OVERSHOOT CONFERENCE

2026 | Beijing

24 - 25 November 2026
Xijiao Hotel, Beijing, China

Book of Abstracts

Jointly hosted by

International Institute for Applied Systems Analysis
IIASA

Tsinghua University

Contents

Program overview **3**

The Overshoot Conference Podcast **7**

Tuesday, 24 November 2026 ..... **8**

Opening 8

Theme 1: Highest possible mitigation ambition under overshoot, peak and decline pathways 9

Theme 2: Earth System responses to net negative emissions and CDR 14

Theme 4: Climate impact (ir)reversibility 18

Theme 6: Health implications of overshoot pathways 22

Theme 3: Technological solutions for decarbonization and negative emissions 25

Theme 5: Overshoot pathway legacy, tipping dynamics and other abrupt changes 31

Theme 7: Adaptation & adaptation limits, and loss & damage under climate overshoot 35

Theme 8: Governance and equity of overshoot pathways 39

Poster Session 44

Wednesday, 25 November 2026 ..... **56**

Plenary 2. Theme to Theme and Report back, Q&A 56

Theme 3: Technological solutions for decarbonization and negative emissions 57

Theme 4: Climate impact (ir)reversibility 60

Theme 6: Health implications of overshoot pathways 63

Theme 8: Governance and equity of overshoot pathways 66

Theme 3: Technological solutions for decarbonization and negative emissions 69

Theme 2: Earth System responses to net negative emissions and CDR 73

Theme 5: Overshoot pathway legacy, tipping dynamics and other abrupt changes 76

Theme 8: Governance and equity of overshoot pathways 79

Joint Session. Theme 1 and Theme 3 83

Joint Session. Theme 2, Theme 4, and Theme 5 88

Joint Session. Theme 6, Theme 7, and Theme 8 91

Plenary 3.Theme report back on central Science and Policy Insights 92

Panel: Relevance of overshoot in Asian context 92

Closing Remarks 92

Author index **93**

Program overview

Click a talk to go to its abstract. Times are talk slots; the presenting author is named.

Tuesday, 24 November 2026

Time	Harmony Hall (Plenary) 和合厅	Cloud Room 云岚厅	River Room 江河厅	Bamboo Room 竹韵厅
08:30 09:00	**Registration**			
09:00 10:30	**Opening** *Location: Harmony Hall (Plenary), 和合厅* Welcome Deliang Chen - Tsinghua University Keywan Riahi - IIASA Keynote: Xiaoye Zhang - IPCC WGI Co-Chair Introducing the UNEP Limiting Overshoot Report - Mirey Atallah - UNEP Introducing the Overshoot Conference - Carl Schleussner and Deliang Chen Moderation: Inga Menke, IIASA			
10:30 11:00	**Coffee break**			
11:00 12:30	**Theme 1: Highest possible mitigation ambition under overshoot, peak and decline pathways** *Chairs: Joeri Rogelj, Mingyu Li* **11:10 Mingyu Li** Mapping the Feasibility Space of a 1.5 °C Future with a Million AI-Generated Pathways **11:23 Ryna Cui** Multispeed mitigation strategies to limit mid-century overshoot and return to 1.5°C **11:36 Meng Hou** From ambition to evidence: quantifying the temperature benefits of mitigation levers for NDC prioritization **11:49 Hannah Daly** National scenarios for return from overshoot — an Irish case study **12:02 Keywan Riahi** China's contribution to managing global temperature overshoot: insights from pathways around SSP2-COM	**Theme 2: Earth System responses to net negative emissions and CDR** *Chairs: Biqing Zhu, June-Yi Lee* **11:03 Soon-Il An** Climate System Inertia: From Hysteresis under CO_2 Mitigation to Continued Warming after Net-Zero Emissions **11:20 Long Cao** Ocean Carbon Cycle Response to Carbon Dioxide Removal: Insights from Earth System Modeling Perspective **11:35 Chao Li** Nonlinear Earth System Responses to Atmospheric CO_2 Forcing and Its Reversal: The Role of Multiscale Ocean Memory **11:50 Xinrui Liu** Land-based carbon dioxide removal under climate overshoot **12:05 Xifeng Zhang** Wetland Methane Emissions under Climate Overshoot: Responses and Reversibility	**Theme 4: Climate impact (ir)reversibility** *Chairs: Debra Roberts, Adriano Vinca* **11:05 Young-Min Yang** Sustained European agricultural risk beyond net-zero and negative CO2 emissions **11:17 Lujia Zhang** Reversibility of Hydroclimate Extremes under Carbon Dioxide Removal: The Role of Atmospheric Rivers **11:29 Kyungmin Park** Joint Analysis of Earth System and Regional Climate Responses Across Global Warming Overshoot, Peak, Decline and Stabilization **11:41 Wendan Zhang** Irreversible and Distributional Impacts of Temperature Overshoot **11:53 Yang Gao** High-Resolution Earth System Modeling Reveals Underestimated and Path-Dependent Heatwave Risks	**Theme 6: Health implications of overshoot pathways** *Chairs: Marina Andrijevic, Kristie L. Ebi* **11:05 Kristie Ebi** The reality of entering an overshoot trajectory necessitates shifts in climate and health research **11:15 Shaohui Zhang** Global air pollution pathways and health outcomes in the new SSPs towards below 2 °C **11:25 Marco Springmann** The health implications of climate change mitigation pathways
12:30 14:00	**Lunch**			
14:00 15:30	**Theme 3: Technological solutions for decarbonization and negative emissions** *Chairs: Alessio Mastrucci, Dabo Guan* **14:00 Fei Teng** Delivering Carbon Dioxide Removal for Climate Overshoot Requires Pathway-Specific Technology Portfolios **14:15 Thanakon Sukuman**	**Theme 5: Overshoot pathway legacy, tipping dynamics and other abrupt changes** *Chairs: Jingfang Fang, Alexander Nauels* **14:05 Hauke Schlesier** Reducing climate tipping risks with fast energy transitions **14:20 Nina Rynne** Cost-optimal recovery timing for 1.5°C overshoot pathways	**Theme 7: Adaptation & adaptation limits, and loss & damage under climate overshoot** *Chairs: Marina Andrijevic, Sindra Sharma-Khushal, Elisa Calliari* **14:05 Koko Warner** Climate Overshoot and Persistent Disruption: Rethinking Design of Adaptation and Loss and Damage Actions **14:20 Architesh Panda**	**Theme 8: Governance and equity of overshoot pathways** *Chairs: Annika Högner, Xianchun Tan* **14:00 Petra Bistricic** Policy Options for Climate Overshoot: A Review and Key Considerations for Design **14:12 Luis Fernandez-Carril**

Time	Harmony Hall (Plenary) 和合厅	Cloud Room 云岚厅	River Room 江河厅	Bamboo Room 竹韵厅
	Is Diversification Always Necessary? Evaluating CDR Portfolios Across Net-Negative Pathways **14:30 Tomoko Hasegawa** Carbon dioxide removal options that are not land-based increase food insecurity **14:45 Yilin Shang** Accelerating unabated coal unit retirement to avoid carbon lock-in on the pathway to net-zero power **15:00 Yiyi Ju** The Under-Explored Role of Sustainable Fuels in Moderating the CDR Reliance under Broad Overshoot Pathways **15:15 Zhengxu Zhou** Toward Carbon Neutrality: A Hydro-PV-Storage Multi-Energy Microgrid System for Mountain Villages	**14:35 Niki Lohmann** Carbon dioxide removal decisive to limit tipping risks in a tipping point emulator **14:50 Teresa Bonserio** Returning to 1°C: How Much CDR Is Needed to Limit Long-Term Tipping Risk, and What Delay Costs Us **15:05 Jerry Tjiputra** Persistent Earth system challenges of using stratospheric aerosol injections to avoid temperature overshoot	Financing Before the Peak: The Welfare Cost of Delayed Adaptation Finance under Climate Overshoot **14:35 Junxi Gong** Financing Loss and Damage under Climate Overshoot: Evidence from Malaysia **14:50 Kareem Buyana** Centering Reflexivity in Climate Overshoot Research	Governing Overshoot: The Politics of Irreversibility and Foreclosed Justice Possibilities **14:24 Jiarui Zhong** Distributional Impacts of 1.5 °C Overshoot Pathways: Food, Energy, and the Limits of Carbon Tax Revenue Recycling **14:36 Xian Zhang** From Temperature Targets to Climate Stabilization: Stability Margins, Governance, and Equity in Overshoot Pathways **14:48 Kejun Jiang** Fighting for 1.5°C Target: Modeling on Speed-up Energy Transition Pathways for China and Asia
15:30 16:00	**Coffee break**			
16:00 18:00	**Poster Session** **Kok Sin Woon**: Exploring Pathways for Reducing Global Solid Waste Emissions to Meet Climate Targets **Hao Pan**: Overlooked irreversibility of China's high-impact climate extremes under large-scale carbon dioxide removal pathways **Zheng Shi**: The durability of CDR: Governing CDR in climate-overshoot pathways **Haiming Luo**: The Timing Paradox: Marine Carbon Removal's Greatest Economic Value Precedes Its Technological Readiness **Alessio Mastrucci**: Carbon storage in urban buildings: The potential of structural wood and biochar-based concrete in global mitigation scenarios **Takuya Hara**: Understanding Technology Choices and Price Formation under Biomass and CCS Constraints in Net-Zero Energy Systems **Hui Yue**: Net-zero roadmap for hard-to-abate sectors in carbon-intensive cities **Anuj Pathak**: The Role of Direct Air Capture in Shaping India's Net-Zero Energy Transition **Weiping Xie**: Ireland's energy system transition under equity-based carbon budgets and carbon dioxide removal uncertainty **Weiwei Xiong**: Comparison of simple climate models under diverse long-term overshoot scenarios **Kaiwen Zhang**: A westward shift of heatwave hotspots caused by warming-enhanced land-air coupling **Qin Wen**: Contrasting marine and terrestrial responses of South Asian summer monsoon system caused by hemispheric insolation **Niklas Schwind**: RIME-X-OS: Towards Emulating Climate Impacts Under Overshoot and Stabilisation Scenarios **Yuying Huang**: Global Mortality Burden Attributable to Heat-Related Sleep Loss **Andrew J Kruczkiewicz**: Climate overshoot impacts on societies: A review of structures and trends in the academic literature **Meizi You**: Public expressed urban heat perception as a signal of adaptation strain in a warming climate **Sibo Li**: Prolonged Nighttime Warming under Climate Overshoot May Amplify Sleep and Mental-Health Burdens in Urban Populations **Limeng Fan**: The effect of North–South economic convergence on the regional allocation of CDR			
18:00 20:00	**Social dinner with dinner speech**			

Wednesday, 25 November 2026

Time	Harmony Hall (Plenary) 和合厅	Cloud Room 云岚厅	River Room 江河厅	Bamboo Room 竹韵厅
08:00 08:30	**Arrival and coffee**			
08:30 09:45	**Plenary 2. Theme to Theme and Report back, Q&A** *Location: Harmony Hall (Plenary), 和合厅* *Chair: Carl Schleussner*			
09:45 10:00	**Shift to Breakout Sessions**			
10:00 11:00	**Theme 3: Technological solutions for decarbonization and negative emissions** *Chairs: Alessio Mastrucci, Dabo Guan* **10:00 Giulio Pistolesi** A Spatially Explicit Roadmap for Agricultural Enhanced Weathering in China. **10:15 Soeren Lindner** From Overshoot Ambition to National Food-and-Land Action: A Global FABLE Scenathon for Rapid Methane Mitigation **10:30 Ron Milo** Eating the Overshoot: Microbes Eat CO_2; We Eat Microbes **10:45 Samuel Lovat** Replacing animal-based foods with microbial alternatives could reduce global greenhouse gas emissions by ≈10 $GtCO_2$-eq/year	**Theme 4: Climate impact (ir)reversibility** *Chairs: Debra Roberts, Adriano Vinca* **10:00 Nico Bauer** Biodiversity impacts of transformation scenarios compatible with the Paris Agreement **10:12 X Wong** A Dynamical System Theory of Climate Overshoot **10:24 Malon Muronzi** Irreversible Climate Impacts and Adaptation Limits in Southern Africa: Pathways, Tipping Points, and Policy Responses under Overshoot **10:36 Bryony Worthington** What does the Earth's Energy imbalance tell us about the next two decades of warming and expected level of overshoot?	**Theme 6: Health implications of overshoot pathways** *Chairs: Marina Andrijevic, Kristie L. Ebi* **10:15 Shuiqing Yin** Nonlinear amplification of heatstroke risk during climate overshoot reversal: evidence from Jiangsu province, China **10:25 Yuanchao Fan** Beyond Peak Temperature: Humidity and Radiation Shape Human Heat-Stress Impacts Along Climate Overshoot Pathways **10:35 John Ji** Residential greenness as adaptation buffer against heat extremes under climate overshoot: evidence from Chinese older adults	**Theme 8: Governance and equity of overshoot pathways** *Chair: Xianchun Tan* **10:00 Tianpeng Wang** Greater temperature overshoot amplifies asymmetric post-net-zero obligations across countries **10:12 Xin Lin** Adaptive governance for climate–social systems facing overshoot risk: A deep reinforcement learning framework **10:24 Chen Huang** Modeling Critical Mineral Access to Inform Equitable Climate Governance under Overshoot **10:36 Lucas Snaije** Governing Cities to Manage Climate Overshoot: Risks, Impacts and Responses
11:00 11:30	**Coffee break**			
11:30 12:30	**Theme 3: Technological solutions for decarbonization and negative emissions** *Chairs: Alessio Mastrucci, Dabo Guan* **11:30 Honglin Dai** Fine-grained technology deployment for plant-level deep decarbonization of China's iron and steel sector **11:45 Deyue Chen** Tracking Divergent City–Industry Decarbonization under Subsector-Specific Mitigation across China's Major Urban Agglomerations **12:00 Xiangyuan Meng** How Do Low-Carbon Policies Affect Firms' Carbon Total Factor Productivity? Evidence from China's Manufacturing Companies **12:15 Sam Krevor** Geophysical and techno-economic growth limits to the global scale-up of geological CO_2 storage	**Theme 2: Earth System responses to net negative emissions and CDR** *Chairs: Biqing Zhu, June-Yi Lee* **11:30 Jingtao Ding** Path-Dependent Climate-Mode Responses to CO_2 Reversal Revealed by AI-Discovered Dynamics **11:45 Daniele Visioni** Solar Radiation Modification in the context of Overshoot Pathways **12:00 Di Sheng** Towards sustainability-aware carbon dioxide removal deployment **12:15 Yue He** Temporary carbon dioxide removal to offset short-lived climate forcers	**Theme 5: Overshoot pathway legacy, tipping dynamics and other abrupt changes** *Chairs: Jingfang Fang, Alexander Nauels* **11:35 Yixuan Li** Confronting Compound Temporal Mismatches Under Temperature Overshoot **11:50 Bo Su** The Cryosphere Beyond a Planetary Safe Operating Space **12:05 Nico Wunderling** Climate Tipping Risks under Paris Target Overshoots: Towards an Emulator for Tipping Elements	**Theme 8: Governance and equity of overshoot pathways** *Chair: Xianchun Tan* **11:30 Yonglong Cheng** Individual carbon inequality and equitable mitigation burden-sharing in China: Implications for climate overshoot governance **11:42 Nariswari Nurjaman** Beyond Carbon Accounting: Governing Social Forestry, Carbon Trading and Food Security under Climate Overshoot in Indonesia **11:54 Aijun Yan** Surface Albedo Modification: A Relatively Equitable Climate Governance Option Combining Local Adaptation with Global Peak-Shaving Benefits
12:30 14:00	**Lunch**			
14:00 15:30	**Joint Session. Theme 1 and Theme 3** *Chairs: Joeri Rogelj, Alessio Mastrucci, Dabo Guan* **Søren Lütken** Countering the Overshoot - Retaining Atmospheric and Biogenic	**Joint Session. Theme 2, Theme 4, and Theme 5** *Chairs: Debra Roberts, June-Yi Lee* **Xia Qu** Asymmetric climate responses to declining CO_2 concentration:	**Joint Session. Theme 6, Theme 7, and Theme 8** *Chairs: Marina Andrijevic, Annika Högner, Sindra Sharma-Khushal* **Adriano Vinca** Mitigation consequences of maladaptation in buildings, power,	

Time	Harmony Hall (Plenary) 和合厅	Cloud Room 云岚厅	River Room 江河厅	Bamboo Room 竹韵厅
	Carbon in the Global Materials Economy **Fan Wu** Persistent Effects of Climate Policy Rollback under Delayed Recovery Pathways **Michiel Schaeffer** High climate sensitivity deepens key failures of solar radiation modification **Roberta Quadrelli** Tracking Mitigation and Technology Deployment: Measurement Foundations for Energy Transitions **Pete Smith** Additional Risks of Using Nature-based CDR in Overshoot Scenarios **Richard Catlow** De-fossilising Chemicals and Fuels	from ocean heat exchange to regional monsoons **Annika Högner** Overshoot pathway fingerprints persist after global temperature stabilization **Niklas Schwind** Cascaded emulation of Earth system models for impact evaluation with SCALES-MESH **Thomas Gasser** Exploring the effect of overshoot magnitude and reversal rate on climate and impact reversibility with a probabilistic reduced-complexity Earth system model	and water systems under climate overshoot.	
15:30 16:30	**Coffee break**			
16:30 16:45	**Plenary 3.Theme report back on central Science and Policy Insights** *Location: Harmony Hall (Plenary), 和合厅* *Chair: Inga Menke* Eight science and policy insights Panel: Relevance of overshoot in Asian context			
16:45 17:35	**Panel: Relevance of overshoot in Asian context** *Location: Harmony Hall (Plenary), 和合厅* *Chair: Inga Menke*			
17:35 18:00	**Closing Remarks** *Location: Harmony Hall (Plenary), 和合厅*			
18:00 20:00	**Dinner (optional)**			

The Overshoot Conference Podcast

The Overshoot Conference Podcast is a series in which experts discuss the challenges, trade-offs and opportunities of overshoot from different perspectives, as a preview of the key themes of the conference. Listen on the conference website: overshootconference.org/the-overshoot-conference-podcast, or on Spotify and Apple Podcasts.

