



Transient Climate Response to cumulative carbon Emissions (TCRE) and Zero Emissions Commitment (ZEC) Workshop Report

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Impressum

This report was written by the TCRE and ZEC Workshop Organizing Committee: Chris Jones, Pierre Friedlingstein, Tatiana Ilyina, Roland Seferian.

The Workshop was co-sponsored by WCRP and ESM 2025.

The World Climate Research Programme (WCRP) (wcrp-climate.org) is co-sponsored by the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC) of UNESCO and the International Science Council (ISC), see www.wmo.int, www.ioc-unesco.org and council.science.

ESM2025 (www.esm2025.eu) is a project aimed at advancing the understanding of the Earth system and its response to human activities by developing the next generation of European Earth System Models including a more comprehensive representation of the Earth's response to anthropogenic emissions and human land-use change.

We express huge thanks to Narelle van der Wel (WCRP Secretariat) for support and expertise on smooth-running of the workshop.

Transient Climate Response to cumulative carbon Emissions (TCRE) and Zero Emissions Commitment (ZEC)

Workshop Report

22–24 Jan 2024, Bristol, United Kingdom

Chris Jones, Pierre Friedlingstein, Tatiana Ilyina, Roland Seferian

Background

This workshop was inspired by previous assessment work undertaken by Sherwood et al. (2020) for Equilibrium Climate Sensitivity (ECS) and Bellouin et al. (2020) for aerosols. We want to develop and kick-off an activity to provide an assessment of Transient Climate Response to cumulative carbon Emissions (TCRE) ahead of next Intergovernmental Panel on Climate Change (IPCC) reporting cycle. Recent developments in science and in the literature make it relevant to include Zero Emissions Commitment (ZEC) in this assessment.

This workshop drew together experts from around the world to plan this activity and brainstorm aspects of how such an assessment could look. Approximately 30 people attended in person (Figure 1) with a further 20 participants online (Participant list, Annex 1). The meeting was scheduled around five sessions (Agenda, Annex 2), with some pre-invited and submitted talks, but also some last-minute “pop-up” talks from people who had relevant findings.

Talks were presented in-person and online and we took every effort to make sure remote participants were fully included. The use of an “Owl” speaker and microphone helped enormously, and several people online commented that the meeting had worked remarkably well. We are extremely grateful to all our remote participants who took the efforts to join despite being across sometimes very unfriendly time-zone differences!



Figure 1: Most of the in-person participants of the TCRE and ZEC Workshop, January 2024.

