A discussion of Earth's climate sensitivity and its long term dynamics

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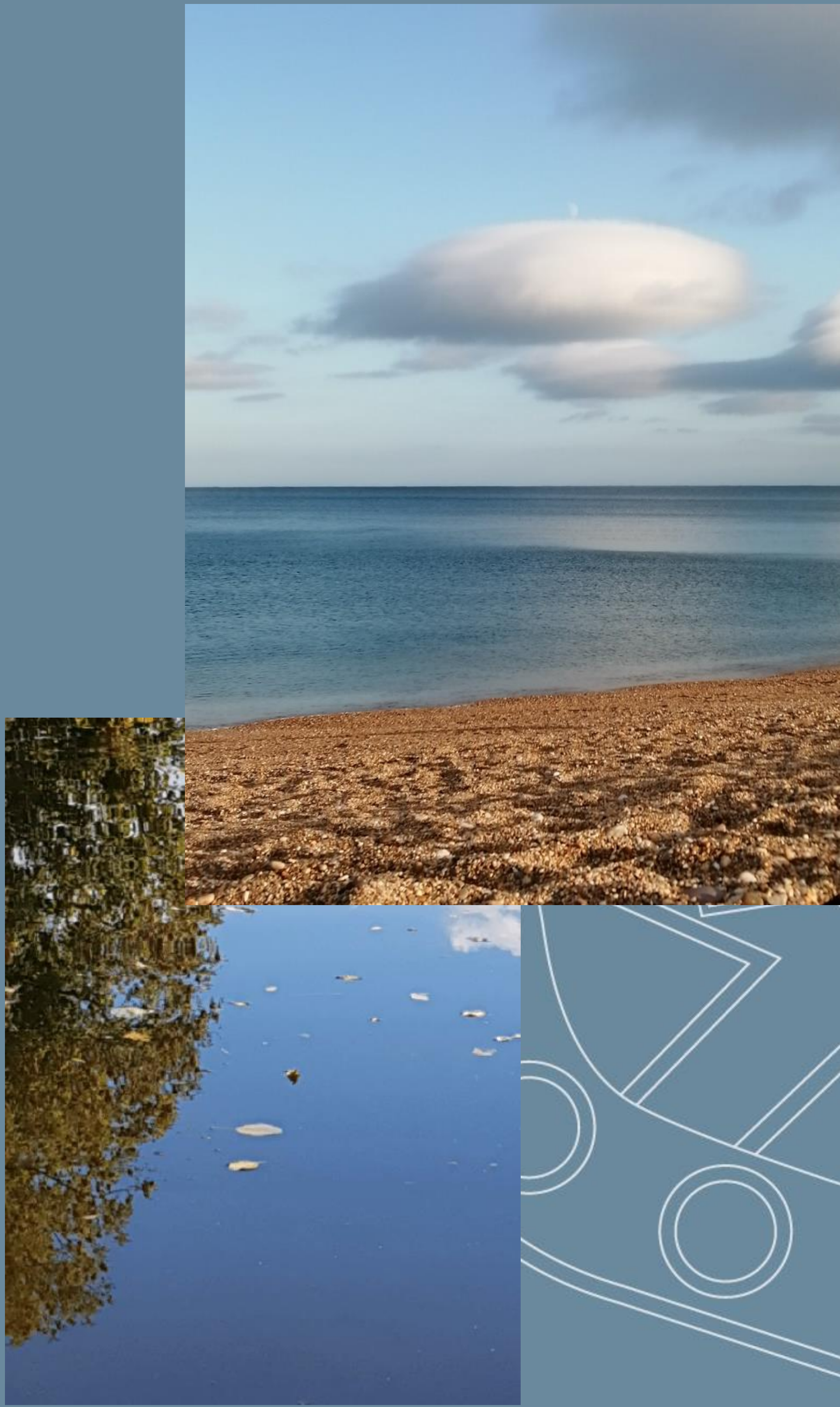


