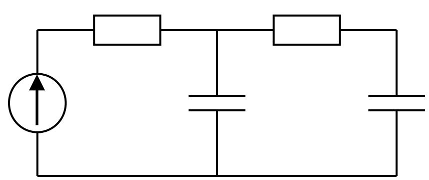
Adjusted radiative forcing, equilibrium climate sensitivity and transient radiative feedback in a two-box energy balance model

Olivier Geoffroy, David Saint-Martin, Aurore Voldoire, Gilles Bellon,
Dirk Olivié, Aurélien Ribes, Sophie Tytéca



EUCLIPSE-CFMIP 2012

Objective

- Quantify the physical parameters that drive the first-order transient response of a given AOGCM.

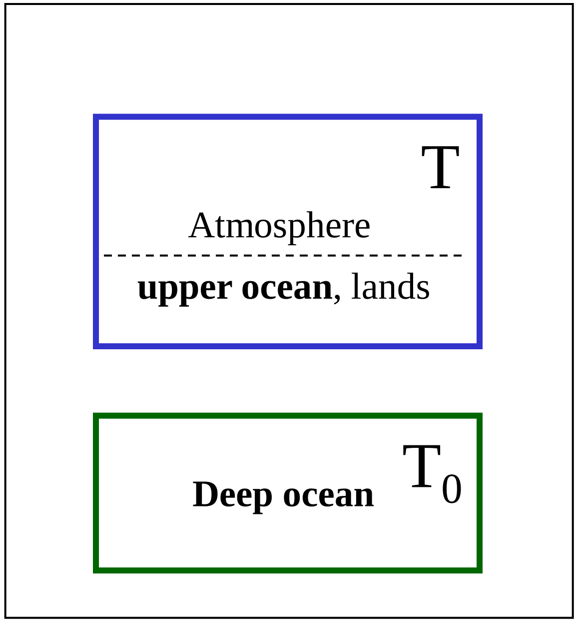
Plan

I) 2-box Energy Balance Model (EBM)

II) 2-box EBM with efficacy factor of deep ocean heat uptake

III) Conclusion and perspective

2-box EBM (version with ε=1)



(Held et al, 2010)

T: change in mean surface air temperature
T_0: change in deep ocean temperature

$$\begin{cases} C\dfrac{dT}{dt} = N - H \\ C_0\dfrac{dT_0}{dt} = H \end{cases}$$

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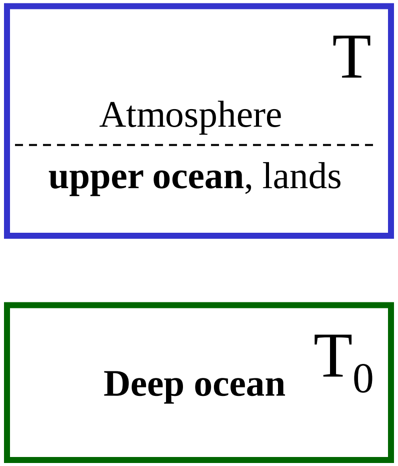

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Change of heat content
of **upper ocean**

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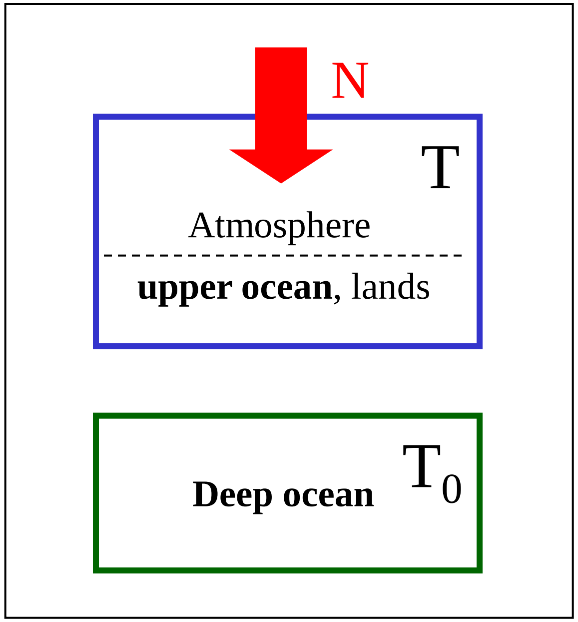

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Radiative imbalance

$$\begin{cases} C\dfrac{dT}{dt} = N - H \\ C_0\dfrac{dT_0}{dt} = H \end{cases}$$

with:

$$N = F - \lambda T$$

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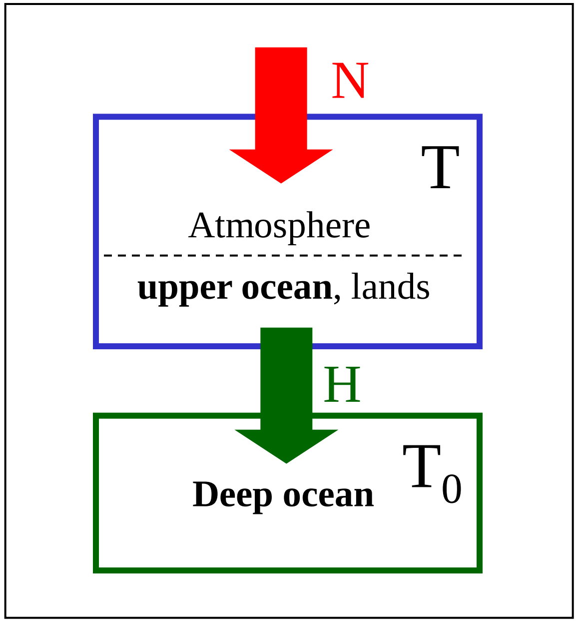

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Deep ocean heat uptake

Change of heat content of **deep ocean**

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$$N = F - \lambda T$$

$$H = \gamma \cdot (T - T_0)$$

5 parameters: F_{2xCO2}, λ, C, C_0, γ

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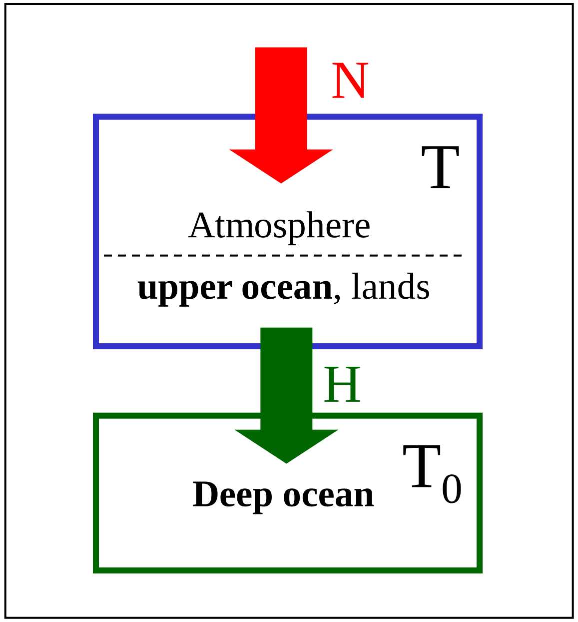
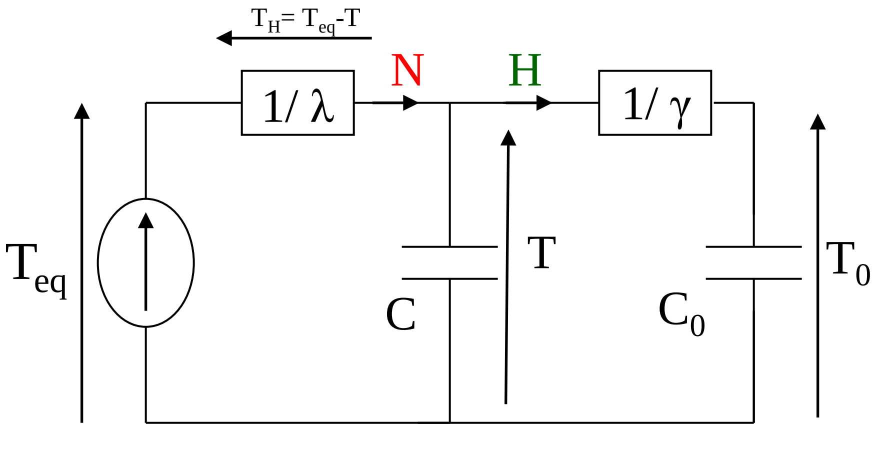


Electrical analogy



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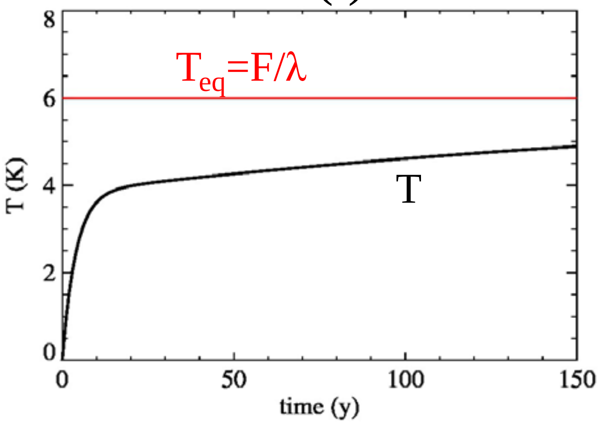
Parameter calibration, method

Analytical solution (step forcing case)

$$T = \frac{F}{\lambda} - \frac{F}{\lambda} a_f e^{-t/\tau_f} - \frac{F}{\lambda} a_s e^{-t/\tau_s}$$

T=(t)



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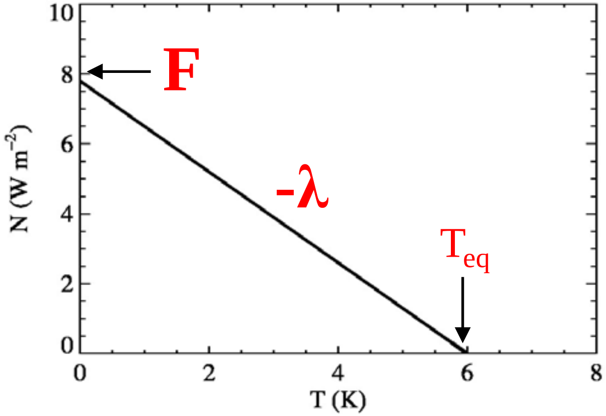
Calibration of F, λ, C, C_0, γ from AB4CO2 only

