Hysteresis and tipping points analysis using the UK Earth System Model

Global consequences of climate overshoot pathways: Annex 4

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CS-NOW

Climate services for a net zero resilient world

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Key messages

1. Global mean land surface temperature can recover from a climate overshoot of approximately 2°C (high confidence).

Widespread increases in land temperature simulated at the middle of the century during the "Very High Overshoot" pathway return to the same levels as in the "No Overshoot" pathway by the end of century. There is no sign of global scale temperature hysteresis following the "Very High Overshoot" pathway considered here.

2. Arctic Sea ice loss increases significantly in the overshoot pathway but by 2100 does not show clear signs of hysteresis (medium confidence).

Arctic sea ice is projected to reduce steadily over coming decades compared to 2020, with a potential tipping point occurring in the "Very High Overshoot" pathway leading to higher loss compared with the "No Overshoot" pathway at end-century. To determine if there indeed has been a tipping point and there is hysteresis would require simulations run out beyond 2100.

3. Long-term rainfall could reduce in the tropics (low confidence).

End-century rainfall is lower in the tropics, particularly in the Sahel and Indian monsoon regions, in the "Very High Overshoot" pathway. Many more versions of each pathway would need to be run to show whether this is statistically significant.

4. This analysis can only definitively show where tipping points and hysteresis do not occur.

As tipping points and hysteresis reverse over a range of timescales from years to centuries it would be necessary to run the simulations over a much longer time horizon to identify whether and when differences identified in 2100 would reverse. This was not possible in this study due to time and computational constraints.

About this report

The “Global consequences of climate overshoot pathways” study has examined the natural and human system consequences of the world overshooting 1.5 °C, but then using carbon dioxide removal technologies to return the global temperature to 1.5 °C by 2100.

The final report summarises the findings from the study. Six annexes present the technical evidence that underpin the final report:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the rate required for overshoot pathways.
- Annex 3: Economic implications of climate overshoot.
- Annex 4: Hysteresis and tipping points analysis using the UK Earth System Model.
- Annex 5: Natural system impacts of overshoot pathways.
- Annex 6: Human system impacts of overshoot pathways.

Around 40 scientists have contributed to these annexes and more than 900 literature sources are cited.

Annex 1 develops several pathways including “No Overshoot” and “Very High Overshoot” pathways. This annex, Annex 4, models these two pathways in the UK Earth System Model to identify natural system changes caused by overshooting 1.5 °C and to explore whether they might persist when the global temperature rise is reduced back to 1.5 °C.

About CS-N0W

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improve accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by **Ricardo** and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

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Acronyms

AA	Arctic Amplification
AR6	IPCC's Sixth Assessment Report (2021-2022)
CH_4	Methane
CMIP6	Coupled Model Intercomparison Phase 6
CO_2	Carbon Dioxide
DESNZ	Department for Energy Security and Net Zero
DJF	December to February
EffCS	Effective Climate Sensitivity
ECS	Equilibrium Climate Sensitivity
ESM	Earth System Model
GCM	General Circulation Model
GHG	Greenhouse Gas
GMST	Global Mean Surface Temperature
HPC	High-Performance Computing
IPCC	Intergovernmental Panel on Climate Change
JJA	June to August
JULES-ES	Joint UK Land Environment Simulator-Earth system model
MAM	March to May
MEDUSA	Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification
N_2O	Nitrous Oxide
NEMO	Nucleus for European Modelling of the Ocean
NO	No Overshoot pathway
NO_x	Nitrogen Oxides
RCP	Representative Concentration Pathways
SLCP	Short-lived Climate Pollutant
SON	September to November

SO_2	Sulphur Dioxide
SSP	Shared Socioeconomic Pathways
TIAM-UCL	TIMES Integrated Assessment Model at University College London
TP	Tipping Point
TRIFFID	Top-down Representation of Interactive Foliage and Flora Including Dynamics
UKCA	UK Chemistry and Aerosol model
UKESM	UK Earth System Model
VHO	Very High Overshoot pathway
VOC	Volatile Organic Compound

1. Executive Summary

Overshooting 1.5 °C could have substantial impacts on natural and human systems. There is particular concern about whether the impacts of overshooting might not dissipate if the global temperature rise were reduced to 1.5 °C by 2100 following the overshoot, or whether tipping points might be reached that cause irreversible impacts to natural or human systems.

The permanence or longevity of changes to the Earth's natural systems following a peak in global temperatures is difficult to ascertain, given the uncertainty in the rate at which some impacts may reduce or reverse as global temperatures fall. Some parts of the Earth's system may even remain in an altered state, which is termed hysteresis. In this annex, the impacts of overshooting on natural systems are examined using the UK Earth System Model (UKESM). The aims of this study were to model a *plausible*[1] overshoot pathway and quantify the impacts of overshooting and returning to 1.5 °C of warming by 2100 on key aspects of the Earth system. The overarching question we aimed to address was whether or not any climate tipping points were simulated and to what degree any hysteresis is simulated using a state-of-the-art Earth system model.

The report examines the impacts of the "Very high overshoot" pathway, which reaches 1.9 °C of warming in around 2065 before returning to 1.5 °C of warming by 2100, as this is likely to have the most substantial impacts of the three overshoot pathways developed by this study. It is compared to a "No Overshoot" counterfactual pathway in which the global temperature never exceeds 1.5 °C. Differences in temperature, precipitation, polar ice and the surface temperature of the oceans are identified and analysed for evidence that tipping points might be reached or that hysteresis might occur.

Modelling the Earth system

The Earth system comprises the physical climate system (atmosphere, ocean, land, sea and land ice), the varying composition of trace gases and air pollutants in the air

[1] By plausible, we mean a pathway consistent with current emission trends in which the global surface average temperature might plausibly be returned to 1.5 °C using atmospheric CO_2 removal technologies following an overshoot. Annex 2 of this report investigates whether the assumed level of CO_2 removal is indeed plausible.

and oceans, and the varying biological cycles present on land and in water. Earth system models such as the UKESM are used to represent the numerous complex interconnections and consider how greenhouse gas (GHG) emissions might affect natural systems in the future.

The UKESM has provided a wealth of model data to help inform scientific studies that were reviewed in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6), including over 10,000 simulated model years. It exhibits a predictable relationship between emissions and surface temperature in a similar way to what has been simulated with other earth system models, which suggests it is appropriate for investigating overshoot pathways in this study. However, in common with several other earth system models, the modelled temperature rise is substantially larger than has been observed over the past few decades and the model exhibits a higher Equilibrium Climate Sensitivity (ECS) than the best estimate from the IPCC AR6.

In contrast to previous literature, which examined hypothetical pathways of climate overshoots in IPCC AR6, TIAM-UCL was used to develop a series of energy-economy-emissions pathways that would lead to realistic levels of climate overshoots. TIAM-UCL made use of the best estimate of ECS from IPCC AR6 to convert between emissions of climate forcers and changes in global mean surface temperature. To replicate the future pathways developed in TIAM-UCL in the UKESM, future CO_2 concentrations were artificially reduced to compensate for the higher temperature rise modelled by UKESM. This approach assumed that most natural system impacts are driven by temperature rather than by CO_2 concentration. By simulating lower CO_2 concentration than would exist for the same temperature rise, growth of some vegetation in the model would have been lower, as the same extent of carbon fertilisation would not occur. UKESM modelling experts determined this would not significantly affect atmospheric responses to changing temperatures.

Earth system impacts of overshoot

Two pathways previously developed in TIAM-UCL were replicated in UKESM: the “Very High Overshoot” pathway, and the “No Overshoot” pathway as a counterfactual.

The two pathways were compared in 2056–2065 (“mid-century”), when the global mean surface temperature (GMST) difference between them is highest, and in 2090–2100 (“end-century”), when both have a GMST of 1.5 °C above pre-industrial.

By mid-century, the “Very High Overshoot” pathway has 0.5–1.0 °C extra warming over most land areas and even larger warming (2.5–4.5 °C) over the Arctic region compared with the “No Overshoot” pathway. This “Arctic amplification” is well-documented in the literature and is the result of a number of complex Earth system mechanisms. The oceans are simulated to have little surface temperature warming. By end-century, land temperatures in the “Very High Overshoot” pathway reduce to a similar level to the “No Overshoot” pathway except at high northern latitudes, where there continue to be differences in spite of GMST being approximately the same. These differences are especially clear in the Arctic region, where temperatures remain substantially higher than in the “No Overshoot” pathway.

The implications of this temperature change are that Arctic Sea ice reaches a tipping point from which it does not recover before the end of the model simulation (the year 2100). However, we cannot rule out recovery of the Arctic beyond 2100.

In both pathways, there is substantial Arctic ice loss compared to today as a result of the global temperature increasing from 1.2 °C to at least 1.5 °C. Yet the “Very High Overshoot” pathway continues to have higher ice loss at end-century (40% higher than in 2020) than the “No Overshoot” pathway (30% higher than in 2020), with particularly large differences in winter and spring. In contrast, while the seas around Antarctica lose ice in mid-century in the “Very High Overshoot” pathway, they have higher sea ice by 2100 than for the “No Overshoot” pathway. This increase in sea-ice in Antarctica is driven by atmospheric circulation changes and has also been documented in the past few decades in observations.

Sea level rise depends on cumulative temperature so would be higher in the “Very High Overshoot” pathway. These UKESM pathways did not fully represent glacial melt, so the full extent of sea level rise could not be estimated directly. Sea-level rise is instead examined in detail in Annex 5 of this study, which examines potential natural system impacts of overshooting. Sea surface temperature differences between the pathways were small throughout the century.

Difference in rainfall of up to ±20% occur at end-century between the pathways, primarily in low-latitude areas. The Sahel monsoon and the early months of the Indian monsoon display differences with substantially lower rainfall. In contrast to the global mean surface temperature and sea ice differences, these changes in rainfall are not statistically significant.

Each pathway was run four times to account for natural climate variability. Only the starting conditions of the model were modified, but this allows a different realisation of the climate pathway to be simulated. This is very important as the climate system exhibits significant amounts of internal (natural) variability so multiple simulations must be analysed to ensure confidence in the insights. For example, two of the "No Overshoot" pathway simulations had a temperature difference of 0.3 °C from 2060 to 2080. Running only four simulations of each pathway meant that it was not possible to identify statistically significant changes in extreme temperature or long-term rainfall, as the natural variability in these was similar to the differences between the simulated pathways. Further investigations with a larger number of runs or advanced machine learning techniques would be required to determine the significance of differences in these areas.

While the study cannot demonstrate significant evidence of hysteresis given the simulations only run until 2100, the absence of a significant difference between the "Very High Overshoot" and "No Overshoot" pathways suggests a lack of hysteresis in that variable/system and that where a difference does exist (as in the case of Arctic Sea ice cover), further study using simulations beyond 2100 could explore this.

Limitations of this study and recommendations for future work

The high ECS of the UKESM model meant that there was a significant difference between the levels of GHG simulated in this model and the TIAM-UCL model used to derive the overshoot pathways. Although we argue that this is not of major impact to the results of this study, it would be desirable to perform similar calculations with a model (or variant of UKESM) with a lower ECS. UKESM can be run using either an emission-driven or lower boundary-driven configuration. A lower boundary-driven configuration was used in this study by forcing the model GHG levels to follow pre-determined pathways from the TIAM-UCL model. The model simulates full Earth system changes but some feedbacks were not considered. For example, any extra GHG emissions from permafrost thaw, or increased wild-fires, that would be simulated by the model were not coupled into the model simulations. Further studies using the emission-driven UKESM configuration would be helpful to explore the impacts of these coupled feedbacks, especially methane feedbacks.

The differences between the two simulated pathways are quite small. Increasing the ensemble size (i.e. the number of UEKSM simulations of each pathway) might enable us to identify further statistically significant insights. The current size of four members means that analysis of temperature and rainfall extremes, and aspects of the climate system that have high natural (sometimes called internal) variability, is limited in scope. Another complementary approach would be to use other models (i.e. different Earth System Models) to simulate these scenarios in a model intercomparison exercise.

2. Introduction

Overshooting 1.5 °C could have substantial impacts on natural and human systems (IPCC, 2018). There is particular concern about whether overshooting could lead to tipping points being reached or whether the impacts of overshooting might not dissipate if the global temperature rise were reduced back to 1.5 °C following an overshoot. Annex 5 examines the potential impacts of overshooting on natural systems, with a particular focus on tipping points, high impact events and hysteresis. Five areas are analysed in that report: (a) atmosphere; (b) ecosystems; (c) biodiversity; (d) oceans and coastal regions; and (e) cryosphere.