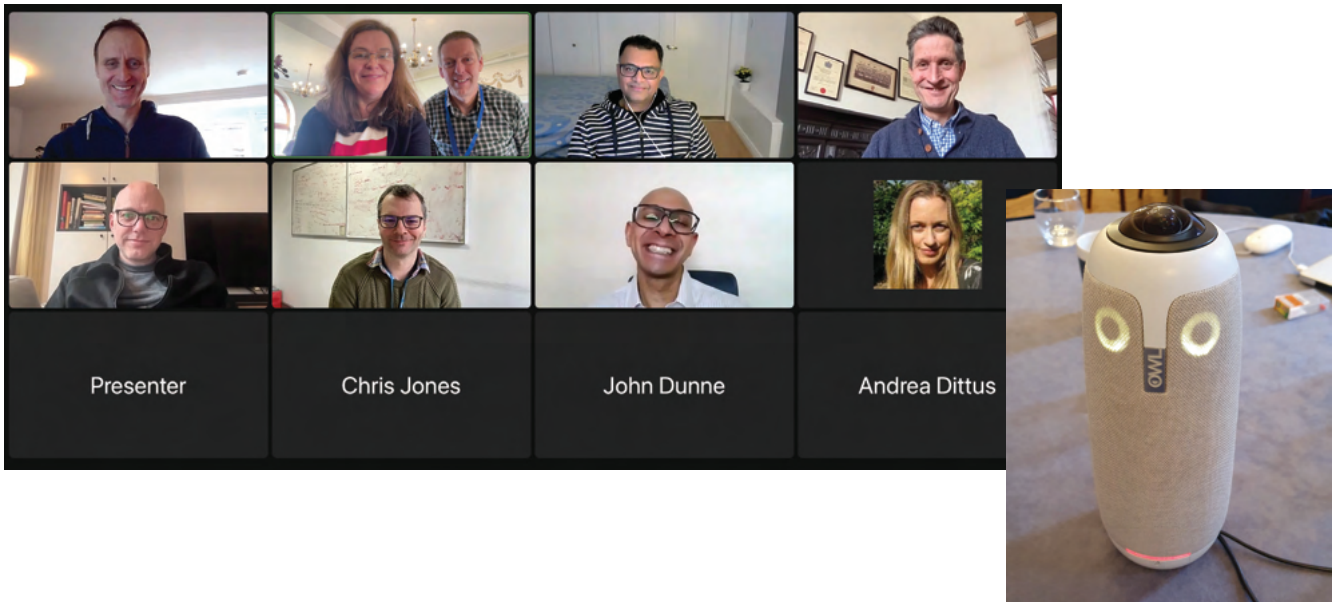


Figure 2: Some of the remote participants (and Chris Jones and Tatiana Ilyina leading the breakout group) of the TCRE and ZEC Workshop and the meeting “Owl” video conferencing camera, mic and speaker.

For those who attended in person, the venue was a lovely example of a historical building, and we are very grateful to the Bristol University Events team and all at Clifton Hill House for very smooth logistics and catering. A workshop dinner on day 2 allowed us some down time and informal chat.

Aims

The workshop goal was to assemble the current knowledge on TCRE and ZEC in the context of carbon budgets and to create a plan to move forward towards an assessment over the next 1–2 years.

A major attraction and success of the workshop was bringing together experts and expertise from different disciplines – explicitly experts in climate feedbacks and the carbon cycle. Although ECS has been assessed recently in Sherwood et al. (2020) and in the sixth assessment report of IPCC (AR6), it (or at least the transient climate response) is central to TCRE and so advances in physical feedbacks are within remit of this work, although the focus is likely to be on carbon cycle and airborne-fraction aspects of TCRE which top date have not been systematically assessed in this way.

Sessions and outcomes

1. Frameworks

The aim of this session was to understand how to assess the system in terms of the different sensitivities of different aspects, where the uncertainties lie, and how to combine aspects again if we can constrain individual terms. Talks covered frameworks such as Jones & Friedlingstein (2020), Williams et. al. (2020) and the Rate of Adjustment to Zero Emissions (RAZE, Jenkins et. al., 2022) and discussed elements of the climate system which materially affect TCRE and ZEC including the relative split of climate-feedbacks and carbon feedbacks and their changing balance between the Coupled Model Intercomparison Project Phase 5 (CMIP5) and Phase 6 (CMIP6).

The RAZE framework was discussed as being an attractive way forward with a fractional rate of change rather than an arbitrary amount, as per ZEC. We also heard about how important the changing sea surface temperature patterns during constant forcing are in changing the climate sensitivity and saw examples of reversibility and symmetry experiments and proposed emissions-driven (“flat-10”) experiments to measure Earth System Model (ESM) sensitivity to forcings.



Figure 3: Chris Jones explaining the goals of the workshop.

2. Processes

The aim of this sessions was to understand what processes drive TCRE and ZEC and how can we better use our knowledge of them. For example, with relation to land, participants discussed the importance of uncertainties in CO₂ fertilisation, permafrost, nutrients, or fire on land. Regarding the ocean we need to understand co-uptake of heat/CO₂ (“nexus”) and the uncertainties introduced from model resolution – e.g. what does eddy-resolving capability tell us?

