Observational study of time-varying climate feedback parameter

Jonathan CHENAL[(a,b)],
Benoît MEYSSIGNAC[(a,c)], **Robin GUILLAUME-CASTEL**[a]

[(a)] : LEGOS, UMR 5566 (CNES, CNRS, IRD, UPS), Toulouse, France
[(b)] : ENPC, Marne-la-Vallée, France
[(c)] : CNES, Toulouse, France

EGU, Vienna, 2022

Equilibrium climate sensitivity

Energy budget equation

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

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

TOA : *Top of atmosphere*

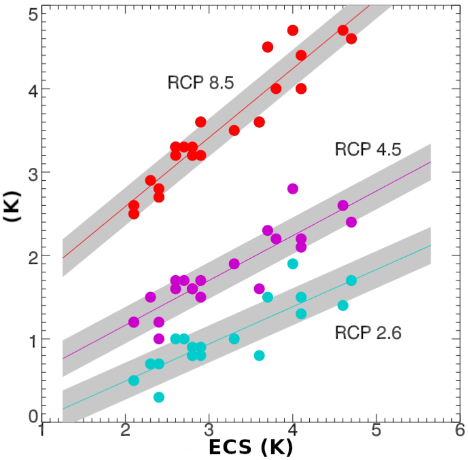
- N : Earth energy imbalance
- F : radiative forcing
- T : surface temperature
- λ : **climate feedback parameter**

Equilibrium climate sensitivity (ECS)

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

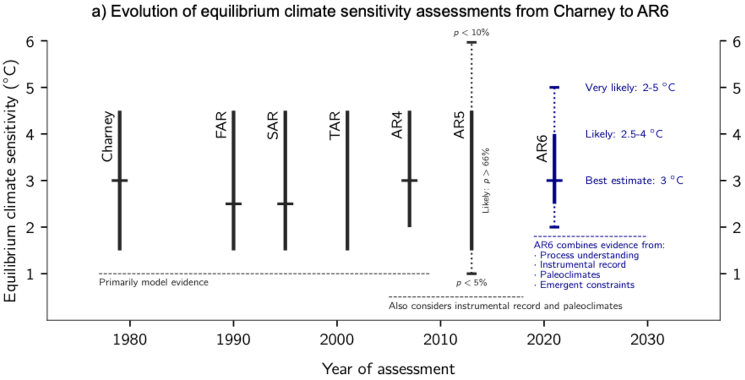
$$ECS = -\frac{F_{2x}}{\lambda}$$

Fundamental metric of climate change amplitude and projections



$T(2100) \propto ECS$ 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]
$2.5 \leq ECS \leq 4.0$ K (likely) [Arias *et al.*, 2021]
$2.0 \leq ECS \leq 5.0$ K (very likely) [Arias *et al.*, 2021]

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

Estimate of ECS over 1971-2017 with observations of :

- F from [Sherwood *et al.*, 2020] (non aerosol) and [Bellouin *et al.*, 2020] (aerosols)
- T from [Cowtan & Way, 2014] scaled by [Richardson *et al.*, 2016]

Estimate of ECS over 1971-2017 with observations of :

- F from [Sherwood *et al.*, 2020] (non aerosol) and [Bellouin *et al.*, 2020] (aerosols)
- T from [Cowtan & Way, 2014] scaled by [Richardson *et al.*, 2016]
- $N \propto dOHC/dt$ where OHC is the ocean heat content from in situ T/S measurements ; we use an ensemble of 5 solutions : [Gouretski & Koltermann, 2007 ; Levitus *et al.*, 2009 ; Levitus *et al.*, 2012 ; Good *et al.*, 2013 ; Cheng *et al.*, 2017 ; Ishii *et al.*, 2017]

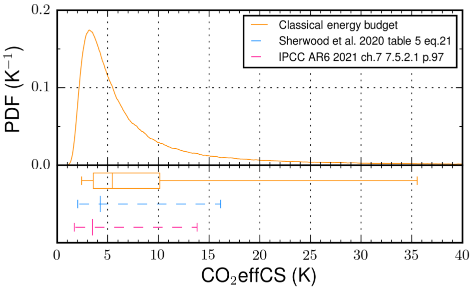
Estimate of ECS over 1971-2017 with observations of :