This annex assesses the Earth system impacts of a climate overshoot using a state-of-the-art Earth system model. While Annex 5 can use the copious literature on the impacts of a 1.5 °C rise and a 2 °C rise, (e.g. IPCC, 2018), there has been little analysis of overshoot pathways that return to 1.5 °C by the end of the century. Changes to the Earth system following the peak temperature are particularly uncertain as some impacts of a global temperature rise to 1.9 °C might not lessen as the temperature is reduced. In order to inform the Annex 5 analysis, this study used the UK Earth System Model (UKESM) (Sellar *et al.*, 2019) to investigate how an overshoot pathway might differ from a pathway that does not overshoot 1.5 °C.

Annex 1 develops three overshoot pathways for use in this study. This report considers a “Very High Overshoot” (VHO) pathway to 1.9 °C of warming that returns to 1.5 °C of warming by 2100, as this is likely to have the most substantial impacts of the three overshoot pathways. It is compared to a “No Overshoot” (NO) counterfactual pathway in which the global temperature rises to but never exceeds 1.5 °C. To inform the natural systems analysis in Annex 5, differences in temperature, precipitation, polar ice and the surface temperature of the oceans are examined.

2.1 Definition of tipping points and hysteresis

The IPCC AR6 WG-I report (IPCC, 2021a) defines a tipping point as occurring on a global or regional scale, often abruptly and/or irreversibly. Similarly, Armstrong McKay *et al.* (2022)

define tipping points as changes in parts of the climate system, known as tipping elements, that become self-perpetuating beyond a warming threshold. These tipping points lead to abrupt, high-impact and often irreversible changes, although Armstrong McKay *et al.* (2022) also include tipping points (e.g. in ice sheets) where "the resulting qualitative change is slower than the anthropogenic forcing causing it, i.e., not abrupt in the sense defined as faster than the cause".

Table 1 summarises tipping points of current concern whose lowest estimate of their global warming temperature threshold are less than 1.9 °C.[2] Timescales and reversibility vary between tipping points. There is concern that exceeding a tipping point in one tipping element could possibly trigger a sequence of further tipping points in others, often referred to as a cascading transition (Kriegler *et al.*, 2009, Lenton *et al.*, 2019). For example, Arctic sea-ice loss could weaken the Atlantic Ocean current that warms Europe, reduce rainfall in the Amazon, weaken the East Asian monsoon and accelerate Antarctic ice loss. Annex 5 also discusses tipping points that might occur at temperatures exceeding 1.9 °C.

Hysteresis is defined as a change to the Earth system that does not reverse when the global temperature reverses. An arbitrary period must be chosen to decide whether or not a change is reversible. For example, Wang *et al.* (2023) denote a change as: (a) reversible if "*reversion to the original system state can occur within a century upon applying the opposite forcing*"; and, (b) irreversible if "*reversion to the original system state requires centuries or longer, and/or different opposite forcing of a significantly larger magnitude than the original change in forcing applied to achieve the altered system state*". So hysteresis refers to changes in the state of the climate and other systems that are potentially reversible but depend on the history of the state. Figure 1 presents a schematic of hysteresis.

[2] Temperature (and a specific temperature threshold or level of global warming) is not the sole determinant of tipping behaviour, adding to the additional uncertainty as to the likelihood or timescale of tipping.

Table 1. Tipping points, temperature thresholds and timescales, with best estimate and confidence levels (minimum–maximum). Sources: Armstrong McKay *et al.* (2022) and timescales for irreversibility and reversibility from IPCC AR6 WG1 (IPCC, 2021b). Irreversibility or reversibility was not assessed for all climate tipping elements in IPCC AR6 WG1; this is indicated by '-'. Confidence levels from Armstrong McKay *et al.* (2022) are authors judgements based on the IPCC's confidence rating system.

Climate Tipping Element (and tipping point)	Temperature threshold (°C)		Timescale (years)[3]		Reversible (R) / Irreversible (I)
	Est. (Min-Max)	Confidence level	Est. (Min-Max)	Confidence level	
(a) GLOBAL					
Greenland Ice Sheet (collapse)	1.5 (0.8–3.0)	High	10k (1k–15k)	Medium	I: for millennia
West Antarctic Ice Sheet (collapse)	1.5 (1.0–3.0)	High	2k (500–13k)	Medium	I: for decades to millennia
Labrador–Irminger Seas /Subpolar gyre Convection (collapse)	1.8 (1.1–3.8)	High	10 (5–50)	High	-
Atlantic M.O. Circulation (collapse)	4.0 (1.4–8.0)	Low	50 (15–300)	Medium	R: for centuries
(b) REGIONAL					
Low-latitude Coral Reefs (die-off)	1.5 (1.0–2.0)		10 (–)		-
Boreal Permafrost (abrupt thaw)	1.5 (1.0–2.3)	Medium	200 (100–300)	Medium	-
Barents Sea Ice (abrupt loss)	1.6 (1.5–1.7)		25 (?–?)		-
Boreal Forest (northern expansion)	4.0 (1.5–7.2)	Low	100 (40+)	Low	I: for multi-decades

[3] From Armstrong McKay et al., 2022, timescale is the time over which the transition to a new state occurs and is determined by the climate (sub)system itself. The resulting (often irreversible) changes may take centuries to millennia to be realised.

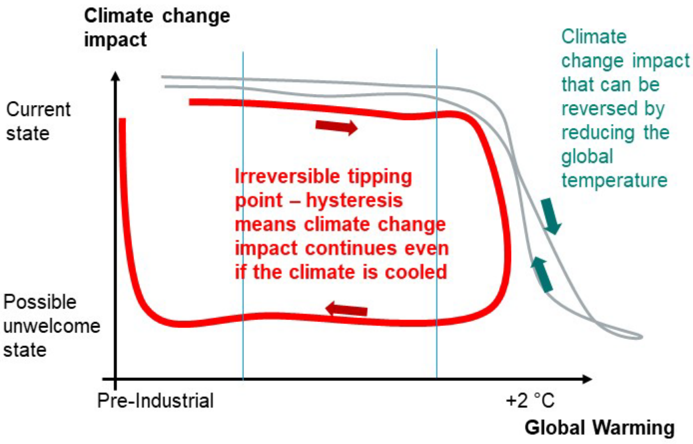

Figure 1. Schematic illustrating reversible and irreversible tipping points. In this figure, we imagine an increase in global warming, followed by a decrease (moving along the “x”-axis and return). The “y” axis slows a decline from a current climatic state to an unwelcome state, which then persists until the temperature is reduced to a low level.

2.2 Purpose and overview of the research reported in this annex

This annex explains how the pathways were translated from the TIAM-UCL integrated assessment model, described in Annex 1, to the UKESM. It then describes some of the climatic impacts of following a VHO pathway and compares these to a NO counterfactual pathway. The two pathways were run to the year 2100 and two 10-year periods were examined.[4] By comparing the two pathways, the differences between an overshoot pathway and a no-overshoot pathway (the counterfactual pathway in this report) can be understood.

First, as the peak overshoot temperature of 1.9 °C is reached in around 2065, the period 2056–2065 was examined to understand the differences between the pathways at the time of peak temperature difference.

Second, as the temperature is returned to 1.5 °C by 2100 in the overshoot pathway, the temperatures in both pathways converge. By identifying differences between the pathways

[4] Periods spanning 10 years were chosen to dampen natural interannual weather variability so climatic differences could be identified.

in the period 2091–2100, parts of the Earth system with no hysteresis and where there might *potentially* be hysteresis and tipping points can be identified.

As tipping points and hysteresis reverse over a range of timescales from years to centuries, this analysis can only definitively show where tipping points and hysteresis do not occur. It would be necessary to run the simulations over a much longer time horizon to identify whether and when differences identified in 2100 would reverse, but this was not possible in this study due to time and computational constraints.

2.3 Structure of this annex

Section 3 has a brief overview of the UKESM. Section 4 explains the method used to represent the pathways in UKESM. The following sections examine temperature impacts (Section 5), polar region impacts (Section 6), oceanic impacts (Section 7) and rainfall impacts (Section 8).

3. Overview of the UK Earth System Model

The Earth system is incredibly complex. The bio-physical Earth system comprises the physical climate system (atmosphere, ocean, land, sea and land ice), the varying composition of trace gases and air pollutants in the air and oceans, and the varying biogeochemical cycles present on land and in water. There are numerous complex interconnections across the Earth system at a range of scales, so Earth system numerical models are widely acknowledged as the best available tools to understand the potential impacts of human actions, such as the emissions of greenhouse gases and land use changes, on the Earth system.

The UKESM comprises a general circulation climate model (GCM) integrated with a number of Earth system model components. The GCM is the Met Office Unified Model (UM), with interactive atmospheric chemistry and aerosols provided by the UK Chemistry and Aerosol model (UKCA) (Archibald *et al.*, 2020). The land surface is simulated with the Joint UK Land Environment Simulator-Earth system model (JULES-ES; Wiltshire *et al.* (2020)) and the Top-down Representation of Interactive Foliage and Flora Including Dynamics (TRIFFID) dynamic vegetation module (Burton *et al.*, 2019). The simulations performed in this study utilised the UKESM-1.0-LL configuration, which is the same configuration discussed in (Sellar *et al.*, 2019, Sellar *et al.*, 2020). The atmosphere resolution is set at 1.875° longitude by 1.25° latitude, with 85 vertical levels resolving the surface to ~84 km in altitude. The ocean representation is the Nucleus for European Modelling of the Ocean (NEMO) ocean run at ~1° with 75 vertical levels, with sea ice calculated interactively but fixed glaciers[5] (Sellar *et al.*, 2019). The Model of Ecosystem Dynamics, nutrient Utilisation, Sequestration and Acidification (MEDUSA) module allows for the calculation of ocean biogeochemistry (Yool *et al.*, 2021).

UKESM is a complex modelling tool and requires dedicated high-performance computing (HPC) resources to run the simulations. Analysing climate change over a century requires around three months' running time for each simulation.

3.1 Previous scientific applications of UKESM

UKESM was the flagship Earth System Model (ESM) that the UK climate modelling community (Met Office and UKRI funded researchers) contributed to the Coupled Model Intercomparison Project Phase 6 (CMIP6, Eyring *et al.*, 2016). Through the auspices of CMIP6, UKESM provided a wealth of model data to help inform scientific studies that were reviewed in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (IPCC, 2021b). Over 10,000 model years were simulated with UKESM covering a huge number of different experiments (Sellar *et al.*, 2020), including several aimed to assess mid-term climate pathways (up to 2100) through the ScenarioMIP project (O'Neill *et al.*, 2016).

The scientific community has defined five Shared Socioeconomic Pathway (SSPs) scenarios of projected socioeconomic global changes up to 2100, denoted SSP1 to SSP5, according to the socioeconomic challenges for mitigation and adaptation. These are summarised in Figure 2. In the notation SSPx-y.y, y.y refers to the related Representative Concentration Pathway (RCP) for the scenario. RCPs are the expected level of radiative forcing in the year 2100 and vary between 1.9 and 8.5 W/m^2. RCPs are matched with

[5] This means that glacial melt causing sea level rise is not considered in the UKESM simulation, but this mechanism is considered in Annex 5.

appropriate SSPs: for example, SSP1 has only low RCPs (1.9 and 2.6) while SSP5 is often matched with RCP8.5.