A discussion of Earth's climate sensitivity and its long term dynamics

- The earth is warming up due to long term Anthropogenic use of fossil fuels.
- A measure of this is the global temperature equilibrium response to a doubling of the atmospheric CO2 (above pre-industrial levels) is the **Equilibrium Climate Sensitivity** (ECS).
- A varied range of estimated ECS values are currently found: e.g. 2.3℃ with 5%-95% range 1.43℃ to 3.14℃ (Young, Allen and Bruun, *ERL*; 2021). Sherwood et al (*Rev. Geophys*; 2020) report a range 2.3℃ to 4.7℃ (midpoint 3.5℃).
- The way ocean thermal layers impact this is important and physical time scales for the equilibrium process are very long term – which appears to impact the current evaluation accuracy.
- While these ECS range and values are an important and much needed quantification – this wide ECS uncertainty range, based largely on uncertainty around total radiative forcing (TRF), is also problematic for our geophysical based community:
  - The ECS value as viewed by policy and global strategy negotiators is currently only understood to a 70% (= 2.4 / 3.5) physically resolved level of resolution.
- An open question (discussed in this talk) is it possible to resolve this physical measurement more accurately and what are the current main issues that need to be accommodated? Can we get a better resolution level?

We cover three aspects in this talk:

- **Climate sensitivity physics**
  - **This talk**: Peter C Young, P Geoffrey Allen and John T Bruun (2021). A re-evaluation of the Earth's surface temperature response to radiative forcing, *Environ. Res. Lett.* 16 054068, https://iopscience.iop.org/article/10.1088/1748-9326/abfa50. Using a dynamic systems analysis approach.
  - **ECS comparisons (inc. with CMIP).**
  - Define *ECS Resolution* = ECS / ECS 5% – 95% range. Currently about 70%.
- **Ensemble concepts**: there is only one planet Earth, use statistical mechanics/physics phenomena more:
  - "*Statistical practice in climate change science simply has to change*": Shepherd, T.G. Bringing physical reasoning into statistical practice in climate-change science. *Climatic Change* 169, 2 (2021). https://doi.org/10.1007/s10584-021-03226-6
  - Nobel Prize of Physics 2021: Manabe, Hasselmann and Parisi (*for the discovery of the interplay of disorder and fluctuations in physical systems from atomic to planetary scales*). Look at the implied gaps.
- **A deliberation of climate sensitivity physics**

