WCRP TCRE Assessment
ESM2025 Workshop and final GA

Toulouse, France
October 7-9, 2025

Met Office

University of BRISTOL

esm 2025 Earth System Models for the future

WCRP World Climate Research Programme

Goals of Workshop

1. Agree and finalise scope and structure of report
2. Agree definitions
3. Agree interpretive model
4. Better articulate questions to sub-groups, including priors
5. Assemble available evidence, including possible use of paleo
6. Decide structure of ZEC and reversibility sections

1. Scope and underlying assumptions on report content

We discussed and agreed some boundary conditions which help constrain the scope of the report. This is not because issues beyond this are unimportant, but in order to keep the assessment concise and focused.

- Our focus is on global temperature, and not regional climate or impacts. We acknowledge that some things continue to change for example after zero-emissions (sea-level, forest cover, ocean circulation etc) but are not the main goal.
- Focus is primarily on CO2 (TCRE as a physical quantity). We need to discuss issues about non-CO2 forcing and effective-TCRE too, but not quantitative part of assessment
- We explicitly DO want to cover reversibility. The symmetry of TCRE under negative emissions is vital.
- Focus is on the direct effects of CO2 rather than bio-physical effects of particular emissions/removal techniques. We do not treat land-use as anything other than a source of CO2, nor various CDR techniques other than as a removal.
- To first order we separate TCRE and ZEC and assess individually. This simplifies assumptions, although we acknowledge it is an approximation. Discussion can cover the role of ZEC as deviation from TCRE.

1. Outline structure and sections

Related to this, we also agreed on a slightly revised outline structure for the report sections. The first two are currently being drafted

1. Introduction and background – history and status of knowledge.
2. Lay out definitions of terms – be clear what we mean by TCRE and ZEC for this assessment
3. Bayesian framework for TCRE
    1. interpretive model, and justification for choosing it
    2. Define what evidence we will use
4. ZEC – quantitative update on numbers, stop short of Bayes analysis
    1. Substantial updates from ZECMIP (MacDougall et al. 2020). Long-term and state-dependence, theoretical frameworks
5. Reversibility
6. Discussion/synthesis / Implications for RCB
    1. Narratives on tails of distribution – e.g. what if TCRE>3
    2. Role of/implications of missing processes and tipping points

2. Definitions in this report

We discussed and agreed definitions of terms and how best to measure TCRE and ZEC from existing and planned ESM simulations. There is currently no clear literature definition, so it is important to be specific for the assessment

- Past assessments have used slightly differing levels of warming or emissions to define metrics.
  - ZECMIP defined both TCRE and ZEC at a common level of 1000 PgC emissions in 1% simulation
  - TCR is commonly defined at 2xCO2 in 1% per year simulation.
  - C4MIP measure carbon cycle feedback metrics at both 2xCO2 and 4xCO2 in a 1% CO2 simulation
  - flat10 experiment (adopted from CMIP7) measures TCRE and ZEC at 1000 PgC emissions.

- Here we recommend that a definition based on a ***common emissions level***, rather than a common concentration level, is more meaningful
- We ***define TCRE as the global temperature rise due to emission of 1000 PgC.***
  - We use the existing 1% simulations and diagnosed emissions to quantify it for CMIP6 ESMs. Going forward we recommend quantifying it***, following 10 PgC/yr emission*** of "flat10" simulations.
- We note ZEC has strong timescale and state dependence and so no single definition can be used.
  - We recommend good practice that discussion of ZEC always be explicit on the timescale and emissions or warming level (e.g. "ZEC^{2}_{50}" denotes ZEC at 2 degrees warming, on 50 year time horizon)
  - ZEC following 1000 PgC is of specific interest to partner TCRE in quantifying remaining carbon budgets
  - Evidence for ZEC which is accumulated across different warming levels or cumulative emissions will be assessed.

3. Interpretive model for TCRE

A Bayesian framework requires a method (interpretive model) to map between components of the assessed quantity (TCRE) and evidence being used.