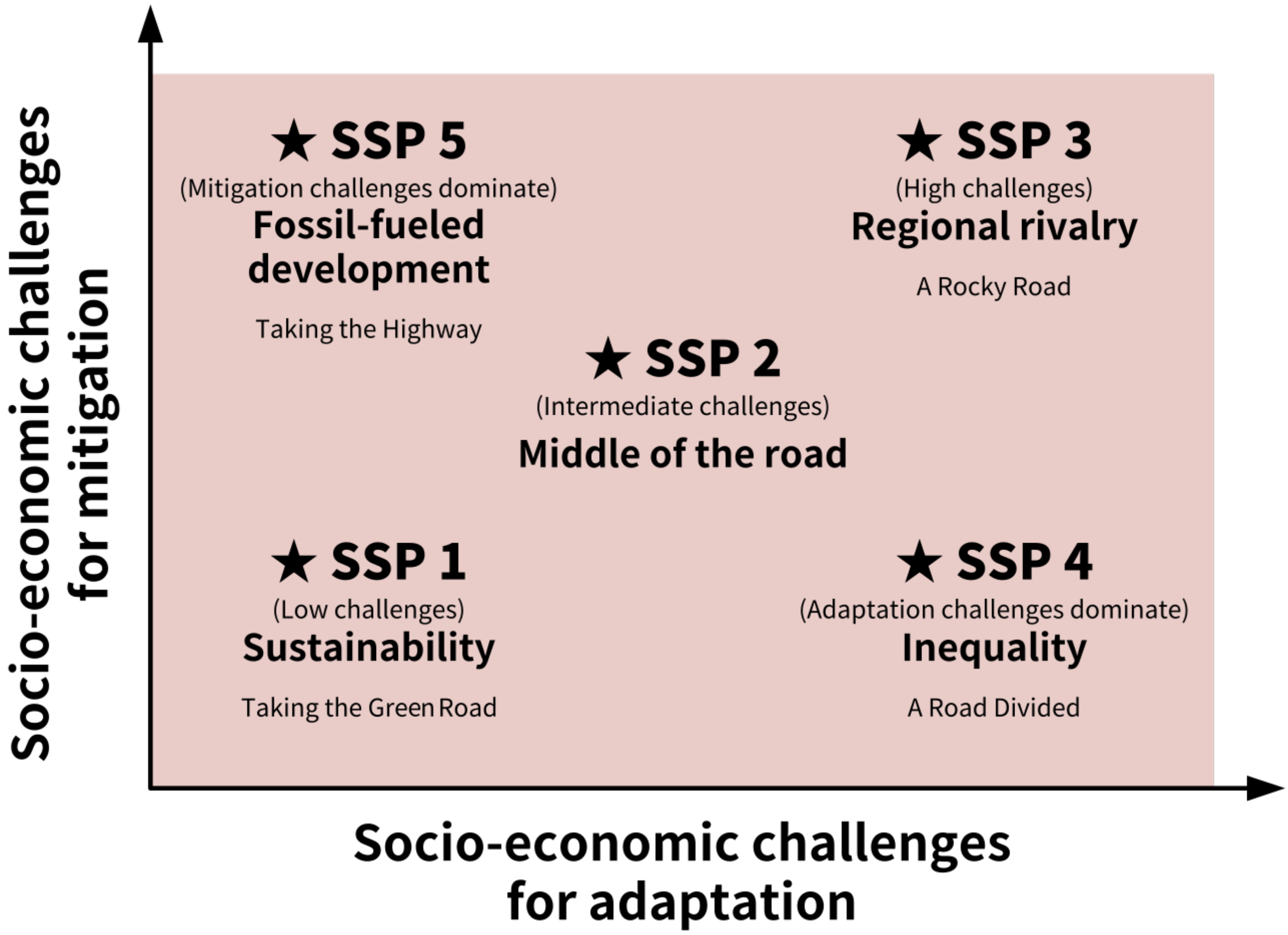

Figure 2. SSPs mapped according to the socioeconomic challenges for mitigation and adaptation. Source: Sfdiversity (undated), CC BY-SA 4.0.

ScenarioMIP (O'Neill *et al.*, 2016) included a specific experiment aimed at looking at overshooting climate targets, SSP5-3.4OS. The SSP5-3.4OS scenario was a Tier 2 scenario produced with the REgional Model of Investment and Development – Model of Agricultural Production and its Impacts on the Environment (ReMIND-MagPIE) (Kriegler *et al.*, 2014). It follows the highest emissions scenario (SSP5-8.5) until 2040, after which it enforces a steep decline in greenhouse gas emissions; becoming negative after 2070. As with all IPCC scenarios, no temperature goal was specified for the overshoot period or the return period, instead a radiative forcing goal of 3.4 Wm^{-2} imbalance by 2100 was specified in this scenario.

To a first order, such a radiative forcing imbalance would roughly lead to 2-3 °C warming above the pre-industrial. Tebaldi *et al.* (2021) analysed the results of the SSP5-3.4OS experiment and concluded that "*a mild overshoot in temperature of a few decades around mid-century, as represented in SSP5-3.4OS, does not affect the end outcome of temperature and precipitation changes by 2100, which return to the same levels as those reached by the gradually increasing SSP4-3.4 (not erasing the possibility, however, that other aspects of the system may not be as easily reversible).*" But this pathway was deemed to result in an end-century warming that does not meet the goals of the Paris agreement, with models simulating 2.5–3 °C warming above the pre-industrial, so was not considered in this study.

3.2 Evaluation of the suitability of the UK Earth System Model

As the IPCC and many others (e.g. Nijsse *et al.*, 2020) have identified, there is a fairly linear relationship between the cumulative CO_2 emission and surface temperature increase since pre-industrial times (Figure 3). This means, to a first order, that the greater the cumulative CO_2 emissions, the greater the total warming will be. The gradient is roughly determined by the Equilibrium Climate Sensitivity (ECS), which is defined as the change in the global surface temperature when atmospheric carbon dioxide (CO_2) levels are instantaneously doubled and a new stable temperature is reached. The ECS is arguably the most fundamental "bulk" parameter that describes how the climate system will alter in response to raised atmospheric greenhouse gas concentrations.

UKESM has a high Effective Climate Sensitivity (EffCS; a very similar metric to the ECS – and hereafter referred to as ECS – but calculated before the model reaches equilibrium, which can take millennia) of 5.4 °C compared to observational constraints and other models. Sherwood *et al.* (2020) conclude that the range of ECS in models and observations is 2.0–5.7 °C, so UKESM approaches the highest estimates. However, UKESM, in common with all CMIP6 models, exhibits a very predictable (linear) relationship between ECS and the Transient Climate Response (TCR) (Figure 4). The fact that UKESM is on the line of best fit in Figure 4 suggests that UKESM is not an outlier model and is an appropriate model for this work.

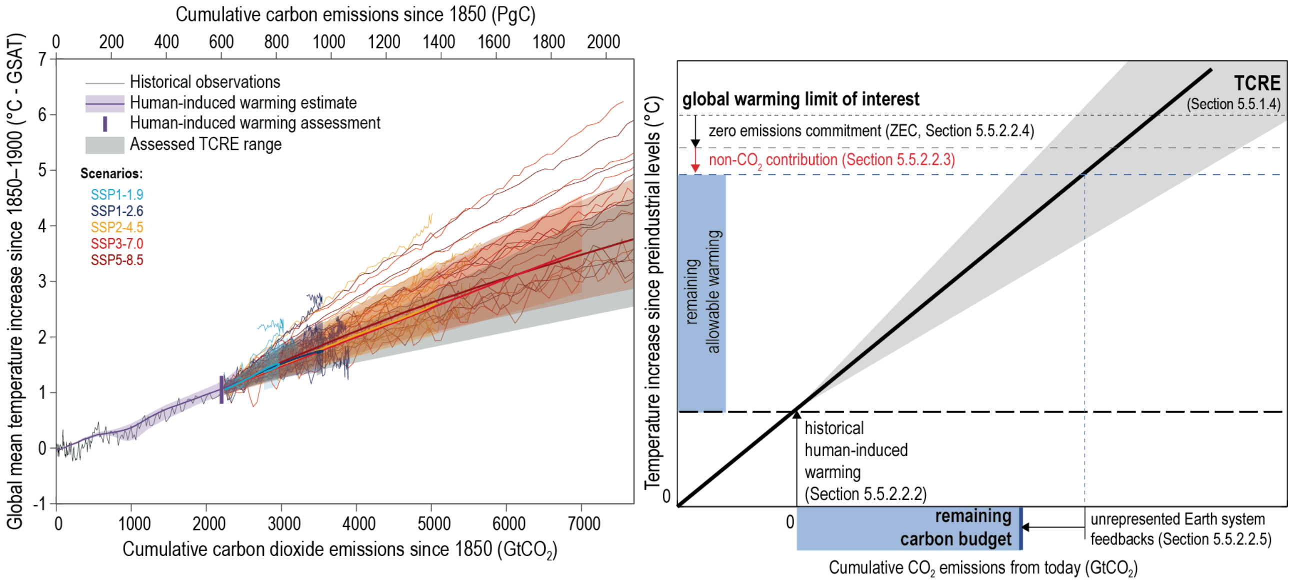

Figure 3. Near linear relationship between cumulative CO_2 emissions and global warming levels defined by the transient climate response to emissions (TCR[E]). Taken from Figure 5.31 in IPCC (2021c) and modified by the authors.

As the TIAM-UCL pathways were developed with an ECS of 3 °C, the higher climate sensitivity of UKESM means that it would produce a much higher temperature rise than the 2°C required of the overshoot scenario if the TIAM-UCL CO_2 concentrations for each pathway were used in UKESM. In addition, the UKESM model would be much higher than 1.5°C in 2100. Instead, the TIAM-UCL CO_2 concentrations were reduced so the UKESM global surface temperature time series would be similar to the TIAM-UCL temperature time series, using the method described in Section 4.

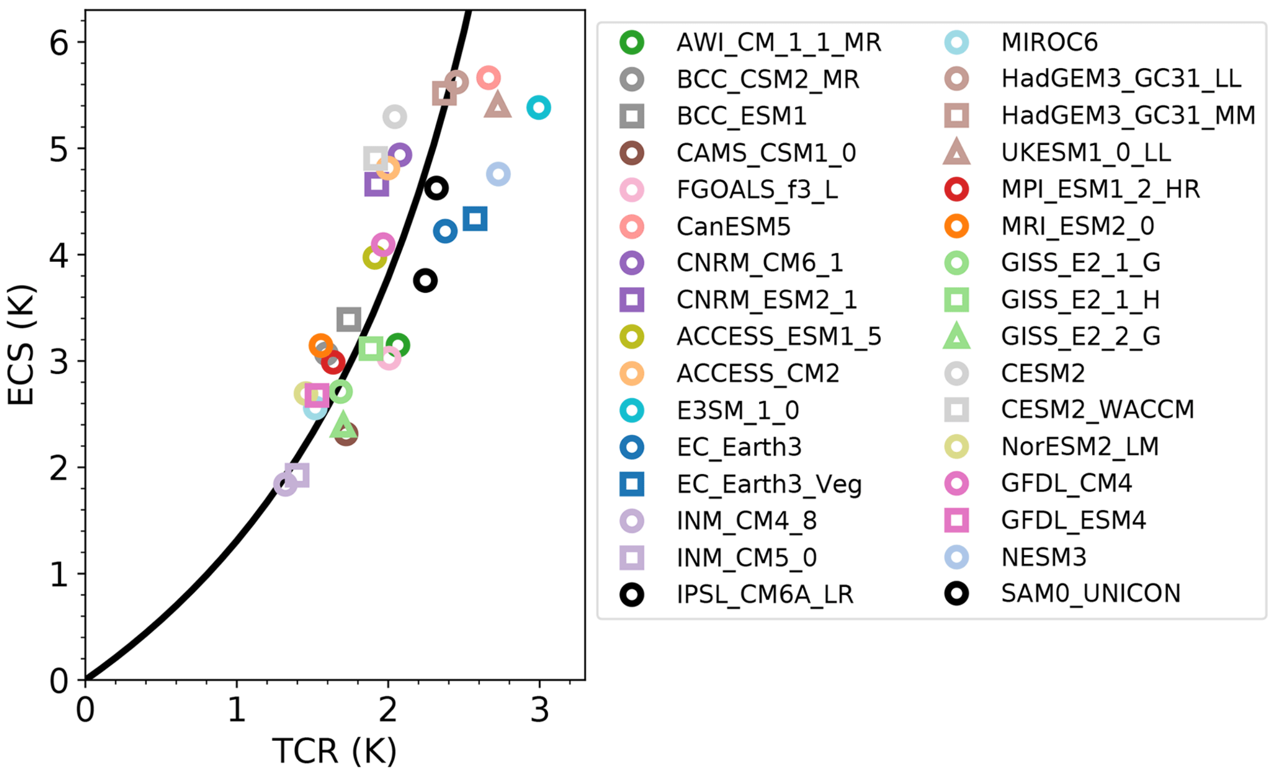

Figure 4. Relationship between TCR and ECS across all CMIP6 models, showing that UKESM (peach triangle) fits within the multi-model spread. Source: Nijsse *et al.* (2020), Figure 2, CC BY 4.0.