Episodes

Episode 1: Climate overshoot: an introduction, with Carl Schleussner

Episode 2: Highest possible ambition under overshoot, with Joeri Rogelj

Episode 3: Carbon dioxide removal: sustainability constraints and opportunities, with Keywan Riahi

Episode 4: Earth system responses up to net zero and beyond, with Deliang Chen

Episode 5: Climate impact (ir)reversibility, with Debra Roberts

Episode 6: Overshoot legacy and tipping elements, with Jonathan Donges

Episode 7: Adaptation and adaptation limits under overshoot, with Kristie L. Ebi

Episode 8: Loss and damage, with Sindra Sharma

Episode 9: Legal and justice implications of overshoot, with Lavanya Rajamani

Episode 10: The Overshoot Conference goes to Beijing, with Carl Schleussner and Deliang Chen

Episode 11: Health implications of overshoot pathways, with Marina Andrijevic and Kristie L. Ebi

Tuesday, 24 November 2026

Opening

09:00 - 10:30, Harmony Hall (Plenary), 和合厅

Welcome
Deliang Chen - Tsinghua University
Keywan Riahi - IIASA
Keynote: Xiaoye Zhang - IPCC WGI Co-Chair
Introducing the UNEP Limiting Overshoot Report - Mirey Atallah - UNEP
Introducing the Overshoot Conference - Carl Schleussner and Deliang Chen
Moderation: Inga Menke, IIASA

Theme 1: Highest possible mitigation ambition under overshoot, peak and decline pathways

11:00 - 12:30, Harmony Hall (Plenary), 和合厅 Chairs: Joeri Rogelj, Mingyu Li

The Paris Agreement requires countries to pursue their "highest possible ambition" in their Nationally Determined Contributions (NDCs), while reflecting principles of equity and fairness. With the world on track to surpass 1.5°C of global warming, the meaning of Paris alignment is increasingly challenged. This session examines how the legal, political, and practical interpretation of highest possible ambition must evolve in the face of overshoot. Bringing together scholars, analysts, and practitioners from diverse disciplines, we invite contributions that explore the implications of Article 4.3 of the Paris Agreement (the need for a progression of the ambition of NDCs, always reflecting 'highest possible ambition') in this new climate reality. How should ambition be assessed in light of historical emissions? What responsibilities in terms of ambition arise for countries that have exceeded their fair share of atmospheric space? What does it imply for long-term carbon removal needs and obligations? How can climate governance adapt to ensure accountability and equity? By reframing ambition through the lens of a 1.5°C overshoot, this session seeks to redefine pathways for meaningful climate action in an era of deepening crisis.

Time	Presenter	Title	Page
11:10 - 11:23	Mingyu Li	Mapping the Feasibility Space of a 1.5 °C Future with a Million AI-Generated Pathways	9
11:23 - 11:36	Ryna Cui	Multispeed mitigation strategies to limit mid-century overshoot and return to 1.5°C	10
11:36 - 11:49	Meng Hou	From ambition to evidence: quantifying the temperature benefits of mitigation levers for NDC prioritization	11
11:49 - 12:02	Hannah Daly	National scenarios for return from overshoot — an Irish case study	12
12:02 - 12:15	Keywan Riahi	China's contribution to managing global temperature overshoot: insights from pathways around SSP2-COM	12

11:10 - 11:23 Submission 44

Mapping the Feasibility Space of a 1.5 °C Future with a Million AI-Generated Pathways

Mingyu Li[1,2], Xudong Zhang[3], Haewon McJeon[4], Rongqi Zhu[1], Joeri Rogelj[2,5,6], Mark Dekker[7,8], Carlos Rodriguez-Pardo[9,10,11], Fan Wu[1], Carl-Friedrich Schleussner[2,12], Peijie Zhou[3,13,14], Yang Ou[1,15]

[1]College of Environmental Sciences and Engineering, Peking University, Beijing, China. [2]International Institute for Applied System Analysis (IIASA), Laxenburg, Austria. [3]Center for Machine Learning Research, Peking University, Beijing, China. [4]Graduate School of Green Growth and Sustainability, Korea Advanced Institute of Science and Technology, Daejeon, Korea, Republic of. [5]Centre for Environmental Policy, Imperial College London, London, United Kingdom. [6]Grantham Institute for Climate Change and the Environment, Imperial College London, London, United Kingdom. [7]PBL Netherlands Environmental Assessment Agency, Hague, Netherlands. [8]Copernicus Institute of Sustainable Development, Utrecht Universiteit, Utrecht, Netherlands. [9]Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Milan, Italy. [10]CMCC Foundation - Euro-Mediterranean Center on Climate Change, Lecce, Italy. [11]RFF-CMCC European Institute on Economics and the Environment, Milan, Italy. [12]Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys) and the Geography Department, Humboldt-Universität zu Berlin, Berlin, Germany. [13]AI for Science Institute (AISI), Beijing, China. [14]National Engineering Laboratory for Big Data Analysis and Applications, Beijing, China. [15]Institute of Carbon Neutrality, Peking University, Beijing, China

Abstract

Efforts to limit warming to 1.5 °C are typically characterized using global indicators such as aggregate emissions, energy, and economic outcomes. However, such global benchmarks do not guarantee feasibility across regions, where rapid decarbonization unfold under heterogeneous constraints on technology deployment, energy system transformation, and development trajectories. Existing scenario benchmarks, including the AR6 database, do not require that all regions simultaneously satisfy these constraints due the limited regional mitigation pathways. Hence IAM ensembles remain structurally limited to identify regionally feasible pathways.

Here, we generate a million internally consistent futures covering global and R10 regions to assess regional feasibility of 1.5°C transitions. We use a generative deep learning framework trained on 1,188 scenarios in the AR6 database to produce trajectories across 48 macroeconomic, energy, and emission variables from 2010 to 2100. Scenario generation is formulated as learning a high-dimensional spatiotemporal distribution conditioned on climate categories (C1-C8), while preserving their cross-variable dependencies and

temporal dynamics. Physical consistency is enforced through constraints on energy balance, emissions accounting, and coherence between related system components.

We define regional feasibility as the ability of all regions to simultaneously satisfy multiple constraints, including realistic technology scale-up rates, energy system transformation speeds, development-related demand dynamics, and emissions reduction responsibilities across regions. Only 27% of pathways remain feasible at the global level, declining to 0.07% when all regions are evaluted simultaneously under 1.5°C transitions. For example, while solar deployment remains within aggregate limits in most pathways, required scale-up rates exceed feasible levels in regions such as India+ (66%) and Middle East (65%), where deployment must accelerate beyond observed or projected capacities. Feasible pathways also require a relocation of mitigation effort, with the Global North undertaking 2.9 percentage points greater emissions reductions of 2020-2050 share, while Global South regions retain later net-zero timings and more gradual transitions.

Comparing pathways within the C1 and C2 ranges reveals that overshoot leads to a trade-off between near-term feasibility and future reliance on carbon removal. At the global level, C2 pathways substantially improve feasibility for mitigation speed (38% to 92%) and solar scale-up (40% to 83%). Yet when every R10 region must comply, their C2 feasibility remains only 17% and 1%, respectively. C2 also improves regional compatibility with total energy-demand transitions (46% to 81%) and fair carbon-budget allocation (37% to 58%). However, this apparent flexibility is accompanied by heavier reliance on future removals: median cumulative BECCS increases from 335 to 354 Gt CO_2, while post-net-zero cumulative emissions become more negative, from −75 to −108 Gt CO_2. Crucially, all-region feasibility declines from 3% to 2% under fair CDR allocation and from 2% to 1% under bioenergy-sustainability constraints. Overshoot therefore eases several near-term constraints but shifts burdens across time and regions, raising governance questions over who deploys, finances, and bears the land-use and residual risks of future carbon removal.

11:23 - 11:36 Submission 115

Multispeed mitigation strategies to limit mid-century overshoot and return to 1.5°C

Ryna Cui, Rick Duke, Christoph Bertram, Nate Hultman, Steven Smith, Vincent Gu, Daniel Rochberg

Center for Global Sustainability, University of Maryland, College Park, USA

Abstract

It is no longer feasible to hold global temperature change to under 1.5°C, but options remain to minimize the duration and extent of mid-century overshoot and reduce temperatures to 1.5°C over the longer term. Achieving these dual objectives requires combining a full set of mitigation strategies to deliver comprehensive carbon dioxide (CO_2) and non-CO_2 emissions reductions. While this concept and the associated behaviors of these gases are well known in the science community, the large set of scenarios, policy options, and mitigation strategies has clouded conversations and precluded strong consensus around actions in international policy discussions. A sharper and simpler approach and staging strategy is needed that is informed quantitatively by the science and also resonates with the activities that can be implemented in the near term. As a first step toward this goal, based on the speed of their implementation and timeframe of their temperature impacts, we group these mitigation strategies into what we term “fast” and “slow” mitigation categories. When combined, we term this approach "multispeed mitigation”.

Using a global integrated assessment model (GCAM-CGS) coupled with a climate model (MAGICC), we develop a “multispeed mitigation” pathway that limits peak warming to 1.9°C in 2060 and returns to 1.5°C by 2130 by combining “fast mitigation” and “slow mitigation” strategies that link to plausible policy actions on appropriate timelines, and a consistent set of decomposition scenarios that deploy only one or multiple fast or slow strategies to quantify the temperature impacts by each policy strategy. We show that the multispeed mitigation pathway greatly lowers long-term temperature compared to the reference case (3.8°C by 2130) and peaks temperature decades earlier at a lower level compared to a pathway that relies solely on slow mitigation (2.3°C post-2100). Fast mitigation levers, particularly reducing key super pollutants and ending deforestation, largely determine temperature overshoot by contributing two-thirds of potential 2050 temperature reduction compared to one-third from slow mitigation levers like the global energy transition. Both levers remain critical for the long-term return to 1.5°C. By 2100, slow mitigation

levers contribute over 60% of the total reduction, while sustained fast mitigation strategies, like methane abatement from agriculture and waste sectors continue to have a strong impact and drive more reductions than carbon removal technologies. Our findings directly inform the ongoing policy discussion how to address global overshoot above 1.5°C, including policy-relevant international coordination strategies that situate energy transition efforts within a broader, structured, multispeed mitigation approach.

11:36 - 11:49 Submission 75

From ambition to evidence: quantifying the temperature benefits of mitigation levers for NDC prioritization

Alicia Hou, Teresa Bonserio, Anna Kanduth, Zarrar Khan, Neil Grant, Lara Welder, Michiel Schaeffer, Bill Hare

Climate Analytics, Berlin, Germany

Abstract

Article 4.3 of the Paris Agreement requires each successive Nationally Determined Contribution (NDC) to reflect a country's "highest possible ambition." With the world on track to surpass 1.5°C, and countries due to submit their next round of NDCs in 2030, fulfilling this requirement necessitates scientific evidence on which mitigation actions most effectively reduce peak temperature, shorten overshoot, and restore the possibility of returning global temperatures to below 1.5°C by the end of the century. It is generally known that different mitigation approaches do not deliver the same results, with some more effective at curbing near-term warming and others better at limiting peak temperature or reducing overshoot duration. However, the exact temperature benefits associated with individual mitigation approaches remain poorly quantified, leaving governments without a clear evidence base for prioritizing actions in their NDCs.

Here, we quantify the relative temperature benefits of three key mitigation measures, fossil fuel phase-out, targeted SLCF reduction, and land-sector mitigation. A key challenge to this quantification is that CO_2 and many short-lived climate forcers (SLCFs) are frequently co-emitted from the same sources, making it difficult to disentangle their individual temperature benefits. We address this challenge by using CO_2 emissions as a "lead gas" to anchor plausible, physically consistent trajectories for co-emitted SLCFs, selected from a large database of published Integrated Assessment Model scenarios — allowing us to separate the emissions reductions attributable to fossil fuel phaseout from those requiring targeted SLCF action. We then build hybrid emissions scenarios that swap in ambitious mitigation for individual measures and use MAGICCv7.5.3 to determine the temperature benefit of each measure.

Our results show that fossil fuel phase-out delivers the largest temperature benefit in both the near term (2050) and long term (2100), regardless of whether we start from an optimistic or pessimistic baseline. While targeted SLCF and land-sector mitigation play secondary roles in the long-term, their combined warming reductions account for roughly half of the total reduction achieved in the near-term. Post-overshoot, fossil fuel phase-out is necessary to plateau temperatures, but additional SLCF mitigation is required to drive temperatures back down. We demonstrate that within SLCF actions, methane mitigation delivers the largest temperature benefit, followed by HFC mitigation. Finally, we find that regardless of the starting baseline, air quality control measures produce only a small aerosol-unmasking effect, as the near-term warming caused by reductions of cooling aerosols is largely compensated by the cooling driven by reductions in CO_2 and warming aerosols. Together, these results provide scientific evidence on the relative importance of different mitigation measures for the next round of NDCs. Crucially, our findings demonstrate that returning temperatures to below 1.5°C by the end of the century requires both fossil fuel phase-out and targeted SLCF mitigation; neither measure can achieve this alone.

11:49 - 12:02 Submission 10

National scenarios for return from overshoot — an Irish case study

Hannah Daly, Roisin Moriarty, Neha Jaggeshar

University College Cork, Cork, Ireland

Abstract

At the first Overshoot Conference, we proposed a framework for how national energy systems models should evolve to inform "highest possible ambition" national mitigation action in an era of climate overshoot. That framework identified four dimensions against which national mitigation pathways should be assessed — adequacy, fairness, feasibility, and the practical mapping of transformation — and argued that most national modelling frameworks, inherited from earlier generations of energy technology transition analysis, are incapable of adequately representing them. This paper takes the framework from diagnosis to demonstration, presenting its first empirical application through new national model scenarios for Ireland.

We develop and contrast (at least) two scenarios with different mitigation logics. The first is a temperature stabilisation pathway, consistent with reaching and sustaining net-zero CO2 emissions from the energy system — the end-point of typical national modelling and policy – as well as temperature stabilisation of emissions from agriculture, forestry and other land use.

The second is a pathway depicting return-from-overshoot, in which Ireland contributes its fair share to peak-and-decline of global temperature, requiring deeper near-term mitigation effort, action on demand, sustained net-negative emissions, explicit mitigation of residual emissions, diversified carbon dioxide removal portfolios, and a transformation of agriculture and land use.

Contrasting the two scenarios demonstrates the practical difference between stabilising warming and actively reversing it, expressed in infrastructure requirements, land and carbon management, and the timing and scale of investment.

We show how such a scenario framework can support societal deliberation across the framework's dimensions. On adequacy: does a national pathway actually contribute to returning global temperature below 1.5°C, and by how much? On fairness: what does an equitable national contribution to global temperature reduction look like, given carbon debt and capability? On feasibility: what deployment rates, land use change, and demand-side action does return from overshoot demand, and are these credible? And on transformation: how can scenarios map actionable pathways and illustrate trade-offs for stakeholders under deep uncertainty?

We are equally explicit about limits. Models cannot internally resolve normative questions of adequacy and fairness, nor adjudicate feasibility, which are ultimately social and political. What they can do is provide quantified reference pathways: transparent, internally consistent benchmarks of what returning from overshoot would require at the national level, against which policy choices can be assessed and contested. We argue this is the appropriate role for national models in informing the required mitigation efforts under overshoot — not to prescribe societal questions, but to give societies the quantitative ground on which to deliberate them. The Irish case, a small open economy with strong fossil fuel dependence and a large land and agriculture sector, but with climate legislation requiring alignment with the Paris Agreement, offers transferable insights for national modelling communities elsewhere confronting the same challenge.

12:02 - 12:15 Submission 114

China’s contribution to managing global temperature overshoot: insights from pathways around SSP2-COM

Keywan Riahi[1], Setu Pelz[1], Tianpeng Wang[2], Junting Zhang[3], Yixiong Lu[3], Da Zhang[2], Xiaoye Zhang[3], Carl-Friedrich Schleussner[1]

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Abstract

Limiting global warming increasingly means confronting the possibility of temporarily exceeding 1.5°C. This raises a critical question for global climate action: what contribution should major emitters make to

minimizing the magnitude and duration of overshoot and enabling temperatures to decline thereafter? We explore this question for China, whose emissions trajectory will be central to both peak warming and the prospects for subsequently bringing temperatures back down.

We use China's SSP2-COM pathway (Zhong et al., 2025) as a concrete reference point. It reflects an ambitious transformation in which China reaches net-zero CO_2 around 2060 and substantial net-negative emissions thereafter. Yet China's contribution to managing overshoot cannot be understood from its national pathway alone: the resulting global temperature outcome depends fundamentally on how China's effort relates to action elsewhere. We therefore ask what different interpretations of this relationship imply for peak warming, the subsequent temperature decline, and the possibility of returning to 1.5°C.

Three perspectives illustrate the range. If China's SSP2-COM pathway represents its cost-effective contribution to global mitigation, global warming peaks at a median 1.85°C (1.70–2.03°C), and only around one-fifth of pathways return below 1.5°C by 2100. From a historical-responsibility perspective, giving every person the same cumulative fossil CO_2 emissions as China under SSP2-COM—around twice the global average—would result in substantially higher warming of 2.4–3.0°C, without subsequent temperature decline. At the other end of the spectrum, if China follows SSP2-COM while the rest of the world achieves the highest levels of mitigation ambition represented in the scenario ensemble, median peak warming can be limited to 1.66°C (1.60–1.76°C), with around 80% of pathways returning below 1.5°C by 2100.

These contrasting outcomes highlight a central challenge for the overshoot debate: national net-zero targets cannot be evaluated independently of the global mitigation effort and the temperature outcome they collectively produce. The relevant question is not simply whether China reaches net zero, but how its pace of reductions, timing of net zero, and subsequent removals contribute to limiting peak warming and enabling global temperature decline—while considering alternative principles for distributing effort internationally.

We use these results to motivate a broader research agenda on China's role in managing overshoot. By systematically exploring stronger and weaker mitigation efforts in China alongside alternative levels of global action and climate-system responses, we can identify combinations that robustly minimize peak warming and overshoot duration, clarify the trade-offs between earlier mitigation and later carbon removal, and assess what would be required to keep a return to 1.5°C within reach.

Theme 2: Earth System responses to net negative emissions and CDR

11:00 - 12:30, Cloud Room, 云岚厅 Chairs: Biqing Zhu, June-Yi Lee

Uncertainties in the Earth System Response during and after a state of overshoot remain substantial and will determine the potential for reversing global warming. This session explores the Earth System's transient responses transition to through net zero and to net negative emissions, as well as and to Carbon Dioxide Removal (CDR). We seek to understand whether the Earth System responds differently to global net negative emissions compared to the period leading up to net zero, as these dynamics determine dictate peak temperatures, overshoot duration, and the effectiveness of CDR. CDR approaches vary widely broadly, from regrowth of natural biomes to engineered extraction and ultimate storage of CO2 from the atmosphere. Each approach has its own unique challenges in terms of scalability, effectiveness, and durability of ultimate storage. In particular, resource requirements and environmental footprints may be limiting factors for future large-scale CDR deployment. In this session, we welcome submissions that improve improving our understanding of the Earth System response up to net zero and beyond, alongside strategies for sustainable CDR deployment. We invite contributions on whole Earth System perspectives, carbon cycle dynamics, and observational insights into climate overshoot. We particularly encourage research on exploring sustainable CDR scaling, mitigation trade-offs, and robust strategies to hedge against risks like carbon re-release. We also welcome submissions that bridge these areas by examining both the Earth System's physical responses and the enabling conditions or barriers related to markets, policy, finance, verification, and public perception.

