Safe Landing Climates Meeting 2023

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with support from *Narelle van der Wel* (WCRP Secretariat)

The Safe Landing Climates Lighthouse Activity is an exploration of the routes to "safe landing" spaces for human and natural systems. It will explore future pathways that avoid dangerous climate change while at the same time contributing to the United Nations Sustainable Development Goals (SDGs).

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Executive Summary

The Safe Landing Climates (SLC) Meeting 2023 took place in London on 7 - 9 March 2023. The aim of the meeting was to discuss the plans and way forward of the activity. This report provides an overview of the proceedings of the three-day meeting and presents the key decisions and outcomes, which includes seven new proposed activities.

In-person participants of the Safe Landing Climates Meeting 2023, Royal Society, London

[Left to right] Standing: Ramia Albakain, Benjamin Keenan, Marion Saint-Lu, Cristaino Chiessi, Hannah Liddy, Pierre Friedlingstein, Roland Séférian, Izidine Pinto, Bette Otto-Bliesner, Heiko Goelzer, Neil Harris, Kevin Reed, Terence Thompson, Steve Sherwood, Gabi Hegerl, Hyungjun Kim, Laura Suarez-Gutierrez, Marco Cabrerizo, Paulo Nobre, and Kazuyoshi Suzuki. Front: Swapna Panickal, Narelle van der Wel, Elisabeth Holland and Mike Evans. Inset: Robin Smith, Svetlana Jevrejeva, Peter Alexander, Ana Bastos and James Mcmahon.

Contents

1. Introduction

The World Climate Research Programme (WCRP) Safe Landing Climates (SLC) Lighthouse Activity (LHA) is an exploration of the routes to "safe landing" spaces for human and natural systems, aiming to explore the future pathways that avoid dangerous climate change and to contribute to the United Nations Sustainable Development Goals. The first in-person meeting of SLC took place at the Royal Society in London, 7 - 9 March 2023. The aim of the meeting was to discuss the plans and way forward of the activity. The full list of participants is provided in Annex 1 and the meeting agenda in Annex 2.

2. Overview of the three-day meeting

The SLC Meeting was held over three days. The first and third days of the meeting were designed to accommodate the strategic discussions of the five SLC Working Groups (WGs): Understanding High-Risk Events, Perturbed Carbon Cycle, Water Resources, Sea Level Rise, and Safe Landing Pathways. The second day was a hybrid meeting, where partner perspectives and break-out room discussions were designed to ensure that the activity builds key collaborations. Below we provide a brief overview of each day of the meeting.

Day 1

Day 1 of the meeting included presentations from each Safe Landing Climates Working Group (each theme), breakout discussions, and individual science presentations (see Annex 2 for details of most of the presentations). Several of the WGs already had specific projects underway, while others were still exploring where they can best contribute.

Key themes identified in breakout discussions that need further exploration were:

1. An assessment of high-impact events that is broader and more interdisciplinary than the many current efforts is needed, including carbon cycle impacts and an assessment of the importance of mean versus extremes in terms of impacts.
2. Knowledge brokering and communication: it is important to understand the pitfalls to avoid (e.g., the overemphasis of worst-case scenarios (especially in communities that can't afford to prepare for them), liability concerns, etc.) and opportunities (e.g., gaming used as a communication tool)
3. Exploring the consequences of "what if" scenarios: what would be the consequences of high-impact, low-likelihood events that might occur (e.g., Atlantic Meridional Overturning Circulation (AMOC) collapse, rapid sea level rise, etc.)
4. How do we develop scenarios in the future? What are the merits of gaming versus other approaches? Do we need more or fewer scenarios?
5. Can we use emulators to efficiently explore uncertainty and enable coupling between Shared Socioeconomic Pathway (SSP) generation, Integrated Assessment Models (IAMs), Global Climate Models (GCMs), and Regional Climate Model (RCM) steps in the chain?

Day 2

Day 2 built on the discussions of Day 1 by seeking input and discussing some of the key themes identified by the lighthouse with a wider group of invited participants via a hybrid meeting format.

