Role of Earth system processes in the Transient Climate Response to cumulative Emissions (TCRE)

Met Office

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Introduction

We have used seven configurations of UKESM1.1 to investigate the process-dependence of the climate-carbon cycle feedback parameters, and the Transient Climate Response to Cumulative Emissions (TCRE).

We performed the standard *1pctCO2* experiments, in which CO_2 concentration rises from pre-industrial level at 1%/yr, with a control configuration and six experimental configurations of UKESM1.1. From these experiments we can calculate the **concentration-carbon feedback parameter, β**, and **the climate-carbon feedback parameter, γ**:

$$\beta = \frac{\Delta C\_LAND_{BGC}}{\Delta CO2} \qquad \gamma = \frac{\Delta C\_LAND_{COU} - \Delta C\_LAND_{BGC}}{\Delta TEMP_{COU}}$$

COU = fully coupled: climate and carbon cycle see CO_2 rising at 1%/yr
BGC = biogeochemically coupled: climate sees 1850 CO_2, carbon-cycle sees CO_2 rising at 1%/yr

ΔC_LAND_{BGC} = change in land carbon in BGC
ΔC_LAND_{COU} = change in land carbon in COU
$\Delta TEMP_{COU}$ = change in global mean temperature in COU

β characterizes sensitivity of land carbon uptake to changing CO_2: the higher β, the more land carbon increases with rising CO_2.

γ characterizes sensitivity of land carbon uptake to increasing temperature: the more negative γ is, the more the land carbon sink will be weakened by a warming climate.

Our six experimental configurations differ from the control by the inclusion or exclusion of one process, as summarised in the table below. Comparison of the experimental configurations with the control illustrates the impact of each process in isolation on the feedback parameters. We ran an additional configuration containing all six processes.

Configuration	Difference relative to ukesm-ctrl
ukesm-nonlim	Nitrogen limitation switched off
ukesm-bvoc	Interactive BVOC emissions
ukesm-nodgvm	Vegetation distribution is fixed
ukesm-wch4	Interactive CH_4 cycle and emissions from wetlands
ukesm-df-int	Diffuse fraction of Photosynthetically Active Radiation is calculated interactively
ukesm-fire	Fire-vegetation interactions
ukesm-allprocs	All six processes are included

Influence of processes on concentration-carbon feedback, β and climate-carbon feedback, γ

Figure 1 shows a) β, concentration-carbon feedback for land, which is the sensitivity of land carbon uptake to changing CO_2, and b) Υ, climate-carbon feedback, i.e. the sensitivity of land carbon to climate.

The processes with the greatest impact are as follows.

Switching off Nitrogen limitation increases β at both 2x and 4x pre-industrial CO_2. In the control configuration, the land carbon uptake is limited by the availability of nitrogen, particularly at high latitudes. When nitrogen limitation is switched off, vegetation growth is unimpeded by the lack of availability of nitrogenous nutrient, so uptake is much stronger, yielding a significantly larger β at both 2x and 4xCO2. By contrast, switching off nitrogen limitation had little impact on γ at 2xCO2 but strengthened it significantly at 4xCO2: this is due to the ever-widening gap between ΔC_LAND_{COU} and ΔC_LAND_{BGC} (see definition of Υ to the left).

Fire-vegetation interactions result in a reduction in tree fraction with an increase in grass fraction, weakening the land carbon sink overall, hence reducing β and strengthening γ.

Fixed vegetation distribution prevents the vegetation distribution from adapting to the changing climate and CO_2; the net biosphere productivity is weaker than in the control configuration which has dynamic vegetation, and hence β is lower in the fixed vegetation configuration, at both 2x and $4xCO_2$.