The sequence of talks assembled an overview of existing knowledge and new/ongoing analysis and experiments. Sofia Palazzo Corner presented a recently published expert assessment of process uncertainty underpinning ZEC (Palazzo Corner, et al. 2023) including a table of key processes and potential avenues for reducing uncertainty. The session then saw a thorough review of the state of land ecosystem modelling and identified where there are gaps in model capability and highlighted some UKESM results exploring process-contribution to TCRE. Intertwined with these were talks on ocean processes – including on Atlantic Meridional Overturning Circulation (AMOC) responses and dependence on the level of emissions. The session also saw a great overview (of the work of 30 people over 5 years boiled down to 10 minutes!) by Mark Webb on the ECS assessment and the process they went through to arrive at a quantitative conclusion.

3. Emergent constraints

The aim of this and the next session was to explore the possible constraints on TCRE and maybe ZEC. Emergent constraints form one avenue of constraint, and multiple studies exist providing some sort of constraint either on the whole system or on individual components. Presentations showed new work constraining the direct link from emissions to observed warming, although this also includes the effect of non-CO₂ forcing (and hence is “effective TCRE”), and work looking at constraints on the carbon cycle response to CO₂, interannual climate variations and spatial patterns of soil carbon. Discussions were around how we might want to combine constraints on different aspects, and whether or not these constraints could be seen as independent. No work currently exists on constraining ZEC in this way, and this remains a gap in our knowledge.

4. Ensembles and simple models

In this session we explored the role of simplified models to constrain processes and combine multiple lines of evidence. We heard about Bayesian and other history matching techniques to constrain model parameters or weigh outputs from large ensembles. We discussed the potential robustness of simple models and tests we would want to perform to ensure they behave robustly. There is evidence from ESMs that heat and carbon uptake do not evolve linearly, but this cannot yet be resolved in observations. Therefore, a process-based assessment of simple models is required beyond observed data to bring in all we can know from ESMs and the relationships between quantities such as heat and carbon.

We also heard about Perturbed Physics Ensembles (PPEs) in ESMs and land-surface models and the requirement to fully sample uncertainty. Emissions-driven ensembles were seen as key to make sure we don't inadvertently over-constrain outputs when prescribing a CO₂ concentration pathway.

The session finished with a discussion on requirements for experimental design as we head (very rapidly!) towards Phase 7 of CMIP (CMIP7). There are some important simulations which simple models need to calibrate more robustly to ESMs. For example 2×CO₂ abrupt changes and pulse experiments. An outcome of the workshop will be to inform the CMIP7 FastTrack and other Model Intercomparison Projects (MIPs) – notably the Coupled Climate–Carbon Cycle Model Intercomparison Project (C4MIP) for their experimental design.

5. Synthesis and experiment design

The aim of this final session was to decide how we can combine ZEC/TCRE assessments meaningfully towards improved carbon budget information, or guidance on system behaviour during reducing net-zero and net-negative emissions. It had become clear by this stage that the question itself is very complex with many nuances requiring attention.

The concept of ZEC as a response 'after' zero emissions is likely too simplistic, and ZEC should be viewed more as a divergence of system behaviour from the simple relationship of warming-to-emissions given by TCRE. In a system where TCRE is a perfect relationship, ZEC will be zero. But we know this is not the case and the two concepts should be considered together. The scenario-dependence of them is important and there was consensus that experiments to measure them should really focus on a more gradual phase out of emissions than the past abrupt-cessation of Zero Emissions Commitment Model Intercomparison Project (ZECMIP) Phase 1.

The session also discussed future directions for non-CO₂ forcing in this context. How does a multi-gas-ZEC behave and how would we measure it. Treatment of some non-CO₂ gases are easy to define, but with aerosols, and more especially land-use, it is very hard to reach clear agreement on experimental design.

The energy in the room was clearly very high – all talks were excellent. There was so much interest and lively questions and discussion that inevitably the session overran despite speakers mainly keeping to time.