A first round of breakout groups was intended to mix up the Working Groups and the four in-person breakout groups were asked to identify new ideas that came up during Day 1. Two separate online breakout groups were also run to solicit ideas and suggestions for the LHA from outside participants. A list of themes/ideas that came from these discussions, synthesized by SLC Chairs Steve Sherwood and Gabi Hegerl, is:

- Resilience (Eco)system workshop: time scales, observations + models
- Probabilistic vs. storyline (and communication): best practices
- Safe Landing Game: aimed at the public, policymakers and/or schools
- Carbon Dioxide Removal (CDR): how, when, and how much should be done?
- Coupling IAM and ESMs (or combining them into one model): how to get there?
- CDR as a pathway element: will there be unintended social feedbacks from studying or doing it?
- Food and biofuels: food security, land use change, water, emissions
- What is the "right" level of complexity/resolution/systems to inform safe landings takeaways?
- Predictability of ENSO and other modes across time scales and connection to extremes
- Investigation of complex, cascading, compound events (modeling, sensitivity analyses, costs/benefits)
- How to engage with economic assessment: connecting with industry experts, public health, and food security
- What is 'safe' (evolving over the LHA lifetime) and do we need a SWOT analysis of burning embers?
- Risk perception: how to deal with this in communication?

An important part of the second day was a set of presentations made by invited participants on the Coupled Model Intercomparison Project (CMIP), Shared Socioeconomic Pathways (SSPs), the Earth System Modelling and Observations (ESMO) Core Project of WCRP, the Tipping Point Model Intercomparison Project (TIPMIP), and the current state of coupled Earth-system modeling. This was followed by a second round of breakouts groups, where a number of project ideas were identified, which were consolidated further on Day 3 and that are outlined in Section 3 of this report.

Day 3

The third day of the meeting began late due to a working breakfast organized by S&P Global Sustainable 1 to bring together a subset of meeting attendees and members of the finance and investment community. Guests at the breakfast discussed a number of concerns in the finance sector, particularly on the disconnect between the short-term focus of markets and the longer-term nature of the climate problem, and the likely underpricing of risk in current frameworks for estimating risk exposure. S&P Global Sustainable 1 expressed interest in a continued collaboration.

Day 3 of the meeting further discussed and progressed the project ideas identified on Day 2, with breakout group meetings held for each topic. Initial discussions led to two of these project ideas being combined into one activity - leading to seven final project ideas. Discussants were asked to identify the activity's objectives, who would lead, who would participate, what groups outside the LHA should be involved, and what activities would be undertaken to meet the activity's objectives. The responses to these questions are outlined in Section 3.

3. Key decisions and outcomes

Discussions on Days 2 and 3 of the meeting identified the following list of Safe Landing Climates activities, together with a number of near- to medium-term objectives. The intention is for these activities, while housed in a particular theme (Working Group), to be open to anyone from the LHA to participate in, including affiliate members. More detailed descriptions of each activity are provided in Annex 4.

3.1. A CMIP-focused project with several components

Objective: To promote highly-coupled model runs in CMIP7; include new scenarios to represent different pathways than previous Representative Concentration Pathways (RCPs) (in particular overshoot scenarios with strong but late mitigation and CDR; and evaluate selected tipping impacts.
Lead WG: Understanding High-Risk Events
Leads: Bette Otto-Bliesner, Pierre Friedlingstein, Gaby Hegerl
External partners: TIPMIP, Ice Sheet Model Intercomparison Project (ISMIP), ESMO and possibly the Zero Emissions Commitment Model Intercomparison Project (ZECMIP)
Activities:

- Proposals to ScenarioMIP (Pierre Friedlingstein)
- Work with other MIPs or propose a new HighRiskMIP (Bette Otto-Bliesner)

3.2. Gaming and decisions/scenario exploration

Objective: to develop future scenarios that are more relevant outside the climate sphere.
Lead WG: Safe Landing Pathways
Leads: Kevin Reed, Neil Harris
External partners: Future Earth Pathways, Aspen Global Change Institute (AGCI)
Activities:

- Workshop #1: Liaise with industries/governments (maybe in the first half of 2024). The outcome may be to form a task force to continue working beyond the workshop.
- Workshop #2: A framework for gaming. The objective would be to provide science input into games (not to produce the game itself)

3.3. Water variability impacts

Objective: Activity addressing resilience of water-use sectors, valuation, and optimal allocation of water, and 'green finance' in various future scenarios of (greater) water variability.
Lead WG: Water Resources
Leads: Hyungjun Kim, Paulo Nobre
External partners: WCRP Global Energy and Water Exchanges (GEWEX) Core Project, the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP), World Resources Institute (WRI), etc.
Activities: Workshop in May 2024 in the Amazon, TBD. A possible meet-up at the WCRP Open Science Conference (OSC) in Kigali in October 2023. Poster Session at WCRP OSC, October 2023

3.4. Signposts for sea level rise

Objective: Identify indicators of sea level change and their implications for the future, and integrate these indicators with communication strategies

Lead WG: Sea Level Rise
Leads: Beth Holland, Molly Mitchell

- Communication sub-theme - leads Marco Cabrizio, Mike Evans
- MIPS signposts sub-theme - leads Heiko Goelzer, Swapna Panickal
- Local community signpost - leads Molly Mitchell, Beth Holland