This choice was based on the assumption that most natural system impacts are driven by temperature rather than by CO_2 concentration. But by simulating lower CO_2 concentration, some natural system processes that depend on CO_2 concentration are affected. These include ocean acidification and growth of vegetation, and hence the terrestrial carbon cycle response, which are simulated using the MEDUSA and TRIFFED models respectively. The simulated terrestrial carbon cycle will have been most affected as simulated growth in plants with the C3 photosynthetic pathway, which includes ~90% of all plants (Gifford and Evans, 1981), will be slower in the pathways modelled in this study than if the plants had been exposed to the original higher CO_2 concentrations from TIAM-UCL.[6] The exact changes are

[6] Only unstressed plants (i.e. those in environments with suitable temperatures and sufficient water) would grow more. Grasses, including most cereal food crops, have a more efficient C4 photosynthetic pathway and do not benefit from CO_2 fertilisation so would not be affected by artificially low CO_2 concentrations.

not trivial to describe and will also be affected by the magnitude of the overshoot pathway. The judgement of the UKESM modelling experts we consulted was that these would have second-order impact and would not substantively affect the climate responses to changing temperatures.

4. Method to represent pathways in UKESM

This section discusses the method used to represent the VHO and NO pathways in UKESM and the challenges in dealing with the high UKESM climate sensitivity when constructing these pathways (Section 4.1), the challenges representing the short-lived climate pollutants that were not simulated by TIAM-UCL (Section 4.1), as well as giving an overview of how the UKESM model output data were analysed (Section 4.3).

The pathways were developed in the TIAM-UCL integrated assessment model. TIAM-UCL contains a detailed energy system model coupled to a climate module that is calibrated to the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) climate emulator (Meinshausen *et al.*, 2020). In Annex 1, it was calibrated to the IPCC AR6 ECS of 3 °C. As the UKESM ECS is much higher at 5.4 °C, the greenhouse gas concentrations calculated by TIAM-UCL could not be used directly in UKESM as the temperature increase would be much too high and the global temperature would not return to 1.5 °C, as shown in Figure 5. This raises a methodological challenge about how the IPCC AR6 median ECS can be represented in UKESM, which has a much higher ECS, to enable a coherent modelling analysis with TIAM-UCL and UKESM. Two options were considered:

1. Artificially reducing the CO_2 concentration produced from TIAM-UCL and hence the emissions budget in UKESM to achieve approximately the same temperature rise as for the IPCC AR6 central ECS in UKESM.
2. Using the TIAM-UCL CO_2 concentrations produced using the IPCC AR6 median ECS in UKESM and then reduce the resulting earth system impacts to mimic a lower GHG concentration.

There are several drawbacks to this second option. First, the principal aim of using the UKESM is to identify potential hysteresis in the earth system that cause the sustained higher impacts than would occur if the global temperature rise were limited to 1.5 °C. With a temperature rise to 3 °C, other mechanisms causing hysteresis might affect the impacts that would not be important in a rise to 1.9 °C, so the impacts of hysteresis might be overestimated. Second, Figure 5 shows that this VHO pathway (dashed black line) does not overshoot but reaches a plateau with a temperature rise of 2.5 °C, so the impacts would not represent the required overshoot pathway. Third, this option is conceptually challenging and difficult to implement in practice. For these reasons, the first option was chosen, accepting the drawbacks listed in Section 3.2.

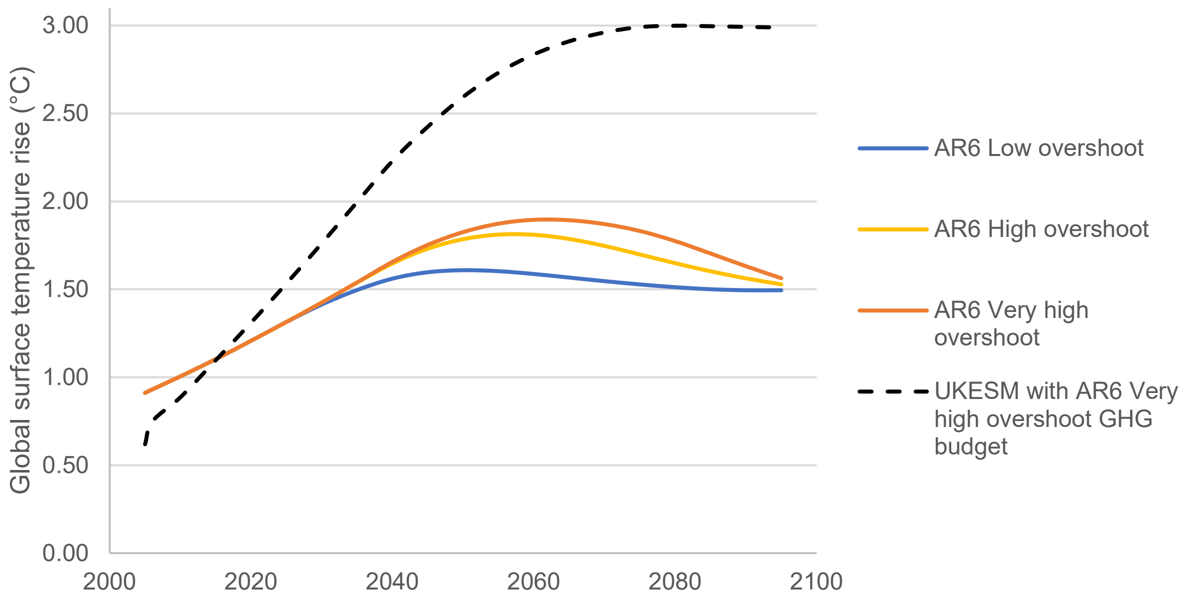

Figure 5. Comparison of AR6 and UKESM temperature profiles for the three overshoot pathways developed in Annex 1. In each AR6 case, the temperature is constrained to not exceed 1.5 °C in 2100. The black dashed line shows the implications of using the AR6 VHO CO_2 concentrations with the UKESM climate sensitivity (ECS of 5.4 °C instead of 3 °C). All temperature pathways were produced using the TIAM-UCL integrated assessment model.

4.1 Method to reproduce AR6 climate sensitivity in UKESM

As the climate module of TIAM-UCL can be calibrated for different climate sensitivities, the chosen method was to calibrate TIAM-UCL to the UKESM climate sensitivity. This was achieved by creating the same temperature profile in TIAM-UCL for IPCC AR6 central and UKESM climate sensitivities, then using the lower UKESM carbon budget in the UKESM pathway. For each pathway, the process was:

1. Analyse the pathways using the IPCC AR6 central ECS in TIAM-UCL. Calibration of the TIAM-UCL climate module is discussed in Annex 1.
2. Produce pathways with the same overshoot temperature curve in TIAM-UCL (using model constraints on temperature), using the UKESM climate sensitivity.
3. Use the GHG atmospheric concentrations from the TIAM-UCL pathway with UKESM climate sensitivity to drive the UKESM overshoot pathway analysis. The global concentrations of CO_2, CH_4 and N_2O from the TIAM-UCL pathway were prepared on annual time steps for UKESM.

The TIAM-UCL representations of three Representative Concentration Pathways (RCPs)[7] calibrated to the IPCC AR6 and UKESM climate sensitivities, are compared with outputs from the CMIP6 experiments in Figure 6. There is very close agreement with the RCP1.9 and RCP2.6 pathways for both the IPCC AR6 and UKESM sensitivities, but poorer agreement for RCP4.5 after 2050.

This is not an exact science. A number of attempts were needed to produce a similar pathway to the TIAM-UCL VHO pathway, each requiring around three months run time.

[7] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. The RCP number refers to the radiative forcing (the change in energy flux in the atmosphere) due to pollution, in units W/m^2.

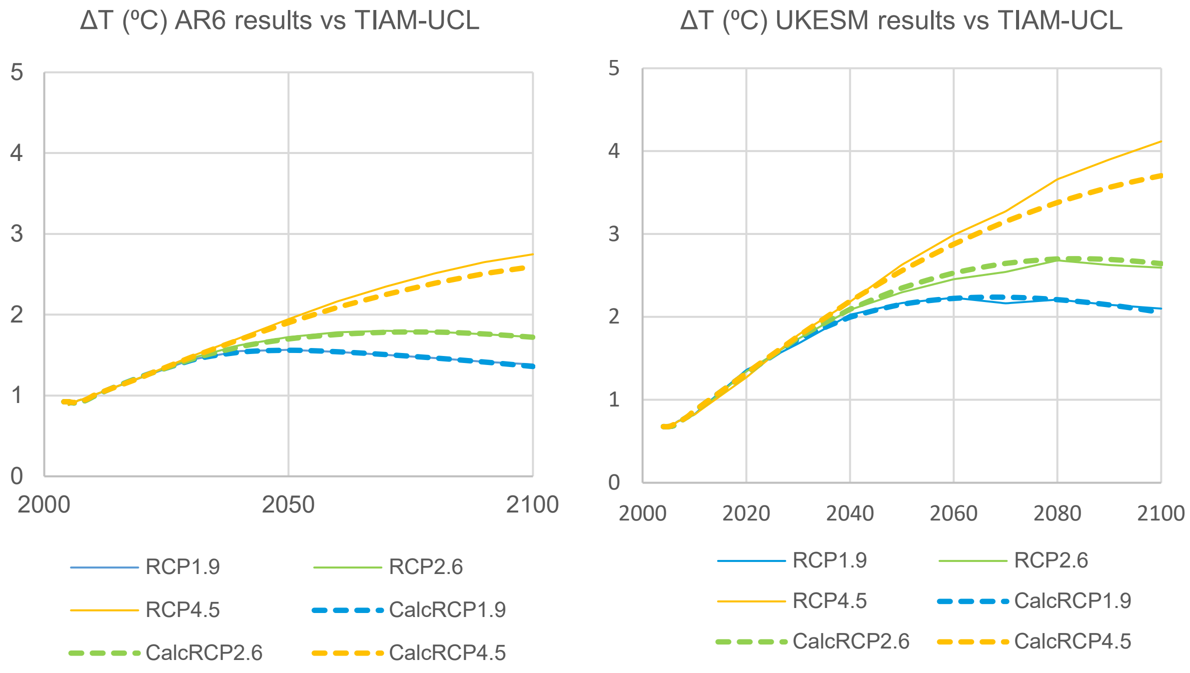

Figure 6. Comparison of TIAM-UCL global surface temperature rise calibration with IPCC AR6 and UKESM calibrations. The IPCC ECS calibration is shown on the left graph and the UKESM ECS calibration on the right graph. The dashed lines are the simulations from TIAM-UCL the solid lines are GSMT profiles created with the IPCC AR6 central climate sensitivity (left panel) or extracted from UKESM respective RCP ensemble mean (right panel).

4.2 Representing SLCPs in the UKESM

Short-lived climate pollutants (SLCPs) such as aerosols have a substantial impact on climate, as highlighted by Figure 7, and are possible explanations for at least some of the discrepancies in climate sensitivity between models (Meehl *et al.*, 2020).[8] For the precursors involved in the chemistry and the microphysics in UKESM (NO_x, SO_2, Volatile Organic Compounds, black carbon), emission datasets have already been produced for UKESM for the CMIP6 analysis (i.e. SSP1-1.9, SSP1-2.6, SSP2-4.5 and SSP3-7.0). As creating future gridded projections of aerosol emissions is challenging, time-consuming and outside the scope of this study, it was necessary to use these datasets in our analysis. The challenge was that none of these datasets were created for overshoot pathways, and that the two

[8] Methane is technically an SLCP but is modelled directly by TIAM-UCL and UKESM so is not treated an SLCP in this report.

datasets with the lowest emissions are for SSP1 rather than for the SSP2 pathways used in this study.

SO_2 is produced primarily from coal power stations so will reduce as the global power sector is decarbonised in the future. NO_x, volatile organic compounds and carbon monoxide will reduce as road vehicles move to electric powertrains. Black carbon will reduce as traditional stoves are replaced by modern stoves in less developed areas.

SO_2 has the greatest impact on temperature, with Figure 7 showing a contribution to cooling of 0.5 °C since pre-industrial times. The uncertainty in the cooling from SO_2 comes about from two aspects: (i) unlike CO_2 and CH_4, which are preserved in ice cores, the pre-industrial baseline conditions for SO_2 are not known; and, (ii) the effect of SO_2 emissions on radiative forcing is largely through the role of SO_2 in modifying cloud properties. This itself is uncertain and models produce varying results. Figure 8 shows projections of global SO_2 emissions from two integrated assessment models for a range of SSPs and RCPs. It is clear that SO_2 reductions over the century are: (i) related primarily to RCP (i.e. the rate of decarbonisation) rather than SSP; and, (ii) model-dependent, particularly for RCP4.5. It was therefore appropriate to choose an SLCP emission dataset based on the rate of decarbonisation in the overshoot pathways.