Climate sensitivity physics

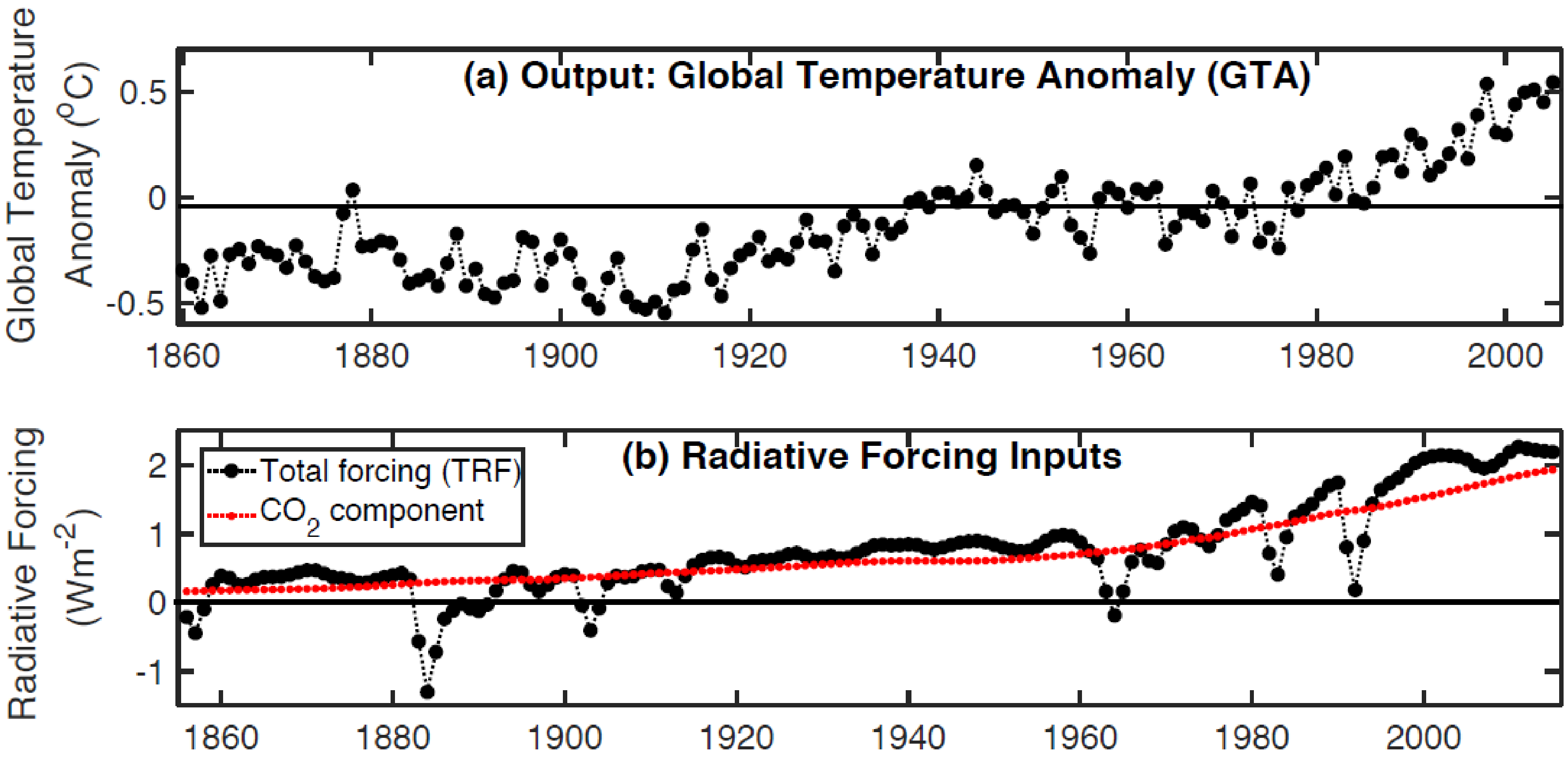


Figure 1: Instrumental era data used in DBM model identification and estimation for ECS.

Climate sensitivity is derived from the relationship between radiative forcing and the global temperature anomaly. Equilibrium Climate Sensitivity (ECS) is calculated using data records and the dynamic systems approach *Data-Based Mechanistic* (DBM) modelling. Note Radiative Forcing has a volcanic induced variability also.

The identified Data-Based Mechanistic (DBM) model is highly accurate

The main reasons for the accuracy of the DBM models is that the 'hypothetico-inductive' approach to modelling takes note of prior hypotheses about climate models but does not allow these to prejudice the statistical, data-based modelling procedure, nor it conclusions.

In this way, it identifies two, climatically meaningful, dominant modes (see Chapter 12 in Young, 2011) that characterize the observed dynamic behaviour:

- The main heat balance equation that relates directly to the standard climate hypothesis.
- An additional 50 year quasi-cycle, identified as a stochastic oscillator activated by perturbations in the total radiative forcing input; suggesting possible major heat exchange with the ocean that relates to observed phenomena, such as the Atlantic Multi-decadal Oscillation.