Time	Presenter	Title	Page
11:03 - 11:20	Soon-Il An	Climate System Inertia: From Hysteresis under CO_2 Mitigation to Continued Warming after Net-Zero Emissions	14
11:20 - 11:35	Long Cao	Ocean Carbon Cycle Response to Carbon Dioxide Removal: Insights from Earth System Modeling Perspective	15
11:35 - 11:50	Chao Li	Nonlinear Earth System Responses to Atmospheric CO_2 Forcing and Its Reversal: The Role of Multiscale Ocean Memory	15
11:50 - 12:05	Xinrui Liu	Land-based carbon dioxide removal under climate overshoot	16
12:05 - 12:20	Xifeng Zhang	Wetland Methane Emissions under Climate Overshoot: Responses and Reversibility	16

11:03 - 11:20 Submission 12

Climate System Inertia: From Hysteresis under CO_2 Mitigation to Continued Warming after Net-Zero Emissions

SOON-IL AN

Yonsei University, Seoul, Korea, Republic of

Abstract

Achieving net-zero or negative CO_2 emissions is essential for limiting climate change, yet the climate system may not retrace its warming trajectory as forcing declines. We investigate this path dependence using CESM1.2 and CESM2 experiments in which atmospheric CO_2 concentrations or emissions are increased and subsequently reduced, including a 600-year zero-emission simulation. A spatial measure of hysteresis shows that approximately 89% of Earth's surface exhibits irreversible surface-temperature responses, with the strongest signals over the Southern Ocean, Arctic and North Atlantic.

During CO_2 ramp-up, a cold anomaly develops in the northern North Atlantic, whereas a warm anomaly appears during ramp-down. This reversal, sluggish Southern Hemisphere cooling and delayed Atlantic Meridional Overturning Circulation adjustment produce pronounced hysteresis in major climate phenomena, including the Intertropical Convergence Zone, monsoons and ENSO. In the zero-emission experiment, global-mean surface temperature continues to rise for centuries even as atmospheric CO_2 declines.

Energy-balance diagnostics link this additional warming to a progressive weakening of radiative restoring strength through evolving cloud and lapse-rate feedbacks associated with slow ocean adjustment and AMOC variability. A nonlinear two-layer energy-balance model with state-dependent feedback reproduces the sustained warming, whereas a constant-feedback model does not. Ocean memory and evolving radiative feedbacks therefore act as complementary sources of climate-system inertia. Climate

stabilization is intrinsically pathway dependent: net-zero emissions are indispensable, but they do not imply an immediate halt to warming or a rapid return toward the preceding climate state.

11:20 - 11:35 Submission 63

Ocean Carbon Cycle Response to Carbon Dioxide Removal: Insights from Earth System Modeling Perspective

Long Cao

ZheJiang University, Hangzhou, China

Abstract

Under the current trajectory of global warming, conventional emission reduction strategies alone appear insufficient to constrain global temperature rise to the safe thresholds targeted by international climate goals. In response, alternative climate intervention approaches—broadly categorized as carbon dioxide removal (CDR) and solar radiation modification (SRM)—have attracted growing scientific and policy interest. CDR refers to a suite of techniques designed to actively lower atmospheric CO_2 concentrations, by amplifying natural carbon sinks in the ocean and terrestrial biosphere, or by directly capturing CO_2 from ambient air. A robust, process-level understanding of how the Earth system responds to CDR deployment and the resulting negative emissions is fundamental to assessing its potential climate outcomes, environmental side effects, and feasibility.

In this presentation, I will share findings from a series of Earth system modeling experiments investigating the global climate and carbon cycle responses to several prominent CDR pathways. The focus will be on the ocean carbon cycle response. CDR methods investigated include direct air CO2 removal, ocean iron fertilization, and ocean alkalinity enhancement. Particular emphasis will be placed on disentangling the interconnected physical, chemical, and biological mechanisms that drive the ocean carbon cycle response and climate feedbacks triggered by large-scale negative emissions.

11:35 - 11:50 Submission 68

Nonlinear Earth System Responses to Atmospheric CO_2 Forcing and Its Reversal: The Role of Multiscale Ocean Memory

Chao Li[1], Hongmei Li[2]

[1]Max Planck Institute for Meteorology, Hamburg, Germany. [2]Max Planck Institute for Marine Microbiology, Bremen, Germany

Abstract

Earth system recovery under declining atmospheric CO_2 need not retrace its response to increasing forcing because ocean circulation, heat and carbon storage, and tropical hydroclimate adjust on different timescales. We investigate these nonlinearities with the Max Planck Institute Earth System Model using idealized CO_2-reversal and freshwater-perturbation experiments, together with large ensembles of emissions-driven MPI-ESM-LR simulations with an interactive carbon cycle. In the reversal experiments, atmospheric CO_2 increases to eight times its preindustrial value, remains fixed for 6,000 years to permit deep-ocean adjustment, and then decreases at the same rate to preindustrial levels.

The Atlantic Meridional Overturning Circulation (AMOC) exhibits no state-dependent hysteresis under either CO_2 forcing or anomalous freshwater input over North Atlantic deep-water formation regions. Its recovery trajectory lies above its weakening trajectory, but this offset reflects transient, rate-dependent adjustment rather than an alternative equilibrium. AMOC stability is governed jointly by anomalous freshwater forcing and intensified tropical evaporation in a warmer climate.

These circulation changes are connected to broader nonlinear responses. During CO_2 ramp-up, Southern Ocean heat uptake and AMOC weakening drive a southward migration of the Intertropical Convergence Zone (ITCZ), which slows sixfold as overturning weakening decelerates. During ramp-down, the ITCZ continues to migrate southward rather than recovering immediately. Persistent Southern Ocean heat release sustains northward cross-equatorial energy transport, while delayed equatorial Pacific cooling places the ITCZ in a high-sensitivity regime, producing its fastest migration of the CO_2 cycle.

Ocean heat and carbon uptake during ramp-up also differ markedly from their release during ramp-down. Strong AMOC recovery enhances the release of stored heat and carbon, contributing to surface cooling. In the emissions-driven ensembles, sustained negative emissions eventually turn both ocean and land from CO_2 sinks into sources after approximately 2100, with substantial uncertainty arising from internal variability.

Together, these results identify multiscale ocean memory as a common control on AMOC stability, carbon-cycle asymmetry, and tropical hydroclimate adjustment. They demonstrate that reducing atmospheric CO_2 does not produce immediate climate recovery and may temporarily amplify regional change, with important implications for deep mitigation and negative-emission strategies.

11:50 - 12:05 Submission 73

Land-based carbon dioxide removal under climate overshoot

Xinrui Liu[1], Thomas Gasser[1,2], Biqing Zhu[1,3], Danni Zhang[1,4], Daniel Goll[2], Julien Alléon[2]

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Abstract

As the 1.5 °C temperature target becomes increasingly difficult to achieve without temporary overshoot, understanding the potential of land-based carbon dioxide removal (CDR), including bioenergy with carbon capture and storage (BECCS) and afforestation/reforestation (A/R), becomes increasingly important. The effectiveness and durability of these CDR options are altered by Earth system feedbacks, including climate and socioeconomic impacts on biomass productivity and carbon losses from disturbances such as wildfire. Therefore, accounting for these feedbacks is essential for assessing the robustness of land-based CDR and its contribution to achieving lower warming levels following overshoot.

Here, we assess the capacity and role of land-based CDR across overshoot scenarios using the reduced-complexity Earth system model OSCAR. We extend OSCAR with new crop and wildfire modules to represent food-crop residue and bioenergy-crop productivity and to quantify wildfire-driven carbon losses in terrestrial ecosystems. We apply this framework to a broad ensemble of RESCUE (Response of the Earth System to overshoot, Climate neUtrality and negative Emissions) scenarios, explicitly accounting for interactions among CDR deployment, land use, climate change, and wildfire risk. This enables a probabilistic assessment of land-based CDR across diverse overshoot magnitudes and durations.

By jointly accounting for CDR deployment and climate-driven carbon dynamics, we evaluate the negative emissions from BECCS and carbon uptake through A/R during both the overshoot and subsequent temperature-decline phases. Our results provide insights into the feasible contribution of land-based CDR to temperature reversal and highlight how Earth system feedbacks and land-use assumptions can influence its effectiveness. These findings demonstrate the importance of representing climate-driven carbon losses and land-use trajectories when assessing mitigation pathways and informing land-use strategies for achieving net-negative emissions after overshoot.

12:05 - 12:20 Submission 90

Wetland Methane Emissions under Climate Overshoot: Responses and Reversibility

Xifeng Zhang[1], Tom Colligan[2], Ben Poulter[2], Juliette Bernard[3], Zhen Zhang[1]

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Abstract

Wetland methane emissions are an important component of the natural methane cycle, yet their response to climate overshoot and subsequent recovery remains poorly understood. Using overshoot simulations from the Wetland and Methane Intercomparison Project (WIEMIP), we examine how the magnitude, timing, and persistence of wetland CH_4 responses vary across overshoot pathways. We initially focus on LPJ-EOSIM and subsequently extend the analysis to other WIEMIP models that provide suitable methane and wetland extent outputs. We compare peak responses, response lags, cumulative anomalies, and recovery

trajectories across overshoot pathways and between the warming and cooling phases. We characterize reversibility by comparing methane–climate relationships along the warming and cooling trajectories and quantify the extent to which methane responses diverge under comparable climate conditions. We also relate changes in methane emissions to wetland extent and key environmental controls to investigate whether delayed ecosystem responses contribute to persistent methane anomalies after peak warming. Together, these analyses allow us to assess whether wetland methane emissions recover as climate conditions stabilize or exhibit hysteresis between warming and cooling. This work will help assess the reversibility of wetland methane responses to climate overshoot and improve our understanding of the persistence of wetland methane feedbacks after peak warming.

Theme 4: Climate impact (ir)reversibility

11:00 - 12:30, River Room, 江河厅 Chairs: Debra Roberts, Adriano Vinca

Achieving global temperature decline after exceeding 1.5C overshoot does not guarantee the reversal of local climate impacts. To further complicate the picture for policy-makers and practitioners, regional climate patterns will continue to change even under global temperature stabilization as Earth System components keep adjusting and equilibrating. Vulnerabilities and exposure dynamics in human and natural communities may differ substantially before and after overshoot, and will be affected by the extent and length of overshoot and the types of CDR deployed. This session tries to advance our understanding of key questions such as how a world after overshoot is different from a world without it, and for whom? What are the consequences of different overshot magnitudes and durations of exceedance? What are the benefits of long-term global warming reversal compared to stabilization at peak warming? Specific focus will be given to understanding irreversible impacts on human timescales, i.e. in oceans, the bio- and cryosphere, and the already at risk ecosystems. Beyond changing climate hazards, and the temporal interrelations of overshoot pathways beyond changing climate hazards.

Time	Presenter	Title	Page
11:05 - 11:17	Young-Min Yang	Sustained European agricultural risk beyond net-zero and negative CO2 emissions	18
11:17 - 11:29	Lujia Zhang	Reversibility of Hydroclimate Extremes under Carbon Dioxide Removal: The Role of Atmospheric Rivers	19
11:29 - 11:41	Kyungmin Park	Joint Analysis of Earth System and Regional Climate Responses Across Global Warming Overshoot, Peak, Decline and Stabilization	19
11:41 - 11:53	Wendan Zhang	Irreversible and Distributional Impacts of Temperature Overshoot	20
11:53 - 12:05	Yang Gao	High-Resolution Earth System Modeling Reveals Underestimated and Path-Dependent Heatwave Risks	21

11:05 - 11:17 Submission 15

Sustained European agricultural risk beyond net-zero and negative CO2 emissions

Young-Min Yang[1], June-Yi Lee[2], Soon-Il An[3]

[1]Jeonbuk National University, JeonJu, Korea, Republic of. [2]Pusan National University, Busan, Korea, Republic of. [3]Yonsei University, Seoul, Korea, Republic of

Abstract

Carbon dioxide removal (CDR) is widely expected to reverse the agricultural impacts of climate warming, yet its net effect on crop production remains uncertain. Here, we assess this assumption for European agriculture by comparing a zero-emissions-commitment simulation with an active CDR simulation using CESM1.2, together with seven Earth system models from ZECMIP. Applying empirical damage functions for wheat, maize, soybean, and rice across 32 European countries, we distinguish the contributions of climate and non-climate drivers. As expected, CDR reduces damages associated with warming, drought, and compound climate extremes. However, it also diminishes the fertilization benefit of elevated atmospheric CO_2, and this effect outweighs the climatic gains. By 80 years after emissions cease, atmospheric CO_2 declines below the present-day level in the CDR scenario, causing the fertilization effect to shift from a benefit to a net loss. Consequently, total crop damage is greater under CDR than under zero-emissions commitment across all countries examined. This conclusion is robust to alternative damage-function formulations. Our findings do not question the value of CDR for climate mitigation, but they highlight an overlooked agricultural trade-off that should be considered when evaluating future carbon removal pathways.

11:17 - 11:29 Submission 40

Reversibility of Hydroclimate Extremes under Carbon Dioxide Removal: The Role of Atmospheric Rivers

LUJIA ZHANG, Laibao Liu, Hao Pan

The University of Hong Kong, Hong Kong, Hong Kong

Abstract

Insufficient global emissions reductions make a temporary overshoot of the Paris Agreement's 1.5 °C warming goal increasingly likely, placing greater reliance on carbon dioxide removal (CDR) to bring global warming back below the target (Schleussner et al., 2024; Rogelj et al., 2023). Although sustained net-negative CO_2 emissions can lower atmospheric CO_2 concentrations and reduce global-mean warming after an overshoot, regional hydroclimate and associated extremes may not retrace their warming trajectories, resulting in widespread hysteresis and incomplete reversibility (Liu et al., 2025; Mondal et al., 2023; Kim et al., 2022). Regional precipitation changes are projected to be irreversible over approximately 58% of the global area, with pronounced hotspots in the tropical Pacific, global monsoon regions and the Himalayas (Kim et al., 2022). For agroecological drought, only 73% of the emissions-driven increase in frequency is reversed when cumulative removals balance prior emissions, whereas drought severity during the CDR phase remains 65% greater than during the corresponding emissions phase (Liu et al., 2025). The frequency of rapid transitions between dry and wet conditions also increases with warming (Tan et al., 2023), but whether precipitation whiplash reverses during CO_2 drawdown remains unknown. More fundamentally, the physical mechanisms governing the asymmetric responses of hydroclimate extremes to warming and subsequent CDR remain poorly understood.

Atmospheric rivers (ARs) are major corridors of water-vapour transport and important regulators of regional hydrological extremes (Zhu and Newell, 1994; Zhu and Newell, 1998). Their frequency and intensity have also been shown to exhibit hysteresis under CDR (Chung et al., 2026), raising the possibility that changes in AR activity may help explain the incomplete reversibility of hydroclimate extremes. Here we analyse daily output from the TIPMIP experiments (Jones et al., 2026), spanning warming to 2 and 4 °C, zero-emission stabilization and subsequent negative-emission cooling pathways. We identify extreme wet and persistent dry events and distinguish isolated events from those forming dry-to-wet and wet-to-dry whiplash sequences. By comparing warming, stabilization and cooling pathways at matched global warming levels, we quantify pathway-dependent changes in event frequency, duration and transition timing, and assess the contribution of changes in AR occurrence and intensity to the reversible and residual components of each event type. This framework provides a process-based assessment of how effectively CDR can reverse regional hydroclimate risks beyond the recovery of global-mean temperature.

11:29 - 11:41 Submission 65

Joint Analysis of Earth System and Regional Climate Responses Across Global Warming Overshoot, Peak, Decline and Stabilization

Kyungmin Park[1,2], Carl-Friedrich Schleussner[3], Camilla Mathison[4], Roland Séférian[5], Andrea Dittus[6], Harry Zekollari[7]

[1]Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan. [2]Tohoku University, Sendai, Japan. [3]International Institute for Applied Systems Analysis, Laxenburg, Austria. [4]Met Office Hadley Centre, Exeter, United Kingdom. [5]Météo-France, Toulouse, France. [6]University of Reading, Reading, United Kingdom. [7]Université libre de Bruxelles, Brussels, Belgium

Abstract

An overshoot, peak and decline (OSPD) pathway followed by post-net-zero CO_2 stabilization contains distinct Earth system (ES) and regional climate responses as they adjust on different timescales and retain a legacy of the preceding forcing and temperature histories. Therefore, Global warming level (GWL) alone is insufficient to determine whether the broader climate system has recovered. We extend conventional target-based GWL analysis into a model-specific comparison framework spanning exceedance, peak, reversal and stabilized warming states. The framework jointly evaluates the response to global warming, the degree of reversibility between pre- and post-peak, outcomes after reversing warming from the peak, and differences associated with overshoot characteristics and pathway histories.

We apply the analysis framework to long-term (~2300 yr) CMIP6 SSP1-2.6 and SSP5-3.4-OS simulations from 12 Earth System Models (ESMs) and global sea level emulators. The integrated analysis includes Earth's energy imbalance (EEI), depth-resolved ocean heat content (OHC), Atlantic Meridional Overturning Circulation (AMOC), total global-mean sea-level rise (GMSLR), and regional temperature and precipitation. The robustness of the results is assessed using paired-model differences and sign agreements across the 12 ESMs.

Results reveal the different ES responses from partial recovery to continued change. EEI decreases as greenhouse gases decrease but recover only partially and asymmetrically across latitude bands. AMOC strengthens after its peak weakening but remains below its pre-industrial state, with different recovery rates among models and pathways. In contrast, OHC, particularly below 700 m, and GMSLR continue increasing during temperature decline and post-net-zero CO_2 stabilization, showing no endpoint reversal by 2300. These different ES adjustments are associated with nonuniform regional climate recovery. Widespread post-peak cooling accompanies declining EEI, while AMOC changes during the OSPD pathway contribute to change in temperature in the high latitude by modifying ocean heat transport. Therefore, regional temperature patterns are not fully restored at approximately matched GWLs. Precipitation responses are less spatially consistent and more model-dependent than temperature responses.

These results demonstrate that returning to or stabilizing at a target GWL reduces surface warming but does not restore an equivalent ES or regional climate states. OSPD assessment should therefore complement endpoint warming with peak warming, cumulative thermal exposure, cooling rate and continuing adjustment of ES components.

11:41 - 11:53 Submission 109

Irreversible and Distributional Impacts of Temperature Overshoot

Wendan Zhang[1], Franziska Piontek[2], Xiaojia He[1], Zhi Wang[1]

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Abstract

Keeping global mean temperature below 1.5 °C without exceedance is now widely considered unlikely, making overshoot pathways increasingly central to climate policy. Yet overshoot is often framed as a temporary detour with limited lasting consequences, which understates the risk. Overshoot can cause irreversible impacts on human timescales, with severity determined by its magnitude and duration and unevenly distributed across regions. Policies that tolerate overshoot may lock in harm that cannot be undone, and addressing these heterogeneous impacts requires differentiated policy attention rather than uniform stabilization targets. We review the literature and synthesize evidence from 72 recent studies spanning physical, ecological, and socioeconomic dimensions to assess irreversible and distributional impacts.