$N = F - \lambda T$

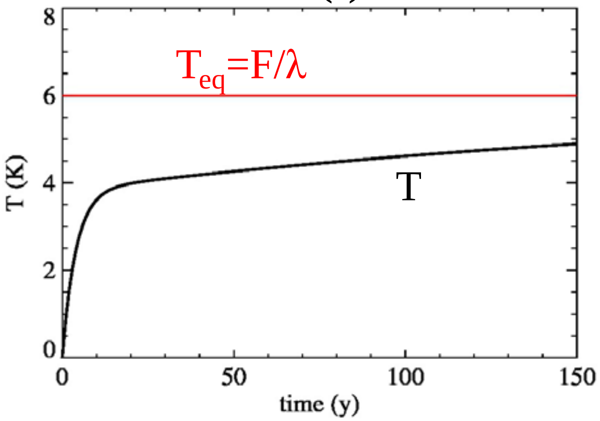


Linear fit (*Gregory et al, 2004*)

↓

F, λ

T=(t)



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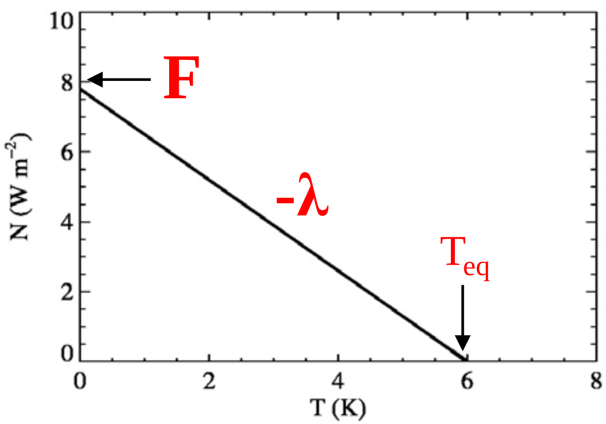

Linear fit (*Gregory et al, 2004*)

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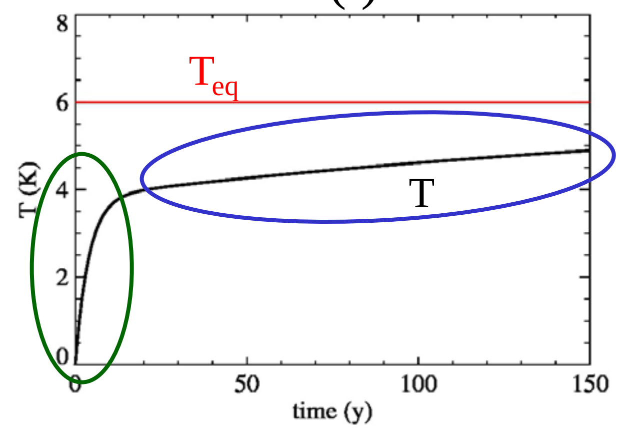


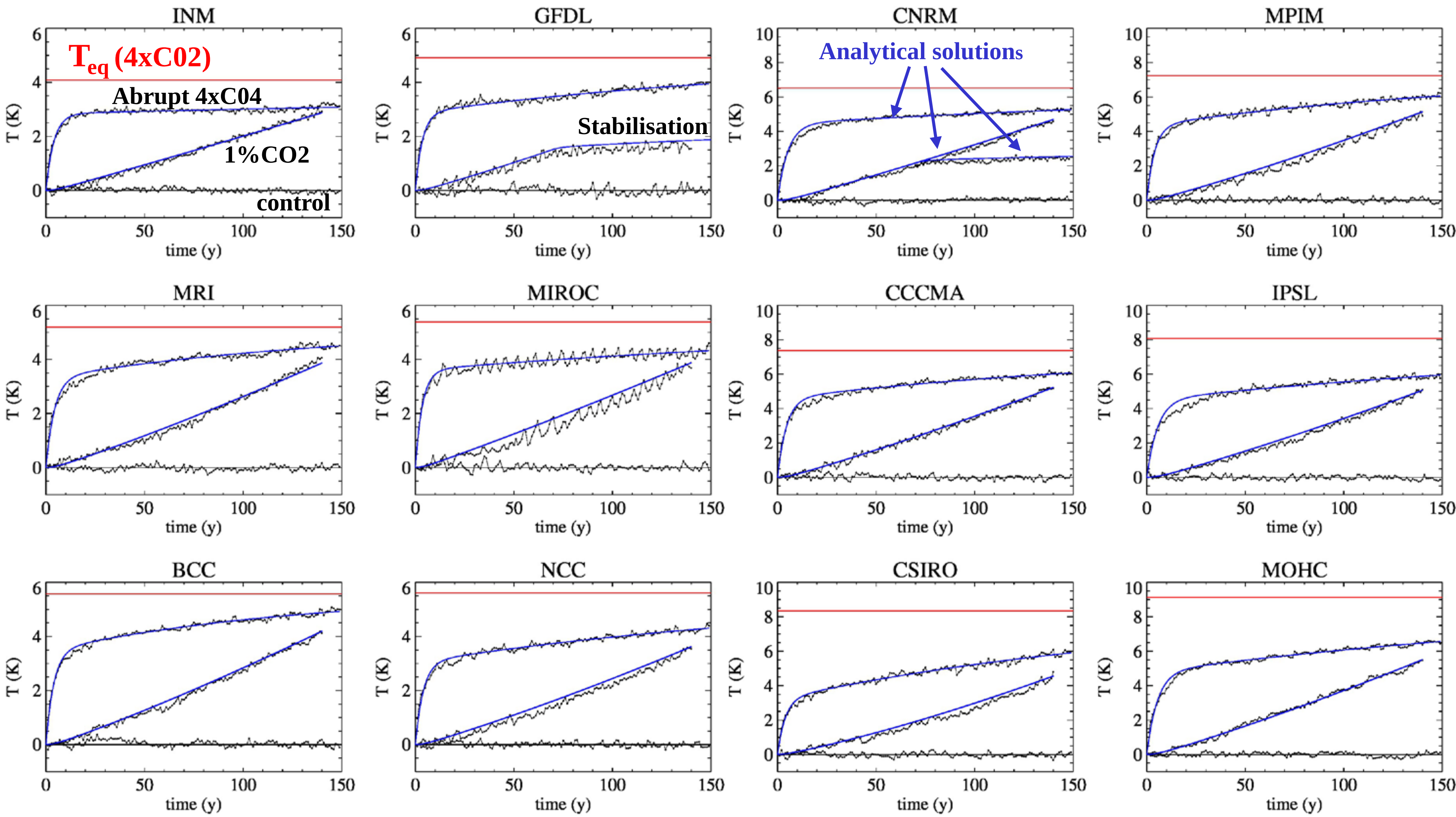
2 Fits (30-150 yr, first 10 yr)

$\mathbf{a_f , a_s , \tau_s, \tau_f}$

C, C_0, γ

CMIP5 AOGCMs global temperature, results

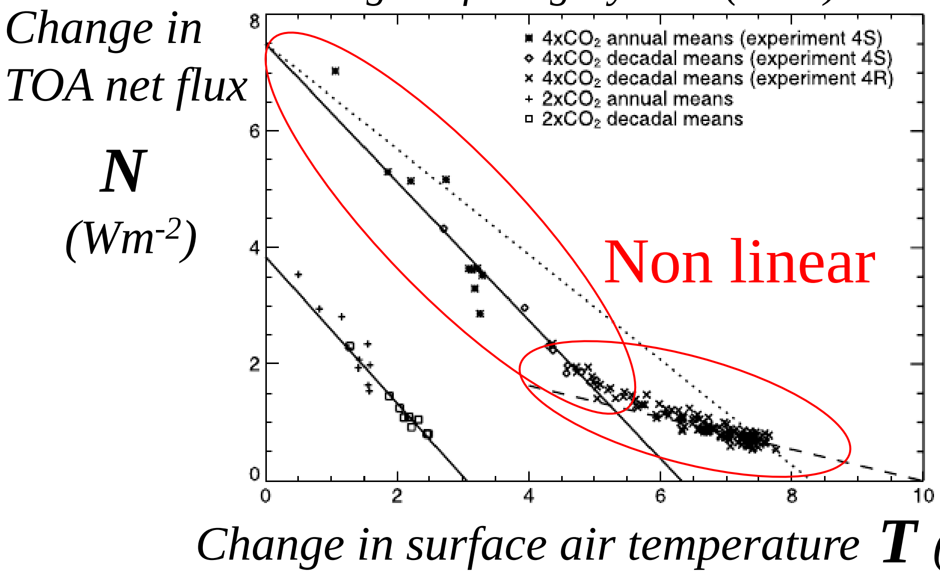
(Geoffroy et al 2012a, submitted)



- Good representation of $\mathbf{T_{AB4CO2}}$ and $\mathbf{T_{UNPCO2}}$

N=f(T): limitations of the linear hypothesis.

Fig. 2 of Gregory et al (2004)



$$\mathbf{N} = \mathrm{F} - \lambda\mathbf{T}$$

Limited validity

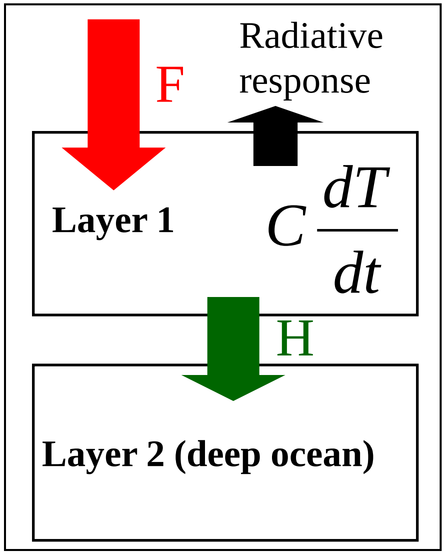
Bias in F and T_{eq} → bias in other parameters

2-box EBM with
efficacy of deep ocean heat uptake $\boldsymbol{\varepsilon}$

(Winton et al., 2010).