For the NO pathway, the most appropriate SLCP dataset was clearly SSP1-1.9, as this was the only pathway consistent with a low or no overshoot pathway in which fossil fuel emissions were reduced rapidly. The VHO pathway presented a more difficult decision. Figure 9 shows the SO_2 emission profiles for the CMIP6 pathways, with coal and oil electricity generation for the NO and VHO pathways superimposed on top as a proxy for SO_2 emissions. In both pathways, coal and oil generation reduce to a low level by 2055, and the only CMIP6 pathways with this behaviour are SSP1-19, SSP1-26 and SSP5-34OS. Initially, we ran the VHO pathway with SSP1-26 SLCP emissions. However, when comparing this test simulation with the NO pathway (using SSP1-19) we found that the increased aerosol emissions in SSP1-26 (driven largely by an increased use of coal) led to cooling compared to the NO pathway. Therefore, we opted to use consistent SLCP emissions in the NO and VHO pathways from the SSP1-19 database.

A disadvantage of using SSP1 or SSP5 is that both assume much lower population growth than SSP2, particularly in Africa. This means that African SLCP emissions, particularly black carbon, will be underestimated. The impact on total SO_2 emissions will be small, as is shown in Figure 9 where almost all scenarios agree on the global SO_2 emissions trends.

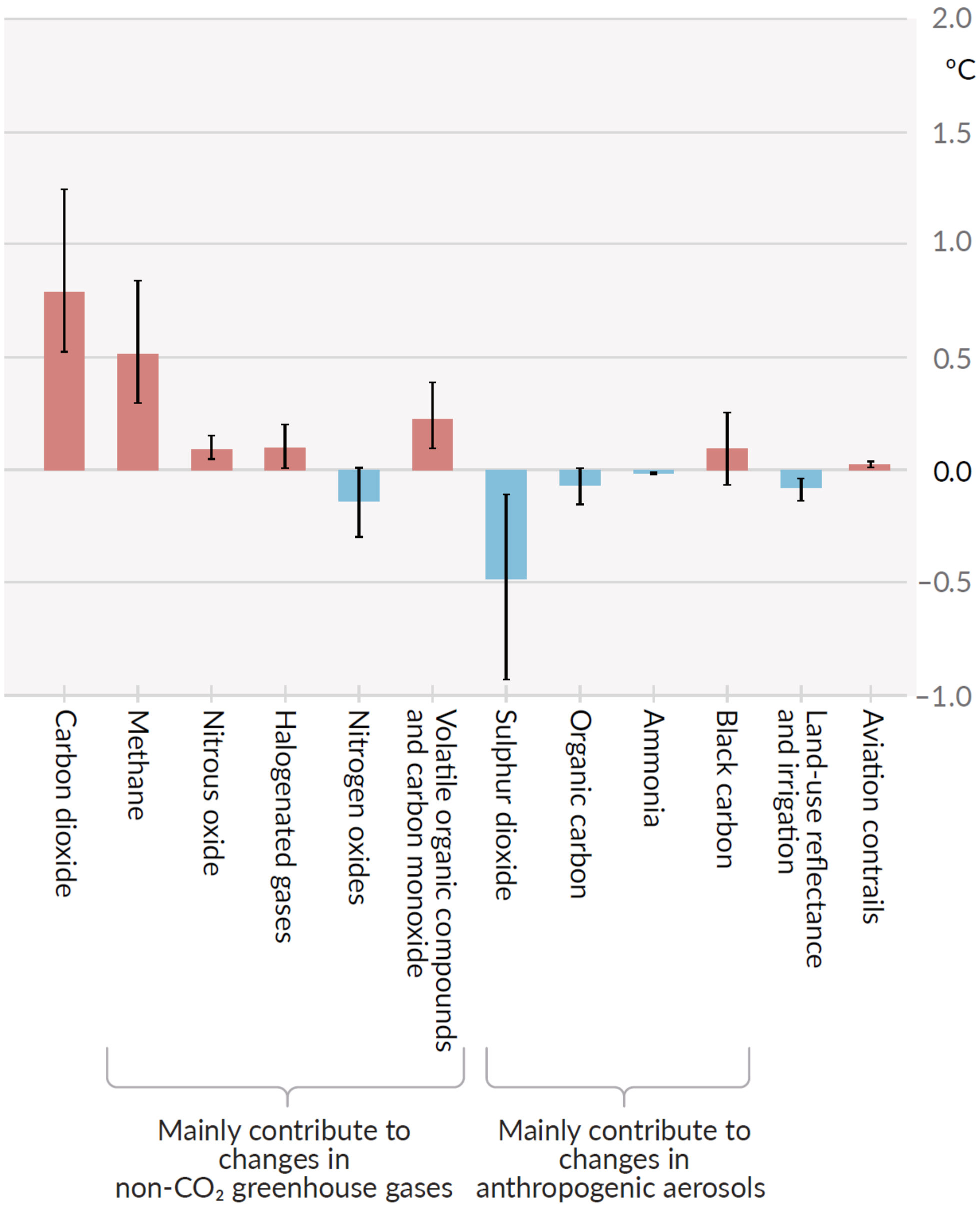

Figure 7. Contributions to 2010–2019 warming relative to 1850–1900, assessed from radiative forcing studies. Source: Figure SPM.2 Panel (c) IPCC (2021d).

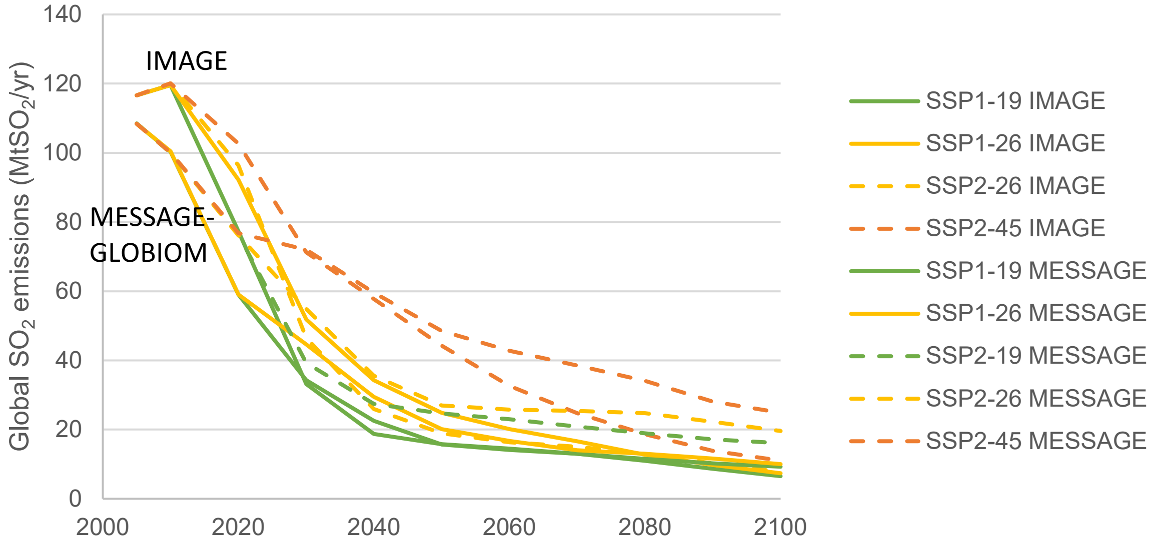

Figure 8. Global SO_2 emission projections for a range of CMIP6 pathways from the Integrated Model to Assess the Global Environment (IMAGE) and Model for Energy Supply Strategy Alternatives and their General Environmental Impact-GLobal BIOsphere Management (MESSAGE-GLOBIOM) integrated assessment models. SSP1 pathways have solid lines and SSP2 pathways dashed lines. The colours differentiate between RCP1.9 (green), RCP2.6 (yellow) and RCP4.5 (orange). Adapted from Riahi *et al.* (2017), CC BY 4.0.

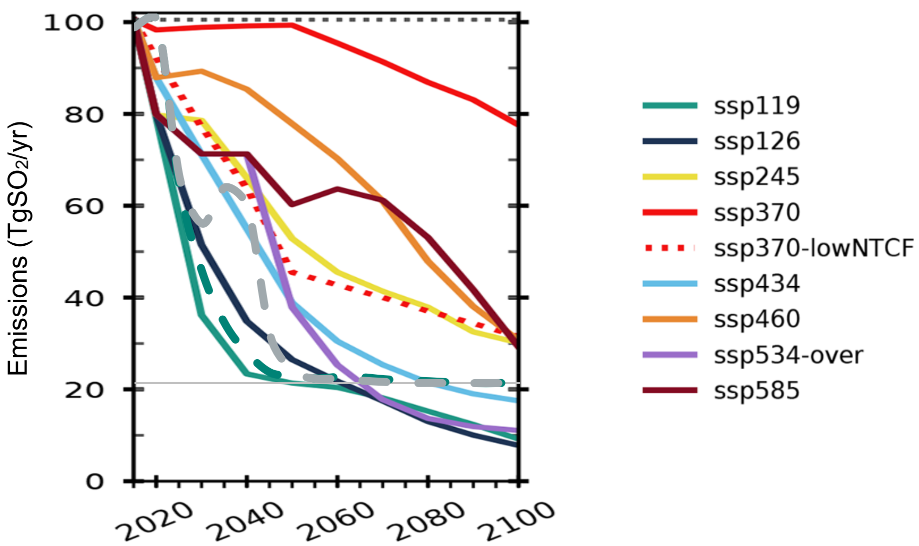

Figure 9. SO_2 emission profiles for the CMIP6 pathways compared against coal and oil electricity generation from the NO and VHO pathways. SO_2 emissions ($TgSO_2$/yr) are from Turnock *et al.* (2020), and superimposed dashed lines are coal and oil electricity generation (arbitrary scale), CC by 4.0.

Figure 10 below shows that following the calibration of TIAM-UCL to the UKESM ECS discussed in Section 4.1, there is good agreement between the UKESM and TIAM-UCL versions of each pathway for the change in the global mean surface temperature (GMST) anomaly since pre-industrial times.

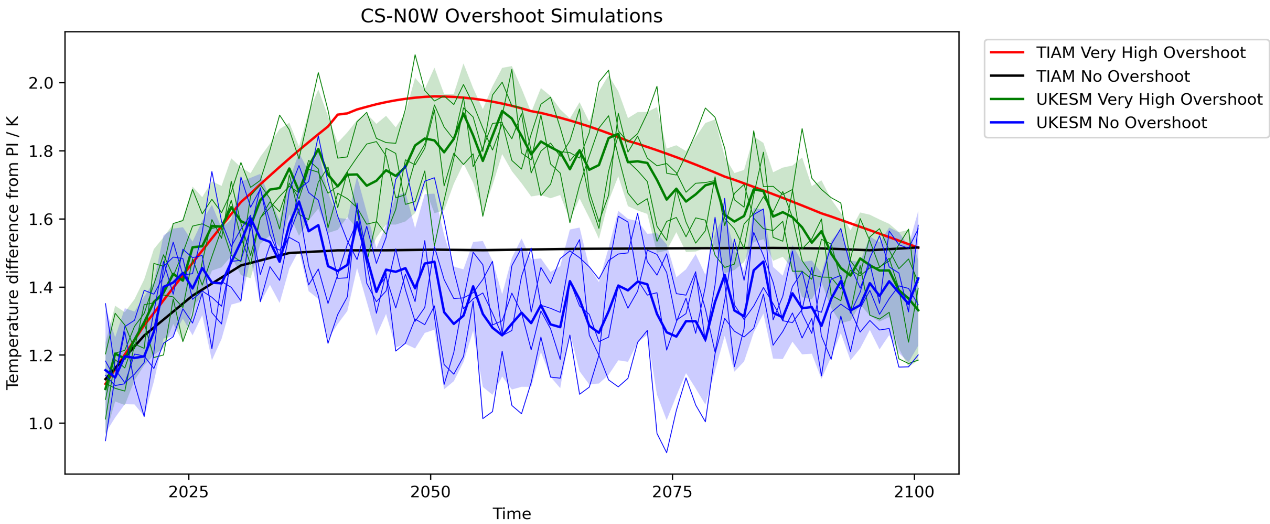

Figure 10. GMST anomaly simulated by the UKESM and TIAM-UCL models using the UKESM ECS.