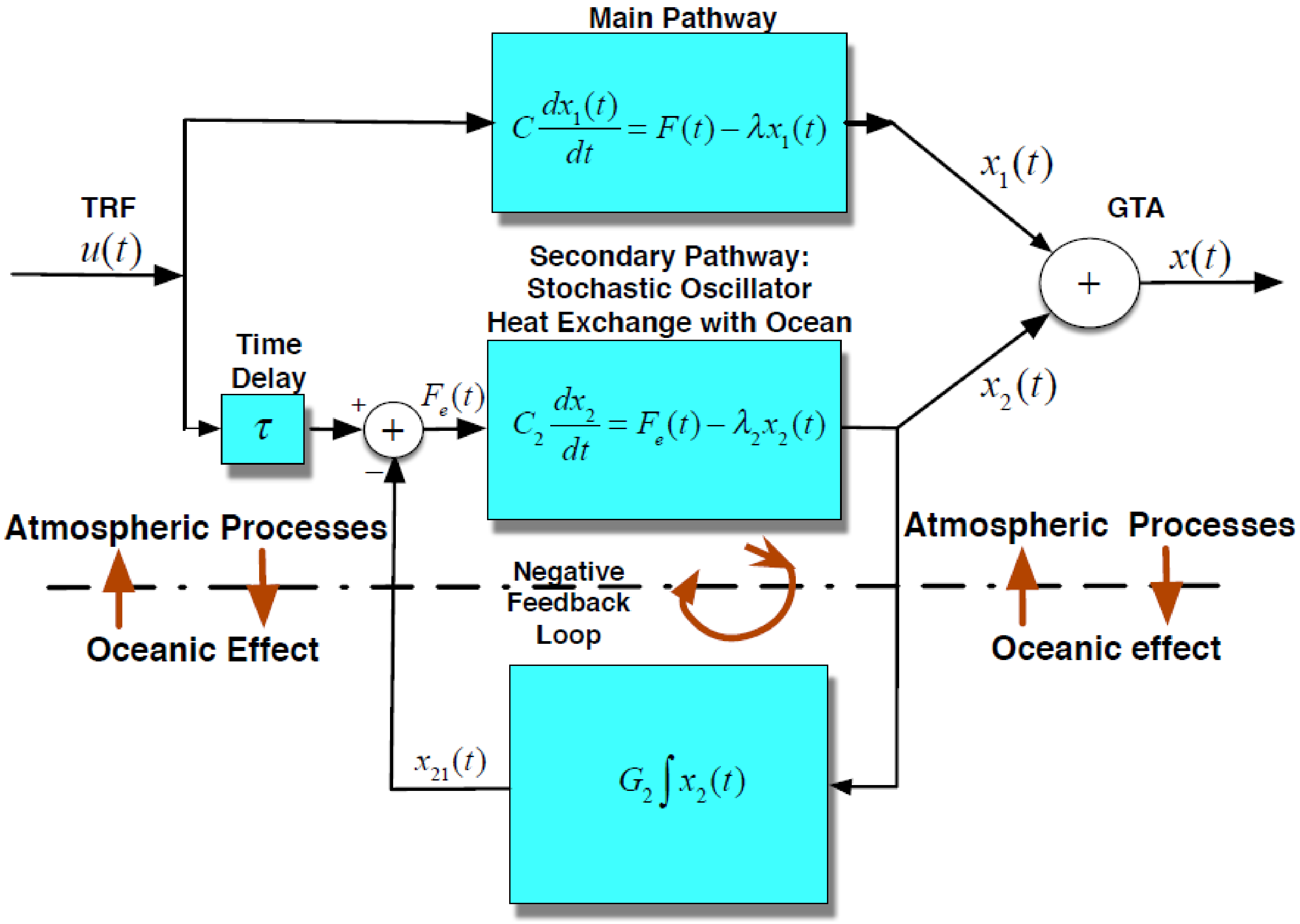


Figure 2: Block diagram of the identified Data-Based Mechanistic (DBM) model.

The paper (Young et al., 2021) and associated report (Young, 2019) show how Data-Based Mechanistic (DBM) models, with low dynamic order, are able to emulate very closely the behaviour of large climate simulation models, at the globally-averaged level and explains the historical, globally averaged climate data better than AOGCM models.

Here we can see the influence of the oceanic related decomposition component $x_2(t)$, its 50 year cyclic property and epochs of apparent 'levelling'.

See also Bruun et al (2017) and Skákala and Bruun (2018) for additional examples of such longer term dynamical oscillatory ocean components.

Note: this DBM modelling approach is also useful for forecasting (Young, 2018).