(Held et al, 2010)

Underlying assumptions



3 « forcings » → Decomposition of the radiative response in 3 radiative responses:

$$F - \lambda T_{eq} = 0$$

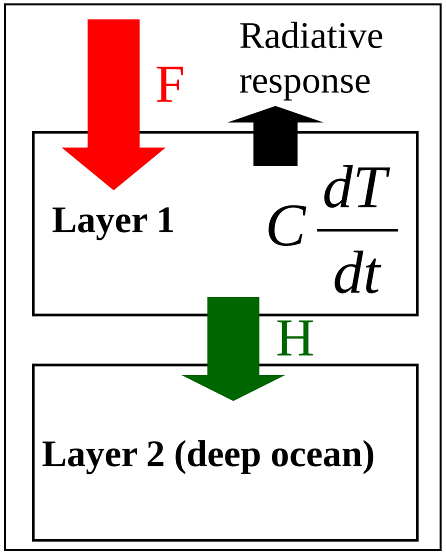
$$-C\frac{dT}{dt} - \lambda T_U = 0$$

$$-H - \lambda_D T_D = 0$$

Assumption of additivity

$$T = T_{eq} + T_U + T_D$$

Underlying assumptions



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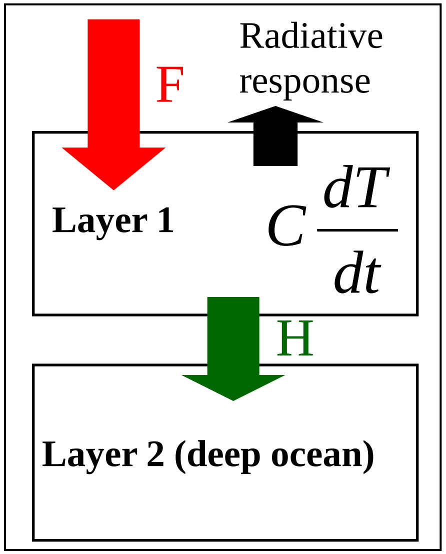
- the pattern of the temperature response associated with deep ocean heat uptake is different from the equilibrium pattern
- the strength of the feedbacks varies geographically

T_D associated with a different feedback parameter $\lambda_D = \frac{\lambda}{\varepsilon} \neq \lambda$

(Winton et al., 2010).

Efficacy (*Hansen et al, 2005*)

Underlying assumptions



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$T = T_{eq} + T_U + T_D$

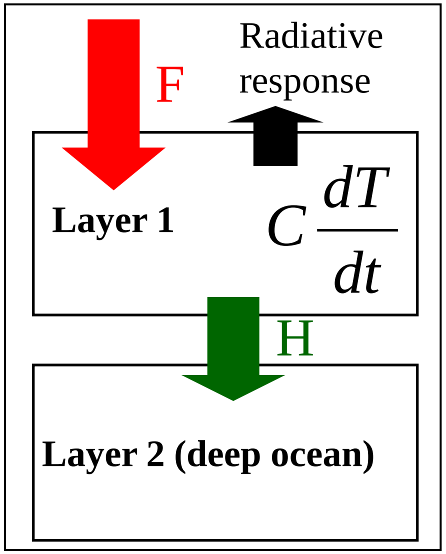
$$C\frac{dT}{dt} = \underbrace{F - \lambda T - (\varepsilon - 1)H}_{N} - H$$

$$C\frac{dT_0}{dt} = H$$

2-box EBM with ε

(Held et al, 2010)

Underlying assumptions



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2-box EBM with ε

(Held et al, 2010)

$$N = F - \lambda_t T$$

Time-dependant:

$$\lambda_t = \lambda - (\varepsilon - 1)\frac{H}{T}$$

Parameter calibration

6 parameters: F, λ, ε, C, C_0, γ

Iterative method

$$N = F - \lambda T - (\varepsilon - 1)H$$

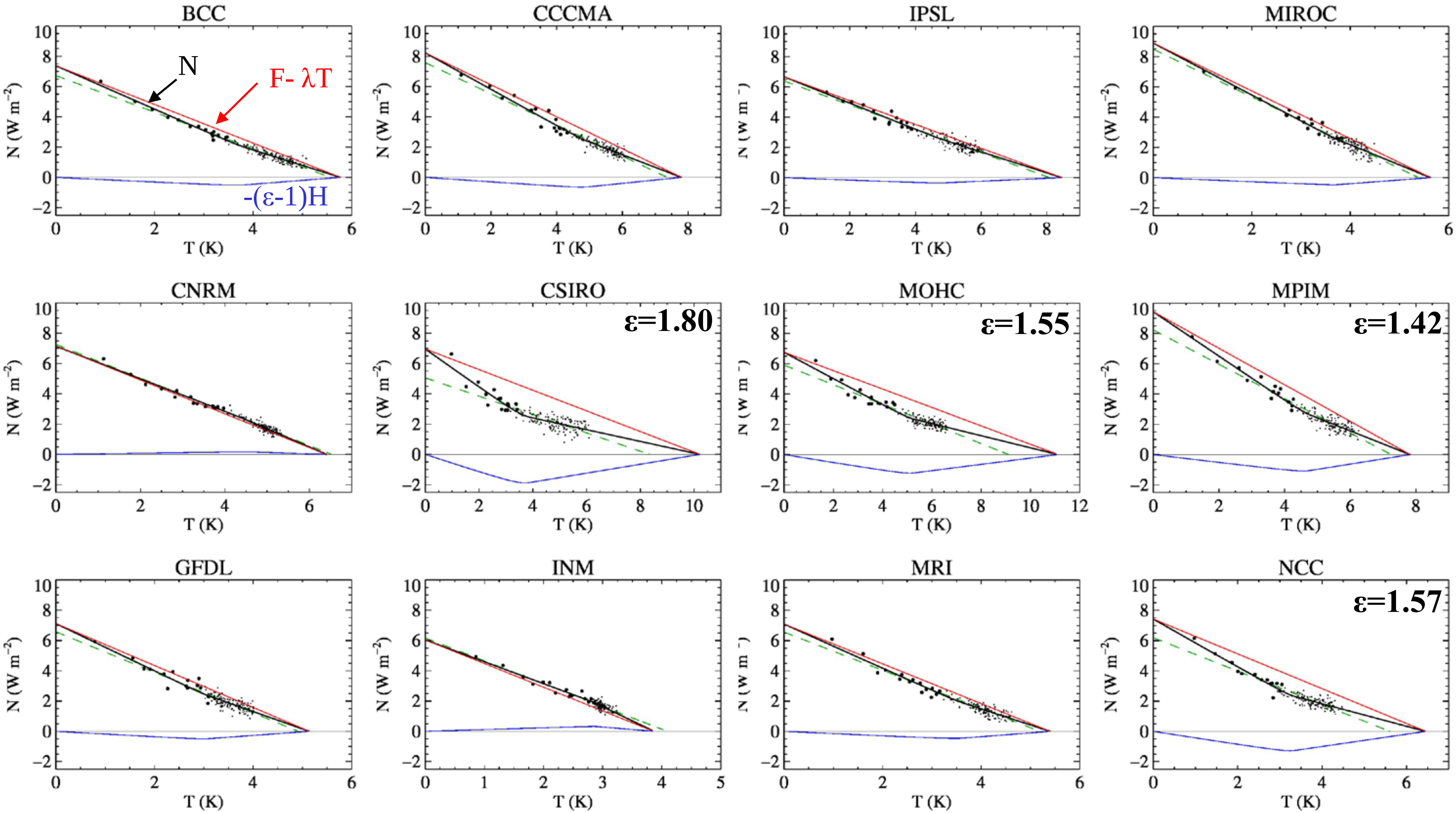
Multiple regression → **F_{4xCO2}**, **λ** and **ε**

Initial value of *H*: solutions of the EBM with ε=1

Results, N=f(T)

N= F- λT -(ε-1)H

(Geoffroy et al 2012b, submitted)

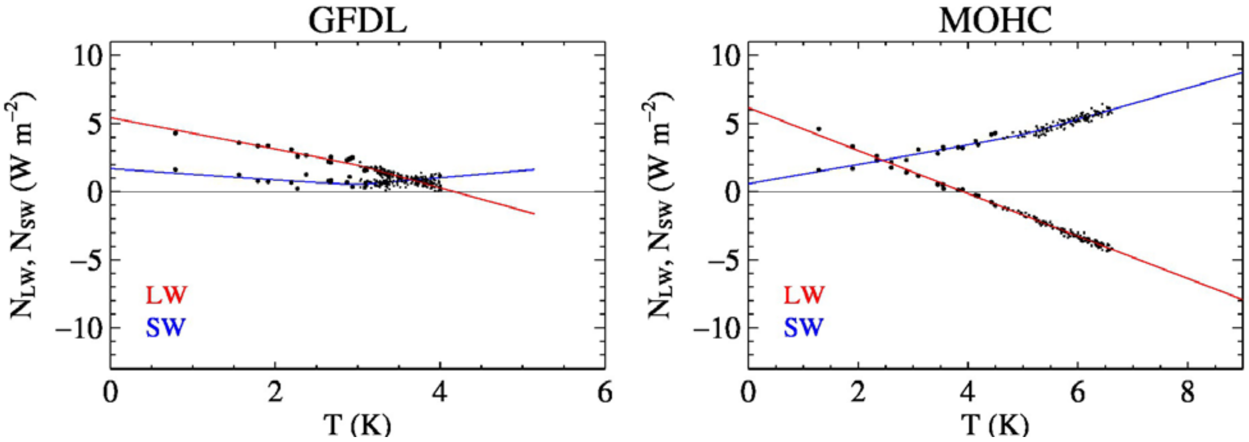


- N-T evolution well represented for all AOGCMs → Better estimation of ECS, F, γ…
- On average, $\mathbf{T_{eq4xCO2}}$ ↗ of 0.5 K (max: ~2K), $\mathbf{F_{4xCO2}}$ ↗ of 0.6 Wm^{-2} (max: ~ 2 Wm^{-2})

Decomposition of N

$$N^i = F^i - \lambda^i T - (\lambda^i - \lambda_D^i)\frac{\varepsilon}{\lambda} H$$

i =[LW,SW].