Next steps

IPCC timelines for the IPCC Seventh Assessment Report (AR7) are emerging. The 60th session of the IPCC had just completed as we were at the workshop and it was announced that the AR7 cycle would conclude with a synthesis report in 2029, with the IPCC Working Group I assessment expected to be completed in 2028. There are no details yet on either CMIP timelines or publication cutoffs, but an assessment would need mature results during at least 2027, ideally 2026, with full publication during 2027. This provides us with a challenge, but one to which we intend to rise.

Specific next steps include:

- Regular meetings of the convenors of the workshop to push forward plans for an assessment process
- Drafting of a technical note to clearly define terms (it was clear even simple concepts such as TCRE and especially ZEC can be used differently). This may be suitable to publish as a position paper, or maybe simply a WCRP report, to be used for future planning of the assessment. All participants in the workshop will be given chance to comment and contribute.
- A summary of experimental design and CMIP7 requirements will be written up and made available to the CMIP International Project Office for use in the finalisation of their FastTrack plans
- We may use the ESM2025 annual meeting in May 2024 to convene a small group in person to agree on a way forward.

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Acronyms

AMOC	Atlantic Meridional Overturning Circulation
AR6, AR7	Sixth and Seventh Assessment Report (IPCC)
CMIP	Coupled Model Intercomparison Project (WCRP)
CMIP5, CMIP6, CMIP7	Phases 5, 6 and 7 of CMIP
ECS	Equilibrium Climate Sensitivity
ESM	Earth System Model
IPCC	Intergovernmental Panel on Climate Change
PPE	Perturbed Physics Ensemble
RAZE	Rate of Adjustment to Zero Emissions
TCRE	Transient Climate Response to cumulative carbon Emissions
ZEC	Zero Emissions Commitment
ZECMIP	Zero Emissions Commitment Model Intercomparison Project

Annex 1: List of Participants

In person

Myles Allen
Ben Booth
Paulo Ceppi
Peter Cox
Andrea Dittus
Pierre Friedlingstein
Tatiana Ilyina
Tereza Jarnikova
Stuart Jenkins
Chris Jones
Charlie Koven
Hugo Lambert
Wei Li
Spencer Liddicoat
Andrew MacDougall
Damon Matthews
Sofia Palazzo Corner
Joeri Rogelj
Natassa Romanou
Alejandro Romero Prieto
Ben Sanderson
Jorg Schwinger
Roland Seferian
Chris Smith
Karou Tachiiri
Jens Terhaar
Narelle van der Wel
Becky Varney
Mark Webb
Ric Williams

Online

Vivek Arora
Rachel Chimuka
John Dunne
Rosie Fisher
Phil Goodwin
Anna Katavouta
Megha Kaveri
Kate Marvel
Thorsten Mauritsen
Glen Peters
Aurélian Ribes
Vassil Roussenov
Ashwin Seshadri
Abby Swann
Claudia Tebaldi
Sabrina Zechlau
Kirsten Zickfeld
Tilo Ziehn

An Assessment of TCRE and ZEC Agenda, Workshop Plan

<https://www.wcrp-climate.org/slc-events-opportunities/tcre-2024>

A contribution to WCRP Safe Landing Climates Lighthouse Activity (<https://www.wcrp-climate.org/slc-themes/slc-carbon>)

22nd–24th Jan 2024. Monday lunch through to Wednesday evening

Hosted at Bristol University, Bristol, UK.

<https://www.bristol.ac.uk/venues/meetings/clifton-hill-house>

Sponsored by WCRP and ESM2025

The workshop goal is to assemble current knowledge on TCRE and ZEC in the context of carbon budgets and create a plan to move forward towards an assessment over the next 1–2 years.