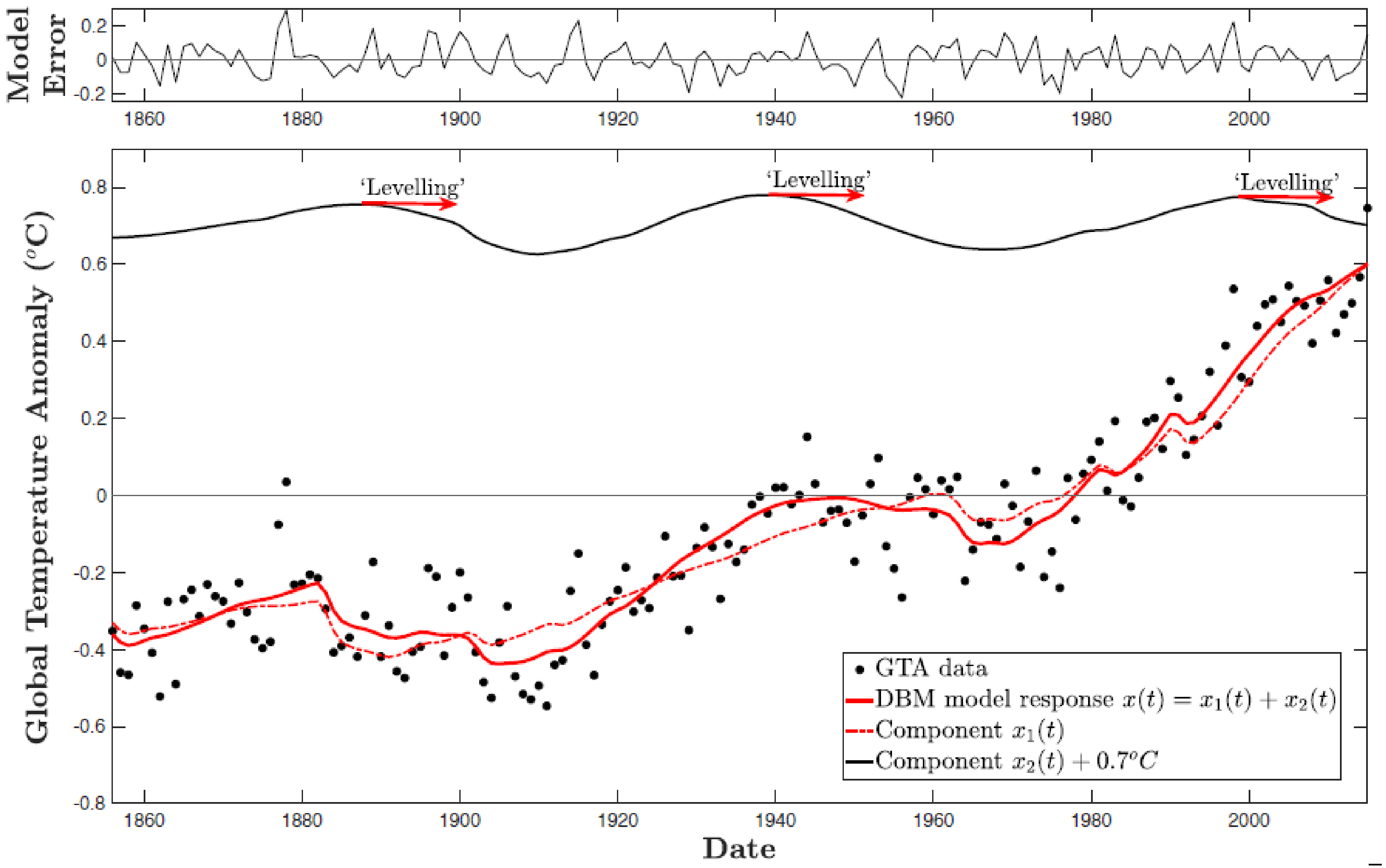


Figure 3: Data-based mechanistic model of the globally averaged temperature anomaly (derived from instrumental era data).

A deliberation of the ECS values

As a community we appear estimate and decompose climate sensitivity as follows:

$ECS \sim \; Baseline$

$+ \; Stochastic$

$+ \; Model\ specification$

$+ \; Measurment\ uncertainty$

$+ \; noise$

$+ \; other?$

a) The 'stable' value.

b) What is the natural physical stochasticity range?

c) **Random effects**: *model parameter choices*

Statistical: *robustness of evaluation method*

Physical specification: *what is in / what is out ?* *How well are stochastic excitation/ sub-grid scale wave mechanics represented (links to b)?*

Numerical precision: *is an equilibrated process really represented?*

d) Aerosol uncertainty, absence of measurements.

e) …

f) …

Current discussions seem to mix b), c) & d)…. ,

b) will include anthropogenic forcing

Some current ECS results

$$ECS \sim \quad Baseline$$

$$+ \; Stochastic$$

$$+ \; Model\ specification$$

$$+ \; Measurment\ uncertainty$$

$$+ \; noise$$

$$+ \; other?$$

Sherwood et al, 2020	Young et al , 2021	Cox et al 2018	Nijsse et al 2020
3.5 (mid range point),	2.29,	2.8	2.2 , 2.6 CMIP5, CMIP6
5 – 95 % range			
(2.3 to 4.7)	(2.22 to 2.49) (1.43 to 3.14, inc. TRF uncertainty)	(1.3 to 4.0 from figure)	CMIP5 (1.0 to 4.0), CMIP6 (1.5 to 4.0)
Multi-record expert judgement based	Dynamic systems identification based on instrumental data, includes an identified ~50 yr Ocean effect.	Emergent constraints analysis, with theory and ensemble simulation data	
Resolution: 70%	Resolution: 75% and 13%. Factor 4 contraction of uncertainty…	Resolution: above 70%	