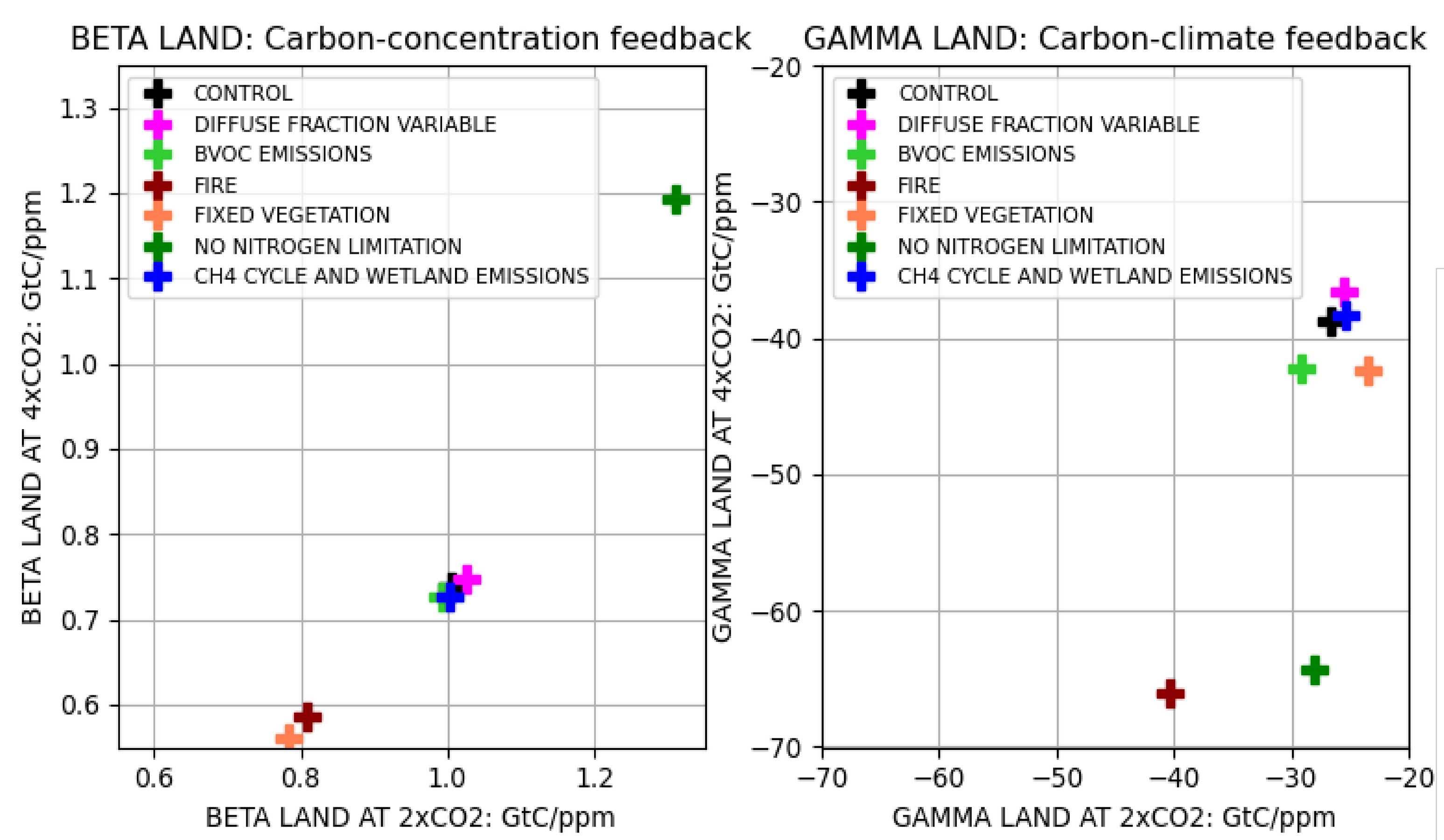

Figure 1: a) β and **b)** γ for land, evaluated at 2xCO2 (x-axis) and 4xCO2 (y-axis)

Process-dependence of Transient Climate Response to cumulative Emissions (TCRE)

TCRE characterizes the approximately linear relationship between the change in global mean temperature and cumulative carbon emissions. **Figure 2(a)** shows this relationship for our UKESM process-ensemble, resulting in a fairly large spread comparable in magnitude to that of the 11 CMIP6 ESMs documented in Arora et al (2020). **Figure 2(b)** shows the **TCRE** on the y-axis, which is the transient climate response at the point of doubling of CO_2 divided by the cumulative CO_2 emissions to that point (shown on the x-axis), expressed in units of °C/1000 GtC.