- F from [Sherwood *et al.*, 2020] (non aerosol) and [Bellouin *et al.*, 2020] (aerosols)
- T from [Cowtan & Way, 2014] scaled by [Richardson *et al.*, 2016]
- $N \propto dOHC/dt$ where OHC is the ocean heat content from in situ T/S measurements ; we use an ensemble of 5 solutions : [Gouretski & Koltermann, 2007 ; Levitus *et al.*, 2009 ; Levitus *et al.*, 2012 ; Good *et al.*, 2013 ; Cheng *et al.*, 2017 ; Ishii *et al.*, 2017]

Method : **regression of $N - F$ over T with rigorous handling of uncertainties**

Results published in *Journal of climate* [Chenal *et al.*, 2022]

ECS $= 5.5$ [2.4 ;35.6] K (very likely)



Estimate of ECS over 1971-2017 with observations of :

- F from [Sherwood *et al.*, 2020] (non aerosol) and [Bellouin *et al.*, 2020] (aerosols)
- T from [Cowtan & Way, 2014] scaled by [Richardson *et al.*, 2016]
- $N \propto dOHC/dt$ where OHC is the ocean heat content from in situ T/S measurements ; we use an ensemble of 5 solutions : [Gouretski & Koltermann, 2007 ; Levitus *et al.*, 2009 ; Levitus *et al.*, 2012 ; Good *et al.*, 2013 ; Cheng *et al.*, 2017 ; Ishii *et al.*, 2017]

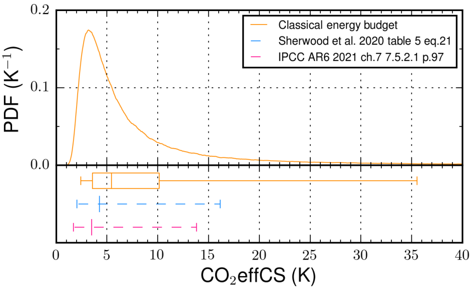
Method : **regression of $N - F$ over T with rigorous handling of uncertainties**

Results published in *Journal of climate* [Chenal *et al.*, 2022]

$ECS = 5.5$ [2.4 ;35.6] K (very likely)

With comparable approach :

- [Sherwood *et al.*, 2020] :
  $ECS = 4.26$ [2.04; 16.13] K
- [Forster *et al.*, 2021] :
  $ECS = 3.5$ [1.7; 13.8] K



Time-varying climate feedback parameter

Influence of the mean epoch and duration of observations on the estimate of parameter λ

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

- thermosteric component of [Frederikse *et al.*, 2020] sea level reconstruction by GMSL - GMBSL (low-pass filter, 15yr)
- in situ solutions (5-solutions ensemble + ARANN [Bagnell & de Vries, 2021]) (low-pass filter, 10yr)

Radiative forcing and temperature : low-pass filter, 10yr

Time-varying climate feedback parameter

Influence of the mean epoch and duration of observations on the estimate of parameter λ

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

- thermosteric component of [Frederikse *et al.*, 2020] sea level reconstruction by GMSL - GMBSL (low-pass filter, 15yr)
- in situ solutions (5-solutions ensemble + ARANN [Bagnell & de Vries, 2021]) (low-pass filter, 10yr)

Radiative forcing and temperature : low-pass filter, 10yr

For all durations longer than 25 years and all possible time-span, we regress $N - F$ over T

Time-varying climate feedback parameter

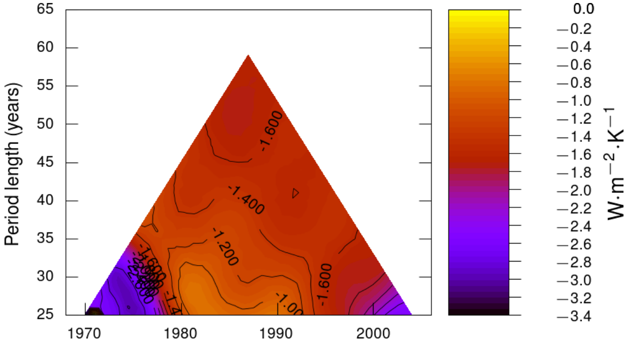
Influence of the mean epoch and duration of observations on the estimate of parameter λ

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

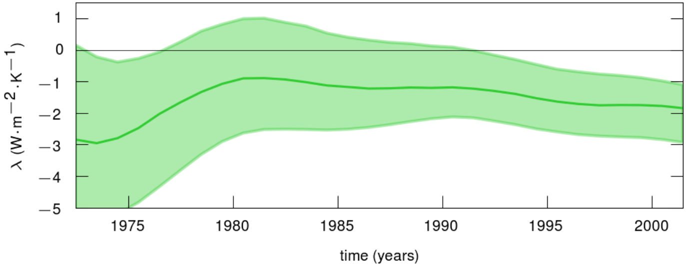
- thermosteric component of [Frederikse *et al.*, 2020] sea level reconstruction by GMSL - GMBSL (low-pass filter, 15yr)
- in situ solutions (5-solutions ensemble + ARANN [Bagnell & de Vries, 2021]) (low-pass filter, 10yr)