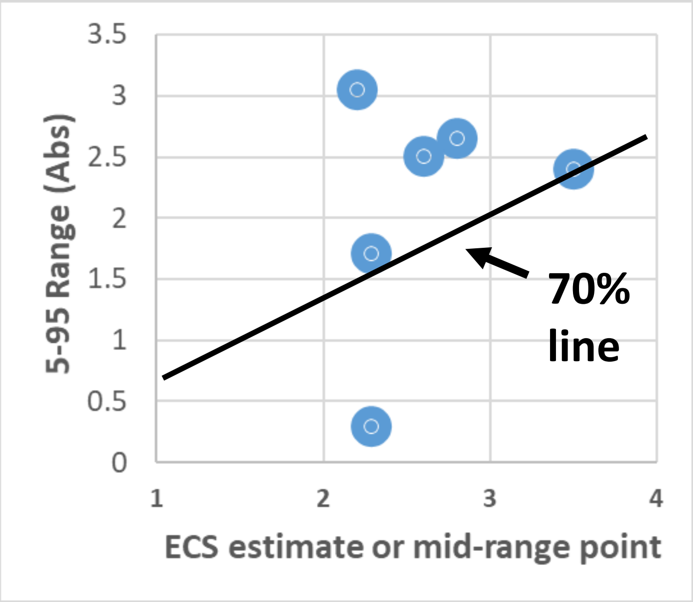


Figure 4: Comparing ECS results.

A deliberation of Climate sensitivity physics & some points

Measurement & [issues]: typically using annual globally averaged climate data 1856 to 2015+.

$T(t)$ is the surface global temperature anomaly: The changes in the globally average surface temperature with a reference level defined by the average of the temperature over the 30 year period 1951-1980.
What are the measurement issues here, paleo-instrumental, modelling study assumptions?

$F(t)$ is the Total Radiative Forcing(TRF): is the sum of radiative forcing components due to CO2 in the atmosphere, volcanic activity, solar variability and all other anthropogenic sources.
However TRF appears very uncertain, detailed record decompositions are point based – do we need more info/is more monitoring required?. Note the large variation in TRF due to volcanic activity are not always considered in climate modelling – however this is useful for total signal support aspects.

Climate modelling derived from heat balance: $C\frac{dT(t)}{dt} = F(t) - \lambda T(t)$, C is a constant Earth Heat Capacity (EHC) per unit area

via CMIP3 ensemble analysis (Knutti et al. 2008), C: $24\ (5\% - 95\%: 6, 42)\ [Wy\ m^{-2}K^{-1}]$

via DBM (Young et al. 2021), with two dynamic timing components C: $31.2\ (5\% - 95\%:\ 26.9, 37.3)\ [Wy\ m^{-2}K^{-1}]$.

What limitations do models present ? Do we need to update the ocean – atmosphere representation?

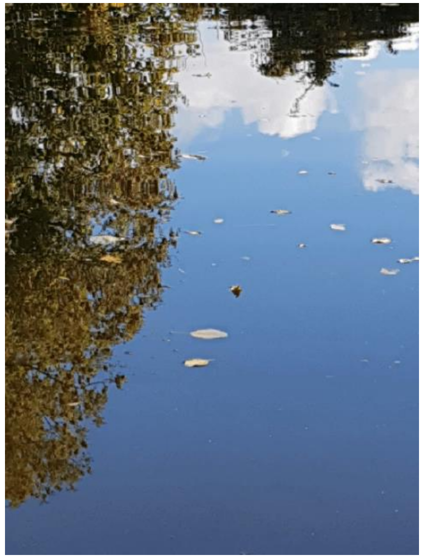
Ensemble logic, there is only one planet Earth. Update our ensemble logic to accommodate the physical processes more...

To conclude

- The earth's climate sensitivity ECS (& related) are currently resolved only to a 70% accuracy.
- Understanding this more accurately, especially looking at how the physical phenomena exhibit, is going to help.
- Using DBM analysis and instrumental era records ECS is found to be:

  2.29 °C (5-95%: 2.22 to 2.49 and 1.43 to 3.14 accommodating TRF uncertainty).

- From this the resolution of the ocean time scale and its processes appear to be especially important.
- We recommend more use of Statistical Mechanics concepts on this topic. These can help better identify the dynamic systems and physical phenomena based properties. The DBM approach is currently being applied further to assess CMIP6 ensemble properties.



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