Irreversibility concentrates in slow-responding Earth system components with large thermal or biogeochemical inertia. Permafrost carbon losses are largely unrecoverable. Deep ocean deoxygenation and steric sea level rise, glacier mass loss, and polar ice sheet retreat persist for centuries after peak warming, with the Greenland Ice Sheet exhibiting hysteresis and does not fully regrow after overshoot. These systems continue to store, transport, or release heat and carbon long after atmospheric temperature stabilize. Coral reefs, the North Atlantic subpolar gyre, and tropical forests may be at risk of tipping. Additionally, regional climate signals, such as precipitation and Intertropical Convergence Zone position, show only partial reversal. Beyond these physical impacts, the most enduring damages fall on socioeconomic systems and human well-being. When adaptive limits are exceeded, economic damages, displacement, health disruptions, loss of cultural heritage, and biodiversity loss are often irreversible.

Impacts are distributed unevenly across social groups and geographies. Non-OECD countries, vulnerable populations, and low-adaptive-capacity communities bear disproportionate harm, such as higher economic damages and elevated heatwave exposure. Regionally, detrimental effects are driven by distinct biophysical processes. Equatorial and low-latitude regions are projected to experience more severe decline in coral calcification, despite larger absolute temperature changes at higher latitude. Northern high-latitude regions face permafrost carbon loss, while glaciated basins experience varying glacier mass loss. Tropical Africa,

the Amazon, and South Asia are subject to altered water availability from Intertropical Convergence Zone shifts, affecting over 1.8 billion people. Overshoot is projected to widen global inequality and compound existing equity and justice challenges, particularly for systems and communities with low adaptive capacity.

The severity of irreversible loss depends on cumulative magnitude and duration of exceedance, often expressed as degree-years of overshoot. Overshoot depth, duration, and the strategy used to end it jointly determine the distribution and scale of locked-in harm. Overshoot-and-recovery policy framings should therefore explicitly account for these uneven, delayed, and irreversible costs, particularly for at-risk ecosystems and communities, rather than treating stabilization at any level as equivalent to avoidance.

11:53 - 12:05 Submission 71

High-Resolution Earth System Modeling Reveals Underestimated and Path-Dependent Heatwave Risks

Yang Gao[1], Xiuwen Guo[2], Xiaojie Guo[1], Deliang Chen[2]

[1]Ocean University of China, QingDao, China. [2]Tsinghua University, BeiJing, China

Abstract

This study develops a new-generation, high-resolution Earth system model to investigate increasingly severe large-scale heatwaves and their environmental impacts under global warming. With spatial resolution improved from 100 km to 10 km, the model explicitly resolves oceanic mesoscale eddies, incorporates global 10 m land-cover data and urban vegetation processes, and refines atmospheric chemistry and aerosol microphysics. These advances substantially improve simulations of sea-surface temperature gradients, vegetation distribution, and aerosols.

The results show that oceanic anomalies enhance atmospheric baroclinicity and modulate the westerly jet, thereby promoting the formation and persistence of Eurasian blocking highs. Blocking systems further intensify heatwaves through persistent subsidence warming and land-surface energy feedbacks. The new model corrects the systematic underestimation of heatwave intensity and strengthening trends in conventional models, suggesting that annual heatwave days could increase more than tenfold in the future.

Notably, high-resolution simulations indicate that organized heatwaves may increase as much under lower warming as under higher warming. Reducing background thermodynamic warming therefore cannot eliminate residual risks arising from atmospheric dynamics. During climate overshoot and subsequent temperature decline, regional extreme-event risks may not decrease in step with global mean temperature. Ocean memory and atmospheric circulation adjustments jointly shape risk evolution, while model resolution critically affects the reliability of risk assessments. Beyond achieving mitigation targets, major challenges remain in identifying key dynamical processes, understanding pathway-dependent climate legacies, and determining the limits of adaptation.

Theme 6: Health implications of overshoot pathways

11:00 - 12:30, Bamboo Room, 竹韵厅 Chairs: Marina Andrijevic, Kristie L. Ebi

Overshoot pathways fundamentally reshape the timing, magnitude and distribution of climate-attributable health risks, with peak temperature, duration of overshoot and rate of decline jointly determining the overshoot health penalty. This theme focuses on quantifying how alternative overshoot profiles translate into changes in mortality, morbidity, and health system stress through pathways such as heat, air pollution, undernutrition, infectious diseases and extreme events, and on attributing these changes to physical and socioeconomic drivers alongside overshoot, peak and decline pathways. We invite contributions that explicitly link overshoot pathway characteristics to health outcomes using tools including epidemiological models, impact functions, integrated assessment models, and health burden projections. Key questions include: How sensitive is the overshoot health penalty to overshoot pathway characteristics in the near- and long-term? How do different overshoot magnitudes and durations affect adaptation requirements, residual health risks and limits to adaptation? How can health outcome metrics be better integrated into scenario design, model evaluation and risk framing for overshoot pathways?

Time	Presenter	Title	Page
11:05 - 11:15	Kristie Ebi	The reality of entering an overshoot trajectory necessitates shifts in climate and health research	22
11:15 - 11:25	Shaohui Zhang	Global air pollution pathways and health outcomes in the new SSPs towards below 2 °C	23
11:25 - 11:35	Marco Springmann	The health implications of climate change mitigation pathways	24

11:05 - 11:15 Submission 99

The reality of entering an overshoot trajectory necessitates shifts in climate and health research

Kristie Ebi[1], Jeremy Hess[1], Tarik Benmarhnia[2]

[1]University of Washington, Seattle, USA. [2]University of California at San Diego, San Diego, USA

Abstract

Exceeding the Paris Agreement goal of 1.5°C is projected to result in significant consequences for population health and health systems, including increased morbidity and mortality from extreme weather and climate events; expansion in the geographic range, seasonality, and intensity of transmission of hundreds of infectious diseases; declines in food and water security and safety; greater nutrition-related illnesses and deaths; more respiratory diseases from declining air quality; and increased health consequences of sea level rise, other environmental changes, and social disruption.

To provide policy-relevant insights under overshoot pathways, climate and health research needs to shift its focus to what overshoot pathways could mean for population health and health systems. First, research needs to recognize the higher likelihood of exposures out of historical range and associated unprecedented impacts, in the content of development. Exposure trends have implications for how population health impacts are studied, projected, and managed. Attention to feedbacks, the impact of these feedbacks on population health inequities, and interactions between inequities and adaptation options are important to assess. Strategies supporting disaster risk reduction and recovery are more important with overshoot trajectories.

Second, most health research continues to study exposures in isolation, yet co-occurring and sequential hazards, like heat with wildfire smoke and drought with food insecurity, typically amplify health effects, highlight the limits to adaptation, and complicate and slow recovery. Overshoot not only increases the probability of more severe hazards and interactions between compound hazard exposures, but also the probability of increasing population vulnerability from repeated shocks. Existing adaptation frameworks rarely account for compound exposures, and the populations most affected are often those with the least institutional and financial capacity to respond.

Third, the community needs to prioritize vulnerability management and adaptation, including strategies for coordinated risk governance. Risk management decisions in one sector (e.g., interruption of electricity transmission to reduce wildfire risk) can complicate risk management in another (e.g., use of mechanical

cooling to protect against extreme heat) and further amplify risks. Research is needed that links responses to interacting hazards, exposures, and vulnerabilities across sectors and scales, and that identifies opportunities to limit maladaptation.

Fourth, overshoot strengthens the case for research where adaptation and mitigation converge, such as active mobility, whose health co-benefits are increasingly well evidenced. This convergence runs in both directions: shifting trips from cars to walking and cycling cuts transport emissions, while the physical activity gained builds the cardiometabolic health and resilience that overshoot conditions will increasingly test. Research priorities therefore include developing shared co-benefit metrics and generating evidence from the low- and middle-income and Indigenous communities most exposed and vulnerable to overshoot pathways; these groups remain underrepresented in the current evidence base.

Finally, climate and health research should explore the interactions between overshoot pathways and other major stressors including demographic shifts, urbanization, technology development (including AI), and governance challenges.

11:15 - 11:25 Submission 18

Global air pollution pathways and health outcomes in the new SSPs towards below 2 °C

Shaohui Zhang, Zbigniew Klimont, Gregor Kiesewetter, Oliver Fricko, Volker Krey

International Institute for Applied Systems Analysis (IIASA), Wien, Austria

Abstract

Air pollution remains a major global environmental and public health challenge despite substantial improvements in air quality in many regions over recent decades. Currently, air pollution pathways used in climate assessments have not fully reflected recent advances in emission-control policies, technological change and energy-system transformation.

Here, within the framework of the Intergovernmental Panel on Climate Change (IPCC) and the Scenario Model Intercomparison Project (ScenarioMIP), we assess the mitigation potential and air-quality implications of greenhouse gas (GHG) and air pollutant emissions in the new Shared Socioeconomic Pathways (SSPs).

Using the integrated assessment framework MESSAGEix–GLOBIOM–GAINS, we quantify sector- and fuel-specific emission pathways and their implications for air quality through 2100 across a range of socioeconomic and climate scenarios.

The SSP2-Low marker scenario limits warming to below 2 °C with a 67% probability, reaching net-zero CO_2 emissions around 2070 and net-zero GHG emissions by 2100. By 2100, renewables provide 82% of primary energy and 97% of electricity. The scenario follows only unconditional nationally determined contributions (NDCs) in the near term and reaches national net zero targets later than currently announced, resulting in a mid-century carbon removal gap that existing commitments do not fully address.

Emissions of major air pollutants, including NO_x, SO_2 and black carbon (BC), decline substantially over the twenty-first century, due to rapid decarbonization and electrification, together with the implementation of stringent air pollution controls, drive particularly large reductions in emissions from the power, industrial, transport and residential sectors.

Despite these reductions, population-weighted mean $PM_{2·5}$ concentrations, including natural sources, remain above the World Health Organization (WHO) air quality guideline of 5 $\mu g\, m^{-3}$ in Africa, India+ and China+ even under the most ambitious scenarios. Anthropogenic $PM_{2·5}$ concentrations, however, fall below the guideline, indicating that natural sources become increasingly important as anthropogenic emissions decline. The combined implementation of climate and air pollution mitigation measures could reduce the associated health burden by approximately 60–70%.

Our results reveal substantial regional and sectoral differences in the air quality benefits of climate mitigation and demonstrate considerable potential for simultaneous reductions in climate and air pollution impacts. The new SSP-based pathways provide an integrated basis for assessing these interactions and

highlight the importance of aligning climate mitigation, energy transformation and air pollution control to maximize health and environmental benefits over the coming decades.

11:25 - 11:35 Submission 84

The health implications of climate change mitigation pathways

Marco Springmann

University College London, London, United Kingdom. University of Oxford, Oxford, United Kingdom

Abstract

The pricing of greenhouse gas emissions is one of the main economic levers for reducing greenhouse gas. The implications that emissions pricing could have for economic output have been well researched. However, less is known about the feedback effects on food demand and the associated health implications.

Here, we use a comparative risk assessment framework of diet and weight-related risks to estimate the potential impacts of price-related changes in food consumption for a set of emissions pricing trajectories. The trajectories include mitigation scenarios of low to high ambition, including overshoot pathways. The comparative risk assessment includes risk factors established in the epidemiological literature such as low intake in fruits, vegetables, legumes, nuts, and whole grains; high intake of red and processed meat; and being underweight, overweight, and obese. In the model, changes in these risk factors are linked to changes in cause-specific mortality, including from coronary heart disease, stroke, site-specific cancers, type-2 diabetes mellitus, and respiratory diseases.

We use a demand model with a new set of food-price elasticities to relate changes in food prices from emissions pricing to changes in food demand. The elasticities are based on a comprehensive meta-analysis of own and cross-price elasticities. We use a machine learning algorithm to adapt the elasticities to each country and its projected food consumption along baseline pathways. To alleviate the potential burden of emissions pricing for food-insecure populations, we implement several compensation mechanisms, including revenue recycling and exemption for health-sensitive foods from emissions pricing. Food security impacts are captured through changes in weight levels, in particular underweight, and in a dedicated analysis, we use an additional statistical model that specifically resolves the association between energy intake and undernourishment.

The results indicate potential health benefits from reductions in diet and weight-related risk factors that increase up to an inflection point after which greater emissions pricing negatively affects population health through increases in food insecurity. Compensation mechanisms increase both near and long-term health benefits, especially in vulnerable populations. In addition, they delay the inflection point such that most mitigation pathways could be achieved without negatively affecting dietary health and mortality.

Theme 3: Technological solutions for decarbonization and negative emissions

14:00 - 15:30, Harmony Hall (Plenary), 和合厅 Chairs: Alessio Mastrucci, Dabo Guan

As the world edges closer to breaching the 1.5°C threshold, technological innovation in decarbonisation and negative emissions is indispensable to managing climate overshoot. This session invites contributions on low-carbon and carbon-removal technologies capable of reducing, neutralising, and reversing cumulative emissions. We welcome submissions on the benefits and pathways of decarbonisation across highly emitting sectors, such as power, industry, and transport, as well as the built environment, buildings, infrastructure, and agriculture, alongside engineered and nature-based carbon dioxide removal (CDR) approaches. Studies examining techno-economic feasibility, co-benefits, scalability, and policy integration are particularly encouraged. The session aims to bring together engineers, economists, policy analysts, and researchers to assess which technological portfolios can credibly limit the magnitude and duration of overshoot, and how innovation, finance, and governance must align at scale. We also welcome submissions on the enabling conditions or barriers related to markets, policy, finance, verification, and public perception.

Time	Presenter	Title	Page
14:00 - 14:15	Fei Teng	Delivering Carbon Dioxide Removal for Climate Overshoot Requires Pathway-Specific Technology Portfolios	25
14:15 - 14:30	Thanakon Sukuman	Is Diversification Always Necessary? Evaluating CDR Portfolios Across Net-Negative Pathways	26
14:30 - 14:45	Tomoko Hasegawa	Carbon dioxide removal options that are not land-based increase food insecurity	27
14:45 - 15:00	Yilin Shang	Accelerating unabated coal unit retirement to avoid carbon lock-in on the pathway to net-zero power	27
15:00 - 15:15	Yiyi Ju	The Under-Explored Role of Sustainable Fuels in Moderating the CDR Reliance under Broad Overshoot Pathways	28
15:15 - 15:30	Zhengxu Zhou	Toward Carbon Neutrality: A Hydro-PV-Storage Multi-Energy Microgrid System for Mountain Villages	29

14:00 - 14:15 Submission 37

Delivering Carbon Dioxide Removal for Climate Overshoot Requires Pathway-Specific Technology Portfolios

Zeyu WANG, **Fei TENG**

Tsinghua University, Beijing, China

Abstract

Whether warming returns below a temperature threshold after overshoot is not settled by an end-of-century carbon dioxide removal (CDR) total alone. It depends on how much net removal is actually delivered, how early deployment begins, and whether the portfolio remains feasible under resource and infrastructure constraints. Integrated assessment pathways, however, usually represent CDR in aggregated terms, obscuring the technology choices and build-out schedules that decide whether peak-and-decline pathways can be implemented. We therefore ask how contrasting 1.5 °C mitigation pathways translate into spatially feasible portfolios and deployment schedules for five CDR technologies.

We develop a spatially explicit global optimization model at 0.5° resolution representing reforestation, biochar (BC), bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), and enhanced rock weathering (ERW). The model resolves resource availability, CO2 transport and geological storage, life-cycle emissions, carbon reversal or leakage, and technology lifetimes. Five IPCC AR6 Illustrative Mitigation Pathways (IMPs) are translated into cumulative CDR targets and temporal trajectories, and we compare one-off deployment with five-year path-foresight recursive deployment under two objectives, minimum net cost and maximum net benefit.

Cumulative gross CDR demand by 2100 ranges from 309 GtCO2 in IMP-LD to 608 GtCO2 in IMP-Neg, equivalent to 24 to 48% of the modelled joint gross technical potential of 1,269 GtCO2. Timing differs as strongly as scale. IMP-LD, IMP-Ren and IMP-SP deliver 30 to 33% of their century-scale targets by 2050 and reach half by 2062 to 2064. The more back-loaded IMP-GS and IMP-Neg deliver only 17 to 18% by 2050 and

reach half in 2074 to 2076, compressing the removals needed for temperature decline into the closing decades of the century.

Under minimum net cost, rising demand shifts the portfolio from BC towards BECCS. The BC share falls from 64 to 43% while BECCS rises from 14 to 42%, reforestation stays at 10 to 14%, ERW at 5 to 8%, and DACCS contributes only 0.30 to 0.34% even in the two highest-demand pathways. Total net cost grows from USD 17.9 trillion to USD 44.9 trillion, and cumulative net CDR reaches only 80 to 81% of the gross target once process emissions and reversals are counted. Maximizing net benefit instead allocates 78 to 86% to BECCS and 11 to 22% to reforestation, lifting net delivery to 85 to 89% and adding 23 to 29 GtCO2 of net removal. Deployment structure matters as well, because minimum-cost one-off solutions allocate 56 to 73% to BECCS and up to 24% to DACCS, in sharp contrast to the BC-dominated five-year pathways.

Overshoot strategies should therefore be judged against time-resolved net removal, resource competition, infrastructure turnover and objective-dependent portfolios rather than cumulative gross CDR. Building diversified removal capacity can hedge the feasibility of temperature reversal, but it should not be read as a substitute for rapid near-term emission cuts.

14:15 - 14:30 Submission 66

Is Diversification Always Necessary? Evaluating CDR Portfolios Across Net-Negative Pathways

Thanakon Sukuman[1], Osamu NISHIURA[2], Ryo Totake[1], Tomoko HASEGAWA[1,3], Junya TAKAKURA[2], Shinichiro FUJIMORI[1,2,4]

[1]Kyoto University, Kyoto, Japan. [2]National Institute for Environmental Studies, Ibaraki, Japan. [3]Research Organization of Science and Technology, Ritsumeikan University, Kyoto, Japan. [4]International Institute for Applied Systems Analysis, Vienna, Austria

Abstract

Achieving the 1.5°C target increasingly relies on overshoot pathways that exceed the threshold before declining back below it, a trajectory that depends on deploying carbon dioxide removal (CDR) at scale to reverse peak warming and reach net-negative CO_2 emissions. Yet the model-based feasibility of different CDR technology combinations across a range of mitigation timelines has not been systematically evaluated. Existing research supports deploying multiple CDR options to distribute burdens across the system, but whether this recommendation is robust across all mitigation contexts is still an open question. Here, we investigate whether maximal technological diversity always outperforms other strategies. Using an integrated assessment model, we test 16 different CDR portfolios, built from subsets of six technologies, including bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), afforestation, enhanced weathering, soil carbon sequestration, and biochar, against five net-negative pathways under the same carbon budget. Our findings indicate that the fully diversified portfolio functions as a reliably feasible option across every pathway. However, it is not uniquely optimal. Several intermediate portfolios match or outperform the fully diversified option across energy, land, and economic dimensions, particularly when BECCS is included under early mitigation pathways. Notably, the inclusion of enhanced weathering offers substantial value, decreasing geological storage needs by up to 7 Gt CO_2 each year. Therefore, contrary to what is commonly assumed, maximizing diversification does not consistently deliver the lowest system burdens. By constructing the first comprehensive feasibility map spanning CDR portfolios and emissions pathway combinations, this study provides a novel basis for technology selection, accounting for mitigation timing, deployment scale, and context-specific trade-offs rather than treating full diversification as a default strategy.