Radiative forcing and temperature : low-pass filter, 10yr

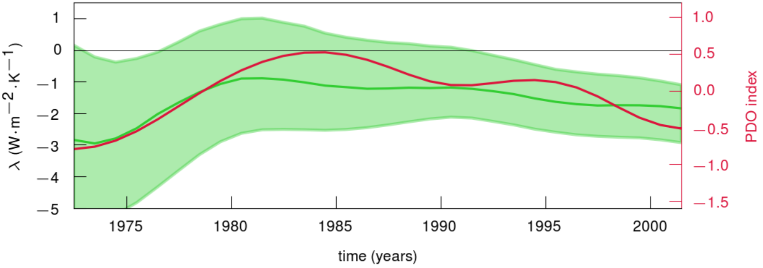
For all durations longer than 25 years and all possible time-span, we regress $N - F$ over T



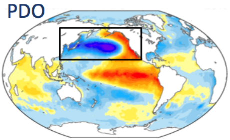
30-yr duration λ estimates [Meyssignac *et al.*, in prep.]



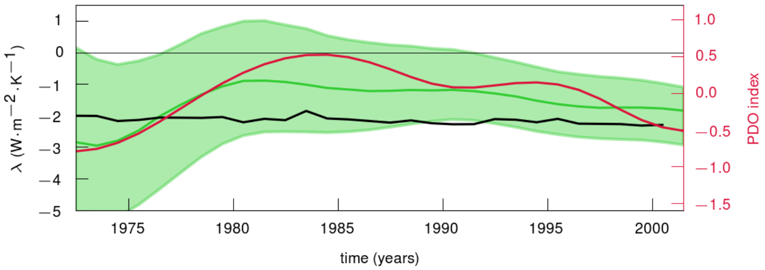
30-yr duration λ estimates [Meyssignac *et al.*, in prep.]

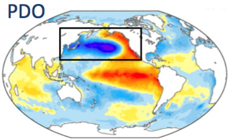


Role of the **Pacific Decadal Oscillation** on parameter λ?
(here NOAA ERSST v5 PDO indexed, low-pass filtered)



30-yr duration λ estimates [MEYSSIGNAC *et al.*, in prep.]

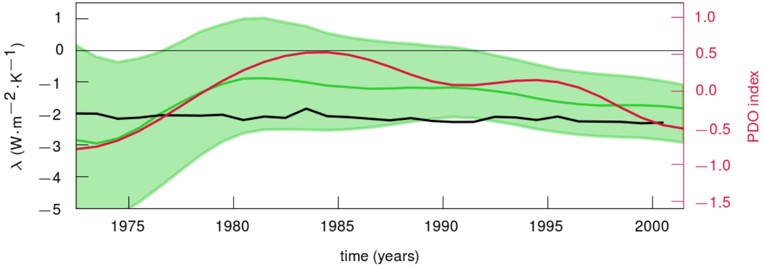


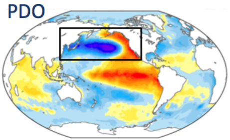


Role of the **Pacific Decadal Oscillation** on parameter λ?
(here NOAA ERSST v5 PDO indexed, low-pass filtered)

However **climate models** poorly reproduce $\lambda(t)$...
(here ensemble-mean from 8 climate models amip-piForcing simulations)

30-yr duration λ estimates [MEYSSIGNAC *et al.*, in prep.]





Role of the **Pacific Decadal Oscillation** on parameter λ?
(here NOAA ERSST v5 PDO indexed, low-pass filtered)

However **climate models** poorly reproduce $\lambda(t)$...
(here ensemble-mean from 8 climate models amip-piForcing simulations)

But very negative λ can be a possible explanation of other observational ECS low estimates

Conclusions

Conclusions

- Rigorous handling of uncertainties due to climate variability in climate sensitivity estimate
  - **low ECS ($\leqslant$ 2.4 K) are very unlikely**
  - Median ECS $\gtrsim$ 3.0 K
  - Reconciliation of observational and models estimates
- **Observational constraint on $\lambda(t)$ for climate models and ECS observational studies**

Thanks for your attention

Some references

Andrews, Timothy, Jonathan Gregory, David Paynter, Levi G. Silvers, Chen Zhou & Thorsten Mauritsen (2018). *« Accounting for changing temperature patterns increases historical estimates of climate sensitivity »*. *Geophys. Res. Lett.* 45, p. 8490-8499.