External partners: TBD
Activities:

- Webinar in SLC Discussion Series — May/June 2023
- Signposts Workshop
- A white paper describing the approach taken (Nature Sustainability)
- Participate in MIPs
- Participation in WCRP OSC in Kigali in October 2023

3.5. High-risk cascading shocks

(Including impacts on the carbon cycle and quantification of costs)

Objective: Interesting examples are multiyear drought and heat waves
Lead WG: Understanding High Risk Events, Perturbed Carbon
Leads: Laura Suarez-Gutierrez, Gabi Hegerl, Ana Bastos
External partners: Explaining and Predicting Earth System Change (EPESC), Climate and Ocean Variability, Predictability and Change (CLIVAR), Risk KAN (Future Earth)
Activities:

- Webinars 2023 - topics including cascading impacts, emulators
- AGU 2023 session proposal
- Workshop (2024) with EPESC, ensuring interdisciplinary participation and marking the start of a continuing activity or taskforce.

3.6. Connecting across the IAM-GCM-impact hierarchy

Objective: To discover the unexpected climate hazards possible in a fully coupled system, and enable a two-way flow of information across hierarchies, with error framing. A possible joint project with ESMO.
Lead WG: Understand High Risk Events
Leads: Hannah Liddy, Steve Sherwood
External partners: ESMO, the Analysis, Integration and Modeling of the Earth System (AIMES) Project
Activities:

- Workshop with ESMO and AIMES- TBC
- Textbook / educational foundation (with the WCRP Academy)

3.7. TCRE assessment

Objective: Assess the pdf of transient climate response to cumulative emissions of carbon dioxide (TCRE) using a similar approach to Sherwood et al. (2020) for Equilibrium Climate Sensitivity (ECS)
Lead WG: Perturbed Carbon
Lead: Chris Jones, Pierre Friedlingstein, Tatiana Ilyina, Roland Séférian

External partners: TBD
Activities:

- Poster Session at WCRP OSC, October 2023
- Webinars on the various strands of TCRE (TBC), including process understanding, sources of uncertainty, latest in manipulation experiments, emergent constraints
- Workshop in late 2023, possibly in Exeter

In addition to these projects, it was resolved that:

1. We can support at most three workshops in 2024 (two per year would be more comfortable). There are more than 3 proposed at present, but some may be mostly externally funded.
2. We want to move away from Narelle having to attend all WG meetings and leave much of the organisation to the WG Chairs and/or Project Leads. In general, it should now be the projects that meet, with progress on them reported back to the Steering Group via the WG leads (of the lead WG for the project)
3. We will try to get some of the projects/WGs to meet at the WCRP OSC in Kigali in October 2023 and might have some limited funds to help support this.
4. We need firm plans for any workshops, including budgets. We will send a request for this shortly after the meeting.

Acknowledgments

Thanks to S&P Global Sustainable 1 for sponsoring lunches at the London Meeting. It is much appreciated.

Annex 1 - List of participants

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Safe Landing Climates Working Groups

WG Members and Affiliate Members

High Risk Events
Sea Level Rise
Water Resources
Perturbed Carbon
Safe Landing Pathways
Affiliate for multiple WGs

Annex 2 - Agenda

WCRP Safe Landing Climates Lighthouse Activity Meeting

Royal Society, London I 7 - 9 March 2023

Final, 7 March 2023

The Safe Landing Climates (SLC) Lighthouse Activity will meet at the Royal Society in London in March to discuss the plans and way forward of the activity. The meeting will take place over three days and is by invitation only. The first and third days of the meeting have been designed to accommodate the strategic discussions of the five SLC Working Groups: Understanding High-Risk Events, Perturbed Carbon Cycle, Water Resources, Sea Level Rise, and Safe Landing Pathways. The second day will be a hybrid meeting, where partner perspectives and break-out room discussions will ensure that the activity builds key collaborations.

Overview

The Safe Landing Climates Lighthouse Activity is an exploration of the routes to "safe landing" spaces for human and natural systems. It will explore future pathways that avoid dangerous climate change while at the same time contributing to the United Nations Sustainable Development Goals (SDGs). There are **two overarching research questions:**

- *Q1: what potential high-impact climate hazards, surprises or irreversible changes should we be genuinely worried about and how do we usefully quantify and communicate the associated risks?*
- *Q2: what do achievable, internally consistent, and safe pathways to a future climate to meet broader human needs look like?*

Meeting Goal

The goal of the WCRP Safe Landing Climates Lighthouse Activity Meeting is to identify processes that will provide answers to our two LHA research questions and plan their implementation.