14:30 - 14:45 Submission 104

Carbon dioxide removal options that are not land-based increase food insecurity

Tomoko Hasegawa[1], Shinichiro Fujimori[2], Kazuaki Tsuchiya[3], Kiyoshi Takahashi[3], Osamu Nishiura[3], Shinichiro Asayama[3]

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Abstract

The large-scale deployment of carbon dioxide removal (CDR) technologies is increasingly considered an important component of pathways for achieving ambitious climate mitigation targets. However, many CDR options, such as afforestation and bioenergy with carbon capture and storage, require substantial amounts of land, raising concerns about potential competition with food production and adverse impacts on biodiversity, water resources, and other sustainability objectives. CDR options that do not require dedicated land could potentially alleviate these pressures. Nevertheless, shifting from land-intensive CDR to alternative CDR options may generate broader socioeconomic and environmental trade-offs that have not yet been fully understood.

This study assesses how a shift from land-intensive CDR options toward CDR options that do not require dedicated land affects multiple dimensions of sustainability, with a particular focus on food security, biodiversity, water use, and energy systems. We compare climate mitigation scenarios characterized by different combinations of CDR technologies and examine their implications for land use, food prices and consumption, mitigation costs, macroeconomic conditions, water use, and energy prices.

We find that reducing reliance on land-intensive CDR substantially lowers land demand and associated pressures on agricultural production and biodiversity. The reduced competition for land also leads to lower food prices, which would generally be expected to improve food accessibility. However, our results reveal an important counteracting effect: shifting toward CDR options that do not require dedicated land increases the overall cost of climate mitigation. Higher mitigation costs negatively affect macroeconomic conditions and household consumption, particularly in developing regions where populations are more economically vulnerable. Consequently, despite lower food prices, the shift can increase the number of people at risk of hunger at the global level. Furthermore, all climate policy scenarios examined in this study, regardless of the dominant CDR technology, increase hunger risk compared with a baseline scenario without climate mitigation. These findings highlight the importance of considering not only food prices and land competition but also income and broader macroeconomic effects when evaluating the food-security consequences of climate policies.

Trade-offs are also observed in other sectors. A shift toward alternative CDR options reduces water use by limiting the expansion of land- and water-intensive mitigation activities, but increases energy prices because some alternative CDR technologies require substantial energy inputs.

Overall, our findings demonstrate that reducing dependence on land-intensive CDR can alleviate pressures on land, biodiversity, and water resources, but may introduce new challenges for food security and energy systems. CDR strategies should therefore be designed within a broader sustainability framework that accounts for cross-sectoral trade-offs and protects vulnerable populations from the socioeconomic consequences of climate mitigation.

14:45 - 15:00 Submission 57

Accelerating unabated coal unit retirement to avoid carbon lock-in on the pathway to net-zero power

Yilin Shang[1], Hui Yue[1,2], Wina Crijns-Graus[2], Shaohui Zhang[3], Fei Guo[4], Christian Moretti[5], Ernst Worrell[2]

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Abstract

Putting the world on a pathway to no more than 1.5°C of global warming calls for the early phaseout of unabated coal to avoid locking in emissions during the transition toward net-zero power. However, an

understanding of how the required coal retirements should unfold at the unit level in terms of prioritization, scheduling and regional distribution is lacking, limiting the translation of global mitigation pathways into actionable power-sector transitions. Here we develop an integrated global framework that links middle of the road trajectory (SSP2) with unit-level turnover of the global coal fleet, explicitly distinguishing natural retirement, accelerated retirement and avoided capacity additions to evaluate fleet evolution across global-to-regional and regional-to-national scales through 2060. Within this framework, a newly incorporated unit-ranking metric prioritizes 6,267 commissioned coal units according to their technical attributes, operating performance and committed emissions, allowing pathway-consistent accelerated retirement requirements to be allocated to individual units. Older and less-efficient subcritical units rank highest for retirement, yet this priority group represents only 3% of installed capacity, indicating that targeted closures alone cannot deliver the required phaseout. Global unabated coal capacity therefore needs to decline by an additional 270 GW in 2030 and 1,247 GW in 2035 relative to natural fleet turnover, with 71% of the cumulative reduction through 2060 realized by 2035 and the phaseout virtually complete by 2045. Accelerated retirement progressing through the unit ranking drives the near-term decline in coal capacity, while the contribution from avoided coal additions increases over time, accounting for 86% of the capacity reduction by 2060. These changes avoid 60 Gt CO_2 cumulatively between 2025 and 2060, substantially reducing emissions locked in by the operating coal fleet. The retirement challenge is highly concentrated in Asia Pacific, which accounts for 94% of the remaining lifetime emissions from the operating fleet and 68% of the required capacity reduction by 2060, with China alone responsible for 68% of locked emissions. Our findings highlight accelerated coal retirement as a scalable near-term power-sector decarbonization strategy, showing how unit- and region-specific transition pathways can reduce cumulative emissions and contribute to limiting the mitigation challenge associated with climate overshoot.

15:00 - 15:15 Submission 78

The Under-Explored Role of Sustainable Fuels in Moderating the CDR Reliance under Broad Overshoot Pathways

Luca Casamassima, **Yiyi Ju**, Volker Krey, Siddharth Joshi

International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

Abstract

Overshoot pathways assume that they exceed the climate target and then return, and that return is typically achieved through net-negative system emissions using Carbon Dioxide Removal (CDR). Recent studies show that deeper abatement of hard-to-abate sectors can reduce this requirement considerably, usually against a fixed end-of-century target. Despite uncertainties regarding the reversibility of peak warming and the sustainability and feasibility of CDR technologies, most studies leave the question about the timing, depth, and duration of CDR requirement open.

Given the uncertainties regarding the reversibility of peak warming, as well as the sustainability and feasibility of CDR technologies, recent studies (Edelenbosch et al., 2024) show that deeper demand and technological interventions in hard-to-abate sectors can still substantially reduce the reliance on CDR. This uptake of CDR in mitigation scenarios can thus serve as a useful metric for identifying the mitigation frontier, revealing the extent to which mitigation options can substitute for future net-negative emissions under overshoot pathways.

This study examines the relationship between deep mitigation efforts and the resulting CDR reliance across a range of overshoot pathways, with particular attention to sustainable fuels (fuels produced from renewable or sustainably sourced feedstocks) as a potential penultimate solution for reducing emissions in hard-to-electrify sectors.

This study answers three related questions: How does the required scale and timing of CDR vary across pathways with different degrees of overshoot? How much of this CDR reliance can be avoided through greater deployment of mitigation options such as sustainable fuels? And how does the timing of deployment of such measures affect the amount of CDR ultimately required?

Using an Integrated Assessment model for the energy and land system (MESSAGEix) linked to a simple climate model (MAGICC), we develop mitigation pathways spanning different degrees of climate overshoot.

We first examine the negative emissions associated with low- and high-overshoot pathways. We then explore how this CDR reliance changes when mitigation options, particularly the deployment of sustainable fuels, are expanded beyond default deployment based on contemporary techno-economic assumptions. Two dimensions of deployment are considered: the depth of deployment -represented by stronger demand drivers for sustainable fuels, and the speed of deployment -representing earlier and more rapid uptake. We undertake this analysis using technology-rich bottom-up modeling, including 13 hydrogen, 9 methanol, 9 ammonia, and 4 ethanol production technologies. Complementing this, we also represent the demand-side technologies in 10 subsectors that take in hydrogen, methanol, ammonia, and ethanol as energy inputs or feedstock.

The results show that requirements for global negative emissions are reduced by approximately 9% under a low-overshoot scenario when sustainable fuels are deployed at their maximum scale alongside electrification. By focusing on penultimate mitigation options and the mitigation portfolio in the overshoot pathways in a holistic manner, rather than treating them as a standalone technology solution, the study highlights how the decisions on the depth and speed of mitigation can shape the magnitude and duration of reliance on CDR under overshoot pathways.

15:15 - 15:30 Submission 17

Toward Carbon Neutrality: A Hydro-PV-Storage Multi-Energy Microgrid System for Mountain Villages

Zhengxu Zhou[1], Song Chen[2,3], Jing Zhang[1], Xinyue Mu[4]

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Abstract

Against the global backdrop of carbon neutrality transitions, remote mountain villages confront persistent challenges including weak grid infrastructure and limited access to clean energy. Yet these same mountainous regions hold substantial untapped potential for small-scale hydropower and solar resources. Decentralized multi-energy microgrids emerge as a promising pathway to decarbonize rural mountain communities while enhancing energy independence. This paper constructs a hydro-photovoltaic-energy storage complementary multi-energy microgrid system tailored for mountain villages to support local carbon neutrality targets, taking a riverside settlement and its surrounding area in Guizhou Province, China—a representative mountainous region—as the case study for simulation and engineering validation.

The study employs the HOMER Pro microgrid design and optimization platform for system simulation and modeling. Using input meteorological data, renewable energy availability, techno-economic parameters, and electrical load profiles, the research performs a full-year dynamic simulation at minute-to-hour time steps to capture long-term operational performance. Through the platform's built-in exhaustive grid search optimization algorithm, the study optimizes capacity configurations of photovoltaic panels, hydro turbines, battery storage, converters, and grid interconnection. Four system schemes are systematically evaluated: (1) PV-hydro-battery-converter-grid hybrid system, (2) hydro-battery-converter-grid system, (3) PV-battery-converter-grid system, and (4) grid-only system, with the total net present cost (NPC) as the objective function for scheme ranking and selection.

The key findings reveal that, compared with conventional external grid supply, the multi-energy complementary system significantly elevates the renewable energy fraction while maintaining competitive economic costs. Among all evaluated configurations, both Scheme 1 and Scheme 2 restrict the total NPC to under approximately 40,000 RMB, while maintaining a renewable fraction exceeding 96%. Taking Scenario 1 as an example, the system exhibits pronounced seasonal operational patterns. In May, abundant hydro and PV output enable near-full self-sufficiency with infrequent battery response. In August, driven by peak loads, the system operates in a collaborative PV-hydro-storage-grid mode with maximum annual grid electricity purchase. In October, PV-hydro synergy dominates with frequent battery charging-discharging cycles and minimal grid reliance. In January, constrained by low stream flow and reduced solar irradiance, the system relies on combined PV-hydro-storage-grid supply, with the grid providing dynamic compensation during deficit periods.

Notably, the proposed system has been translated into on-site engineering practice through the restoration of a traditional water-powered grain mill and the retrofitting of its integrated energy system, with continuous performance validation currently underway. Preliminary field results confirm that the system achieves a 100% renewable energy fraction during summer. Site-specific conversion of such abandoned water conservancy heritage into clean energy infrastructure not only delivers low-carbon, reliable power support for rural buildings and reduces fossil energy consumption, but also realizes the organic integration of vernacular hydraulic heritage preservation and green energy technology advancement, yielding remarkable dual ecological and cultural benefits.

This study demonstrates the considerable low-carbon renewal potential and broad promotion prospects of mountain villages under advancing carbon neutrality strategies. As the clean energy technology supply chain matures, the declining combined costs of PV modules, micro-hydro units, and storage batteries further strengthen the economic feasibility of zero-carbon or low-carbon retrofits in rural mountain areas.

Theme 5: Overshoot pathway legacy, tipping dynamics and other abrupt changes

14:00 - 15:30, Cloud Room, 云岚厅 Chairs: Jingfang Fang, Alexander Nauels

Overshoot will leave a long-lasting climate system legacy, in particular if nonlinear and irreversible dynamics of physical and ecological Earth System tipping elements were triggered during target exceedance. Emerging insights suggest that global warming reversal to levels below present-day may be required to limit tipping risks on centennial timescales. Yet, there is still limited understanding of how the climate system behaves after reaching net-zero CO2 emissions and if declining global mean temperatures can be achieved at the required scale. Also, temporal dynamics and reversibility of potential tipping elements under those conditions are not well understood. This session welcomes contributions that shed light on the legacy of committed climate changes and dynamics of global tipping elements, threshold responses and other nonlinear and abrupt changes under global temperature peak and decline pathways. Specific focus will be put on determining long-term consequences of near-term climate (in)action up to peak warming, and the possibilities and limits of reducing long-term risks by reversing global warming.

Time	Presenter	Title	Page
14:05 - 14:15	Hauke Schlesier	Reducing climate tipping risks with fast energy transitions	31
14:20 - 14:30	Nina Rynne	Cost-optimal recovery timing for 1.5°C overshoot pathways	32
14:35 - 14:45	Niki Lohmann	Carbon dioxide removal decisive to limit tipping risks in a tipping point emulator	32
14:50 - 15:00	Teresa Bonserio	Returning to 1°C: How Much CDR Is Needed to Limit Long-Term Tipping Risk, and What Delay Costs Us	33
15:05 - 15:15	Jerry Tjiputra	Persistent Earth system challenges of using stratospheric aerosol injections to avoid temperature overshoot	34

14:05 - 14:15 Submission 5

Reducing climate tipping risks with fast energy transitions

Hauke Schlesier

Empa – Swiss Federal Laboratories for Materials Science and Technology, St. Gallen, Switzerland

Abstract

Limiting global warming to 1.5°C is increasingly unlikely, raising concern that several climate tipping elements may exceed critical thresholds beyond which they could undergo self-reinforced transitions. It remains, however, unclear how far these tipping risks can still be reduced through rapid mitigation and large-scale carbon dioxide removal. We assess this gap by combining three modelling tools: the 3-Machines energy transition model to describe technically feasible, fastest-possible defossilization pathways only constrained by the feedback between energy supply and energy needed to build new energy capacity; the FaIR climate emulator to translate emissions pathways into temperature trajectories; and the stylized tipping network model PyCascades to estimate the probability of triggering four interacting tipping elements. These four tipping elements include the Greenland and West Antarctic Ice Sheet, the Atlantic Meridional Overturning Circulation, and the Amazon rainforest.

Using this model pipeline, we evaluate tipping probabilities under energy transition pathways and carbon removal pathways that return global temperature to 1.0°C before 2300. Compared with a Current Policies pathway, fast energy transitions could reduce the mean probability of triggering at least one tipping element from 5.8% to 0.1% over the next century. Over a 50,000-year horizon, the mean tipping probability reduction amounts to 78.0 percentage points. In addition to lowering tipping probabilities, earlier transitions can delay tipping events by centuries, thereby extending the time available for adaptation. Our results further indicate that keeping long-term tipping probabilities below 0.5% requires limiting peak warming to no more than 2.0°C and returning temperatures to 0.8°C or lower in the long term.

14:20 - 14:30 Submission 30

Cost-optimal recovery timing for 1.5°C overshoot pathways

Nina Rynne

Griffith University, Brisbane, Australia

Abstract

Carbon dioxide removal (CDR) is central to any pathway that returns global temperature to the Paris Agreement's 1.5°C target after overshoot, but the speed and scale at which CDR can realistically be deployed sets hard limits on what is achievable this century.

Extending our optimal control climate-economic model MACROM into a free terminal time problem, we determine, for different CDR speed-scale (r, K) combinations, the cost-optimal year in which temperature returns to 1.5°C. We isolate the r/K combinations that failed to recover by 2100 under a fixed end-of-century horizon, and instead ask how long recovery actually takes, and at what peak temperature and overshoot duration, once that artificial boundary is removed. We characterise the distribution of cost-optimal return years and the relationship between deployment speed and scale and additional recovery time beyond 2100.

Our results speak directly to the legacy of overshoot: how near-term choices about implementing and scaling CDR shape the length and severity of the overshoot world we will have to live in, long after 2100. Understanding these possible temperature trajectories is a first step toward examining the longer-term impacts of current mitigation ambition.

14:35 - 14:45 Submission 26

Carbon dioxide removal decisive to limit tipping risks in a tipping point emulator

Niki Lohmann[1,2], Jonathan Donges[2,3,4], Sina Loriani[2], Manjana Milkoreit[5], Nico Wunderling[1,2]

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Abstract

The target to limit global warming to 1.5°C above preindustrial levels can now only be reached with a temporary temperature overshoot [1,2]. However, beyond 1.5°C of global warming, several important subsystems of the Earth might be at risk of irreversible destabilization [3,4]. These elements include the Atlantic Meridional Overturning Circulation, the polar ice sheets, the Amazon rainforest and permafrost. We assess the risks of triggering such irreversible dynamics with a newly developed tipping point emulator calibrated to simulations of complex Earth system models and further process-resolving models. Our results suggest that it is imperative to limit climate overshoot to below 2°C at all times and return temperatures to a safe level below 1°C within the 22nd century, as to avoid a high tipping risk of more than 10%. Such temperature reductions would require large-scale carbon dioxide removal: If global warming reaches 2°C, annual rates of 30GtCO2 (5-95% confidence interval: 21-50GtCO2) should be reached around 2100, and the total global carbon storage capacity would need to be expanded to more than 1.0°C storage equivalent (representing 1590-3700GtCO2). Our findings may inform assessments of highest possible ambition efforts [5], including informed tradeoffs between mitigation, carbon dioxide removal and tipping risks [6,7]. Overall, our results stress that mitigation and carbon dioxide removal are two policy priorities that must be pursued simultaneously and with higher ambition than now in order to avoid high tipping risks.

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14:50 - 15:00 Submission 102

Returning to 1°C: How Much CDR Is Needed to Limit Long-Term Tipping Risk, and What Delay Costs Us

Teresa Bonserio[1], Zarrar Khan[1], Alicia Hou[1], Neil Grant[1], Lara Welder[1], Fahad Saeed[1], Bill Hare[1], Michiel Schaeffer[1], Gunnar Luderer[2,3], Fabrice Lecuyer[2]

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Abstract

Overshoot pathways that peak above 1.5°C before declining leave a legacy of tipping-point risk that returning to 1.5°C alone does not resolve. Because changes such as ice sheet loss and ocean acidification unfold over centuries and are difficult or impossible to reverse once underway, real protection may require bringing temperature down further, to around 1°C, over a timeframe extending well past 2100 — a horizon most current pathway assessments do not extend to. How much risk remains on the way to that point depends on two things: First, the magnitude and duration of the overshoot, and secondly, the pace at which warming occurs. The higher the peak and the longer it lasts, the more time fast-responding systems, such as coral reefs, spend above a critical threshold, raising the chance that a temporary exceedance triggers an irreversible shift. Second, the pace of warming may matter on its own: forcing that changes too quickly can push some tipping elements past a threshold before the warming alone would otherwise cause tipping, a mechanism shown for the Atlantic Meridional Overturning Circulation (AMOC).

Existing assessments already estimate that returning to 1.5°C could require 7-10 GtCO2 of removal per year (up to five times today's rate of around 2 GtCO2 per year) and that this return would need to happen within this century to limit long-term tipping risk. It is far less clear what timeframe applies to a further decline to around 1°C, how much removal that requires, how that requirement would grow if near-term cuts were delayed, and how the picture changes beyond 2100.