Arias, P. A., N. Bellouin, E. Coppola, R. G. Jones, G. Krinner, J. Marotzke, V. Naik, M. D. Palmer, G-K. Plattner, J. Rogelj, M. Rojas, J. Sillmann, T. Storelvmo, P. W. Thorne, B. Trewin, K. Achuta Rao, B. Adhikary, R. P. Allan, K. Armour, G. Bala, R. Barimalala, S. Berger, J. G. Canadell, C. Cassou, A. Cherchi, W. Collins, W. D. Collins, S. L. Connors, S. Corti, F. Cruz, F. J. Dentener, C. Dereczynski, A. Di Luca, A. Diongue Niang, F. J. Doblas-Reyes, A. Dosio, H. Douville, F. Engelbrecht, V. Eyring, E. Fischer, P. Forster, B. Fox-Kemper, J. S. Fuglestvedt, J. C. Fyfe, N. P. Gillett, L. Goldfarb, I. Gorodetskaya, J. M. Gutierrez, R. Hamdi, E. Hawkins, H. T. Hewitt, P. Hope, A. S. Islam, C. Jones, D. S. Kaufman, R. E. Kopp, Y. Kosaka, J. Kossin, S. Krakovska, J-Y. Lee, J. Li, T. Mauritsen, T. K. Maycock, M. Meinshausen, S-K. Min, P. M. S. Monteiro, T. Ngo-Duc, F. Otto, I. Pinto, A. Pirani, K. Raghavan, R. Ranasinghe, A. C. Ruane, L. Ruiz, J-B. Sallée, B. H. Samset, S. Sathyendranath, S. I. Seneviratne, A. A. Sörensson, S. Szopa, I. Takayabu, A-M. Treguier, B. van den Hurk, R. Vautard, K. von Schuckmann, S. Zaehle, X. Zhang & K. Zickfeld (2021). *« Technical Summary »*. *Climate Change 2021 : The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Sous la dir. de Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou. Cambridge, United Kingdom et New York, NY, USA : Cambridge University Press.

Arrhenius, Svante (1896). *« On the influence of carbonic acid in the air upon the temperature of the ground »*. *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science* 41.251, p. 237-276.

Bagnell, A. & T. de Vries (2021). *« 20th century cooling of the deep ocean contributed to delayed acceleration of Earths energy imbalance »*. *Nature Communications* 12.1, p. 1-10.

Bellouin, N., J. Quaas, E. Gryspeerdt, S. Kinne, P. Stier, D. Watson-Parris, Olivier Boucher, K. S. Carslaw, M. Christensen, A.-L. Daniau, Jean-Louis Dufresne, G. Feingold, Stephanie Fiedler, Piers M. Forster, Andrew Gettelman, J. M. Haywood, U. Lohmann, F. Malavelle, Thorsten Mauritsen, Daniel T. McCoy, G. Myhre, J. Mülmenstädt, D. Neubauer, A. Possner, Maria A. A. Rugenstein, Y. Sato, Michael Schulz, S. E. Schwartz, O. Sourdeval, Trude Storelvmo, V. Toll, D. Winker & Bjorn Stevens (2020). *« Bounding global aerosol radiative forcing of climate change »*. *Reviews of Geophysics* 58.1, e2019RG000660.

Charney, Jule G., Akio Arakawa, D. James Baker, Bert Bolin, Robert Earl Dickinson, M. Goody Richard, Cecil E. Leith, Henry M. Stommel & Carl I. Wunsch (1979). *Carbon Dioxide and Climate : A Scientific Assessment*. The national Academies press. Washington D.C. : National research council.

Chenal, Jonathan, Benoît Meyssignac, Aurélien Ribes & Robin Guillaume-Castel (2022). *« Observational constraint on the climate sensitivity to atmospheric CO_2 concentrations derived from the 1971-2017 global energy budget »*. *Journal of climate* TBD.TBD, TBD-TBD. doi : 10.1175/JCLI-D-21-0565.1.

Cheng, Lijing, Kevin E Trenberth, John Fasullo, Tim Boyer, John Abraham & Jiang Zhu (2017). *« Improved estimates of ocean heat content from 1960 to 2015 »*. *Sc. Adv.* 3.3, e1601545.