Short scientific presentations: We invite the members of the Safe Landing Climates Working Groups and invited guests to self-nominate for short scientific presentations on Day 1 related to the lighthouse, from either their own research or bringing science ideas or important viewpoints they would like us to think about from other work. If there is insufficient time for all proposed talks, preference will be given to those not speaking elsewhere in the program and/or to ideas not already covered in the WG presentations. Please provide us with a talk title by filling out this page (no abstract needed at this time).

Remote access: Day 2 the meeting will be hybrid to allow additional online attendance, but with maximum in-person attendance of 30 participants. On Days 1 and 3 the meeting will be in-person only, to allow the five SLC Working Groups to have effective strategic discussions.

Draft Agenda

Day 1: 7 March 2023, 9:00 - 17:45 (GMT)

Morning 9:00-12:40

9:00 Opening remarks from the convenors

9:05 Presentations from each working group (WG) (15 minutes each + questions). These should address:

a. Current plans/activities

b. How will the WG address the two LHA Research Questions (see above)

9:05 High-Risk Events
9:25 Perturbed Carbon
9:45 Water Resources
10:05 Sea Level Rise
10:25 Safe Landing Pathways

10:45 Coffee

11:15 Breakout groups (across individual tables): Discuss where we are, identify themes across working groups, missing issues and gaps

11:45 Breakout groups report back to plenary, and discussion. Organizers collect suggestions/concerns

Lunch 12:40 - 13:45

Afternoon 13:45 - 17:45

13:45 Science presentations by individual attendees [12 mins per person incl. Questions] including discussion and a short coffee break.

Dinner (TBC)

Day 2: 8 March 2023, 9:00 - 18:00 (GMT)

[Hybrid day including extra WG members and external invites]

Morning; 9:00 - 12:00

9:00 Brief introduction round of guests

9:10 Recap of outcomes/questions arising from day one (convenors)

9:25 Breakout groups I: identify & explore new key ideas from Day 1 (presentations)

- What were the most interesting/compelling science ideas that emerged?
- How well are these aligned with the current WG plans?

Breakout groups organized by tables, hybrid attendants by zoom breakout rooms

9:55 Breakout I Groups report back to plenary, and discussion

10:30 Coffee

Presentations and discussion on key strategies. Talks should summarise current activities, identify gaps/opportunities. Talks should use ~⅓ of the allocated time, discussion ~2/3.

11:00 Scenario building and SSPs - current plans - Ben Sanderson

11:30 Risk frameworks across the human/earth system - Jana Sillmann [Risk KAN]

12:00 CMIP7 plans - Helene Hewitt

Lunch 12:30 - 13:40

Afternoon 13:40 - 18:00

13:40 Modeling capacity for addressing global risk (coupling, etc.)
ESMO plans - Cath Senior
Vegetation modeling - Victor Brovkin
Ice modeling - Robin Smith

14:40 TIPMIP plans - Jonathan Donges and Sina Loriani

15:10 Discussion

15:30 Coffee

16:00 Safe landing input to CMIP: Bette Otto-Bliesner followed by discussion
16:30 Breakout groups II: discuss the WG plans in light of new information
a. Are the WG plans feasible? Which ones can we do in partnerships, and which ones are better addressed by others?
b. New ideas for the WGs/LHA to consider
17:30 Breakout II groups report back to plenary, pitching ideas to take forward, and discussion; vote for key ideas of activities (number of activities TBD)

Self-Organized Dinners

Day 3: 9 March 2023, 10:00 - 16:45 (GMT)

Morning (10:00 - 1:00)

10:00 Reflections from S&P (reflecting industry/economy risks) & convenors

10:30 Breakout groups III: progress major key activity ideas [One group per idea; World cafe style, using poster boards and ticks to clarify support to select most productive ideas - 1-2 rounds where people can visit a different table]. Coffee included.
- Ideas can (and if possible should) be cross-WG
- How would we do it
- By whom, or with whom (do we lead, collaborate or contribute?)
- Desired tangible outcome(s) and time frame
- Timeline with goals for leading near-term and longer-term activities

Lunch (12:30 - 13:40)

Afternoon (13:40-16:45)

13:40 Breakout III groups report back to plenary (+ brief questions)

14:40 Plenary discussion, prioritization and identification of timeline. Identify leads for each activity, and a time plan/resources. Coffee break around 15:30

- Outcome: confirmed/reshaped action plan for next year and next 5 years

16:40 Meeting adjourns

End of meeting

Annex 3 - Science talk descriptions

Simulating and analyzing rare heat extremes
Gabi Hegerl for Erich Fischer

This is a talk that presents work in Erich's group on ensemble boosting and analysis of record-shattering extreme events. I think it is useful input for the Lighthouse to know about. It presents a method to encourage the simulation of very rare extreme events and their characteristics in climate models. It will also contain information on observed links to fire.