We test this by extending several existing pathways (Climate Analytics' Highest Possible Ambition (HPA) pathway, the CMIP7 Very Low pathway, and RCP-1.9) to 2300, and by testing different pairings of near-term emissions-reduction pace, long-term levels of residual emissions, and carbon removal deployment trajectories across them. We explore the temperature implications of the resulting emissions pathways under a range of climate sensitivities. This allows us to explore a range of options for bringing temperature back down. This separates three drivers of the removal requirement: how much delaying/deferring mitigation inflates the removal needed later; how much removal is required in the long term to maintain net-negative emissions once net zero is reached; and how much both may shift under different assumptions about climate sensitivity.

Because many tipping risks can only be evaluated once temperature assessments are extended to beyond 2100, our results provide a clearer basis for judging how much protection these three drivers offer against risks such as coral reef loss, ice-sheet collapse, and a weakening AMOC, both by limiting the size and duration of the overshoot and by controlling its pace.

15:05 - 15:15 Submission 22

Persistent Earth system challenges of using stratospheric aerosol injections to avoid temperature overshoot

Jerry Tjiputra[1], Dirk Olivié[2], Jörg Schwinger[1], Nadine Goris[1], Norman Steinert[3], Rosie Fisher[3], Huiji Lee[4]

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Abstract

Recent trends in CO2 emissions suggests that achieving the Paris Agreement's temperature target represents a great challenge and that an overshoot will likely occur. Here, we apply a fully-interactive Norwegian Earth system model to perform an idealized temperature overshoot simulation as well as simulations with Stratospheric Aerosol Injection (SAI) deployed in three regions: the tropics, Northern Hemisphere mid-latitudes, and Southern Hemisphere mid-latitudes, designed to avoid the temperature overshoot. We find that the climatic consequences of SAI depend strongly on deployment location, which affects the pathway evolution of the Atlantic Meridional Overturning Circulation (AMOC). While all experiments exhibit an initial CO2-driven AMOC weakening, Northern Hemisphere SAI most effectively mitigates this decline by reducing northern high-latitude warming and preserving North Atlantic deep-water formation. Southern hemisphere SAI induces the least influence on Northern Hemisphere high-latitude warming and therefore does not substantially mitigate the AMOC decline. These contrasting AMOC responses propagate throughout the Earth system, influencing Northern Hemisphere surface temperature, sea-ice evolution, tropical precipitation patterns, ocean ventilation, carbon uptake, and regional ocean acidification. Furthermore, Our model demonstrates that the early AMOC response is a key overshoot legacy that persistently affects the slow components of the climate system, including the deep ocean, sea-level rise, and permafrost, for centuries.

Theme 7: Adaptation & adaptation limits, and loss & damage under climate overshoot

14:00 - 15:30, River Room, 江河厅 Chairs: Marina Andrijevic, Sindra Sharma-Khushal, Elisa Calliari

To be effective and efficient, adaptation planning needs to incorporate the possibility of an overshoot, and what that could mean for adaptation limits and resulting losses and damages for society and nature. This session will explore key questions such as how prospects of potential long-term impact reversal matter for adaptation needs and decision making, and the extent to which exceeding limits to adaptation translates into economic and non-economic loss and damages. We welcome contributions exploring how climate overshoot might lock societies into trajectories that they cannot simply reverse when temperature declines, including loss of ecosystems, resettled populations, abandoned infrastructure, loss of traditional livelihoods and cultural practices, and early signals of these dynamics in markets, institutions, and behaviours, among others. We also call for a focus on responses to loss and damage at various scales, including the policy contexts and institutional arrangements, and discussing the role of transformational adaptation.

Time	Presenter	Title	Page
14:05 - 14:20	Koko Warner	Climate Overshoot and Persistent Disruption: Rethinking Design of Adaptation and Loss and Damage Actions	35
14:20 - 14:35	Architesh Panda	Financing Before the Peak: The Welfare Cost of Delayed Adaptation Finance under Climate Overshoot	36
14:35 - 14:50	Junxi Gong	Financing Loss and Damage under Climate Overshoot: Evidence from Malaysia	37
14:50 - 15:05	Kareem Buyana	Centering Reflexivity in Climate Overshoot Research	37

14:05 - 14:20 Submission 105

Climate Overshoot and Persistent Disruption: Rethinking Design of Adaptation and Loss and Damage Actions

Koko Warner[1], Michael Weisberg[1], Zinta Zommers[2]

[1]University of Pennsylvania, Philadelphia, USA. [2]OCHA, New York City, USA

Abstract

Authors: Dr. Koko Warner (confirmed); Prof. Michael Weisberg (tbd), Prof. Erol Ackay (tbd), Dr. Zinta Zommers (tbd)

The prospect of exceeding 1.5°C challenges prevailing approaches to adaptation and loss and damage. Many adaptation and risk-management institutions continue to operate on assumptions of temporary disruption and recovery. Yet under overshoot conditions, climate impacts increasingly become recurring features of economic and social life, shortening recovery windows, compounding vulnerability, and altering the conditions upon which societies depend. The challenge shifts to ensuring that institutions continue to function when disruption becomes persistent.

We develop a conceptual framework for assessing institutional fitness under overshoot conditions using evidence from loss-and-damage funding modalities. Our paper examines how institutions recognise vulnerability, determine eligibility for support, and reach affected populations. Drawing on evidence from climate risk governance and loss-and-damage finance, the paper shows that exclusion frequently occurs after eligibility has been established. Administrative requirements, verification procedures, and delivery systems systematically filter out populations with the least capacity to navigate them. These patterns are not implementation failures but predictable consequences of institutional design.

Under episodic disruption, exclusion leads to unequal recovery. Under persistent disruption, exclusion becomes a mechanism through which vulnerability is reproduced and accumulated over time. As vulnerability deepens and spreads, coping capacity erodes, fiscal pressures increase, and social stresses intensify. The central policy question therefore becomes whether institutions can reduce vulnerability before repeated impacts become entrenched sources of economic and political strain. Evidence from adaptation finance, social protection, disaster response, and loss and damage mechanisms and funding modalities suggests that effectiveness depends less on the formal availability of support than on the ability of institutions to reach vulnerable populations under recurring climate stress.

We argue that the implications of overshoot extend beyond climate impacts themselves to the institutions responsible for managing them. Its findings will be of interest to researchers and policymakers concerned with adaptation, loss and damage, and the design of policies capable of maintaining social and economic stability under persistent climate disruption.

14:20 - 14:35 Submission 14

Financing Before the Peak: The Welfare Cost of Delayed Adaptation Finance under Climate Overshoot

Architesh Panda

Stockholm Environment Institute, Bangkok, Thailand

Abstract

Socioeconomic systems need not follow the same path of climate temperature overhsoot. Climate shocks can deplete productive assets, raise debt and push vulnerable households below minimum-consumption thresholds, producing welfare losses substantially larger than their measured asset losses (Hallegatte et al., 2017). Once critical thresholds are crossed, the resulting losses might not be reversed. This paper asks when delays in adaptation and disaster-risk finance convert temporary climate stress into persistent socioeconomic harm.

I develop a stylized stochastic dynamic welfare model in which households accumulate productive assets, earn climate-sensitive income and face recurrent shocks under minimum consumption requirements and borrowing constraints. I compare stabilization, moderate-overshoot and higher-overshoot temperature trajectories informed by the IPCC AR6 Scenario Database. Alternative hazard-response functions translate these trajectories into plausible ranges of shock frequency, severity and inter-arrival time.

Four financing regimes are examined: anticipatory support triggered by a forecast; rapid finance delivered within 14 days; delayed assistance arriving after 30–90 days; and prolonged delay beyond 90 days. These windows are informed by documented anticipatory interventions, parametric payout records and reported humanitarian funding timelines, while sensitivity analysis tests alternative boundaries. Evidence from Bangladesh indicates that cash delivered before peak flooding can improve welfare and reduce subsequent asset losses (Pople et al., 2026). Early finance is nevertheless not treated as costless. Anticipatory transfers incur false-alarm costs under imperfect forecasts, while parametric instruments incur premiums and basis risk. Any timing advantage must therefore remain after accounting for these costs.

Household-loss and recovery parameters are calibrated using anticipatory cash-transfer evaluations and disaster-recovery studies. CCRIF and African Risk Capacity records discipline plausible rapid-financing windows: CCRIF provides qualifying payouts within approximately 14 days, while ARC reports payouts within two to four weeks after the defined end of a season (CCRIF, 2025; ARC, 2026). Sovereign payouts are not assumed to represent direct or one-to-one transmission of finance to households. Three household archetypes vary in savings, credit access and proximity to the consumption floor. Monte Carlo simulations test sensitivity to shock recurrence, recovery speed, overshoot duration, adaptation effectiveness, forecast skill, basis risk and initial vulnerability.

I estimate three outcomes: the timing premium, defined as the welfare gain from early rather than delayed finance; an overshoot amplification factor, measuring how much overshoot increases this premium relative to stabilization; and socioeconomic commitment thresholds, beyond which losses persist after climatic pressure declines. The contribution is not simply to show that timing matters, a model containing consumption floors could generate that result mechanically, but to identify where these thresholds arise, how large the timing premium becomes and whether it survives realistic forecast-error, basis-risk and financing costs.

The paper hypothesize that the timing premium rises non-linearly when shocks recur before recovery is complete. The greatest premiums may arise not where absolute losses are largest, but where recurrent climate stress overlaps with poverty, weak self-insurance and slow financial response. If supported, these results imply that adaptation under overshoot should be financed for peak climate stress rather than planned only around end-of-century conditions.

14:35 - 14:50 Submission 8

Financing Loss and Damage under Climate Overshoot: Evidence from Malaysia

Junxi Gong, Ying Ying Tiong, Hongxuan Yang

Faculty of Business, Curtin University Malaysia, Miri, Malaysia

Abstract

The floods of December 2021 cost Malaysia RM6.1 billion — 0.40% of GDP — in a world roughly 1.2 °C above pre-industrial. Most Paris-consistent mitigation pathways now imply a temporary overshoot of 1.5 °C, yet the fund designed to absorb such losses, the Fund for Responding to Loss and Damage (FRLD), holds pledges of only USD 822 million against estimated developing-country needs of USD 290–580 billion per year by 2030. Critically, the FRLD's disbursement architecture is being designed around static damage estimates, while overshoot makes damages dynamic and path-dependent: two pathways with the same peak can imply very different cumulative losses depending on how long temperatures stay above 1.5 °C and how fast they decline. Where sustained extremes exceed limits to adaptation, residual impacts become financing needs — the central concern of this theme.

We provide, to our knowledge, the first empirically grounded, pathway-dependent estimates of loss-and-damage (L&D) financing needs for a developing country. Stage A estimates a climate–damage function on a 1990–2024 panel combining EM-DAT disaster losses — cross-checked against Malaysia's DOSM state-level flood-impact surveys — with NASA POWER reanalysis (temperature anomalies, extreme-heat days, RX5day rainfall), PSMSL sea-level records, and World Bank/OpenDOSM macroeconomic data. Because disaster losses are zero-inflated and heavily skewed, we estimate a two-part model (occurrence; severity by Poisson pseudo-maximum likelihood) with unit and year fixed effects, and we test explicitly for convex, threshold-like responses using binned specifications of heat and rainfall extremes. Estimation pools an ASEAN-6 country panel for statistical power; a 16-unit Malaysian state panel (2005–2024) provides the headline application.

Stage B applies the fitted function out of sample to overshoot pathways from the IPCC AR6 scenario database and a custom FaIR ensemble spanning a peak (1.6–1.8 °C) × duration-above-1.5 °C (10–50 years) × decline-rate grid. Global trajectories are localized through empirically estimated pattern-scaling coefficients, an auxiliary heat-day mapping, and Clausius–Clapeyron scaling of rainfall extremes. Coefficient uncertainty (block bootstrap) is propagated jointly with pathway uncertainty by Monte Carlo simulation, yielding probabilistic financing-need fan charts. Projected needs are benchmarked against Malaysia's federal disaster-relief and flood-mitigation budget lines and summarized in five policy metrics, including the gap-onset year and a 'duration elasticity of financing need' — the percentage increase in cumulative 2025–2100 financing need per additional decade spent above 1.5 °C.

We hypothesize that overshoot duration and decline rate, not peak temperature alone, dominate cumulative financing needs, because sustained exposure interacts with a convex damage response. The results speak to live design questions for the FRLD and pre-arranged risk finance: if needs are duration-driven, disbursement rules indexed to peak-temperature milestones will systematically lag realized losses. The pipeline uses only open data and open-source tools (EM-DAT, NASA POWER, PSMSL, World Bank/OpenDOSM, FaIR) and is fully reproducible.

Links to paste at the end of the text box (the form accepts references only as in-text links): DOSM 2022 flood report — dosm.gov.my/portal-main/release-content/special-report-on-impact-of-floods-in-malaysia-2021 · FRLD pledges — frld.org/pledges · EM-DAT — public.emdat.be · NASA POWER — power.larc.nasa.gov · AR6 scenarios — data.ece.iiasa.ac.at/ar6 · FaIR — doi.org/10.5194/gmd-14-3007-2021

14:50 - 15:05 Submission 2

Centering Reflexivity in Climate Overshoot Research

Kareem Buyana

Makerere University, Kampala, Uganda

Abstract

While policy and local community collaborations are rarely treated as core variables in quantitative climate modelling, they are vital for addressing the socio-economic and governance impacts of overshoot

irreversibility. Indeed, irreversible outcomes that ultimately limit adaptive capacity—such as extreme heat, catastrophic flooding, and climate-related diseases—call for a paradigm shift toward climate overshoot research grounded in reflexive and diverse methodologies. Such approaches intentionally allow non-scientists to contribute knowledge that provides both deep local context and valuable cross-societal comparability. This paper explores the role of reflexivity at three distinct, interlocking levels: researcher roles, institutional structures, and methodology.

Researcher reflexivity focuses on how scientists position themselves relative to the communities and policies they study. It demands that modelers acknowledge their own biases, privileges, and epistemic limitations, moving away from the detached "objective observer" persona to become collaborative partners who co-produce knowledge with affected populations.

Structural reflexivity examines how institutional environments support or hinders cross-sector partnerships with boundary organizations. This level emphasizes the need for funding agencies, universities, and policy bodies to create flexible governance structures and sustained funding pipelines that actively bridge the gap between academic science and grassroots action.

Methodological reflexivity redefines the modelling process itself by actively engaging stakeholders in the formulation and testing of climate scenarios. This co-production allows non-scientists to interrogate and integrate their lived experiences, historical coping mechanisms, and unique perspectives on impact reversibility directly into the data, particularly regarding the lived realities of peak and decline temperature periods.

The reflexive approach aims at shedding light on how stakeholder contributions—whether through involvement in modelling processes or collaboration on addressing the impacts—can be incorporated in projections and actions for limiting overshoot magnitudes and durations, within policy, local community and governance institutional arrangements for adaptation planning.

Theme 8: Governance and equity of overshoot pathways

14:00 - 15:30, Bamboo Room, 竹韵厅 Chairs: Annika Högner, Xianchun Tan

Overshoot pathways raise critical questions about how governance and policy regimes shape who bears the risks and who controls the responses. Emerging national and international strategies increasingly rely on carbon dioxide removal (CDR) to return temperatures below agreed targets, yet the design of these strategies— including how CDR is embedded in Nationally Determined Contributions (NDCs) and Long-Term Low-Emission Development Strategies (LT-LEDS) under the UNFCCC— has profound implications for equity, accountability and credibility of such strategies. This session examines how different governance arrangements for overshoot pathways and CDR allocation influence the distribution of mitigation effort, residual climate risks and co-impacts across countries, communities and generations. It invites analyses of how overshoot-compatible pathways are being institutionalized in policy and planning, how responsibilities for deploying and financing CDR are framed, and how these choices interact with broader development, energy and land-use priorities. We particularly welcome contributions that: critically assess the role of CDR in NDCs and LT-LEDS; explore governance options to constrain overshoot magnitudes and durations; and evaluate mechanisms to prevent overshoot pathways from deepening existing inequalities or creating new forms of dependency and lock-in. Empirical, modelling and conceptual work on governance innovations that center equity in overshoot planning is especially encouraged.

Time	Presenter	Title	Page
14:00 - 14:12	Petra Bistricic	Policy Options for Climate Overshoot: A Review and Key Considerations for Design	39
14:12 - 14:24	Luis Fernandez-Carril	Governing Overshoot: The Politics of Irreversibility and Foreclosed Justice Possibilities	40
14:24 - 14:36	Jiarui Zhong	Distributional Impacts of 1.5 °C Overshoot Pathways: Food, Energy, and the Limits of Carbon Tax Revenue Recycling	41
14:36 - 14:48	Xian Zhang	From Temperature Targets to Climate Stabilization: Stability Margins, Governance, and Equity in Overshoot Pathways	42
14:48 - 15:00	Kejun Jiang	Fighting for 1.5°C Target: Modeling on Speed-up Energy Transition Pathways for China and Asia	43

14:00 - 14:12 Submission 45

Policy Options for Climate Overshoot: A Review and Key Considerations for Design

Petra Bistričić[1], Johannes Bednar[2], Ingrid Sundvor[1], Andy Reisinger[3], Anders Lyngfelt[4], Michael Obersteiner[1]

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Abstract

Exceed and decline pathways, defined as pathways that temporarily exceed 1.5°C but then achieve a return to or below this level, are becoming increasingly central to strategies aimed at limiting long-term warming, given the unavoidable exceedance of the 1.5°C target. In the context of climate overshoot, a sole focus on net zero emissions is insufficient, as it fails to account for the need to draw down temperatures following peak warming, and risks stabilising temperatures at elevated levels. Despite this, exploration of what policy for a post-net zero, or overshoot, era should look like is limited.

This paper initiates a discussion of what successful overshoot governance could look like by developing an evaluation framework for overshoot policy, informed by relevant literature and refined through engagement with academic experts. The framework is designed to assess four key dimensions of overshoot policy: economic feasibility, political feasibility, integrity, and robustness.

The study applies the framework preliminarily to national-scale policy approaches proposed to date in the literature. As such, the paper synthesises existing thinking in the field of overshoot governance, providing a comprehensive mapping of the emerging overshoot policy ecosystem. It identifies three key axes along which policy approaches differ: whether emissions are linked to responsibility for their removal across time, who bears the financial liability for procuring removal, and who holds the operational responsibility for doing so.

Through the preliminary application of the framework, the study identifies the benefits and trade-offs of the identified approaches, alongside the policy pathways they imply for decision-makers. The application highlights limitations associated with contemporaneous approaches, which do not maintain a link between

emissions and responsibility for their eventual removal, and therefore do not account for a challenge inherent to overshoot – the decoupling of the time of emission from the time of removal. The analysis demonstrates how intertemporal approaches, which maintain this link across time, perform better against certain evaluation criteria, particularly economic feasibility. However, they present other challenges, especially with respect to political economy, as they require novel governance arrangements.