Cowtan, Kevin & Robert G. Way (2014). *« Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends »*. *Quart. J. Roy. Meteor. Soc.* 140.683, p. 1935-1944.

Forster, Piers M., Trude Storelvmo, Kyle C. Armour, M. Collins, Jean-Louis Dufresne, D. J. Frame, D. J. Lunt, Thorsten Mauritsen, Matthew D. Palmer, Masahiro Watanabe, M. Wild & H. Zhang (2021). *« The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity »*. *Climate Change 2021 : The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Sous la dir. de Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu & B. Zhou. Cambridge, United Kingdom et New York, NY, USA : Cambridge University Press.

Frederikse, Thomas, Felix W. Landerer, Lambert Caron, Surendra Adhikari, David Parkes, Vincent W. Humphrey, Sönke Dangendorf, Peter Hogarth, Laure Zanna, Lijing Cheng & Yun-Hao Wu (2020). *« The causes of sea-level rise since 1900 »*. *Nature* 584.7821, p. 393-397.

Good, Simon A, Matthew J Martin & Nick A Rayner (2013). *« EN4 : Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates »*. *J. Geophys. Res. : Oc.* 118.12, p. 6704-6716.

Gouretski, Viktor & Klaus Peter Koltermann (2007). *« How much is the ocean really warming ? »* *Geophys. Res. Lett.* 34.1. doi : https://doi.org/10.1029/2006GL027834.

IPCC (2013). *« Summary for policy makers »*. *Climate Change 2013 : The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Sous la dir. de T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, Myles R. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex & P. M. Midgley. Cambridge, United Kingdom et New York, NY, USA : Cambridge University Press.

Ishii, Masayoshi, Yoshikazu Fukuda, Shoji Hirahara, Soichiro Yasui, Toru Suzuki & Kanako Sato (2017). *« Accuracy of global upper ocean heat content estimation expected from present observational data sets »*. *Sola* 13, p. 163-167.

Levitus, Sydney, J. I. Antonov, Tim Boyer, Olga K. Baranova, Hernan Eduardo Garcia, R. A. Locarnini, Alejandro Ricardo, A. V. Mishonov, J. R. Reagan, Dan Seidov, Evgeney Yarosh & M. M. Zheng (2012). *« World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010 »*. *Geophysical Research Letters* 39.10.

Levitus, Sydney, J. I. Antonov, Tim Boyer, R. A. Locarnini, Hernan Eduardo Garcia & A. V. Mishonov (2009). *« Global ocean heat content 1955-2008 in light of recently revealed instrumentation problems »*. *Geophys. Res. Lett.* 36.7. doi : https://doi.org/10.1029/2008GL037155.

Manabe, Syukuro & R. T. Wetherald (1967). *« Thermal equilibrium of the atmosphere with a given distribution of relative humidity »*. *J. Atmos. Sci.* 24.3, p. 241-259.

Meyssignac, Benoît, Jonathan Chenal & Robin Guillaume-Castel (in prep.). *« Historical observations of the earth energy budget confirm that the climate feedback parameter has changed with time »*. *Nature Climate Change* TBD.TBD, TBD-TBD. doi : TBD.

Ramanathan, V. (1987). *« The role of earth radiation budget studies in climate and general circulation research »*. *J. Geophys. Res. : Atmos.* 92.D4, p. 4075-4095. doi : 10.1029/JD092iD04p04075.

Richardson, Mark, Kevin Cowtan, Ed Hawkins & Martin B. Stolpe (2016). *« Reconciled climate response estimates from climate models and the energy budget of Earth »*. *Nature Climate Change* 6.10, p. 931-935.

Sherwood, S., Mark J. Webb, J. D. Annan, Kyle C. Armour, Piers M. Forster, J. C. Hargreaves, Gabriele C. Hegerl, Stephen A. Klein, Kate Marvel, Eelco J. Rohling, Masahiro Watanabe, Timothy Andrews, Pascale Braconnot, Christopher S. Bretherton, G. L. Foster, Zeke Hausfather, A. S. von der Heydt, Reto Knutti, Thorsten Mauritsen, Joel R. Norris, Cristian Proistosescu, Maria A. A. Rugenstein, Gavin A. Schmidt, Katarzyna B. Tokarska & Mark D. Zelinka (2020). *« An assessment of Earth's climate sensitivity using multiple lines of evidence »*. *Reviews of Geophysics* 58, e2019RG000678. doi : 10.1029/2019RG000678.