Session Topics - summary:

1. Understanding TCRE and ZEC components
 - a. Frameworks for investigating the processes and contributions to TCRE, ZEC and where uncertainty comes from (e.g. Jones & Friedlingstein or Williams et al)
 - b. Land/Ocean processes (e.g. Land: CO₂ fertilisation, permafrost; ocean: co-uptake of heat/CO₂ (“nexus”), role of different basins)
2. Observational constraints
 - a. Emergent constraints - e.g. on whole system? Or components, any other observational constraints across timescales?
3. Combining lines of evidence
 - a. Use of simple models/emulators and model hierarchy.
 - b. Combining TCRE and ZEC into constrained carbon budget information

Organising Committee:

Chris Jones, Pierre Friedlingstein, Tatiana Ilyina, Roland Seferian

Day 1

Arrive: Monday lunchtime. Buffet lunch available 12–1pm. Registration

Monday afternoon. 1:30pm

10 minute welcome/intro. Chris

1a. Frameworks for investigating the processes and contributions to TCRE, ZEC and where uncertainty comes from

Chairs: Chris Jones, Ric Williams

Aim is to understand how to assess the system in terms of different sensitivities of different aspects, where the uncertainties lie, how to combine aspects again if we can constrain individual terms.

1:30 – 3:10pm Talks

- 1:30 Chris Jones, Welcome, intro, TCRE assessment plans
- 1:40 Ric Williams, TCRE framework
- 1:55 Charlie Koven, ZEC and TCRE
- 2:10 Stuart Jenkins, RAZE framework
- 2:25 Paulo Ceppi, clouds and pattern effect
- 2:40 Rachel Chimuka, TCRE (a)symmetry
- 2:55 Ben Sanderson, flat-10 experimental design for TCRE and ZEC

Coffee: 20-minute break

4:00 - 5pm Breakouts (round tables). Topics:

1. We have numerous frameworks for understanding TCRE and ZEC – is it possible to combine or create an over-arching “one framework to rule them all”?
2. How can/should we design experiments to quantify TCRE and ZEC and they’re inter-dependence? Can/how can they be separated or should they be treated in tandem?
3. Are TCRE and ZEC over-simplistic metrics? How can/should they be used and what are their limitations or range of applicability? Considering especially overshoot and recovery scenarios for example

5 - 5:30 report back/discussion

5:30 drinks/ice-breaker reception.

Day 2

Tuesday morning. 9:00am

1b. Land/Ocean processes

Chair: Roland Seferian

- a. Land: CO₂ fertilisation, permafrost, nutrients, fire, ...
- b. Co-uptake of heat/CO₂ (“nexus”), role of different basins (Southern ocean, north atlantic?), model resolution - what does eddy-resolving give us?

Aim is to understand what processes drive TCRE and ZEC and how can we better use our knowledge of them. Assemble overview of existing knowledge and new/ongoing analysis, experiments etc.

9-10:45 a.m. talks

- 9:00 Sofia Palazzo Corner, ZEC review
- 9:15 Rosie Fisher, land processes
- 9:30 Jorg Schwinger, ZEC and AMOC
- 9:45 Spencer Liddicoat, TCRE dependence on processes in UKESM
- 10:00 Anna Katavouta, Ocean processes
- 10:15 Mark Webb, ECS assessment
- 10:30 Natassa Romanou - GISS ocean model results

Coffee: 20-minute break

11:10 - 12:10 breakouts (round tables). Topics:

- What are the priority areas/processes which control TCRE and ZEC?
 - Specifically can we build on Palazzo Corner et al (<https://www.frontiersin.org/journals/science/articles/10.3389/fsci.2023.1170744/full>) to develop concrete ideas?

- Are there ways to reduce current uncertainty in TCRE/ZEC through knowledge of processes – e.g. if there is evidence current models are over/under sensitive in some areas? Or completely miss a process (e.g. for CMIP5 we knew almost all models had too large land carbon uptake due to lack of nutrient limitations – are there examples of persistent biases like this we can exploit to adjust estimates of TCRE/ZEC?)
- What lessons can we learn from other communities such as cloud feedbacks? How did ECS assessment treat individual processes?

12:15 - 12:45 report back/discussion

12:45 - 2pm Lunch.