The findings suggest that successful overshoot governance will require moving beyond existing frameworks of policymaking to address the novel, long-term governance challenges posed by overshoot. The evaluation framework lays the groundwork for future research and policy discussion on the specific policy details that will necessitate design and tailoring at the national level.

14:12 - 14:24 Submission 4

Governing Overshoot: The Politics of Irreversibility and Foreclosed Justice Possibilities

Luis Fernandez Carril

Tecnologico de Monterrey, Monterrey, Mexico

Abstract

Emerging debates on climate overshoot increasingly focus on how temporary exceedances of temperature targets should be governed, including the role of carbon dioxide removal (CDR), the allocation of mitigation responsibilities, and the distribution of risks across countries, communities, and generations. While these questions are important, they largely begin from a shared assumption: that overshoot is the condition within which questions of justice must now be addressed. Rather than asking how overshoot should be governed, this paper asks a different question: what political work does the concept of overshoot governance perform?

The paper argues that framing overshoot primarily as a governance challenge risks obscuring the political processes through which overshoot itself came into being. The prospect of exceeding the Paris Agreement temperature goals was widely anticipated long before current projections emerged, yet climate governance frameworks continued to accommodate pathways that made such exceedance increasingly likely. Overshoot should therefore be understood not merely as an unintended failure, but as a politically produced condition emerging from decisions, investments, and institutional arrangements that enabled continued fossil fuel dependence, normalized delay, and reproduced unequal power relations while maintaining the appearance of climate commitment. By shifting attention toward managing overshoot and planning future returns to target temperatures, contemporary overshoot discourse may inadvertently treat overshoot as a neutral starting point rather than as an outcome requiring justice scrutiny in its own right.

Building on climate justice scholarship and critical approaches to governance, the paper argues that the significance of overshoot extends beyond questions of distributive equity. Contemporary debates rightly focus on the allocation of future risks, responsibilities, and response measures. Yet this focus may obscure a more fundamental question: how the political production of overshoot has altered the conditions under which justice itself can be pursued. Species extinctions, ecosystem transformations, lost territories, foreclosed development pathways, and diminished life opportunities for future generations are not simply harms requiring compensation or redistribution. They are the legacy of choices that knowingly increased the likelihood of irreversible losses and constrained the possibility of repair. The challenge is therefore not only that some harms are irreversible, but that political and economic decisions have contributed to making them irreversible, narrowing the possibilities for justice available to future generations.

The paper proposes that overshoot should not be understood merely as the context within which climate justice must be pursued, but as a politically produced condition that fundamentally reshapes what climate justice can mean. Future generations may be born not only vulnerable to climate change, but into worlds already constituted by harms they did not choose and that cannot be fully undone. This raises a fundamental question: what does justice mean when responsibility can be established, yet some possibilities for justice have already been foreclosed? Addressing climate justice in an overshoot world therefore requires more than the equitable governance of future risks. It requires confronting how overshoot was produced, how irreversible harms became politically acceptable, and how the deliberate accommodation of those harms continues to shape the horizons of justice in the present and future.

14:24 - 14:36 Submission 7

Distributional Impacts of 1.5 °C Overshoot Pathways: Food, Energy, and the Limits of Carbon Tax Revenue Recycling

Jiarui Zhong[1], Franziska Piontek[1], Benjamin Bodirsky[1], David Chen[1,2], Leonard Missbach[1], Robin Hasse[1,3], Leon Merfort[1,3], Tabea Dorndorf[1,2], Anne Merfort[1,3], Benjamin Peeters[1], Johannes Koch[1], Elmar Kriegler[1,4]

[1]Potsdam Institute for Climate Impact Research, Potsdam, Germany. [2]Humboldt-Universität zu Berlin, Berlin, Germany. [3]Technische Universität Berlin, Berlin, Germany. [4]University of Potsdam, Potsdam, Germany

Abstract

Integrated Assessment Modelling (IAM) frameworks typically represent each region with a single average household, limiting their ability to capture within-country distributional effects. This omission is important because mitigation costs are transmitted through consumer prices, especially energy and food, which account for different budget shares across income groups. Overshoot pathways add a further challenge: they shift mitigation and Carbon Dioxide Removal (CDR) financing burdens over time, potentially misaligning inequality pressures with the availability of carbon-pricing revenues, which are often viewed as a key instrument for governments to reduce mitigation-induced inequality.

We link a low- (LO) and a high-overshoot (HO) scenario from the IAM framework REMIND–MAgPIE under SSP2 to a post-processing micro-distributional framework. Regional aggregate consumption from IAM is downscaled to expenditure deciles using SSP2-consistent Gini projections. Decile-specific consumption baskets are estimated with regional and pooled Engel curves using harmonized household expenditure data covering 88 countries. Category-level price changes from the IAM scenarios are then mapped to decile-specific real-consumption effects using a cost-of-living index. We evaluate distributional outcomes under an inequality-neutral recycling benchmark and under progressive equal-per-capita transfers supported by carbon-pricing revenues and a stylized global climate fund.

The results reveal a central intertemporal trade-off between near-term mitigation pressure and late-century distributional risk. LO generates higher near-term welfare losses and earlier increases in consumption inequality, yet these early burdens occur while carbon-pricing revenues are still substantial and can potentially support redistribution. HO reduces near-term pressure, but late-century welfare costs and inequality rise sharply as CDR expands and net carbon revenues turn negative, creating a mismatch between compensation needs and fiscal capacity late in the century. Decomposing inequality changes across consumption categories shows that energy-price shocks dominate early in the transition but fade as energy systems decarbonize, whereas food-price pressures persist and become increasingly important, especially through animal products and staples. This sectoral shift implies that distributional impacts do not simply follow aggregate mitigation costs; they depend on how decile-specific consumption baskets interact with evolving energy and land-system prices. On the financing side, net-negative CDR from the cost-efficient IAM is geographically concentrated, so a responsibility-sharing global climate fund is introduced to reallocate financing burdens across regions and over time, but doing so requires substantial intertemporal coordination. Domestic equal-per-capita recycling can reduce within-region inequality when positive revenues are available, particularly in early low-overshoot periods. However, redistributive effectiveness declines as revenues shrink in both scenarios. Together, the results indicate that overshoot governance is not only a question of technological feasibility and aggregate cost, but also of fiscal timing, compensation design, and distributional equity. They also highlight potential policy levers for mitigating future inequality impacts, including dietary change and intertemporal financing.

14:36 - 14:48 Submission 113

From Temperature Targets to Climate Stabilization: Stability Margins, Governance, and Equity in Overshoot Pathways

Xian Zhang[1], Zheng Shi[1], Jing Meng[2]

[1]The Administrative Center for China's Agenda 21, Beijing, China. [2]University College London, London, United Kingdom

Abstract

Global warming is expected to exceed 1.5 °C this decade, with peak warming near 1.8 °C even if pledges and net-zero targets are fully implemented. Overshoot—temporary exceedance of a temperature target followed by decline—is therefore a central problem for climate governance. This assessment synthesizes observed change, destabilization mechanisms, and monitoring and intervention options, and their governance and equity implications.

Across the Earth system the integrating diagnostic is a persistently positive Earth energy imbalance, widening as greenhouse-gas forcing rises. The ocean absorbs about 90% of the excess heat: heat content is at a record high, stratification has grown about 5.3% since 1960, and the carbon sink has plateaued since 2016. The land sink, about 2.4 Pg C yr−1 or 21% of emissions, has stagnated since 2000. Glaciers lose 267 Gt yr−1, Greenland about 4.9 trillion tonnes since 1992, and Arctic summer sea ice may vanish before mid-century.

These changes rest on coupled mechanisms. Cloud feedback is net positive but remains the largest source of climate-sensitivity uncertainty; ice sheets, glaciers and permafrost involve albedo, hydrological and carbon feedbacks with multi-decadal to millennial memory; ocean heat uptake, stratification and ventilation couple warming to oxygen and nutrient loss; the land sink is destabilized by drought, hydraulic failure and fire; and moisture–energy partitioning drives dry–hot extremes. Coupled spheres transfer and amplify local changes across scales and regions. Four gaps recur: identifying thresholds and recovery, observing slow variables long enough, representing subgrid and nonlinear processes, and scaling local processes to global risk.

Closing these gaps depends on what capability can and cannot see. Observing—Argo floats, flux towers, cryosphere campaigns—resolves heat, carbon and ice trends invisible two decades ago, while early-warning indicators register declining resilience, not collapse timing. Modelling spans cloud-resolving to Earth-system models, with vegetation demographic models and long-term warming experiments testing ecosystem response and overshoot pathways explicitly. Intervention options, from marine cloud brightening to carbon dioxide removal, face one test: reversibility, verifiability and transboundary effects differ, and none substitutes for deep emission reduction; ocean-based removal remains small-scale.

Convergence of global mean temperature is an insufficient criterion for stabilization: the peak, duration and rate of overshoot and cumulative exposure above the target change critical-transition probability, and transient overshoot can amplify long-term risk through cascades in tipping-element networks. Slow-response systems may remain altered after temperature returns to the same level, so assessment must be explicit about path information and reframed around a stability margin. Mitigation speed is itself a stability variable; carbon dioxide removal complements rather than substitutes mitigation; and for ocean-based removal and solar radiation modification, governance must precede deployment. We propose a risk-tiered, stage-gated and polycentric architecture with predefined stop conditions. Equity is not an add-on: benefits, risks and the capacities to observe, compute and finance are unevenly distributed, so governance should embody distributive justice, common but differentiated responsibilities, broad participation, transparency, accountability and periodic reassessment, with the Global South as co-designer. China should couple national capacity building with active participation in rule-making and South–South cooperation.

14:48 - 15:00 Submission 116

Fighting for 1.5°C Target: Modeling on Speed-up Energy Transition Pathways for China and Asia

Kejun Jiang

The Hong Kong University of Science and Technology(Guangzhou), Guangzhou, China

Abstract

Fighting for 1.5℃ Target： Modeling on Speed-up Energy Transition Pathways for China and Aisa

Jiang Kejun

The Hong Kong University of science and Technology(Guangzhou)

Recently there are talks about the 1.5℃ climate change target is already failed because recent temperature rise could go beyond 1.5℃ in near future, and the report from UNEP on overshooting pathway caused some discussion whether UN already thought the target is already impossible. However there is no change from the IPCC SR1.5 and AR6 on the finding for emission pathways. There is very limited scenarios in IPCC assessment process to have no overshooting in future, almost all scenarios are overshooting scenario, and now we are still on the way towards to 1.5℃. However pib trouble is recent temperature rise is much more faster than IPCC WGI scenario analysis, and bringing us an urgency to move much more faster. Therefore our research team's recent effort is to fighting for 1.5℃. Good news is technology progress is significant, especially in last 12 months. This presrntation will talk about the possibility for China and many Asian countries to move faster to make GHG emission reduction to get us still on the way towards to the target. Our modeling analysis results for China, Nepal, Pakistan, Bangladesh etc., shows there could be big potential for many developing countries to move to much earlier reduction and bring economic benefit.

Poster Session

16:00 - 18:00

Theme	Presenter	Title	Page
Theme 1	Kok Sin Woon	Exploring Pathways for Reducing Global Solid Waste Emissions to Meet Climate Targets	44
Theme 2	Hao Pan	Overlooked irreversibility of China's high-impact climate extremes under large-scale carbon dioxide removal pathways	45
Theme 2	Zheng Shi	The durability of CDR: Governing CDR in climate-overshoot pathways	45
Theme 3	Haiming Luo	The Timing Paradox: Marine Carbon Removal's Greatest Economic Value Precedes Its Technological Readiness	46
Theme 3	Alessio Mastrucci	Carbon storage in urban buildings: The potential of structural wood and biochar-based concrete in global mitigation scenarios	46
Theme 3	Takuya Hara	Understanding Technology Choices and Price Formation under Biomass and CCS Constraints in Net-Zero Energy Systems	47
Theme 3	Hui Yue	Net-zero roadmap for hard-to-abate sectors in carbon-intensive cities	48
Theme 3	Anuj Pathak	The Role of Direct Air Capture in Shaping India's Net-Zero Energy Transition	49
Theme 3	Weiping Xie	Ireland's energy system transition under equity-based carbon budgets and carbon dioxide removal uncertainty	49
Theme 4	Weiwei Xiong	Comparison of simple climate models under diverse long-term overshoot scenarios	50
Theme 4	Kaiwen Zhang	A westward shift of heatwave hotspots caused by warming-enhanced land-air coupling	50
Theme 4	Qin Wen	Contrasting marine and terrestrial responses of South Asian summer monsoon system caused by hemispheric insolation	51
Theme 5	Niklas Schwind	RIME-X-OS: Towards Emulating Climate Impacts Under Overshoot and Stabilisation Scenarios	51
Theme 6	Yuying Huang	Global Mortality Burden Attributable to Heat-Related Sleep Loss	52
Theme 6	Andrew J Kruczkiewicz	Climate overshoot impacts on societies: A review of structures and trends in the academic literature	53
Theme 7	Meizi You	Public expressed urban heat perception as a signal of adaptation strain in a warming climate	53
Theme 7	Sibo Li	Prolonged Nighttime Warming under Climate Overshoot May Amplify Sleep and Mental-Health Burdens in Urban Populations	54
Theme 8	Limeng Fan	The effect of North–South economic convergence on the regional allocation of CDR	55

Poster, Theme 1 Submission 112

Exploring Pathways for Reducing Global Solid Waste Emissions to Meet Climate Targets

Kok Sin Woon

The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China

Abstract

Human activities have led to a global surface temperature rise of 1.1°C compared to preindustrial levels as of the end of 2020. As one of the greenhouse gases, methane concentrations surged to 1911.8 parts per billion in 2022, more than double the preindustrial levels. Because of its short atmospheric lifetime, methane emerged as a key topic at COP26 for its potential to rapidly mitigate global warming. This talk addresses a gap in global analysis by exploring how improved solid waste management can mitigate warming and support the Paris Agreement's 1.5° and 2°C targets, along with the commitments outlined in the Global Methane Pledge. We found that abrupt technical and behavioral changes could lead to a net-zero warming solid waste system. However, these changes necessitate rapid adoption within 9 to 17 years to align with the Global Methane Pledge.

Poster, Theme 2 Submission 48

Overlooked irreversibility of China's high-impact climate extremes under large-scale carbon dioxide removal pathways

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Abstract

Large scale CDR can reverse atmospheric CO_2 and global temperature, but climate extremes and its impacts induced by atmospheric CO_2 increase may not fully following them to be reverse along the preset pathways. So far, there is limited understanding of the link between climate reversibility at the global scale and at regional scales, which may impede communication of the regional significance of reducing CO_2 emissions and scaling up CDR. China is crucial for global climate policy, as it accounts for the largest share of global CO_2 emissions and may strongly influence the global emissions trajectory. As we are increasingly likely to enter an overshoot pathway, it is highly relevant for climate policy in countries such as China to understand the implications of global climate targets for regional climate reversibility, which may in turn affect China's climate ambitions.

Here, we investigate this question by utilizing an idealized CO_2 emission and removal experiment from the CDR Model Intercomparison Project, involving seven Earth system models. We find that increases in heat extremes, heavy precipitation, agroecological drought, and river flooding cannot be fully balanced by equivalent CDR over most regions of China. By decomposing the hysteresis of climate extremes into global and regional climate response asymmetries, we demonstrate that it arises from both global warming hysteresis and asymmetric regional climate responses at the same global warming level. Our findings imply that global CO_2 and temperature targets alone might overlook irreversible regional climate risks under highly idealized CDR within the considered timescale.

Poster, Theme 2 Submission 92

The durability of CDR: Governing CDR in climate-overshoot pathways

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Abstract

Carbon dioxide removal (CDR) is moving from a supplementary mitigation option to a central component of strategies for navigating climate overshoot. It is expected to offset residual emissions after deep decarbonization to achieve net-zero emissions and, in some pathways, to drive net-negative emissions and return global warming towards the Paris Agreement's temperature goals, particularly 1.5 °C. Yet a central premise of CDR-based net-zero governance remains unresolved: for how long must a tonne of removed CO_2 remain stored to count as durable? The IPCC defines CDR as the anthropogenic removal of CO_2 from the atmosphere followed by its durable storage, but neither science nor policy has converged on whether durability should be measured in decades, centuries or millennia.

We argue that CDR durability cannot be defined solely by a fixed number of years. It depends on two dimensions: where the removed CO_2 is stored and how the removal is used. The storage reservoir determines the carbon's expected residence time and reversal risk. The intended accounting or policy use determines whether the storage can support national inventory reporting, a tradable credit, a temporary climate contribution or a claim of permanent fossil-CO_2 neutralization. Ambiguity creates three governance problems. Temporary CDR may be counted or credited as permanent neutralization of fossil CO_2, creating a deferred carbon liability when stored carbon is released and shifting future removal obligations across generations. A common CO_2-equivalent metric may misrepresent the relative value of removals with different storage lifetimes, while treating all pathways as interchangeable may produce portfolios that fail to align technologies with their durability, risks, resource requirements and climate functions.

These problems reflect a tension between the physical behaviour of CO_2 in the climate system and the assumptions used to compare climate effects over time. The near-linear relationship between cumulative anthropogenic CO_2 emissions and global warming provides the physical basis for net-zero targets. Because

a fraction of fossil-derived CO_2 remains in the atmosphere for centuries to millennia, removals used to neutralize fossil CO_2 face stringent durability requirements. The climate–carbon-cycle response to CO_2 emissions and removals is also not strictly symmetric. Estimates of temporary-storage value therefore vary with the selected time horizon, discount rate, climate-damage function and greenhouse gas being offset.

Temporary CDR can help limit peak warming, facilitate the transition to durable removals, contribute to ecosystem restoration and, under explicit conditions, offset part of the warming effect of some short-lived non-CO_2 gases. It cannot, however, by itself permanently neutralize fossil CO_2 emissions. These findings call for governance that separates temporary climate contributions from permanent neutralization claims, matches emissions to sinks with compatible storage lifetimes, applies differentiated MRV and durability-specific credit labels, and assigns enforceable liability for renewal, replacement or reversal. CDR durability should therefore be treated as a condition of credible and equitable overshoot governance, rather than reduced to a single threshold applied uniformly to every tonne.

Poster, Theme 3 Submission 9

The Timing Paradox: Marine Carbon Removal's Greatest Economic Value Precedes Its Technological Readiness

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Abstract

Meeting the Paris Agreement temperature goals requires evaluating carbon dioxide removal alongside conventional mitigation. We developed a modular extension of the DICE climate-economy model to assess marine CDR (mCDR) pathways using Ocean Alkalinity Enhancement and Ocean Iron Fertilisation as case studies. Our analysis reveals that mCDR deployment to achieve a 0.1°C cooling yields net benefit-cost ratios of 2.3:1 (OAE) to 2.9:1 (OIF) for a 1.9°C target, and remains economically favourable under the more demanding 1.5°C target. However, we identify a critical temporal mismatch: mCDR's greatest economic value occurs in scenarios requiring near-term implementation, while the technologies remain years from deployment readiness. Postponing this readiness is costly: a five-to ten-year delay in reaching gigatonne-scale deployment raises the cumulative economic penalty from 1.03 to 2.29 trillion-dollar consumption-equivalent. This asynchrony is pronounced for 1.5°C pathways where emission reductions must peak before 2030, but less problematic for 1.9–2.0°C scenarios where mCDR can substitute for the most expensive conventional abatement and thereby lower the present-value cost of meeting the target. Preserving the option of mCDR within this narrowing window represents a strategic hedge against the economic risks of rapid decarbonization while potentially enhancing the feasibility of ambitious climate targets.