Difference with the linear fit:

	GFDL	MOHC
F^{LW} (Wm^{-2})	-0.68	0.05
F^{SW} (Wm^{-2})	+1.21	0.78

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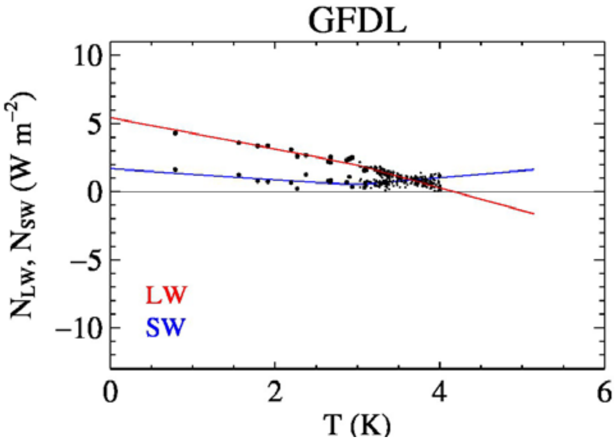

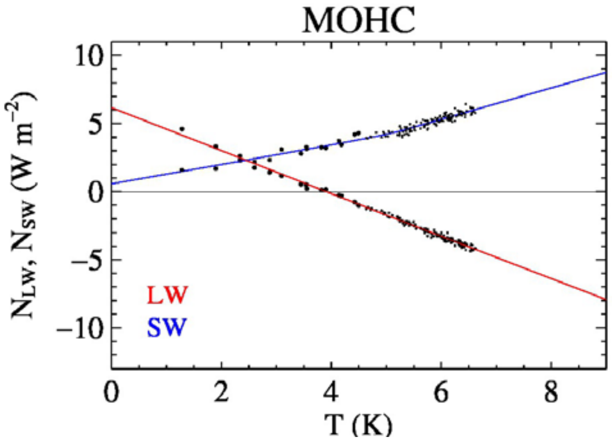

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PRP in transition (*Colman and Mc Avaney, 2011)*

- PRP over the **first 15 years** and the **last 10 years** of CNRM-CM5 AB4CO2

+ **linear fit** (ε close to 1 for CNRM-CM5) of each partial radiative flux:

Equal.

	CO2	T	W	A	C	O_3	Sum		N=f(T)
F (W m^{-2})	8.6	-0.73	-0.55	-0.15	0.64	-0.44	**7.4**		**7.4**
λ (W m^{-2} K^{-1})	0.04	-3.85	2.11	0.45	0.17	0.00	**-1.08**		**-1.10**

Contribution of each component to F and λ

The N=f(T) fit method can be extended to each component of a N decomposition such as LW/SW, cloudy/clear sky fluxes and **partial radiative fluxes (PRP, kernel).**

Contributors to the spread of the multimodel T response

Ojective: use the EBM framework to quantify the contribution of each parameter (F_{4CO2}, λ, ε, C, C_0, γ) to the spread of the CMIP5 AOGCMs temperature response (1% CO2 yr^{-1} experiment)

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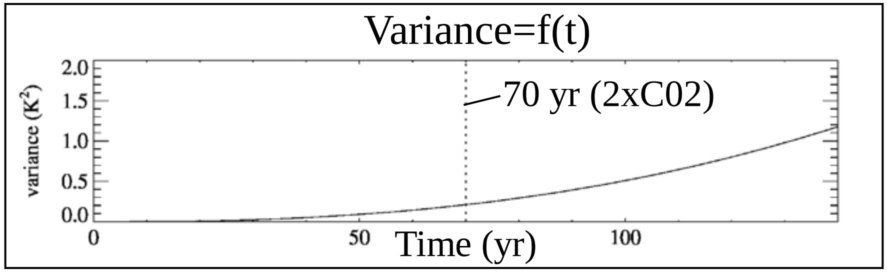
Method: analysis of variance.

$$f(F^i_{4CO2}, \lambda^j, \varepsilon^k, C^l, C_0^m, \gamma^n) = f_0 + f_1(F^i_{4CO2}) + f_2(\lambda^j) + f_3(\varepsilon^k) + f_4(C^l) + f_5(C_0^m) + f_6(\gamma^n) + I$$

Results



Geoffroy et al (2012c, to be submitted)

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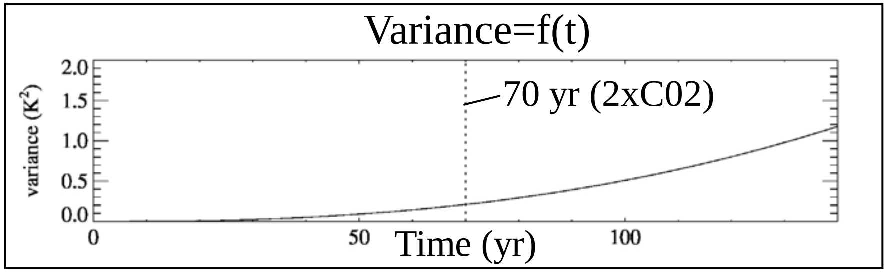
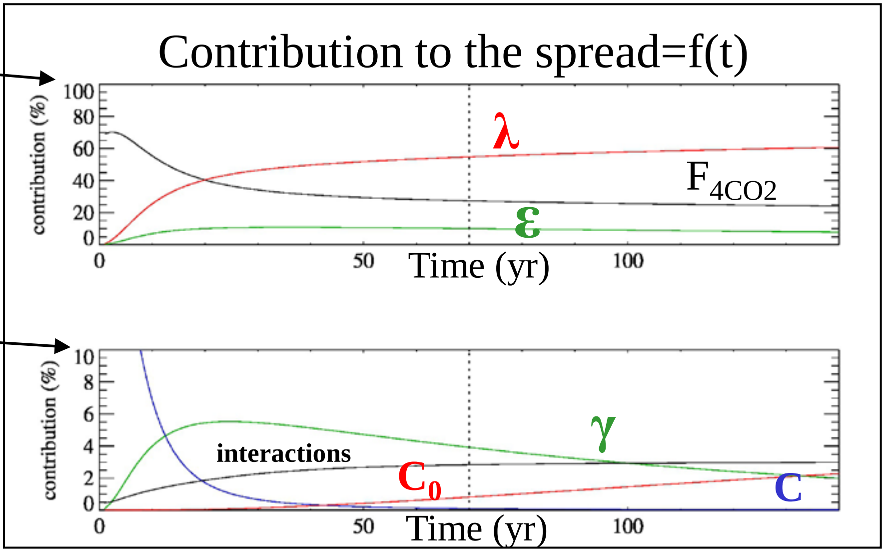


100 %

10 %



Contribution to the TCR spread

λ: 55 %
F: 27 %
ε: 10 %

Radiative parameters: **92%** of the spread

γ: 4 %
C_0: 0.8 %
C: 0.1 %
Inter: 2.8%

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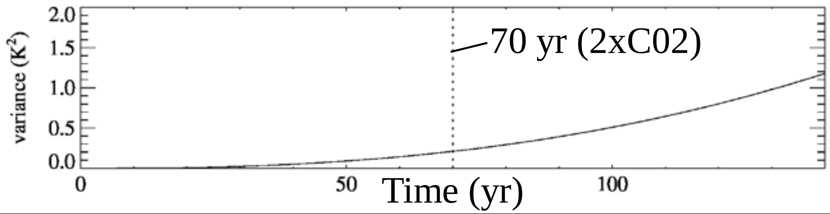
Results

Geoffroy et al (2012c, to be submitted)

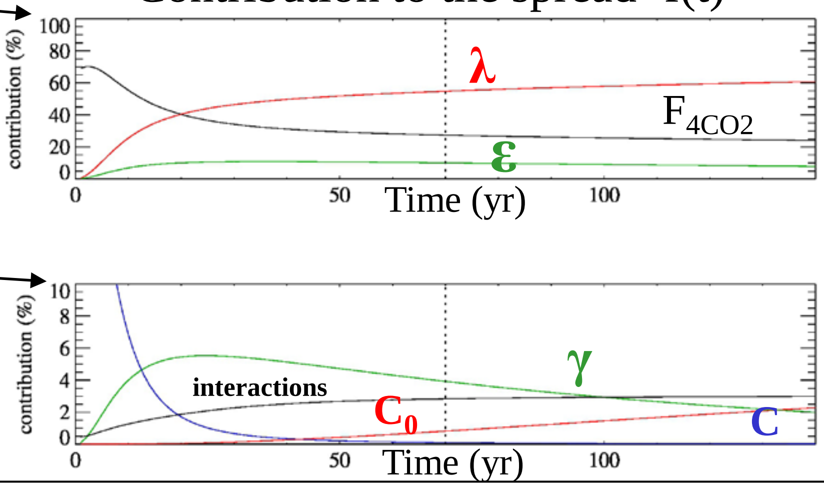
Variance=f(t)



Contribution to the spread=f(t)

100 %

10 %



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ECS

- λ: 87 %
- **F**: 12 %
- Inter: 1 %

Conclusion and perspectives

- Analytical solution of the 2-box EBM → **Physically-based method** for calibration
- **Good representation of the temperature response** for AB4CO2 and 1% CO_2 yr^{-1}.
- **Efficacy of deep ocean heat uptake** allows to take in account the time-evolution of the feedback strength in transient regime due to the impact of the deep ocean heat uptake on the temperature pattern and the spatial heterogeneity of the strength of the feedbacks.

→ G**ood representation of the evolution of the radiative flux imbalance as a function of the temperature response** for all AOGCMs.