Tuesday afternoon. 2:00pm

2. Observational constraints

Chair: Peter Cox

- Emergent constraints - on whole system? Or components - e.g. ECS, Carbon cycle/AF. Different regions/time period (seasonal, IAV etc)
- Any other observational constraints across timescales?

Aim is to understand what past and present obs tell us and if/how we can assemble into a constraint on system sensitivity or metrics like TCRE and ZEC.

2:00 - 3:30pm Talks

2:00 Peter Cox, emergent constraint on TCRE

2:20 Becky Varney, soil carbon and spatial constraints

2:40 Jens Terhaar, AMOC and heat uptake

3:00 Sabrina Zechlau/Peter Cox, GPP and seasonal cycle

Coffee: 30-minute break.

4:00 - 5pm Breakouts (round tables). Topics:

- Opportunities to constrain the whole system vs sub-components?
- How to combine multiple constraints (e.g. tropical carbon and temperate carbon from IAV and seasonal cycle)
- No emergent constraint work yet on ZEC – what opportunities are there, and where should we look for process-constraints on ZEC?

5 - 5:30 report back/discussion

Tuesday Evening: Workshop Dinner

Zero Degrees Bristol

<https://www.zerodegrees.co.uk/restaurants/zerodegrees-microbrewery-bristol>

53 Colston St

Bristol BS1 5BA

Circa 20 minute walk from Workshop

Arrive from 7pm

Dinner from 7:30

Kindly sponsored by ESM2025

Day 3

Wednesday morning. 9:00am

3a. Use of simple models/emulators and model hierarchy. From simple emulators, through EMICs to ESMs

Chair: Tatiana Ilyina

Aim is to understand the role of simplified models to constrain processes and combine multiple lines of evidence – Bayesian or other techniques. PPE, History Matching. How simple is too-simple? Can we define eval metrics to build confidence in emulator performance?

9–10:30 a.m. talks

9:00 Roland Seferian, simple models and heat/carbon uptake constraints
9:15 Chris Smith, FaIR calibration
9:30 Ben Booth, carbon cycle PPEs
9:45 Phil Goodwin, History matching
10:00 Hugo Lambert, assessing feedbacks in the CLOUDSENSE programme
10:15 Glen Peters, simple modelling for ZEC

Coffee: 30-minute break

11:00 – 12:00 breakouts (round tables). Topics:

- Evaluation – how to know if simple models are reliable. Can we assemble a minimum quality set/criteria for their use?
- Calibration – which ESM experiments do we need (and diagnostics) to more fully calibrate simple models and emulators?
- Ensemble design – what is the role of PPEs to constrain ZEC and TCRE, and what techniques exist (history matching, ...)?

12–12:30 report back/discussion

12:30 – 2pm Lunch.

Wednesday afternoon. 2:00pm

3b. Combining TCRE and ZEC into constrained carbon budget information

Chair: Pierre Friedlingstein

Aim is to decide how we can combine ZEC/TCRE assessments meaningfully towards improved carbon budget information, or guidance on system behaviour during reducing, net-zero and net-negative emissions

2:00 – 3:30pm Talks

2:00 Ben Sanderson, reconciling ZEC and RAZE
2:15 Jens Terhaar, AERA-MIP initial results
2:30 Damon Matthews, effective TCRE and non-CO₂ forcing
2:45 Andrew MacDougall, Moving towards ZECMIP-II
3:00 Kate Marvel, Stats/Bayesian approaches for synthesis

Coffee: 30-minute break

3:45 – 4:45pm Breakouts (round tables). Topics:

- How can we take everything from this week into an assessment?
- What analysis, experiments are needed, or possible now?
- What is missing?
- Who is missing? – people or communities to reach out to
- What are IPCC (and wider) needs for such an assessment?

4:455 – 5:30 report back/discussion

Next steps – decision on future work areas, and leads. Paper plans.

5:30 workshop close/depart