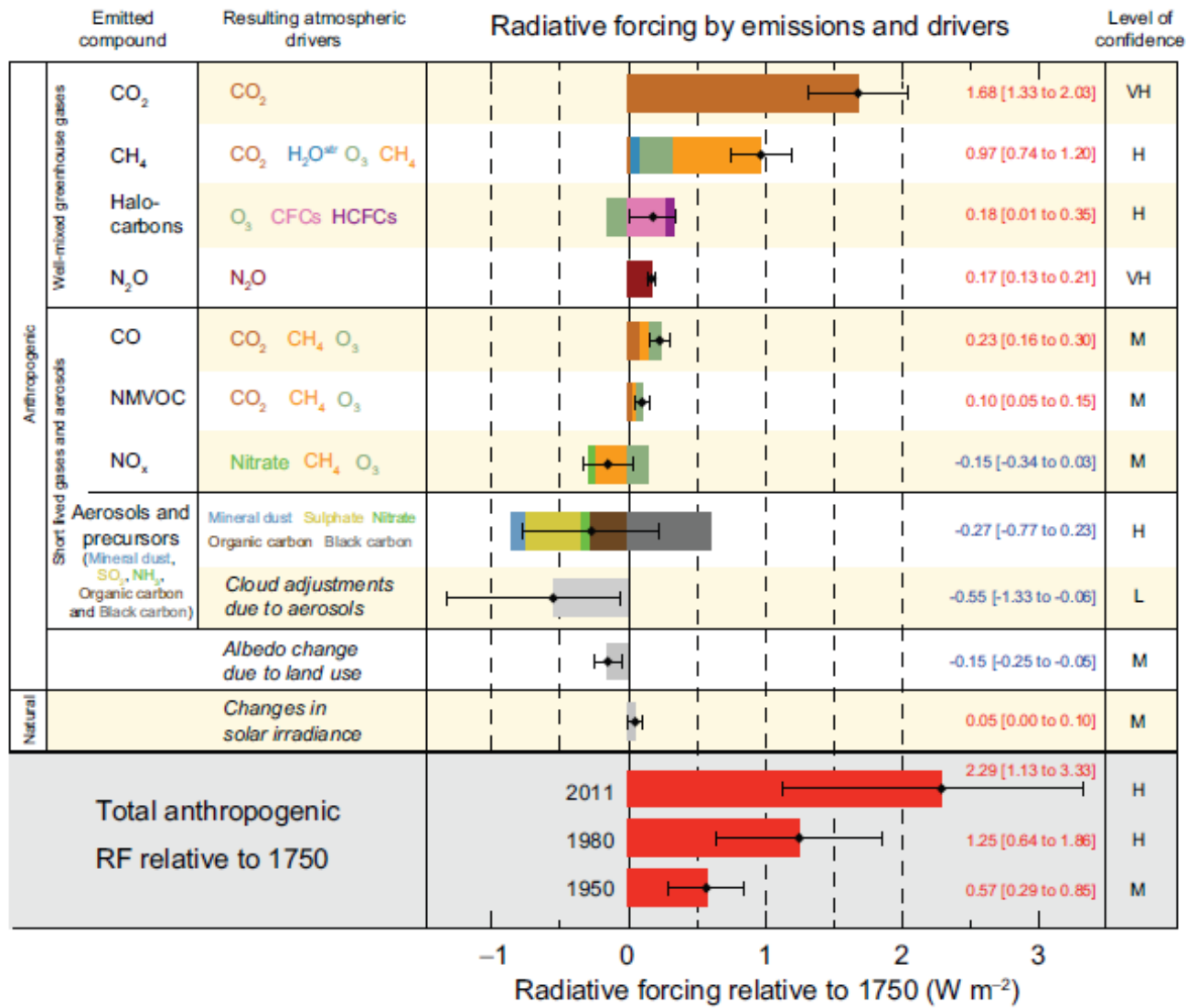
Models & Processes

ECS: [2, 4.5 K]

Paleoklimaat

[1,6 K]

# Schattingen van stralingsforceringen tov 1750



# Conclusies

Robuste Feedbacks suggereren ECS van 2.65K plus/min 0.5 K

Lagere ECS heeft extra plausible negatieve cloud feedback processen "nodig"

Observationele schattingen geven een ruimere bandbreedte van ECS [1 , 8K]

Betere schattingen van Forcing (met name aerosols (in)direct) kunnen tot betere observationele schattingen van ECS leiden.