→ **Determination of an AOGCM first-order parameters** (link with other properties e.g. MLD?)

- This framework combined with an an analysis of variance method has been used to quantify the **contribution of the parameters to the spread of CMIP5 AOGCM response** (1% CO2 yr^{-1} runs). The radiative parameters are the **main contributors to the spread**: **equilibrium feedback parameter (55%)**, **forcing (27 %), efficacy of deep ocean heat uptake (10%)**.
- The calibration method can be extended to **partial radiative flux** (PRP or kernels method) and then compute the contribution of each component (temperature, water vapor, surface albedo, clouds) to the fast adjustment of the radiative forcing, to the equilibrium feedback parameter and to the deep ocean heat uptake feedback parameter.

- Geoffroy O., D. Saint-Martin, D. J. L. Oliviè, A. Voldoire, G. Bellon, S. Tytéca: *« Transient climate response in a two-box energy-balance model. Part I: analytical solution and parameter calibration using CMIP5 AOGCM experiments »*, submitted to Journal of Climate.
- Geoffroy O., D. Saint-Martin, G. Bellon, A. Voldoire, D. J. L. Oliviè, S. Tytéca*: « Transient climate response in a two-box energy-balance model. Part II: representation of the efficacy of deep-ocean heat uptake and validation for CMIP5 AOGCMs»*, submitted to Journal of Climate.
- Geoffroy O., D. Saint-Martin, A. Ribes: «*Contribution of global thermal properties intermodel differences to the spread of CMIP5 AOGCMs transient response*», to be submitted to GRL.

Parameters, T_{eq} and time scales

2-box EBM with ε free parameter

Model	$\mathcal{F}_{4xCO_2}$ (W m^{-2})	λ (W m^{-2} K^{-1})	ε	T_{4xCO_2} (K)	C (W y m^{-2} K^{-1})	C_0 (W y m^{-2} K^{-1})	γ (W m^{-2} K^{-1})	τ_f (y)	τ_s (y)
BCC (BCC-CSM1-1)	7.4	1.28	1.27	5.8	8.4	56	0.59	4.1	152
CCCMA (CanESM2)	8.2	1.06	1.28	7.8	8.0	77	0.54	4.5	139
CNRM (CNRM-CM5.1)	7.1	1.12	0.92	6.4	8.3	95	0.51	5.2	266
CSIRO (CSIRO-Mk3-6-0)	7.0	0.68	1.82	10.2	8.5	76	0.71	4.2	316
GFDL (GFDL-ESM2M)	7.1	1.38	1.21	5.1	8.8	112	0.85	3.6	233
INM (INMCM4)	6.0	1.56	0.83	3.9	8.5	271	0.67	4.0	546
IPSL (IPSL-CM5A-LR)	6.7	0.79	1.14	8.5	8.1	100	0.57	5.5	327
MIROC (MIROC5)	8.9	1.58	1.19	5.6	8.7	158	0.73	3.6	338
MOHC (HadGEM2-ES)	6.8	0.61	1.54	11.1	7.5	98	0.49	5.4	457
MPIM (MPI-ESM-LR)	9.4	1.21	1.42	7.8	8.5	78	0.62	4.0	220
MRI (MRI-CGCM3)	7.1	1.31	1.25	5.4	9.3	68	0.59	4.4	181
NCC (NorESM1-M)	7.4	1.15	1.57	6.5	9.7	121	0.76	4.1	328
Multimodel mean	7.4	1.14	1.29	7.0	8.5	109	0.64	4.4	300
Standard deviation	1.0	0.32	0.27	2.1	0.6	58	0.11	0.7	113

Radiative parameters and T_{eq}

2 box EBM
ε=1

Model	$\mathcal{F}_{4xCO_2}$ (W m^{-2})	λ (W m^{-2} K^{-1})	T_{4xCO_2} (K)
BCC (BCC-CSM1-1)	6.7	1.21	5.6
CCCMA (CanESM2)	7.6	1.03	7.4
CNRM (CNRM-CM5.1)	7.3	1.11	6.5
CSIRO (CSIRO-Mk3-6-0)	5.1	0.61	8.3
GFDL (GFDL-ESM2M)	6.6	1.34	4.9
INM (INMCM4)	6.2	1.51	4.1
IPSL (IPSL-CM5A-LR)	6.4	0.79	8.1
MIROC (MIROC5)	8.5	1.58	5.4
MOHC (HadGEM2-ES)	5.9	0.65	9.1
MPIM (MPI-ESM-LR)	8.2	1.14	7.3
MRI (MRI-CGCM3)	6.6	1.26	5.2
NCC (NorESM1-M)	6.2	1.11	5.6
Multimodel mean	6.8	1.11	6.5
Standard deviation	1.0	0.31	1.6

2 box EBM
ε free parameter

Model	$\mathcal{F}_{4xCO_2}$ (W m^{-2})	λ (W m^{-2} K^{-1})	ε	T_{4xCO_2} (K)
BCC (BCC-CSM1-1)	7.4	1.28	1.27	5.8
CCCMA (CanESM2)	8.2	1.06	1.28	7.8
CNRM (CNRM-CM5.1)	7.1	1.12	0.92	6.4
CSIRO (CSIRO-Mk3-6-0)	7.0	0.68	1.82	10.2
GFDL (GFDL-ESM2M)	7.1	1.38	1.21	5.1
INM (INMCM4)	6.0	1.56	0.83	3.9
IPSL (IPSL-CM5A-LR)	6.7	0.79	1.14	8.5
MIROC (MIROC5)	8.9	1.58	1.19	5.6
MOHC (HadGEM2-ES)	6.8	0.61	1.54	11.1
MPIM (MPI-ESM-LR)	9.4	1.21	1.42	7.8
MRI (MRI-CGCM3)	7.1	1.31	1.25	5.4
NCC (NorESM1-M)	7.4	1.15	1.57	6.5
Multimodel mean	7.4	1.14	1.29	7.0
Standard deviation	1.0	0.32	0.27	2.1

Thermal inertia parameters and time scales

2 box EBM
ε=1

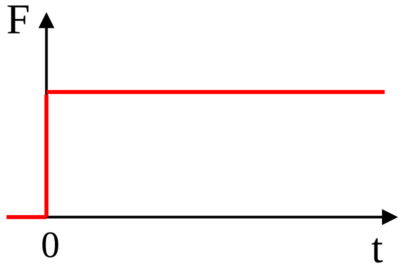
Model	C (W y m^{-2} K^{-1})	C_0 (W y m^{-2} K^{-1})	γ (W m^{-2} K^{-1})	τ_f (y)	τ_s (y)
BCC (BCC-CSM1-1)	7.6	53	0.67	4.0	126
CCCMA (CanESM2)	7.3	71	0.59	4.5	193
CNRM (CNRM-CM5.1)	8.4	99	0.50	5.2	289
CSIRO (CSIRO-Mk3-6-0)	6.0	69	0.88	3.9	200
GFDL (GFDL-ESM2M)	8.1	105	0.90	3.6	197
INM (INMCM4)	8.6	317	0.65	4.0	698
IPSL (IPSL-CM5A-LR)	7.7	95	0.59	5.5	286
MIROC (MIROC5)	8.3	145	0.76	3.5	285
MOHC (HadGEM2-ES)	6.5	82	0.55	5.3	280
MPIM (MPI-ESM-LR)	7.3	71	0.72	3.9	164
MRI (MRI-CGCM3)	8.5	64	0.66	4.3	150
NCC (NorESM1-M)	8.0	105	0.88	4.0	218
Multimodel mean	7.7	106	0.70	4.3	257
- without INM	7.6	87	0.70	4.3	217
Standard deviation	0.8	71	0.13	0.7	150
- without INM	0.8	26	0.14	0.7	60

2 box EBM
ε free parameter

Model	C (W y m^{-2} K^{-1})	C_0 (W y m^{-2} K^{-1})	γ (W m^{-2} K^{-1})	τ_f (y)	τ_s (y)
BCC (BCC-CSM1-1)	8.4	56	0.59	4.1	152
CCCMA (CanESM2)	8.0	77	0.54	4.5	139
CNRM (CNRM-CM5.1)	8.3	95	0.51	5.2	266
CSIRO (CSIRO-Mk3-6-0)	8.5	76	0.71	4.2	316
GFDL (GFDL-ESM2M)	8.8	112	0.85	3.6	233
INM (INMCM4)	8.5	271	0.67	4.0	546
IPSL (IPSL-CM5A-LR)	8.1	100	0.57	5.5	327
MIROC (MIROC5)	8.7	158	0.73	3.6	338
MOHC (HadGEM2-ES)	7.5	98	0.49	5.4	457
MPIM (MPI-ESM-LR)	8.5	78	0.62	4.0	220
MRI (MRI-CGCM3)	9.3	68	0.59	4.4	181
NCC (NorESM1-M)	9.7	121	0.76	4.1	328
Multimodel mean	8.5	109	0.64	4.4	300
Standard deviation	0.6	58	0.11	0.7	113

Analytical solution (temperature response T)

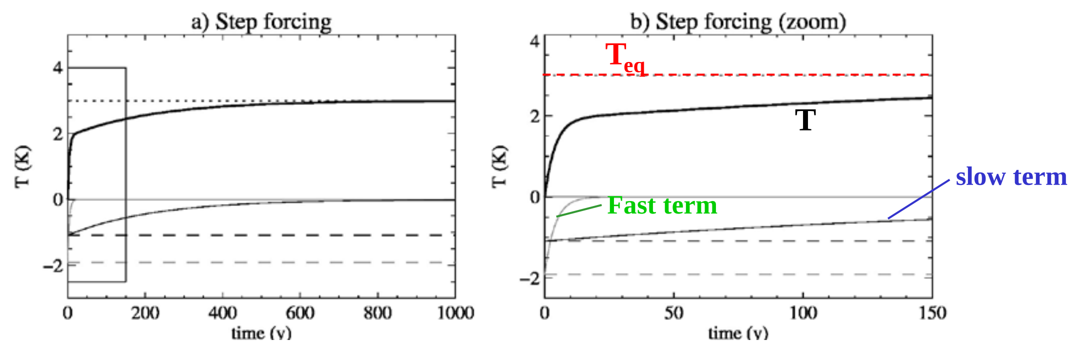
Abrupt forcing (e.g. AB4CO2)