Operational event attribution frameworks for quantifying climate change impacts
Kevin Reed

Significant advances have been made in attribution frameworks to quantify climate change impacts on individual extreme events, including devastating hurricanes. Here we present the results of the hindcast attribution methodology throughout the entire hurricane season using the Community Earth System Model. The implementation of the framework systematically throughout the hurricane season demonstrates the feasibility of such tools for operational attribution applications more broadly.

TCRE assessment
Chris Jones & Pierre Friedlingstein*

Proposal and rationale for a community-driven assessment of TCRE and uncertainty.

Some possible hydroclimate tipping elements
Hyungjun Kim

Under a warming climate, numerous hydroclimate processes exhibit non-stationary behaviors, such as irreversible and/or accelerated changes, which are referred to as tipping elements. In this presentation, several recent studies are briefly introduced, including: 1) an abrupt shift to a hotter and drier climate beyond the tipping point in inner East Asia, 2) the observed influence of anthropogenic climate change on heavy rainfall from typhoons, 3) the timing of unprecedented hydrological droughts under climate change, and 4) global aridity changes resulting from differences in surface energy and water partitioning.

Risk: Can the past inform the present... and the future?
Michael Evans

Paleoclimatology can inform risk assessment in a changing climate, via estimation of: (1) baseline event probabilities; (2) extreme event definitions; (3) the amplitude and structure of the unforced variability, regime shifts and tipping points; (4) analog ecosystem resilience; and (5) identification (or not) of mechanisms of climate change, on timescales not well replicated in the historical climate record.

Global and regional health and food security under strict conservation scenarios
Peter Alexander

Global biodiversity is rapidly declining, and goals to halt biodiversity loss, such as the Aichi Biodiversity Targets, have not been achieved. To avoid further biodiversity loss, area-based protection will form part of new biodiversity targets. We use a state-of-the-art global land-use model, the Land System Modular Model, to explore global and regional human health and food security outcomes under strictly enforced 30% and 50% land protection scenarios, such as Half-Earth. We find protection scenarios cause additional human mortality due to diet- and weight-related changes. Low-income regions such as South Asia and sub-Saharan Africa experience the highest levels of underweight-related mortality, causing an additional 200,000 deaths related to malnutrition in these regions alone. High-income regions, by contrast, are less affected by protection measures. Our results highlight that radical measures to protect areas of biodiversity value may jeopardize food security and human health in the most vulnerable regions of the world.

Irreversible loss in marine ecosystem habitability after a temperature overshoot
Roland Séférian

Anthropogenic warming of the oceans and consequent deoxygenation are altering marine ecosystems. Current knowledge suggests that these changes might be reversible in the centennial timescale in the ocean surface if global warming were to decline. However, knowledge on the persistence of their combined effects on marine ecosystems remains limited. Here we explore to what extent global warming will drive alterations on marine habitats by following the evolution of a metabolic index that captures the ecophysiological response of marine organisms to both changes in temperature and oxygen, through an idealised ramp-up ramp-down atmospheric CO2 concentration experiment. Using a multi-model approach, we find that changes in ocean temperature and oxygen drives a centuries-long irreversible loss of ~4% in the habitable volume of the upper 1000 m of the world ocean. These results suggest the combined effect of warming and deoxygenation will diminish the capability of the ocean to hold life far after recovering from a temperature overshoot.

Role of permafrost and snowpack in hydrological cycle
Kazuyoshi Suzuki

Permafrost is one of the tipping points of global warming. We will present an example of studies on the effects of permafrost on the terrestrial hydrological cycle and vegetation, as well as the impact of snowpack on extreme winter precipitation. Finally, an ongoing international project on "The status of mountain snow cover" will be presented.

Paleoclimate perspectives on the Atlantic Meridional Overturning Circulation as a tipping element of the climate system and its effect over tropical precipitation
Cristiano Mazur Chiessi

The paleoclimate record allows the investigation of different modes of the Atlantic Meridional Overturning Circulation (AMOC). During the last glacial (ca. 71-19 kilo years before present (ka)) and deglaciation (ca. 19-11.7 ka), the AMOC showed a number of millennial-scale rapid departures from its strong mode. These departures into weaker modes of operation were most

probably triggered by freshwater input into the high latitudes of the North Atlantic. The apparent existence of a hysteresis behavior in the AMOC response to freshwater forcing prompted its characterization as a tipping element of the climate system. In this presentation we will explore the effects that a substantial slowdown of the AMOC had over past tropical precipitation.