- Here we choose a framework which allows to construct Bayesian analysis of multiple lines of evidence
- Alpha, beta, gamma feedback terms (from C4MIP feedback analysis) allow to construct TCRE from processes/sensitivities and disaggregate below global level as required by the evidence

$$TCRE = \frac{\alpha}{k + \beta + \alpha\gamma}$$

$$\beta = \beta_{land} + \beta_{ocean}$$

$$\gamma = \gamma_{land} + \gamma_{ocean}$$

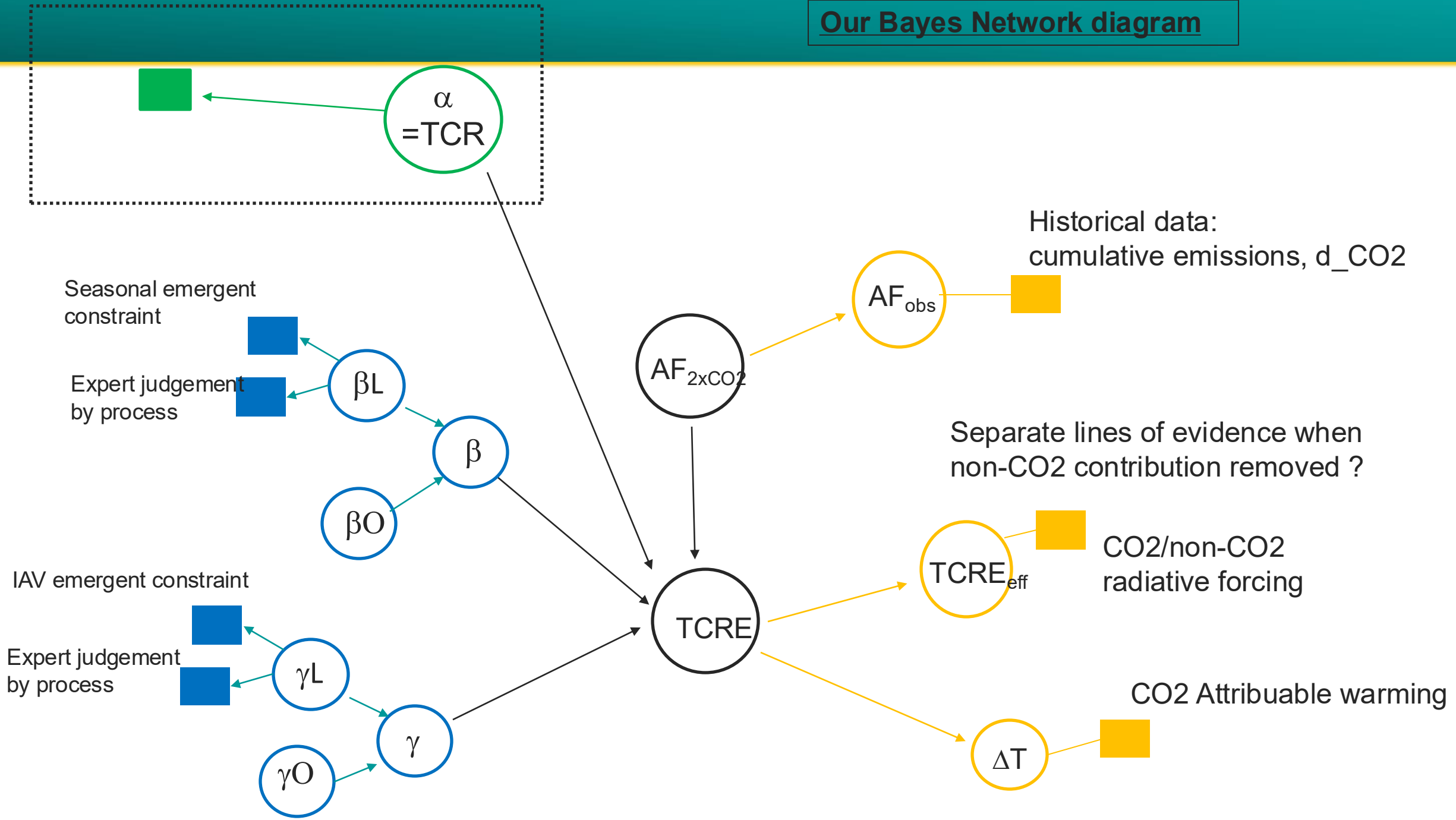
$$\gamma_{land} = \gamma_{tropics} + \gamma_{extra-tropics}$$