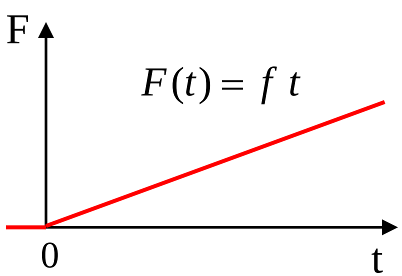
Simulations CMIP5:
Abrupt 4xCO2

$$T = \frac{F}{\lambda} - \frac{F}{\lambda} a_f e^{-t/\tau_f} - \frac{F}{\lambda} a_s e^{-t/\tau_s}$$

T_{eq} — Fast term — slow term

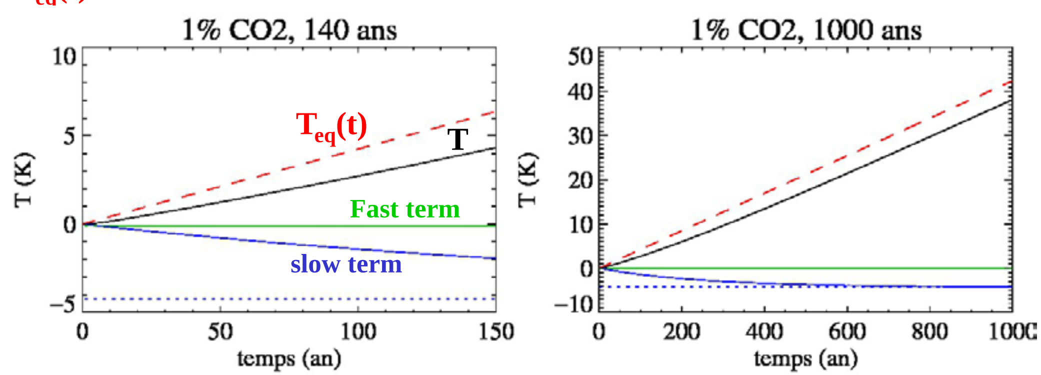


Linear forcing (e.g. 1% yr^{-1} CO2)



$$T = \frac{f}{\lambda} t - \frac{f}{\lambda} a_f \tau_f (1 - e^{-t/\tau_f}) - \frac{f}{\lambda} a_s \tau_s (1 - e^{-t/\tau_s})$$

$T_{eq}(t)$ — Fast term — slow term

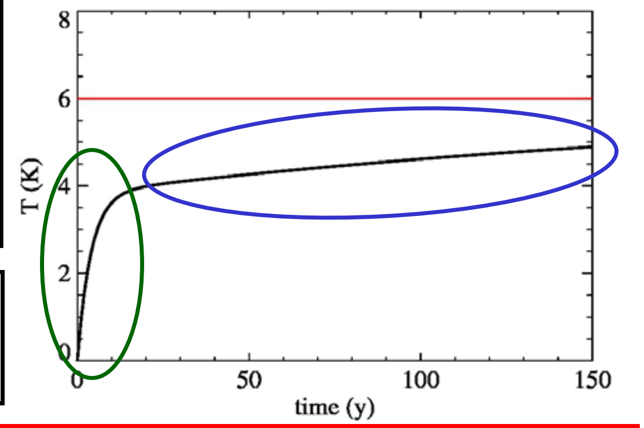


Parameter calibration, method

Analytical solution (step forcing case)

$$T = \frac{F}{\lambda} - \frac{F}{\lambda} a_f e^{-t/\tau_f} - \frac{F}{\lambda} a_s e^{-t/\tau_s} \quad (1)$$

Calibration of F_{4CO2}, λ, C, C0, γ from AB4CO2



→ **Linear fit** N=f(T) (**Grégory et al, 2004):** ⟶ **F, λ**

→ (1) $\xrightarrow{t \gg \tau_f}$ $\log\left(\frac{T_{eq} - T}{T_{eq}}\right) = \frac{-t}{\tau_s} + \log(a_s)$ — **Fit** over 30-150 yr ⟶ $\mathbf{a_s}$, $\boldsymbol{\tau_s}$

→ Analytical relationship — $a_f + a_f = 1$ ⟶ $\mathbf{a_f}$

→ (1) $\Rightarrow \tau_f = \frac{-t}{\log\left(\left(\frac{T_{eq} - T}{T_{eq}} - a_s e^{-t/\tau_s}\right)/a_f\right)}$ — **Mean** of the first 10 yr ⟶ $\boldsymbol{\tau_f}$

→ Analytical relationships $C = \frac{\lambda}{\frac{a_f}{\tau_f} + \frac{a_s}{\tau_s}}$ ⟶ **C**

$C_0 = \lambda(\tau_f a_f + \tau_s a_s) - C$ ⟶ $\mathbf{C_0}$

$\gamma = \frac{C_0}{\left(\tau_f + \tau_s - \frac{C + C_0}{\lambda}\right)}$ ⟶ **γ**

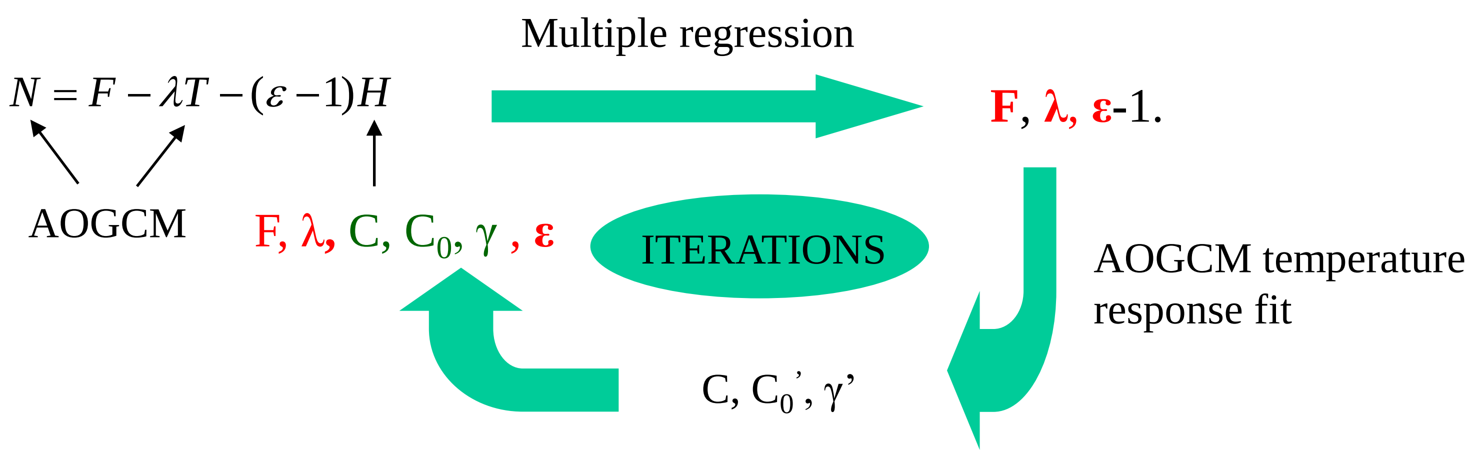
Parameter calibration, method

6 parameters: F, λ, ε, C, C_0, γ

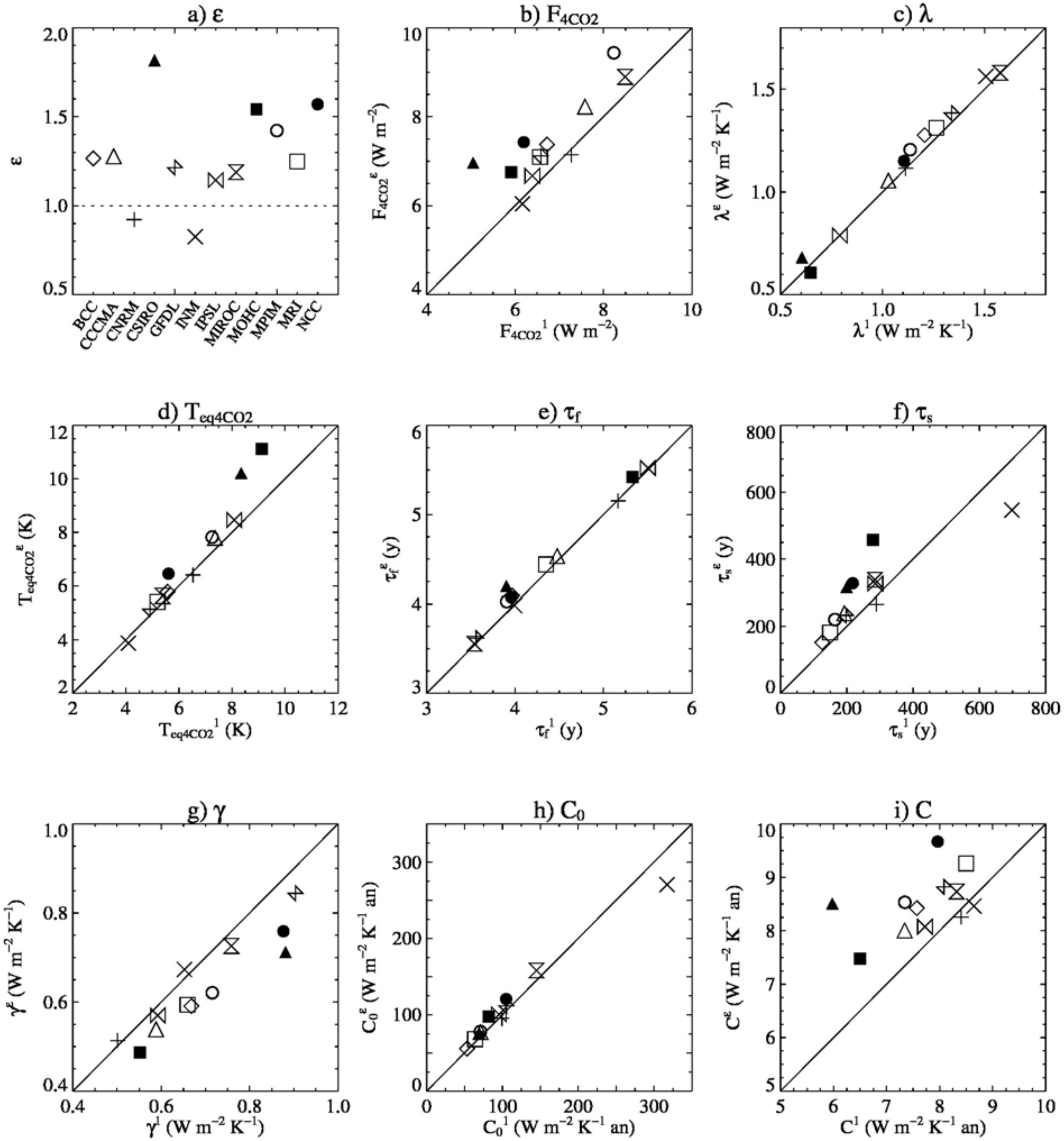
$$\begin{cases} C\dfrac{dT}{dt} = F - \lambda T - \gamma'(T - T_0) \\ C_0'\dfrac{dT_0}{dt} = \gamma'(T - T_0) \end{cases}$$