The Amazon rainforest and global climate modeling
Paulo Nobre

The talk covered the combined roles of the Amazon rainforest and global warming on the continental water cycle over South America. Also, the importance of the proper representation of atmospheric convection over the Amazon for global atmospheric and oceanic circulation were commented on.

Could global warming produce a fungal pandemic?
Steve Sherwood

I will review suggestions that the emergence of dangerous new fungal infections could be driven by the closing gap between environmental and human core body temperatures, and consider whether this could represent a possible unexpected climate tipping point related to heat extremes.

Annex 4 - Detailed project descriptions

A1. A CMIP-focused project with several components

Global climate change is often thought of as a steady and approximately predictable physical response to increasing forcings, which then requires commensurate adaptation. But adaptation has practical, cultural, and biological limits, and climate change may pose unanticipated global hazards, sudden changes or other surprises, as may societal adaptation and mitigation responses. Climate science must attempt to identify and quantify physical risks even–or especially–when they are highly uncertain. This improves the chances of identifying and communicating "safe landing" pathways that avoid the worst consequences of climate change.

The goal of the HighRisk Project is to coordinate simulations across the Coupled Model Intercomparison Project Phase 7 (CMIP7) suite of coupled models to identify and assess risks associated with tipping points, cascading impacts, and interacting feedbacks in the Earth system on multi-decadal to centennial time scales and beyond. Special attention will be paid to identifying the model output required for a broad range of stakeholders (e.g., the Intergovernmental Panel on Climate Change (IPCC), food supply, vulnerable and indigenous populations, the energy and financial sectors, etc.). As such, the HighRisk Project will provide key input to all three working groups of the IPCC. In addition, to make the HighRisk Project output useful to stakeholders, we will partner with the WCRP Regional Information for Society (RIfS) Core Project and COordinated Regional climate Downscaling EXperiment (CORDEX) as well as the Extremes Platform (under RIfS).

We are currently discussing two sets of coupled climate model experiments that could potentially contribute to CMIP7, IPCC, and other international and national assessments. These sets of experiments have the potential to identify and assess risks associated with tipping points, cascading impacts, and interacting feedbacks in the Earth system on multi-decadal to centennial time scales and beyond.

(1) A set of experiments taking advantage of the CMIP DECK 1% yr-1 CO_2 concentration increase (1pctCO_2) experiment and its companion experiment with CO_2 concentrations maintained at 4x pre-industrial concentrations until the end of the simulation (Eyring et al., 2016). To this, could be added the proposed TIPMIP protocols for complementary experiments to assess commitment and reversibility, and to include the additional contributions of predictive ice sheets and vegetation, working with the ISMIP and the Land Use Model Intercomparison Project (LUMIP).

a) ISMIP6 included such an experiment for CMIP6, their Tier 1 1pctCO_2to4x-withism [Nowicki et al., GMD, 2016]: a simulation with interactive ice sheet forced by 1% per year CO_2 increase to 4 x CO_2 (subsequently held constant to quadruple levels). We would also encourage this simulation in CMIP7.

b) We would also like to propose a simulation with vegetation feedbacks switched on for groups who have the capability to do so but have chosen not to for their DECK experiments as a Tier1 experiment, in order to allow rapid vegetation transitions triggered by extreme events for example, highlighted as a possibility in the LUMIP protocol (Lawrence et al., 2016), with the hope of better sampling and evaluating such

possible transitions. It will also be important for groups to clarify which feedbacks are switched on in models to allow diagnostics.

(2) A set of 'whatif' experiments. The DECK 1%CO_2 to 4x coupled simulations may not cross a tipping point. Yet these tipping points, if they would have been crossed, could have local and remote impacts and interacting risks. The magnitudes and locations of these impacts across multiple CMIP7 models are critical to inform adaptation and uncertainties for taking action.

One way is to run existing models and impose ice sheet collapse; savannah in Amazon; boreal forest northward expansion in North America and Siberia; complete thaw of permafrost; or freshwater input to the North Atlantic and see the model response. For example, in CMIP6, LUMIP included a Tier 1 experiment an idealized transient global deforestation experiment (idealized-global-deforest) and Tier 3 paired idealized time slice control and deforestation experiments for specific regions (e.g. tropical, boreal, temperate) [Lawrence et al., 2016]. The North Atlantic Hosing Model Intercomparison Project (NAHosMIP) organized a set of idealized experiments with CMIP6 unflux-adjusted, coupled climate models to investigate the sensitivity of the AMOC to freshwater forcing [https://www.tipes.dk/na-hosing-mip/].