Four processes increased TCRE: fire-vegetation interactions by 14.6%; nitrogen limitation of vegetation by 9.7%; diffuse radiation effects on vegetation by 8.5%, and climate impacts from wetland methane emissions by 5.1%. TCRE was reduced by including changes in vegetation distribution (-1.5%) and climate impacts from biogenic volatile organic compounds (-1.4%).

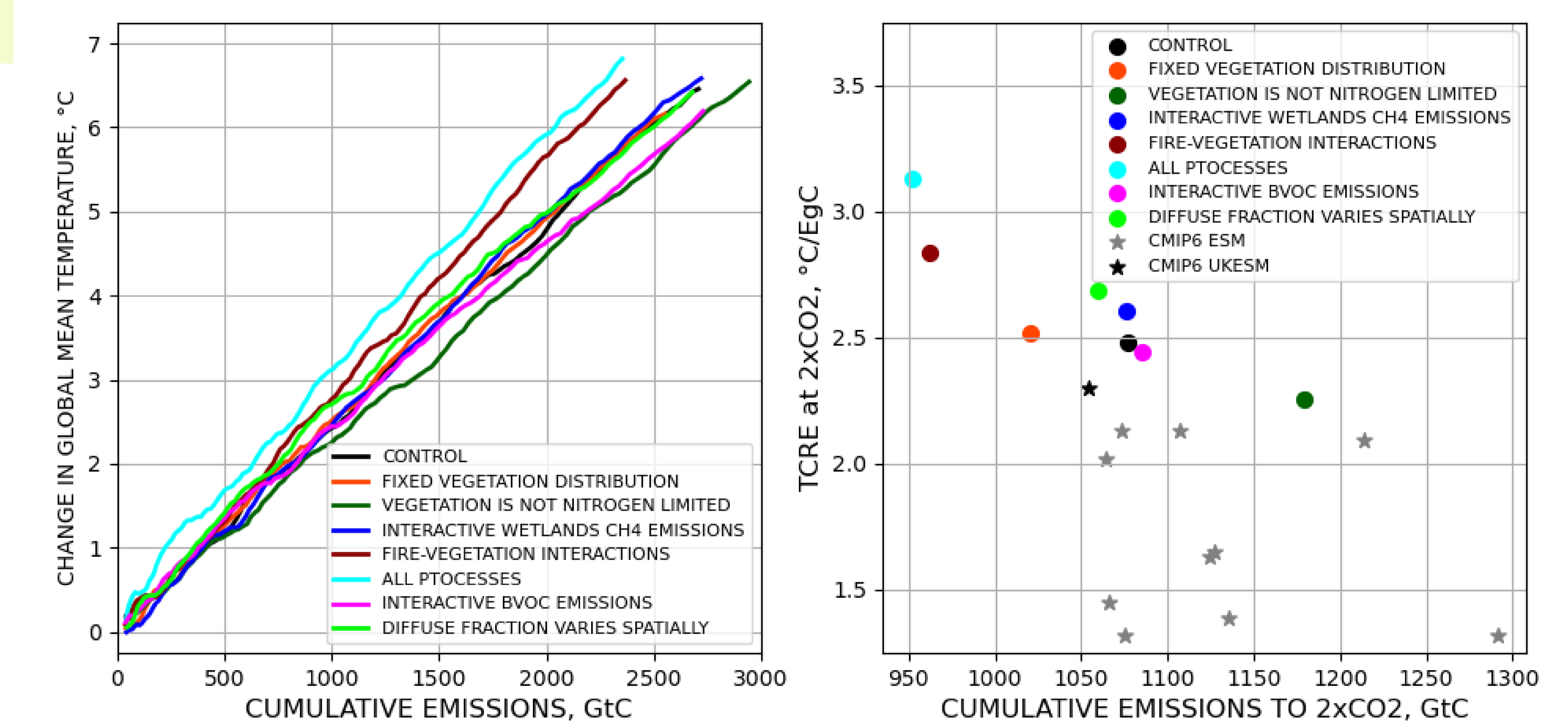

***Figure 2**: **a)**TCR vs cumulative emissions for the UKESM process ensemble **b)** TCRE vs cumulative emissions of the UKESM ensemble (coloured circles) and 11 CMIP6 ESMs (grey stars)*

Recalculating the TCRE of 11 CMIP6 ESMs as if each had all six processes

From our process-ensemble of UKESM configurations we derived a scaling factor to emulate the influence of each individual process on TCRE and Cumulative Emissions, and applied them to the CMIP6 ESMs for each process absent from each ESM.