4.3 Pathway analyses

Four versions of the VHO and NO pathways were produced to account for natural variability – these four “members” together comprise an “ensemble”. Each ensemble member was started with a slightly different initial value of atmospheric, oceanic and land surface conditions (e.g. temperature, winds, soil moisture). Twelve unique UKESM simulations of the historical climate evolution from 1850–2014 have been created in the past by starting each simulation with a slightly different set of initial conditions in 1850. In effect, this means that there are 12 different “realisations” of the weather for the 31 December 2014 that we can use as the starting conditions for our model runs. Using exactly the same emissions and CO_2 concentrations with these different initial conditions leads to different “random” climate trajectories that enable a calculation of the internal variability. This calculation of internal variability is distinct from a representation of natural variability as it is calculated using model data rather than real-world data. However, model internal variability is commonly thought of as being synonymous with natural variability. This calculation of internal variability is very important as the climate system exhibits significant amounts of internal variability that mean that the detection of robust climate signals require large ensembles with typically 10–50 members. Each ensemble member of UKESM evolves with its own “random” climate noise – similar to the noise we experience in day-to-day weather. Owing to the coupled nature of the Earth system, this modelled variability can cascade through multiple components of the Earth system and lead to longer time-scale (e.g. decadal) differences between ensemble members. This key feature of the weather-climate system is why all weather forecasts are probabilistic (we are offered the likelihood of a weather event). Climate is considered the average over time of weather and the common practice in the climate modelling community is to run ensembles of simulations and analyse the mean response.

As the HPC cost of running the simulations are so high (Section 3), each pathway ensemble was limited to 4 members. To increase the statistical significance of some of the results presented in this annex, it would be desirable to run a further 6-8 ensemble members. However, even with only 4 ensemble members, some clear, statistically significant results are simulated and discussed in this report.

As hysteresis is of interest, an analysis for the years 2091–2100 is presented when hysteresis is likely to be most pronounced. In each case, the VHO pathway is compared with the NO counterfactual pathway. In both pathways, the increase in temperature compared to the preindustrial baseline is just below 1.5 °C in 2100, compared to around 1.2 °C today, so the modelled climate will be different to today.

5. Global surface temperature impacts

We begin with an analysis of surface temperature differences between the VHO and NO pathways averaged over the periods 2056–2065 (hereafter denoted mid-century), and 2090–2100 (hereafter denoted end-century).

Although the GMST of the VHO returns to a mean climate target that is in agreement with the NO pathway (Figure 10), Figure 11 demonstrates that there are significant regional differences at the end of the century. Based on the definition of hysteresis given in Section 2.1, we tentatively assign this as hysteresis in that the regional temperature field does not return to the same value as in the NO pathway at the end of the century. Yet these differences are unlikely to reflect true hysteresis in the climate system. Figure 10 shows that there is little time when the VHO and NO scenarios both simulate the 1.5°C target. Such little time means that there could still be a lag in the response of the Arctic Sea ice to the GMST in the VHO scenario coming back to the Paris target, and sea ice could converge in the two scenarios over the following decades.

During mid-century (Figure 11a) there are marked differences in surface temperature across wide regions of the globe. The VHO pathway results in 0.5–1.0 °C extra warming above the NO pathway over most land areas and even larger warming (2.5–4.5 °C) over the Arctic region.[9] Mid-century warming in the VHO pathway is also seen in the Antarctic but there are much lower levels of warming simulated in the Antarctic than the Arctic, and the warming is very localised to regions around the Antarctic peninsula. Figure 11b and Figure 11d show the striking levels of Arctic hysteresis in surface temperature at end-century following the VHO pathway. The increases in surface temperature compared to the NO pathway are similar to the increases seen at mid-century when the concentrations of GHGs are most divergent. Parts of the Kara Sea and Barents Sea continue to have levels of warming of up to 4.5 °C above the NO pathway by end-century. This effect of Arctic amplification (AA) of climate change is well documented and reviewed in the recent IPCC AR6 reports. Many General Circulation Model (GCM) simulations have revealed that AA is not a consequence of a larger radiative forcing of CO_2 at the poles than at lower latitudes, as one might imagine (Liang *et al.*, 2022). Counterintuitively, the radiative forcing is larger at the equator than the poles for increases in CO_2. Liang *et al.* (2022) have recently summarised the causes of AA as: "*local positive feedbacks, poleward heat and moisture transport, oceanic heat exchange mechanisms, and, possibly, complex interactions among these factors. While the seasonal evolution of AA is a complex phenomenon, involving multiple coupled mechanisms with different seasonal features, it is widely accepted that the sea-ice conditions—and the accompanying atmosphere-ocean heat exchange—are an important player. The amplified*

[9] K denotes Kelvin, a unit of temperature. A change of 1 K is the same as a change of 1 °C, but the scales have a different zero point as 0 K is at absolute zero and equivalent to -273.15 °C.

Arctic warming, ultimately caused by GHG increases, is thus closely tied to the seasonal evolution of sea ice. During Northern Hemisphere summer, sea-ice reduction allows absorbed solar radiation to warm the ocean mixed layer, a process enhanced by the sea-ice albedo feedback. Then, in the following autumn and winter, when the atmosphere rapidly cools, the enhanced air-sea thermal contrast results in stronger surface heat and moisture fluxes entering the atmosphere, and these produce stronger lower-tropospheric warming, enhanced by the sea-ice insulation effect and longwave feedback processes, which amplify the changes in surface temperature."

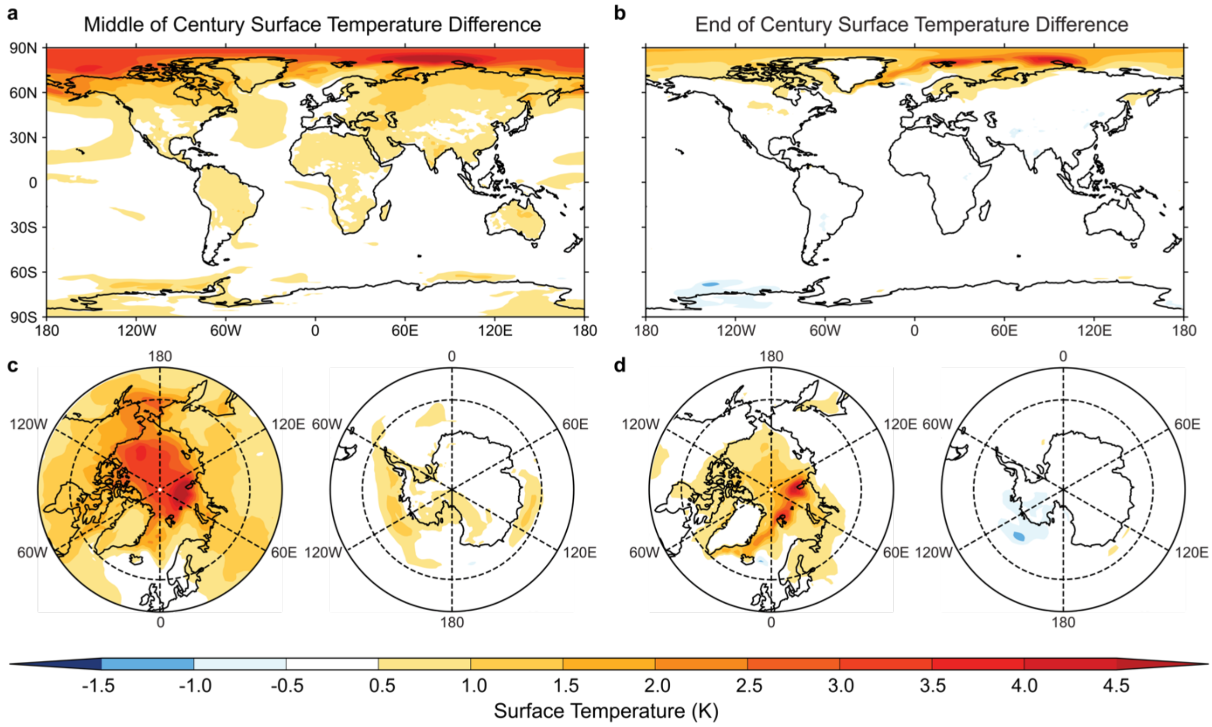

Figure 11. Comparisons of the surface temperature changes for the VHO-NO pathway at different time epochs (panels a and b). Panels c and d highlight polar changes for each epoch.

Figure 12 shows the seasonal changes in surface temperature focused over the Arctic for the two pathways during mid-century and end-century. Broadly speaking, the differences in temperature between the VHO and NO pathways are largest during mid-century winter seasons (DJF in the Northern Hemisphere). In this decade, when the change in the CO_2 concentration is highest and the GMST peaks (Figure 11a), warming extends across the Antarctic as well as the Arctic across all seasons (not shown). However, by end-century, when the GMST is the same in both pathways, the warming persists in the Arctic but the Antarctic displays very minor localised cooling around the peninsular in Autumn (March–May) through to Spring (September–November) (Figure 11d).

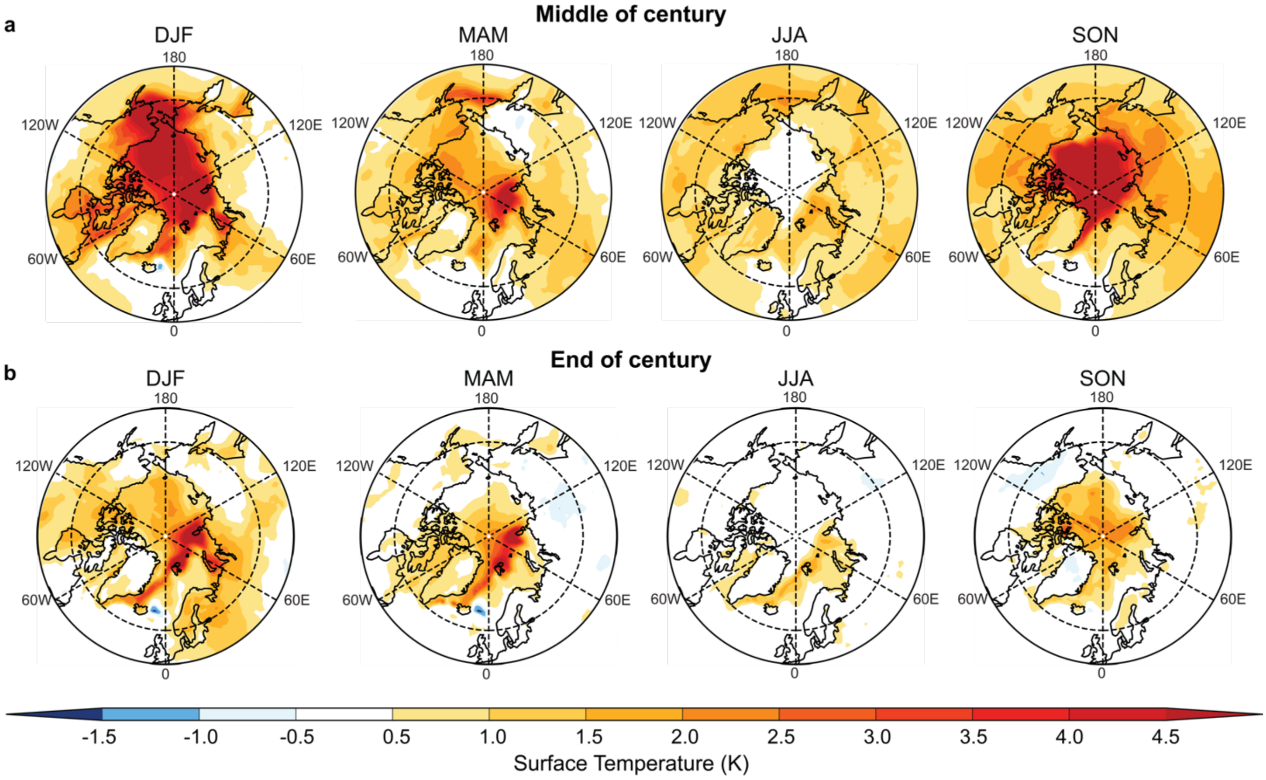

Figure 12. Seasonal comparisons of the Arctic surface temperature changes for the VHO-NO pathway at different time epochs (mid-century and end-century). Rows denote the different time epochs.