References:

Eyring, V. and Bony, S. and Meehl, G. A. and Senior, C. A. and Stevens, B. and Stouffer, R. J. and Taylor, K. E., 2016. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. Geoscientific Model Development, 9(5), pp. 1937-1958.

Lawrence, D. M. and Hurtt, G. C. and Arneth, A. and Brovkin, V. and Calvin, K. V. and Jones, A. D. and Jones, C. D. and Lawrence, P. J. and de Noblet-Ducoudr\'e, N. and Pongratz, J. and Seneviratne, S. I. and Shevliakova, E., 2016. The Land Use Model Intercomparison Project (LUMIP) contribution to CMIP6: rationale and experimental design. Geoscientific Model Development 9(9), pp. 2973-2998.

A2. Gaming and decisions/scenario exploration

Analytical gaming exercises can often illuminate the intricacies and feedbacks of complex scenario planning and decision (or tipping) points that lead to unexpected outcomes. Moreover, communicating climate change is often fraught with challenges, which the use of gaming can help overcome. This activity will explore the potential for the use of "climate pathways" gaming exercises to inform various scenarios relevant for climate science, planning and modeling. The development and implementation of an initial series of "climate pathways" gaming workshops could allow for an assessment of ever-evolving scenario pathways to safe (or unsafe) climates on decadal and century timescales.

The success of such a venture would require inclusive groups of scientists, stakeholders, industry partners, community groups and policymakers to include input on recent geopolitical, societal, technological, and sustainable advances and ideas. Building on ongoing international initiatives in the future, the output of these activities could help to inform more nimble scenarios for climate modeling, international and local policies, and behavioral change, and could provide an understanding of the range of plausible and timely pathways to safe landing climates. Finally, such an approach to scenario planning would benefit from the inclusion of early career professionals in educational settings. A first workshop will discuss and debate the useful needs of "climate pathways" gaming and the practical aspects of implementing this technique more

widely in climate science. With this workshop we seek to (1) understand relevant gaming approaches (including those already in use by the sustainability research community), (2) gain perspectives of applications of gaming of relevant industries and disciplines, and (3) assess the potential to design possible games to inform climate scenarios.

A3. Water variability impacts

In this activity we will investigate climate and social processes that lead to global and regional water variability and its socioeconomic impacts. We will achieve this by categorizing the water availability question into three main areas: (i) multi-scale temporal and spatial water availability; (ii) natural processes determining water availability; and (iii) water management and quality. All three subject areas will be considered in terms of cross-cutting aspects of the Lighthouse Activity, such as "whatif" scenarios and tipping elements.

Our approach to achieving this is twofold: (1) to use state of the art Earth system models and available supercomputing infrastructure and IT tools (e.g., artificial intelligence, machine learning, data assimilation) to fill the gaps between the several orders of magnitude processes related to drinkable water availability; from raindrop formation to planetary scale oceanic-atmospheric-forests coupled processes; and (2) to put together a concept paper encompassing the role of water stressors, such as water use for agriculture, industry, and the energy sector, domestic water supply, and ecosystem needs, that impact water demand and socio-economic impacts.

In order to do this, we will call for the contributions of experts across several fields, including Earth system modeling and climatology, and ecological, agricultural, economic impacts assessment and health. This will include contributions from both the physical and social sciences to identify and quantify potential stressors and the coupled processes that modulate water availability in a warmer and more populous world. We will identify case studies that exemplify these coupled interactions between climate phenomena and water demand to anticipate the impacts on society and the environment.

A4. Signposts for sea level rise

In this activity, we will investigate geographically specific signposts of accelerating sea level rise in locations around the globe and translate this information for practitioner use. We will achieve this by combining expertise regarding changes in drivers of sea level rise, their impacts to sea level rise trajectories, and modifying factors (storm surge and resource loss) with practitioner-identified decision points. Our goal is to provide guidance that will allow practitioners to accurately assess current and future risk from sea level rise in their decision-making.

A5. High-risk cascading shocks

In this activity we will investigate high-risk events where climate hazards lead to cascading climatic, ecological, and socioeconomic impacts. We will achieve this by combining expertise and methodologies across varied multidisciplinary fields including climate science, ecological and agricultural impact assessment, financial risk assessment, and social sciences. Furthermore, we will utilize innovative state-of-the-art applications made possible by advances in high-performance computing, machine learning and state of the art modelling techniques. Our goal is not only to bridge along the chain from climate hazards to their cascading impacts, but also to identify and quantify potential links and coupled effects that ultimately make this not a chain, but an interlinked system.