Thus, we have recalculated the TCRE of the 11 CMIP6 ESMs as if each included all six of the processes listed in the table: emulating the missing processes increases the TCRE of all 11 ESMs (grey stars shift to salmon stars in **Figure 3**).

Using their original and rescaled TCREs, the impact of emulating all six processes in all 11 ESMs is to reduce by 18.2 ± 0.7% the carbon emissions budget from 1.5°C to 2.0°C (averaged over all ESMs).

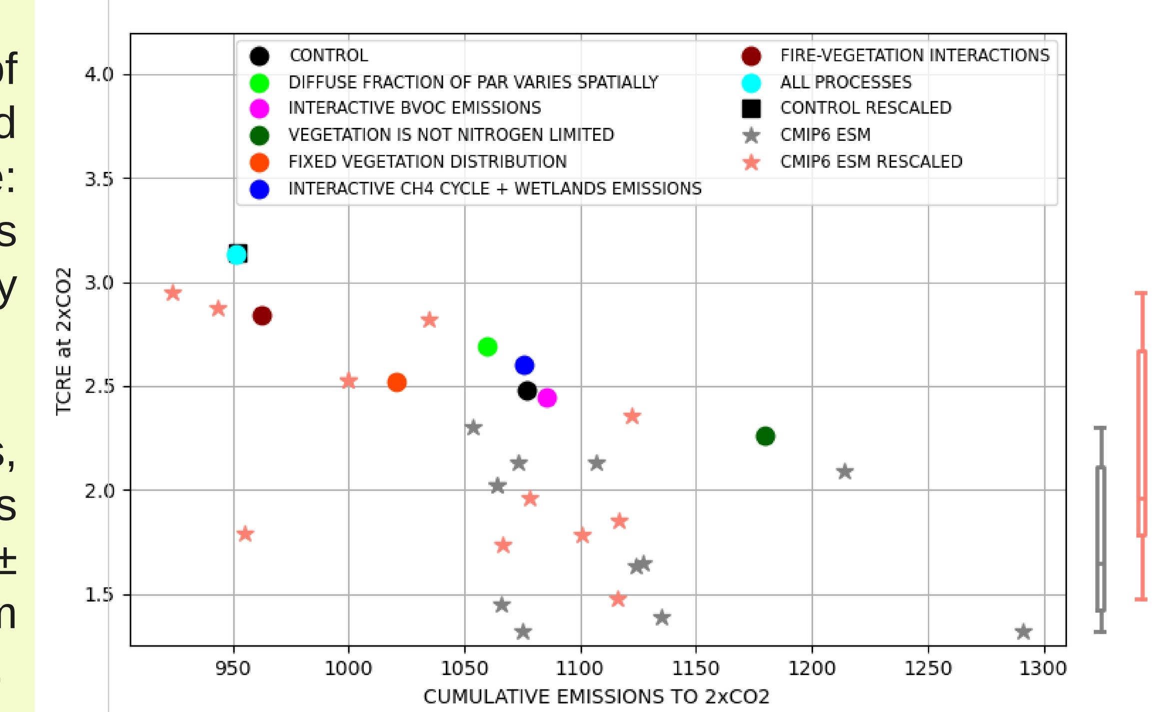

***Figure 3:** TCRE vs Cumulative Emissions of the UKESM process ensemble, and of 11 CMIP6 ESMs before (grey stars) and after (salmon stars) recalculated as if each included all six processes.*

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Arora, V. K. and co-authors (2020): Carbon–concentration and carbon–climate feedbacks in CMIP6 models, and their comparison to CMIP5 models. Biogeosciences, 17, 4173–4222 (2020