Antarctic surface cooling has been demonstrated over recent decades (1979–present). The mechanisms behind this observed trend of Antarctic cooling, which is not well simulated by GCMs, has been fiercely debated in the literature (e.g. Chung *et al.* (2022) for an overview and new perspectives). The scale of cooling in the Antarctic is much less significant than the warming that persists in the Arctic under the VHO. Section 6 examines the role of sea ice changes in driving these temperature changes in the poles.

Figure 13 contrasts with Figure 10 in showing the range of GMST simulated across the ensemble members run for this study compared with reference IPCC AR6 scenarios from UKESM (SSP1-1.9 and SSP2-4.5). Both Figure 10 and Figure 13 highlight that there is considerable interannual variability in the ensemble members relative to the changes in the ensemble mean. This is always going to be the case when the difference in two pathways is close to the natural year-to-year variability in the climate system. What is also clear is that there is no evidence that the interannual variability – defined here as the ensemble range – increases with time. This supports our approach of analysing ensemble means.

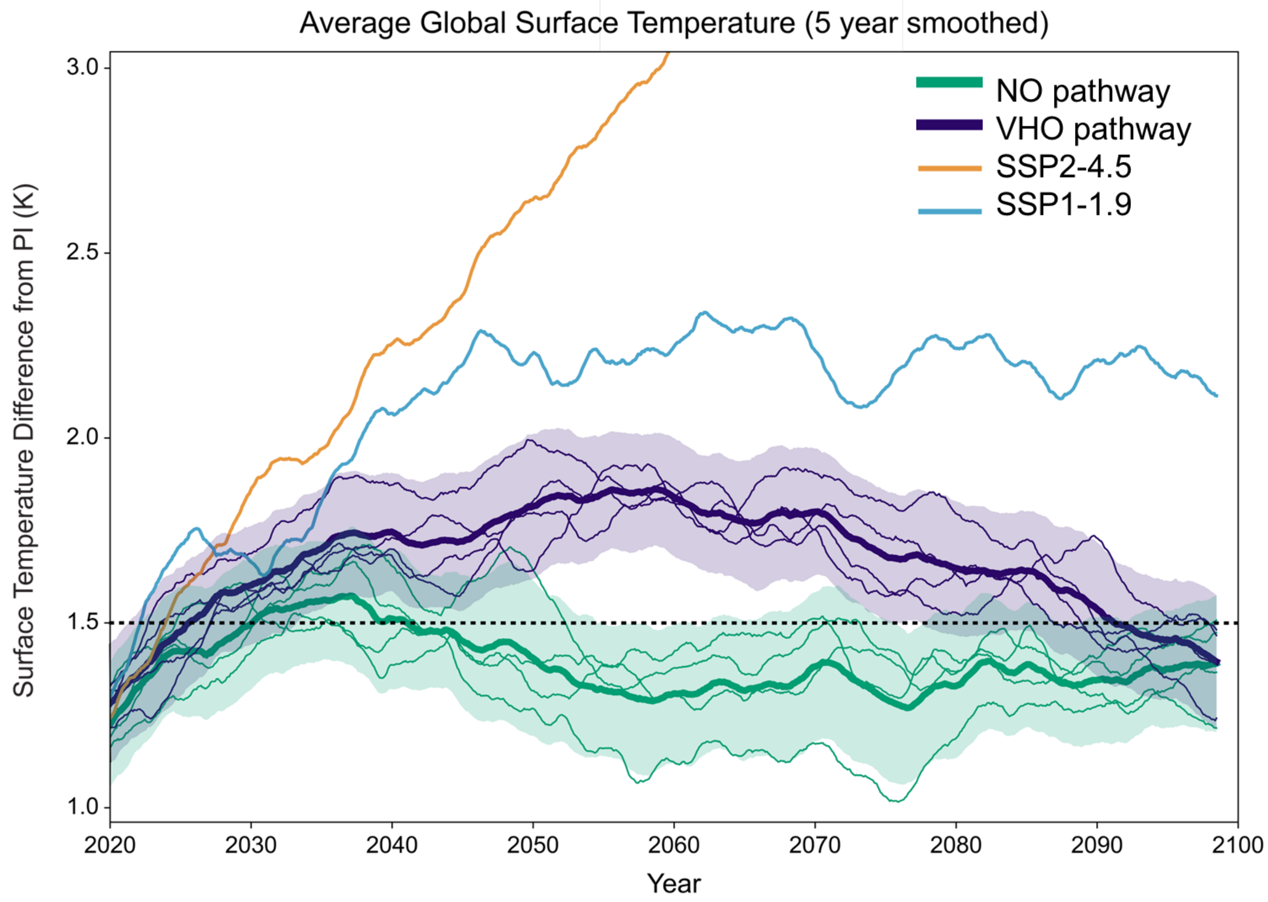

Figure 13. GMST timeseries for the two pathways (green and purple) compared with UKESM SSP1-1.9 (blue) and SSP2-4.5 (orange). Thin green and purple lines show the individual ensemble members for the NO pathway and VHO pathway, respectively. Thick green and purple lines show the ensemble mean results for the NO and VHO pathways respectively (i.e. the mean of the ensemble members).

6. Polar region impacts

Figure 14 displays a seasonal decomposition for sea ice changes between the VHO and NO pathways during mid-century (left-hand columns) and end-century (right-hand columns). By comparing Figure 12 and Figure 14, it is visually clear that there are many areas that exhibit a strong correlation between loss of polar sea ice and higher surface temperatures during mid-century. It is not clear whether the loss of sea ice would recover if the model had been run beyond 2100, so further work to extend the time length of the model simulations out to 2110 or 2120 to examine if there is significant hysteresis in Arctic Sea ice would be valuable. At present, we cannot conclude that the differences in Arctic Sea ice between VHO and NO at the end of the century reflect hysteresis or that there has been a tipping point that the Arctic Sea ice has crossed. The reduction in sea ice persists in the Arctic through to end-century, but by a smaller amount – potentially reflecting that even in the NO pathway there is sea ice loss compared to the present day, as the GMST increases from 1.2 °C to 1.5 °C. Interestingly, by end-century there is an expansion of sea ice around the Antarctic continent. This increase in Antarctic Sea ice correlates well with the decrease in surface temperature shown in Figure 12.

Figure 15 shows the timeseries of sea ice volume changes in the Arctic for the VHO and NO pathways using the same colour labelling as in Figure 13. As with Figure 13, the changes in Arctic Sea ice volume show large variability between ensemble members; however, clear patterns can be seen in the two pathways. Both pathways simulate much lower levels of sea ice volume loss than the SSP1-1.9 and SSP1-4.5 pathways. Figure 15 shows that there is a point in time, around 2030, when there is strong divergence in both surface temperature and sea ice volume in the Arctic between the VHO and NO pathways. This divergence occurs well before the peak difference in GMST (~2065) at a time when the GMST first crosses the 1.5 °C mark. We tentatively attribute this as a tipping point, but longer time period (out to 2120 or 2150) simulations would be required to be certain. This insight motivates clearly the need to limit global warming to below 1.5 ˚C to protect Arctic Sea ice volume.

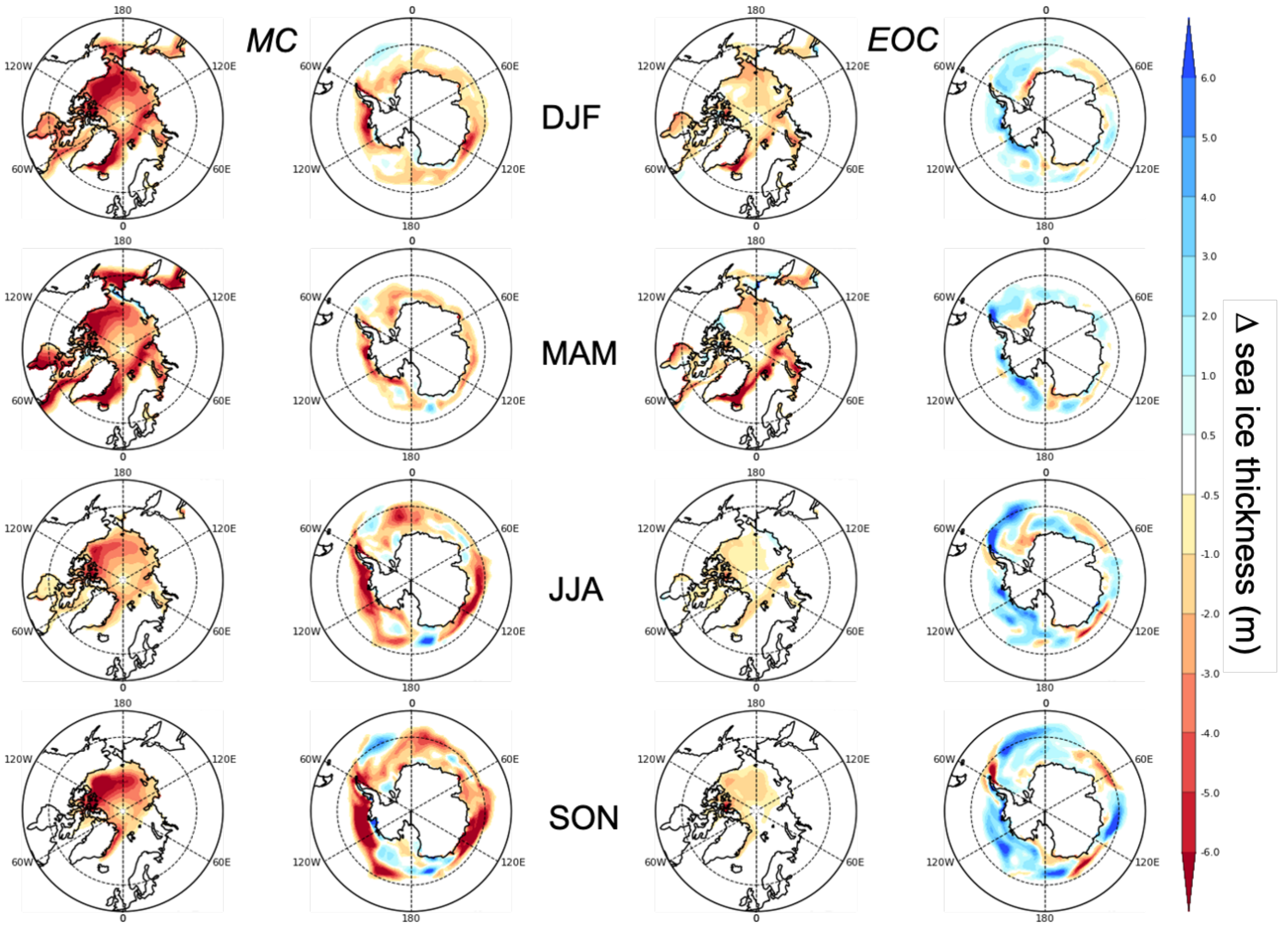

Figure 14. Seasonal differences in projections of sea ice thickness changes in the Arctic and Antarctic seas between the VHO and NO pathways at the mid-century (MC) and end-century (EOC) time epochs. Each row shows a different season, represented by the first letters of the months in the season.

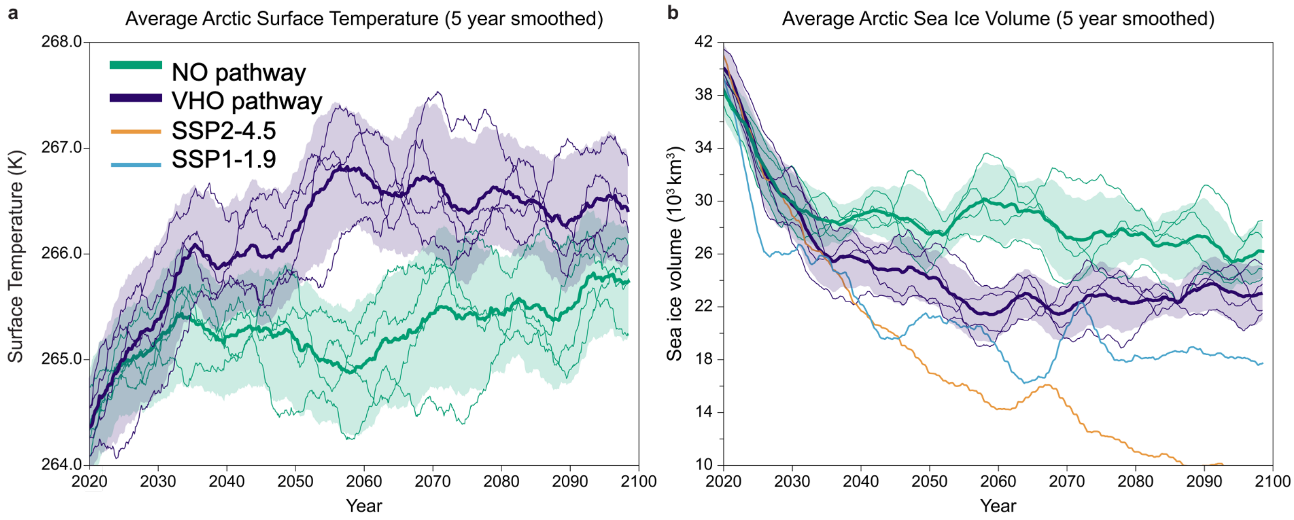

Figure 15. Timeseries of Arctic surface temperature and sea ice volume across the VHO and NO ensemble members. In addition, the CMIP6 UKESM1 results from the SSP2-4.5 and SSP1-1.9 pathways are shown in panel (b). The VHO and NO ensemble mean are shown as five-year averages in thick purple and green lines, respectively.