We will identify several cascading shocks study cases that best exemplify these coupled interactions between climate hazards and their cascading ecological and socioeconomic impacts (e.g., forest mortality events triggered by compound heat and drought leading to economic and ecological loss, but also leaving the region more vulnerable to climate hazards in the following years due to land-cover changes). Then, we will assess whether this cascading or coupled linkages, commonly ignored in traditional climate-risk assessments, lead to systematically underestimated risks, and, ultimately, we will quantify these risks using relevant metrics for socio-economic and ecological loss.

A6. Connecting across the IAM-GCM-impact hierarchy

In this activity, we will investigate if the societal response to the impacts of a changing climate are significant enough to include in a coupled modeling system and whether new risks emerge in a coupled behaviour. The global trajectory of anthropogenic greenhouse gas emissions is the main determinant of global temperature, but this key driver, dependent on human activity, is treated as an exogenous forcing in nearly all climate models. This is largely due to the fact that emissions pathways are a product of a complex system involving interactions between social, political, economic, and technological systems and are often analyzed separately. This activity will explore the interactions between these systems.

The status quo for modeling the climate, mitigation, adaptation, and impacts follows a linear exchange of model output beginning with emissions and land use trajectories quantified by integrated assessment models to meet a range of future socio-economic and political projections (Meinshausen et al., 2020). These emissions trajectories are used by climate models to explore the climate response to anthropogenic forcing. Climate models then produce globally gridded results of climate metrics such as near-surface temperature change that can be used as forcing data for impact models to estimate metrics such as crop yields, forestry stocks, and marine ecosystems and fishing potentials completing the chain of information exchange.

While this exchange of information is fit-for-purpose given the history of modeling and development of modeling centers, the potential dynamics of a coupled human-Earth system and the significant feedbacks, linkages, and thresholds between the systems are largely unknown. Due to assumptions of economic equilibrium in IAMs, the processes that may give rise or prevent rapid societal change are not considered. However, high impact-low likelihood climate risks and exposure to extreme events may have implications for the societal response to climate through changes in infrastructure, ecosystem services, demographics, and public perceptions of climate change. There is a small but growing body of literature that explores feedbacks between climate and society ranging from approaches ranging from more stylized models (Woodard et al., 2019) to hard coupling between integrated assessment models and Earth system models through the land component (Thornton et al., 2017).

This activity will explore the possible feedbacks and interactions between natural and social systems by working across modeling groups focused on climate, mitigation, adaptation, and impacts to discover the unexpected climate hazards possible in a fully coupled system, and enable a two-way flow of information across hierarchies, with error framing. This effort will be highly interdisciplinary and will forge new collaborations between colleagues working at the interface of climate, socio-economics, and impacts. We will also explore the role of novel methodologies such as emulators and machine learning to improve the representation of human activities on the Earth system in current modeling structures.

References:

Meinshausen, Malte, et al. "The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500." Geoscientific Model Development 13.8 (2020): 3571-3605.

Thornton, Peter E., et al. "Biospheric feedback effects in a synchronously coupled model of human and Earth systems." Nature Climate Change 7.7 (2017): 496-500.

Woodard, et al., "Economic carbon cycle feedbacks may offset additional warming from natural feedbacks." Proceedings of the National Academy of Sciences 116.3 (2019): 759-764.

A7. TCRE Assessment

Following IPCC Sixth Assessment Report (AR6) release and update of carbon budgets, the transient climate response to cumulative emissions of carbon dioxide (TCRE) remains a key uncertainty in determining remaining carbon budgets to achieve climate goals. Recent advances in climate sensitivity and aerosol forcing make it timely for TCRE/carbon cycle response to be formally assessed. In this activity we will assess the latest knowledge on climate and carbon cycle feedbacks which determine the response of the climate system to CO_2 emissions, i.e., TCRE. We will achieve this by bringing together expertise on land and ocean carbon cycle, process models, ESMs and observational constraints.

Specifically, we will address process level understanding of what drives TCRE, with a focus on carbon cycle feedbacks which affect the airborne fraction of CO_2 emissions; sources of current TCRE uncertainty - what components and processes of the natural global carbon cycle and climate system are mostly responsible for TCRE uncertainty; multiple time periods - combining evidence from a range of time periods and targeting information from past climates and the historical record. We will also draw on understanding derived from observational data and site-level stations (FluxNET) and manipulation experiments (FACE, soil warming) and the latest understanding of the ocean heat/carbon nexus. We will draw on improved models, and also novel techniques to constrain their output such as emergent constraints or machine learning techniques.

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