So now we can bring in evidence at this level of detail

3. Interpretive model for TCRE

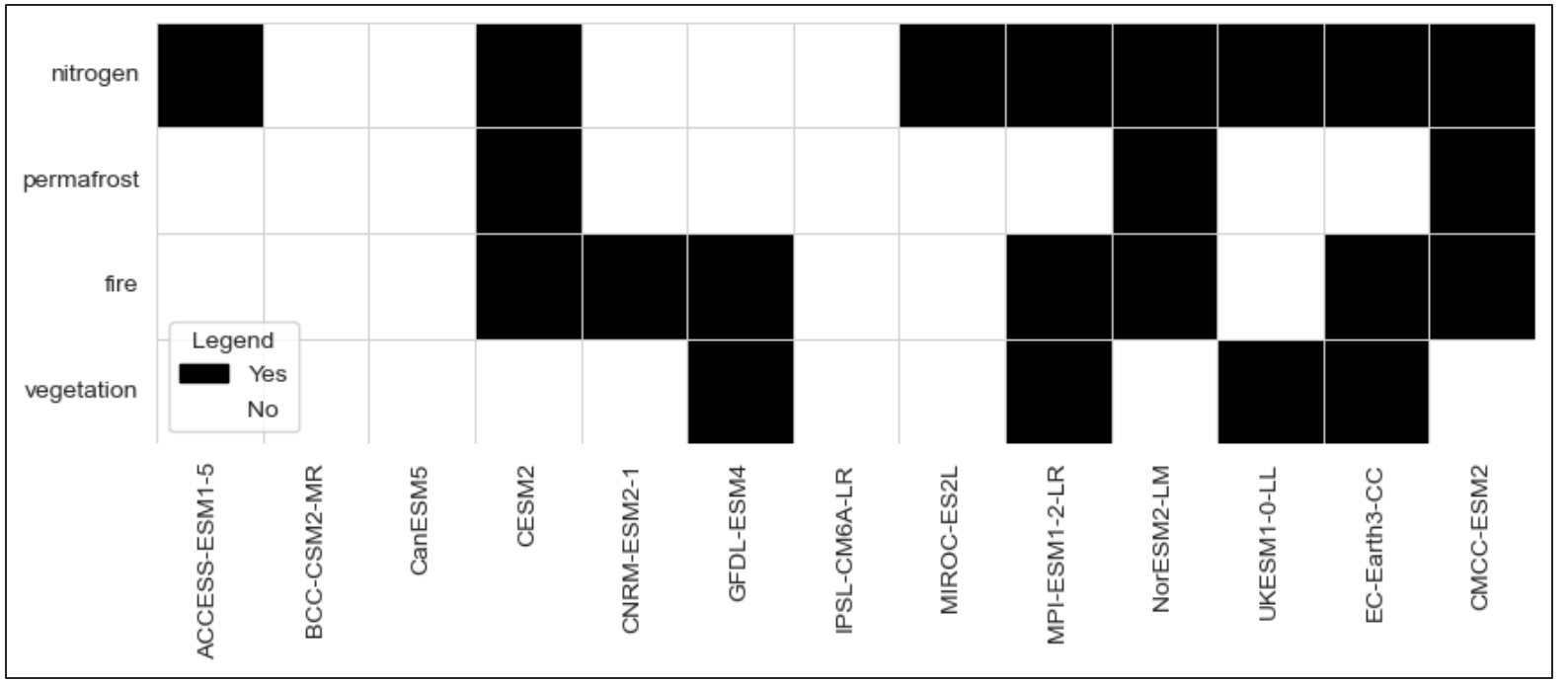
- Pros of interpretive model
  - Breaks down along process lines, allowing understanding of drivers
  - Aligns with existing CMIP generations of analysis
  - Allows ingestion of lines of evidence from published studies including emergent constraints
- Cons of interpretive model
  - Alpha, beta, gamma are scenario dependent, not invariant system properties
  - So need to quantify these in 1% scenario
  - Might create barrier to using observations unless they can be mapped to 1% pathways

Our Bayes Network diagram



Land processes

- Land group discussed extracting role of individual processes
- Focus on nitrogen cycle permafrost, fire, vegetation dynamics
  - These are (a) big effects, (b) evidence exists (at least model based) on their impacts



Ocean processes

- Ocean group discussed potential for constraining beta or gamma from historical record
- Options exist, e.g. related to Terhaar et al: https://bg.copernicus.org/articles/19/4431/2022/bg-19-4431-2022.html

What lines of evidence do we have?