7. Oceanic impacts

The global 3-dimensional ocean model Nucleus for European Modelling of the Ocean" (NEMO) (Storkey *et al.*, 2018) was used to simulate changes in the physical ocean state under the VHO and NO pathways.

As Figure 11 shows, there is no robust signal of sea surface temperature differences between the VHO and NO pathways. This is expected as the changes in surface temperature simulated by the pathways are relatively small compared with the variability. Land tends to be more sensitive to climate change, so statistically-significant differences in surface temperature change are found over land rather than over oceans for these pathways.

Sea level change was not assessed in the UKESM scenarios as that requires a substantial off-model assessment. An assessment of overshooting on sea level rise is presented in Annex 5 on natural system impacts.

8. Precipitation impacts

The distribution of end-century precipitation (the sum of rainfall and snowfall) is shown in Figure 16a for the NO pathway. Broadly speaking, UKESM shows the precipitation patterns consistent with many CMIP6 models, and observations, with precipitation flux (measured in millimetres per day or mm d^{-1}) peaking in the tropics and lowest in the sub tropics and polar regions (Sellar *et al.*, 2019). Sellar *et al.* (2019) evaluated precipitation in UKESM against observations for the recent past and found an overall high bias in precipitation flux compared to satellite data of 1.5 mm d^{-1}, globally averaged. The largest biases in UKESM in the present day can be found in the South Asian region, where the model bias is ~8 mm d^{-1} in the Indian monsoon season (JJA). The VHO and NO pathways have large relative precipitation differences in the Sahel region of North Africa and the Indian subcontinent (Figure 16b to Figure 16f). These insights should be treated with caution as Figure 16a shows that these regions receive very little rainfall in total, so small absolute changes will manifest as large percentage changes.

Figure 16b indicates that several large regions could have differences in total precipitation of ±20%, including the South Atlantic Ocean, the Eastern Pacific, the Sahel and the Indian subcontinent. Although these changes are large, none have been calculated as being statistically-significant – in other words, the ensemble spread is larger than the difference in the ensemble means between the VHO and NO pathways. This finding is not uncommon when looking at precipitation in ESMs. To determine statistically significant signals, either a much larger forcing/emissions change would be required (elevating temperature far beyond 2 °C) or a much larger ensemble size would be required. Similarly, statistically significant changes in extreme precipitation events cannot be calculated using only four members as these events are by their nature rare. Dedicated experiments have been performed with ensemble sizes of 40+ members to detect these changes with ESMs, but this was not feasible within this study. Recent work has shown that Machine Learning may provide a route to enable the extraction of statistically significant signals in extreme events from climate models without having to simulate large ensemble sizes (Jose *et al.*, 2022).

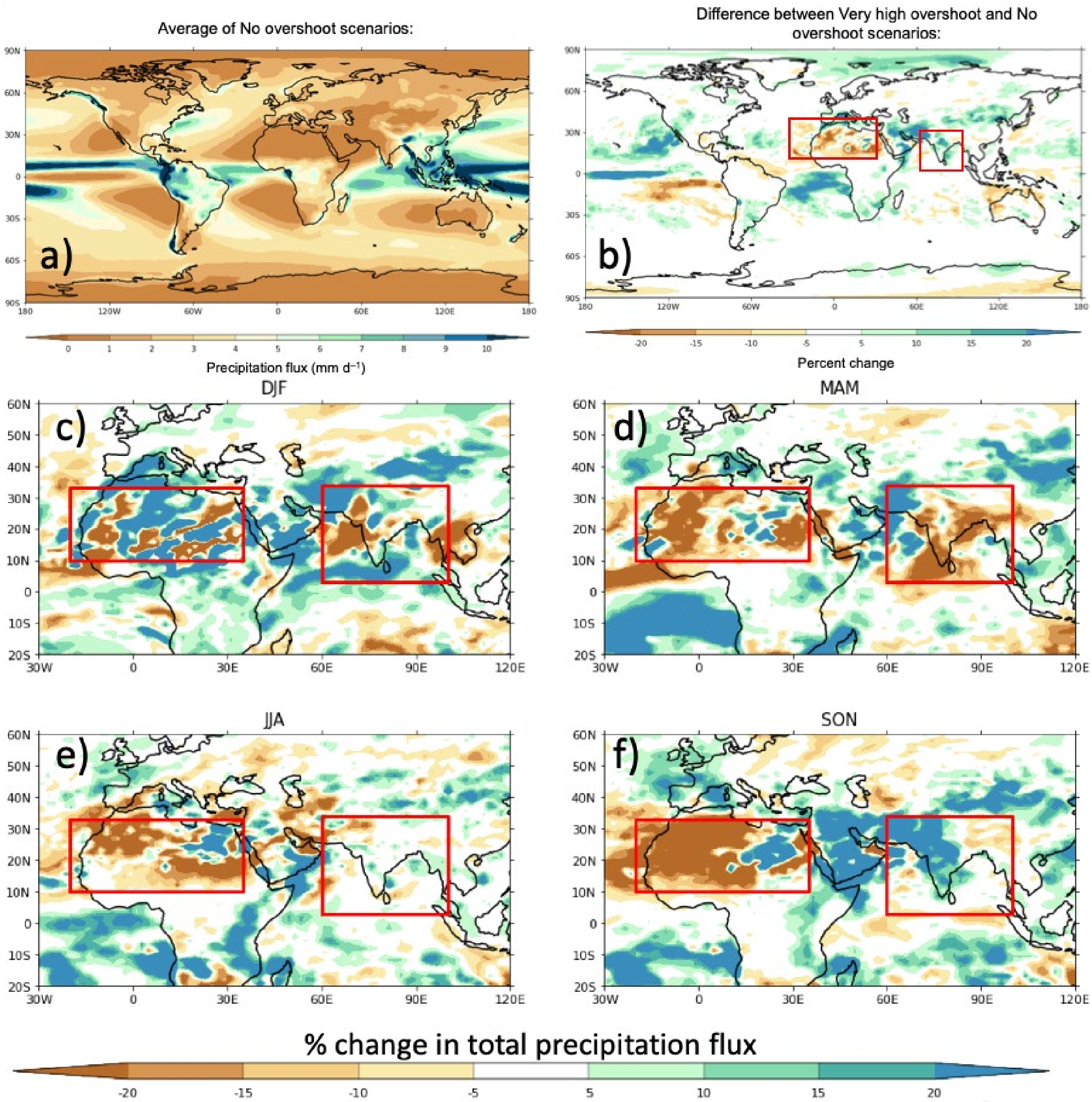

Figure 16. Total precipitation at end-century. Panel (a) shows annual mean precipitation flux (mm d^{-1}) in the NO runs. Panel (b) shows the difference (%) between VHO and NO pathways. Panels (c) to (f) show the seasonal decomposition of the annual mean changes shown in Panel (b).

Mid-century changes in precipitation are also not statistically significant so have been omitted from the analyses presented here. A further note of caution with the interpretation of precipitation fields in simulations with ESMs is that precipitation tends to be affected by both changes in temperature (thermodynamics) and changes in aerosols (cloud microphysics) (Samset *et al.*, 2016). Regional precipitation changes are also heavily impacted by changes in circulation features (e.g. dynamical) (Liu *et al.*, 2018). Changes in aerosols have been interactively simulated in both the VHO and NO pathways using the SSP1-1.9 aerosol precursor emissions inventory, as discussed in Section 4.1. As displayed in Figure 9, this inventory leads to the lowest simulated SO_2 emissions of the SSP-RCP database used in CMIP6 and these are not consistent with the SO_2 emissions that would be generated from an energy-economy-climate model (such as TIAM-UCL) when modelling the VHO and NO pathways. As such, we add a caution to not over emphasise the precipitation response from these simulations as our confidence in the insights is low.

As a result of the lack of statistical significance in the precipitation insights, it is not possible to determine if there is any hysteresis in precipitation from following the VHO pathway. However, based on the lack of significant changes, we can be fairly confident that if further ensemble members were included and statistically significant signals were to be found, they would not be large. The area that undergoes the most significant temperature change, the Arctic, is a region of very low precipitation flux (Figure 16) and so even large fractional changes in precipitation in this region would not lead to large absolute changes.

9. Conclusions

This study has assessed the potential physical climate system response to a VHO pathway compared to a NO pathway using the UK Earth System Model, using scenario data from the TIAM-UCL energy system model. As the UKESM has a high Equilibrium Climate Sensitivity (ECS), the CO_2 concentrations from TIAM-UCL model had to be significantly modified to reproduce a similar temperature curve in UKESM. This means that the pathways modelled in UKESM had lower CO_2 levels than would be expected based on using a CMIP6 mean ECS. However, through a trial-and-error approach, it enabled UKESM to simulate the two pathways.

The VHO pathway itself is novel and allows for the first time an assessment of a short-term failure to meet the goals of the Paris agreement. Tebaldi *et al.* (2021) reviewed the SSP5-3.4OS, which used the SSP5-8.5 counterfactual. Their analysis didn't examine regional changes and so this work is the first analysis (to the authors' knowledge) to assess this aspect.

Within the constraints of our modelling (i.e. the uncertainty in emissions scenarios and inherent model uncertainties) we have shown that by the end of this century, it is possible to overshoot to 1.9 °C and return to the 1.5 °C set out in the Paris Agreement at the global mean level. By end-century, it is possible to have a small climate overshoot and still get back to a specified climate target (in our case the 1.5 °C Paris target) at the global mean level. However, by crossing 1.5 °C, we may reach an apparent tipping point in Arctic Sea ice that does not recover by end-century. This result is robust across the range of ensemble members. However, this apparent tipping point may not be irreversible and is not necessarily a robust sign of hysteresis. If the model simulations performed here were continued beyond 2100, it is very likely, based on the trends in simulated sea ice and surface temperature, that the VHO and NO pathways would re-converge.

This study used the concentration-driven version of UKESM. Future work in this area using UKESM in CO_2 and CH_4 emission mode would allow the natural sources and sinks of CO_2 and CH_4 to respond and influence the atmospheric concentrations. This could lead to non-symmetric responses in both land and marine carbon uptake and in vegetation.

There are further climate impacts that show interesting differences but require more ensemble members to determine. These include:

- Changes in extreme temperature: the limited number of ensemble members prohibited an in-depth analysis of these changes. A larger ensemble size would allow important questions on the impacts of an overshoot on the likelihood of extremes to be answered and should be followed up with future work.
- Changes in precipitation: although differences in precipitation between the VHO and NO pathways were identified, these changes were not statistically significant (unlike the temperature and sea ice changes). They suggest there could be some regional impacts of small climate overshoots, but a larger ensemble size of simulations, or the use of new advanced machine learning techniques, would be required to determine their significance.

- Sea level rise and coastal risks: the relatively modest overshoot meant that there were no significant changes in sea surface temperature between the two pathways. Further work incorporating a more complete representation of glaciers into the UKESM model setup would be beneficial to determine if this missing component would lead to more significant changes in sea surface height and, as a result, coastal risks from storm surges.

This study presents a novel climate overshoot pathway that in many respects further underscores the extensive literature on the sensitivity of the Arctic region to climate change. Further work, beyond increasing the ensemble size of the UKESM simulations, should target the drivers of the Arctic amplification in UKESM and the role of important climate feedbacks in establishing and maintaining the hysteresis seen in this region.

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Quality assurance

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