$$\gamma' = \varepsilon\gamma$$

$$C_0' = \varepsilon C_0$$



Comparison of parameters EBM -1 vs EBM-ε



- X-axis: EBM-1 estimation
- Y-axis: EBM- ε estimation

$\varepsilon > 1$:

→ F ↗ , ECS ↗
γ ↘
τ_{slow} ↗
C ↗

Correlations ?

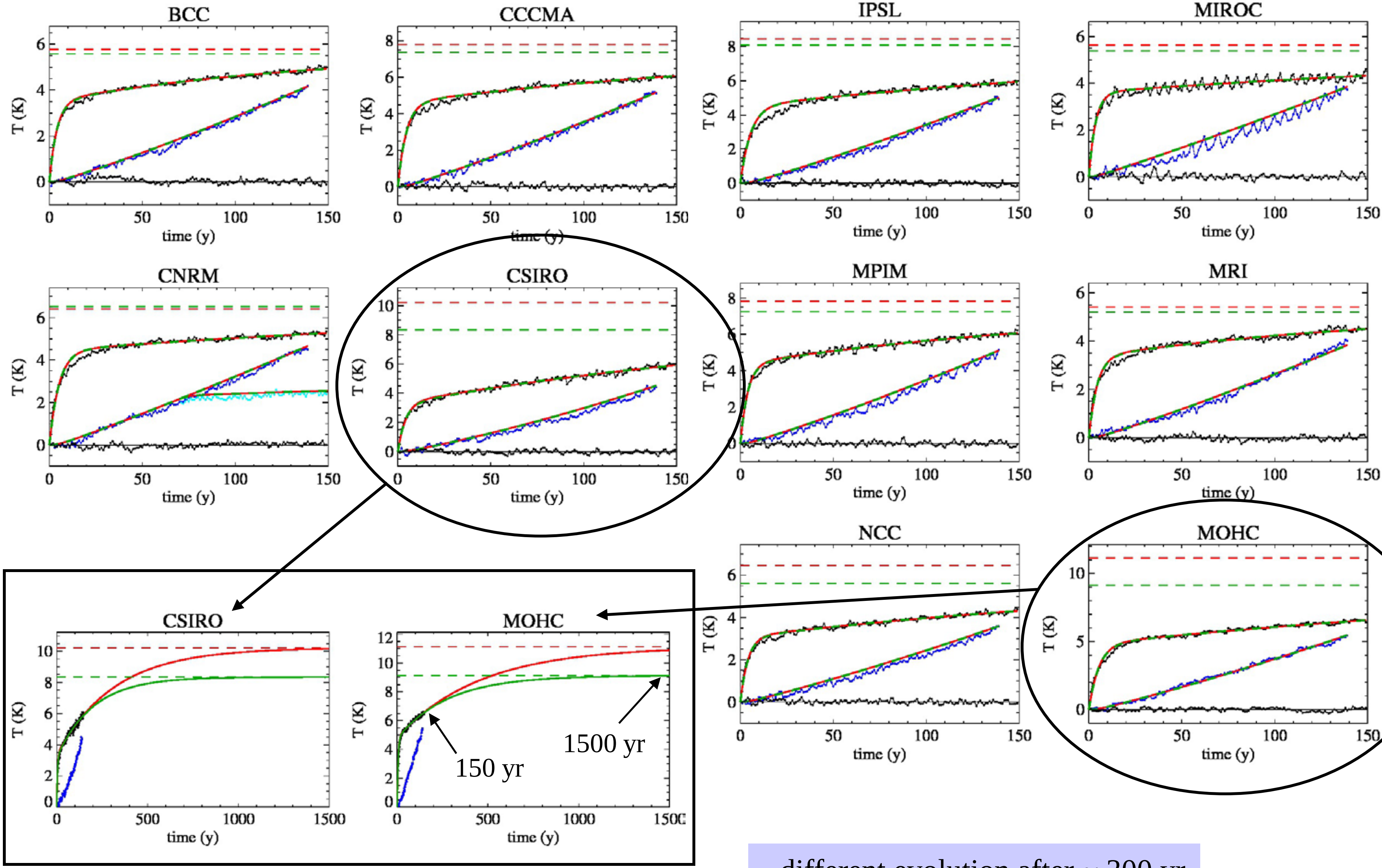
TABLE 3. Intermodel correlations between the equilibrium temperature at $4xCO_2$ T_{4xCO_2} and the physical parameters $\mathcal{F}$, λ, ε, γ, C_0, C of the EBM-ε for the 12 CMIP5 AOGCMs.

	T_{4xCO_2}	$\mathcal{F}$	λ	ε	γ	C_0	C
T_{4xCO_2}	1	0.02	**-0.86**	**0.64**	-0.38	-0.45	-0.51
$\mathcal{F}$		1	0.23	0.18	0.06	-0.28	0.12
λ			1	-0.55	0.42	0.46	0.47
ε				1	0.14	-0.48	0.09
γ					1	0.29	**0.62**
C_0						1	0.06
C							1

- No corrélation between λ and γ.
Agreement with Gregory and Foster (2002).
Not with Raper et al. (2002)

- light corrélation ε - ECS.

Results, net flux TOA N=f(T)

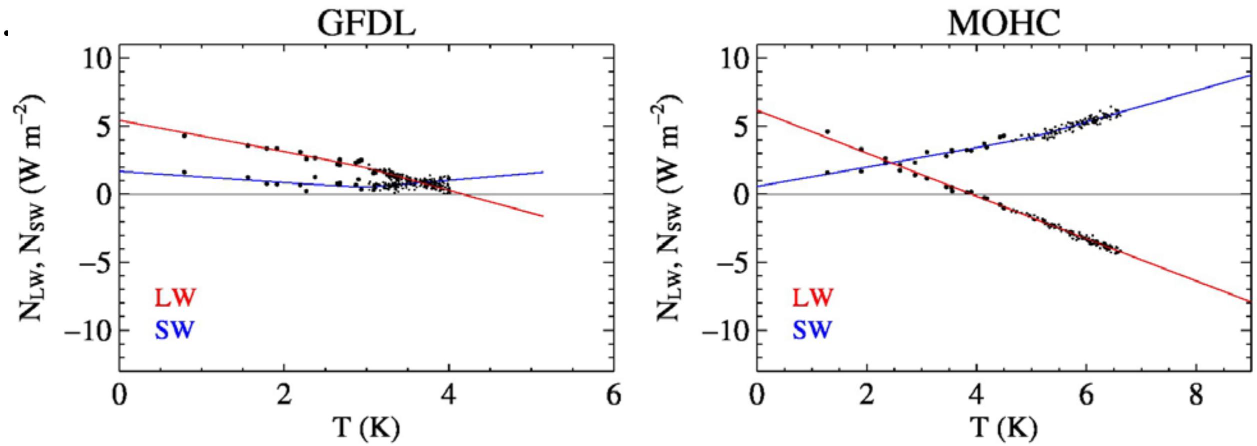


- different evolution after ~ 300 yr

Decomposition of N

$$N^i = F^i - \lambda^i T - (\lambda^i - \lambda_D^i)\frac{\varepsilon}{\lambda}H$$

Multimodel: i =[LW,SW].



Model	$\mathcal{F}^{LW}$ (W m^{-2})	$\mathcal{F}^{SW}$ (W m^{-2})	λ^{LW} (Wm^{-2}K^{-1})	λ^{SW} (Wm^{-2}K^{-1})	λ_D^{LW} (Wm^{-2}K^{-1})	λ_D^{SW} (Wm^{-2}K^{-1})
BCC	6.4	1.0	1.69	-0.42	1.68	-0.68
CCCMA	6.2	2.0	1.42	-0.37	1.38	-0.57
CNRM	5.1	2.1	1.62	-0.50	1.67	-0.46
CSIRO	7.4	-0.4	1.97	-1.29	1.81	-1.43
GFDL	5.4	1.7	1.37	0.01	1.68	-0.54
INM	6.8	-0.7	2.12	-0.55	2.65	-0.76
IPSL	3.4	3.3	1.92	-1.13	1.89	-1.20
MIROC	6.9	2.0	1.93	-0.35	1.70	-0.37
MOHC	6.2	0.6	1.56	-0.96	1.55	-1.16
MPIM	7.0	2.5	1.67	-0.46	1.50	-0.65
MRI	6.6	0.5	2.24	-0.93	2.16	-1.11
NCC	6.3	1.1	1.82	-0.67	1.67	-0.93
Mean	6.1	1.3	1.78	-0.63	1.78	-0.82
STDV	1.1	1.2	0.27	0.37	0.34	0.34

Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**

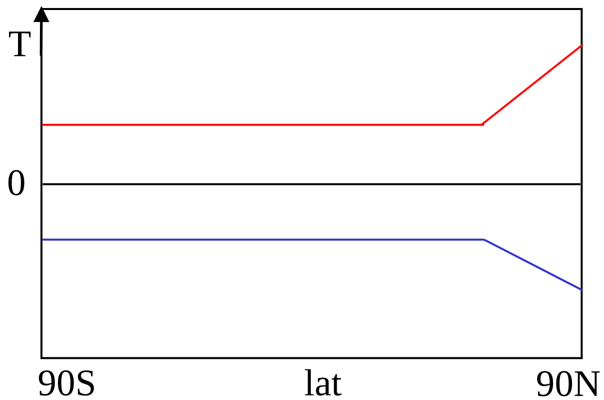
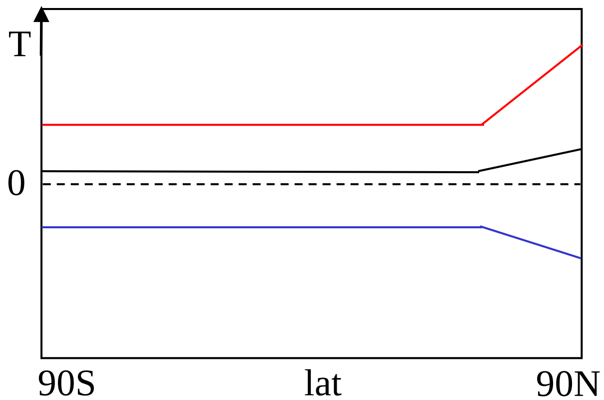


Schéma: moyenne zonale de T

$$T = T_{eq} + T_U$$

Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**



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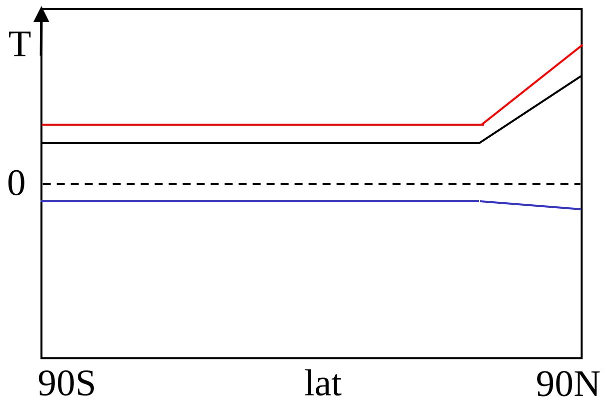

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Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**

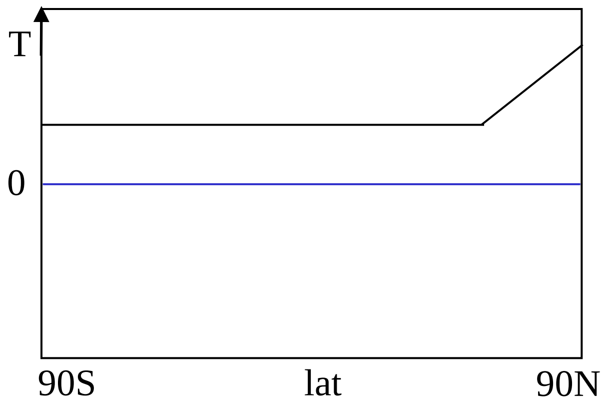

Schéma: moyenne zonale de T

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Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**

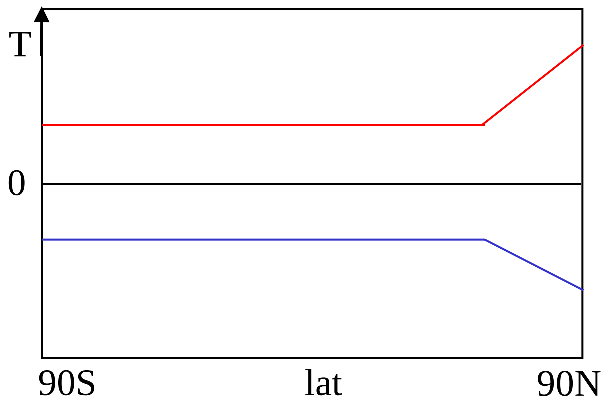

Schéma: moyenne zonale de T

$$T = T_{eq} + T_U + T_D$$

Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**

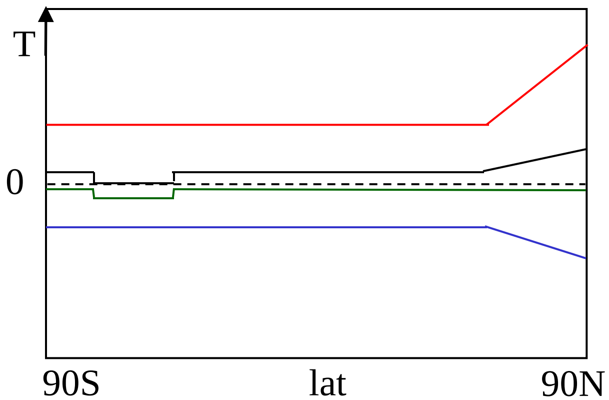

Schéma: moyenne zonale de T

$$T = T_{eq} + T_U + T_D$$

Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage ε

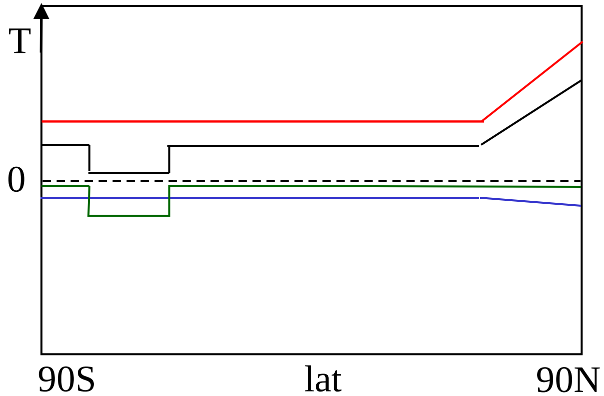

Schéma: moyenne zonale de T

$$T = T_{eq} + T_U + T_D$$

Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage ε

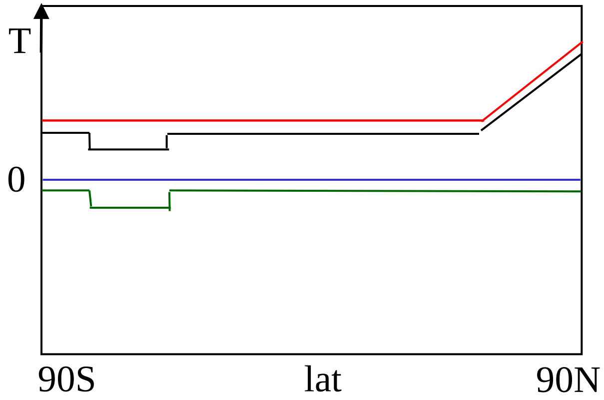

Schéma: moyenne zonale de T

$$T = T_{eq} + T_U + T_D$$

Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**

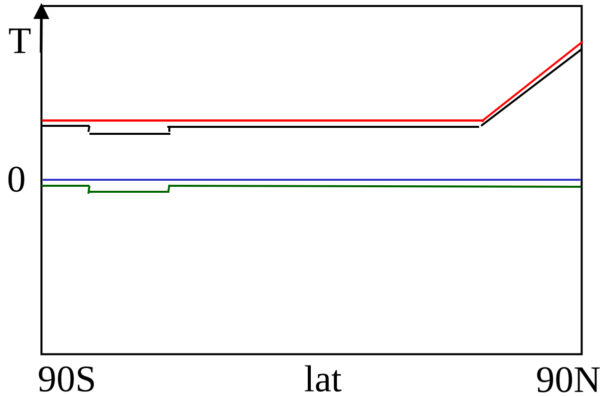

Schéma: moyenne zonale de T

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Flux de chaleur accumulé dans l'océan: introduction d'une efficacité de forçage **ε**

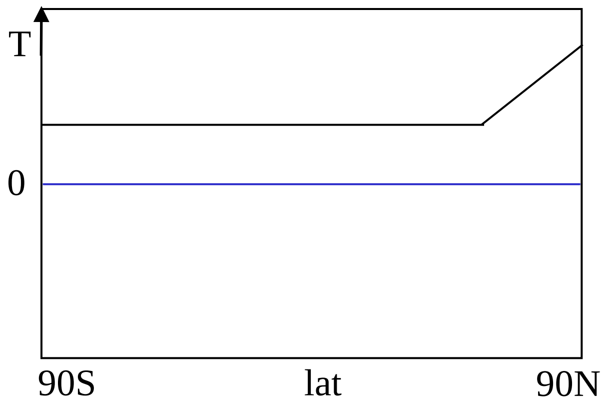
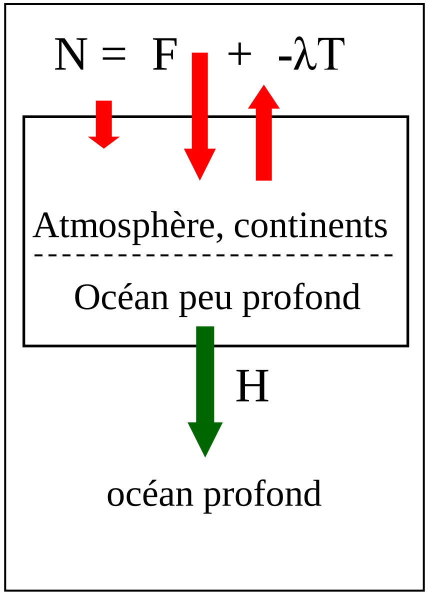


Schéma: moyenne zonale de T

$$T = T_{eq} + T_U + T_D$$

1-box EBM



Energie accumulée océan peu profond (+continents +atmosphère)

Déséquilibre radiatif N

Energie accumulée dans l'océan profond

$$C\frac{dT}{dt} = F - \lambda T - H$$

avec $H = \kappa \cdot T$

(Gregory and Mitchell, 1997)