It is important to know in advance what lines of evidence we want the Bayes framework to be able to process. We discussed and compiled a list of possible lines of evidence and associated with each component of the interpretive model. Som eof these require further development to see how they may be used

- Alpha (equivalent here to TCR)
  - Historical warming
  - Bottom up understanding of feedbacks, updates since Sherwood and Web
- Beta land
  - Wenzel et al seasonal cycle constraint – how to map from delta-GPP to beta?
  - CMIP models
- Gamma land
  - Cox/Zechlau IAV constraint – robust across CMIP generations
  - CMIP models
- Beta ocean
  - CMIP models
- Gamma ocean
  - CMIP models
- Airborne fraction
  - Historical AF
- TCRE
  - CO2-attributable warming from DAMIP
  - Eff-TCRE?

Limitations on lines of evidence

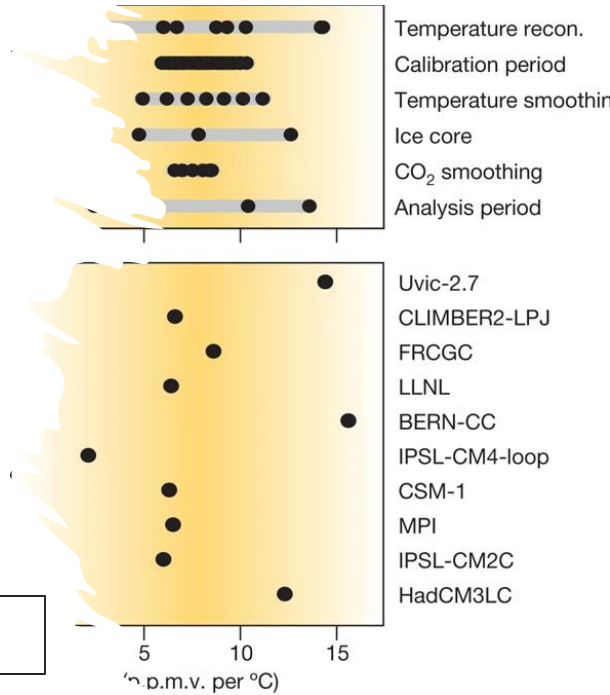
The interpretive model requires that we are able to map from the 1% alpha/beta/gamma to an observable line of evidence. E.g. Cox et al (2013) IAV constraint maps from IAV to gamma_1%, and in this way observations of variability can constrain the long term gamma.

We discussed if or how other lines of evidence could be mapped in this way

- **Historical record?**
- Land/ocean uptake jointly informed by beta/gamma, not individually. Provide bounds on priors
  - Can we quantitatively map observed sinks to 1% beta/gamma? Historical beta/gamma can be calculated – some CMIP6 models submitted data for Hist-BGC

- **Paleo evidence?**
- gamma_paleo =/= gamma_1%
- Frank et al tried to compare 1% values at equivalent warming level
- Paleo community will discuss how they can contribute

evidence which can be used in this framework



Frank et al., fig 4

ZEC and reversibility

- Enough evidence exists to build Bayesian analysis for TCRE
- But not for ZEC or TCRR (transient climate response to removals)

- We know ZEC is state and rate dependent – we can go beyond MacDougall to map out ZEC as function of cumulative emissions or GWL on different time horizons
- ZEC closely related to reversibility

- The ZEC and reversibility sections will therefore not attempt a Bayesian assessment but will lay out state of knowledge and developments since IPCC AR6.

timeline

- Now (October 2025) – basic framework and list of evidence
  - The Toulouse workshop provided an opportunity to take stock of progress to date and bring people together in person to discuss and develop ideas
- March 2026 – Kyoto workshop – we hope for draft set of results
  - There will be a TCRE session and also side event
- Summer(ish) 2026 – paper to submit (likely to Reviews of Geophysics)
- Throughout – engage with IPCC
  - Esp. chapters 5 and 9
  - Chapter 5 - scenarios and projections includes: “relationship between carbon cycle, energy balance and global temperature”
  - Chapter 9 - stabilisation and overshoot includes: “Global … responses to pathways … including to global net-zero”