Poster, Theme 3 Submission 19

Carbon storage in urban buildings: The potential of structural wood and biochar-based concrete in global mitigation scenarios

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Abstract

Rapid urbanization is expected to substantially increase demand for construction materials, intensifying greenhouse gas (GHG) emissions associated with the built environment. Bio-based construction materials offer the opportunity to both reduce embodied emissions and store carbon within long-lived building stocks. However, the magnitude of their climate mitigation potential, and the extent to which it depends on circular economy strategies and material availability, remain poorly quantified at the global scale.

This study evaluates the carbon storage and embodied GHG mitigation potential of substituting conventional construction materials with structural wood and biochar-based concrete in global urban building stocks. We assess material substitution scenarios until 2100 at 10%, 30%, and 50% adoption levels and examine their interactions with sufficiency and circular economy strategies that reduce floor space and material demand. Our assessment integrates biogenic carbon inflows and outflows, embodied emissions, and feasibility constraints associated with biomass supply and material performance.

Structural wood substitution provides the largest climate benefits, resulting in cumulative net carbon storage of 11.0–24.8 $GtCO_2eq$ by 2100 and reducing cumulative net embodied GHG emissions by 20–100 $GtCO_2eq$ (8–40%) relative to conventional construction. In contrast, biochar-based concrete stores 7.9–14.5 $GtCO_2eq$ and achieves embodied emission reductions of up to 8 $GtCO_2eq$ (4%), with mitigation constrained by the limited proportion of cement that can be replaced while maintaining structural performance.

The greatest mitigation potential is achieved by combining bio-based material substitution with sufficiency and circular economy measures. These integrated strategies reduce cumulative net embodied emissions by up to 64% for wood-based construction and 41% for biochar-based concrete by 2100. However, realizing the full carbon storage potential of biochar would require substantial expansion of sustainable biochar production, while the scalability of wood-based construction depends on feasible substitution rates and sustainable timber supply.

Our results demonstrate that bio-based materials can make a significant contribution to decarbonizing the global building sector, particularly when deployed alongside demand reduction and circular material strategies. The findings provide a quantitative assessment of the opportunities, limitations, and feasibility of long-term biogenic carbon storage in urban buildings, offering evidence to inform climate mitigation pathways and future construction policy.

Poster, Theme 3 Submission 51

Understanding Technology Choices and Price Formation under Biomass and CCS Constraints in Net-Zero Energy Systems

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Abstract

Limiting climate overshoot requires the earliest possible transition to net-zero (and eventually net-negative) energy systems. Net-zero energy system analyses using energy system models (ESMs) and integrated assessment models (IAMs) rely on key assumptions regarding the availability of carbon-neutral energy resources, carbon capture and storage (CCS) capacity, and techno-economic parameters. These assumptions strongly influence model outcomes, including technology choices, resource use, energy and carbon flows, and energy and carbon prices.

Insights from ESMs and IAMs have traditionally been gained through multi-model comparisons under different assumptions. Single-model studies, in contrast, have largely focused on sensitivity analyses, with limited attention to the mechanisms linking key assumptions to model outcomes. In cost-optimization models, technology choices and energy and carbon prices are interdependently determined under stringent emission constraints. Examining the relationship between price formation and technology choices can therefore reveal how key assumptions shape model outcomes.

In this study, we use an open-source linear programming model representing a simplified global net-zero energy system to quantitatively analyze and explain how assumptions regarding biomass and CCS availability affect technology choices and energy and carbon prices. We comprehensively visualize the resulting energy and carbon flows and compare two cases: a Base case, in which no upper limits are imposed on biomass and CCS availability, and a Constrained case, in which biomass availability is limited to 64 EJ/year and CCS availability to 3.8 GtCO2/year.

In the Base case, gaseous and liquid fuel demands are supplied by fossil fuels, with the resulting CO2 emissions offset by biomass-based carbon dioxide removal (CDR) combined with CCS. Biomass is also

used for power generation and hydrogen production, thus serving both as an energy source and as a carbon carrier for CDR.

In the Constrained case, limited biomass and CCS availability restricts biomass-based CDR and fossil fuel use. Consequently, zero-carbon electricity supply increases substantially to support direct air capture (DAC) and synthetic fuel production from electrolysis-based hydrogen. DAC offsets residual CO2 emissions, while synthetic fuels reduce fossil fuel use. Furthermore, as biomass cannot provide sufficient carbon feedstock for synthetic fuel production, DAC also serves as a carbon source for synthetic fuels.

Technology choices differ substantially between the two cases, with higher-cost technologies such as DAC and synthetic fuels selected in the Constrained case. Biomass and CCS constraints raise energy and carbon prices, making these technologies economically competitive. In turn, these prices can be understood as being formed by cost differences among substitutable technologies under the system constraints.

The simplified model, combined with energy and carbon balance visualization and marginal price analysis, provides an intuitive and quantitative understanding of net-zero energy systems. Although this study considers a single global region, the framework could be extended to generalized analyses using normalized regional settings. Furthermore, direct application of matrix- and vector-based analyses to large-scale models could enable similar analyses of more detailed ESMs and IAMs.

Poster, Theme 3 Submission 54

Net-zero roadmap for hard-to-abate sectors in carbon-intensive cities

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Abstract

Cities, particularly in low- and middle-income countries, host the industries that supply steel, glass, cement, and electricity—sectors among the largest contributors to greenhouse gas emissions. These hard-to-abate sectors have historically lagged behind in climate action, resulting in uneven progress in keeping cities green. Nevertheless, an in-depth understanding of city-driven, industry-led pathways for deep decarbonization that are central to human well-being remains lacking. This study takes a fresh look at the city-industry-climate nexus by developing an internally-consistent, city-level integrated assessment framework that explores pathways to break urban hard-to-abate bottlenecks. This framework incorporating technological solutions and shared socioeconomic pathways provides analysis capabilities at finer levels of technology and spatial resolution than previously available. Scenario-based modeling of over ninety detailed industrial processes indicates an early peak in demand-driven manufacturing emissions from iron and steel, cement, and glass in the mid-2020s, whereas coal-intensive power generation shows pathway-dependent variations. Mapping hard-to-abate emission dynamics onto cities reveals marked spatial heterogeneity in decarbonization trajectories, driven by location-specific industrial and resource profiles. Cost-optimized efficiency interventions deliver the majority of near-term reductions, while scaling up carbon capture, utilization, and storage contributes an additional 21% of abatement. Yet, long-lived infrastructural lock-ins delay progress in heavy-industry cities while coal-to-clean transitions and scrap recycling support earlier net-zero outcomes in industrial transfer hubs. These findings highlight the need to engage cities in addressing hard-to-abate emissions through integrated urban–industrial–decarbonization strategies that move beyond top-down mitigation and achieve tangible and equitable benefits by better bridging long-term climate objectives with on-the-ground delivery.

Poster, Theme 3 Submission 91

The Role of Direct Air Capture in Shaping India's Net-Zero Energy Transition

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Abstract

India aims to achieve net-zero emissions by 2070, requiring substantial carbon dioxide removal (CDR) to offset residual emissions from hard-to-abate sectors. While previous studies have highlighted the roles of bioenergy with carbon capture and storage (BECCS) and hydrogen, the implications of different DACCS deployment pathways for India's broader energy transition remain uncertain. This study uses the AIM-Technology model to investigate how the availability and timing of DACCS deployment influence India's net-zero pathway. Multiple scenarios are developed to examine alternative assumptions regarding DACCS cost and availability. The results show that early DACCS deployment increases the availability of CDR and reduces the scale and pace of hydrogen deployment required for net zero. In contrast, delaying or excluding DACCS requires earlier and more rapid expansion of hydrogen supply and infrastructure, with hydrogen exceeding 20% of final energy in the net-zero year when DACCS is unavailable. Earlier DACCS deployment also reduces cumulative investment requirements by more than US$900 billion between 2050 and 2070, primarily by reducing the transformation required in the transport sector. These findings highlight the importance of considering DACCS alongside hydrogen and other mitigation options when planning India's long-term net-zero transition.

Poster, Theme 3 Submission 107

Ireland's energy system transition under equity-based carbon budgets and carbon dioxide removal uncertainty

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Abstract

The prospect of climate overshoot raises questions about how responsibilities and capabilities for emissions reductions and carbon dioxide removal (CDR) should be shared across countries. Equity-based national remaining carbon budgets (NRCBs) provide a framework for translating fairness principles into national contributions to the Paris Agreement's temperature goals. However, translating these budgets into energy system transition pathways requires accounting for uncertainty in future CDR deployment. Using NRCB allocations for Ireland based on different equitable principles, we examine how alternative equity-based carbon budgets and multidimensional CDR uncertainties jointly shape Ireland's energy system transition pathways. We focus on bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS).

We develop and contrast scenarios with different 1.5°C-consistent NRCBs from Williges et al. and consider different timescales for returning from carbon budget overshoot (2050, 2070 and 2100). We generate input vectors for CDR technologies (for example, costs, growth rates, and CO_2 storage availability) using the Latin hypercube sampling (LHS) method (N = 1000 runs per scenario). This framework allows us to examine how much CDR will be needed to return from carbon budget overshoot by different deadlines. We use Optimal Transport-based sensitivity indices as a global sensitivity analysis (GSA) tool to assess how variation in modelled CDR deployment can be attributed to variation in model inputs. In other words, GSA is a way to systematically address the role of numerical assumptions (the inputs) in supporting the decision-making process in Ireland.

We acknowledge that this study focuses on the energy system and excludes CO_2 emissions from land use, land-use change and forestry (LULUCF), as well as land-use competition associated with large-scale CDR deployment. The resulting pathways should therefore be interpreted as conditional energy-system scenarios, rather than comprehensive assessments of national CDR feasibility or sustainability. Within this scope, our framework connects equity-based carbon budgets, alternative deadlines for returning from carbon budget overshoot, and multidimensional CDR uncertainty. It provides a basis for examining how

near-term mitigation and longer-term removal requirements respond to different equity principles and return deadlines. Global sensitivity analysis helps identify which assumptions most strongly influence modelled CDR deployment, making reliance on uncertain future removals explicit. Rather than prescribing a single equitable pathway, the study supports informed deliberation on national mitigation ambition and CDR reliance under overshoot. Its transferable contribution is a framework for translating equity-based commitments into energy system pathways while exposing the assumptions on which those pathways depend.

Poster, Theme 4 Submission 61

Comparison of simple climate models under diverse long-term overshoot scenarios

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Abstract

Long-term overshoot pathways are becoming increasingly important in climate assessment because returning to a low temperature target after exceedance requires times scales extending well beyond 2100. Simple climate models (SCMs) are widely employed to evaluate temperature outcomes, yet longer-term outcomes with overshoot remain under-assessed. Here we compare three SCMs (ACC2, FaIR, and OSCAR) across 13 extended long-term overshoot scenarios up to 2300 developed as part of the Horizon Europe RESCUE and OptimESM projects. Our scenarios are generated using REMIND-MAgPIE up to 2100 and further extended using an IAM emulator, providing cost-effective pathways to achieve long-term temperature targets with overshoot of a range of lengths and magnitudes. Complementing the broader RCMIP Phase 3, our analysis focuses on long-term overshoot response.

We find that the three SCMs show broadly comparable temperature projections up to peak temperatures; however, they diverge substantially in the post-peak period, resulting in distinct overshoot levels and overshoot durations. CO_2 forcing differences explain much of the forcing spread, but forcing differences alone do not fully explain the post-peak temperature disparities. Cumulative CO_2 uptake increases with overshoot level in all three SCMs, but the response is stronger in ACC2 than in FaIR and OSCAR. Ocean heat content cumulation also increases with overshoot but is greatest in FaIR and lowest in ACC2. We also find that ACC2 exhibits an approximately symmetrical relationship between ocean heat content change and CO_2 uptake, whereas FaIR and OSCAR show pronounced hysteresis. These results identify model-specific carbon cycle responses and ocean thermodynamics that help explain why identical emissions pathways lead to different post-peak outcomes across SCMs.

Poster, Theme 4 Submission 100

A westward shift of heatwave hotspots caused by warming-enhanced land-air coupling

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Abstract

Heatwaves pose serious risks to human health and lives, but how their occurrence patterns may change under global warming remains unclear. Here, we reveal a systematic westward shift of heatwave hotspots across the northern midlatitudes around the late 1990s. Both observational analysis and numerical simulation show that this shift is caused by intensified soil moisture-atmosphere coupling (SAC) in eastern Europe, Northeast Asia, and western North America under recent background warming. The strengthened SAC shifted atmospheric high-amplitude Rossby wave number-5 pattern westward to a preferred phase position, which increased the probability of the occurrence of high-pressure ridges over these three hotspots by a factor of up to 39. Our results highlight the importance of SAC in shaping heatwave patterns

and large-scale atmospheric circulation and challenge the conventional view that the land surface only passively responds to atmospheric forcing.

Poster, Theme 4 Submission 111

Contrasting marine and terrestrial responses of South Asian summer monsoon system caused by hemispheric insolation

qin wen

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Abstract

South Asian summer monsoon (SASM) delivers substantial rains to the Indian subcontinent and drives strong upwelling in the Arabian Sea, making marine upwelling records and terrestrial rainfall records two primary proxies for reconstructing past SASM variability. However, on orbital timescales, these two sets of records vary largely in opposite directions: the upwelling records are in-phase with Southern Hemisphere (SH) summer insolation, whereas the rainfall records are in-phase with Northern Hemisphere (NH) summer insolation. This leaves a long-standing debate on whether SASM is driven by NH or SH insolation. Here, combining paleoclimate records with transient climate simulations that explicitly separate the effects of the NH and SH insolation forcing, we show that the SASM rainfall is dominated by the NH insolation, whereas the Arabian Sea upwelling is forced predominantly by the SH insolation. When boreal summer occurs at perihelion, insolation is strongly enhanced not only in the NH but also in the tropical-subtropical SH. The former enhances the SASM rainfall through Eurasian warming, while the latter weakens the Arabian Sea upwelling by inducing South African warming and subsequent atmospheric teleconnections over the Indian Ocean. Our study reconciles the long-standing debate, and more broadly, reveals that warming in South Africa could exert a significant and previously overlooked remote forcing on the SASM system in past and future climate changes.

Poster, Theme 5 Submission 60

RIME-X-OS: Towards Emulating Climate Impacts Under Overshoot and Stabilisation Scenarios

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Abstract

RIME-X (Rapid Impact Model Emulator eXtended) is an emulator approach that extends simple climate model (SCM) outputs by translating global mean surface air temperature (GMT) distributions into distributions of regional climate or climate impact indicators. RIME-X uses simulations from climate and impact modeling intercomparison projects, such as CMIP and ISIMIP, to extract distributions of regional indicators at specific GMT levels from those and combines them with scenario-dependent GMT distributions extracted from probabilistic SCM ensembles. RIME-X produces scenario-dependent distributions of these indicators over time, integrating multiple sources of uncertainty along the modeling chain, including uncertainty in the global climate response, model uncertainty in translating the global climate response to the regional scale, and internal variability.

A key limitation of RIME-X, shared by many emulators, particularly those based on pattern scaling and global warming level approaches, is that they assume an approximately stable relationship between GMT and the indicator of interest. This assumption limits the method's applicability to overshoot scenarios, since in such scenarios, pattern and adjustment effects can break the stationarity between GMT and the distribution of regional indicators.

In this work, we explore whether this limitation can be addressed with RIME-X-OS, an approach that splits the simulation period according to its position relative to the global temperature peak and derives a distinct

GMT–indicator relationship for pre- and post-peak temperature periods. We compile a dataset of ssp534-over and ssp126 scenario simulations extended to 2300, as well as idealized model experiments from flat10MIP and TIPMIP, which we then apply jointly to emulate new overshoot scenarios. We present results for temperature and precipitation indicators, and show how pre- and post-peak responses, and associated uncertainties, vary by indicator and region. Critically we also make comparison of the same indicators using the original overshoot-naive methodology, and are thus able to show by region, for what indicators and by how much the responses vary. While the differences for temperature indicators are predominantly not large, hysteresis effects and larger uncertainties are more prominent in precipitation indicators.

Poster, Theme 6 Submission 50

Global Mortality Burden Attributable to Heat-Related Sleep Loss

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Abstract

Extreme heat increases mortality over short exposure windows. However, urban heat exposure extends beyond episodic daytime extremes. More persistent and relatively modest increases in temperature, particularly at night, can prolong thermal exposure across repeated sleep periods. Warmer nights reduce sleep duration at the population level, which may, in turn, increase the risk of all-cause mortality associated with short sleep. Together, these findings point to a potential cumulative pathway through which recurrent, incremental sleep loss shifts population sleep-duration distributions toward short sleep and ultimately contributes to mortality burden. Despite growing evidence for each component of this climate-sleep-mortality pathway, its downstream health burden has not been quantified.

We developed an integrated nighttime temperature-sleep-mortality framework following comparative risk-assessment principles. Daily nighttime temperature was translated into sleep-duration loss and population-weighted to derive country-level exposure. For each country, the observed sleep distribution was contrasted with a counterfactual distribution in which the estimated temperature-associated loss was removed. A short-sleep mortality risk function was then applied to estimate attributable mortality among adults aged 20-69 years across 61 countries from 2016 to 2019. We further extended the framework to 2031-2100 under four Shared Socioeconomic Pathway (SSP) scenarios and compared projected burdens between emerging market and developing economies (EMDEs) and advanced economies.

Across the 61 countries, a mean shift of approximately 2.6 min/night increased the prevalence of <7 h sleep from 47.71% under the counterfactual distribution to 49.72% under the observed distribution, equivalent to approximately 20 additional adults with short sleep per 1,000 population. Nighttime-temperature-associated sleep loss accounted for an estimated 22,454 all-cause deaths during 2016-2019, or an annual average of 5,613 deaths. Low-latitude countries accounted for 72.4% of cumulative attributable deaths and had a pooled attributable mortality rate of 0.276 deaths per 100,000 person-years, compared with 0.085 at middle latitudes and 0.034 at high latitudes. Future projections indicated widening inequalities relative to the historical baseline across all SSP scenarios: pooled attributable mortality rates in EMDEs were more than 4 times those in advanced economies during 2031-2100, compared with approximately 3 times during 2016–2019.

Our findings identify a cumulative sleep-mediated pathway through which repeated nighttime heat may contribute to population health burden. Although modest on any given night, recurrent minute-scale sleep losses accumulated into substantial short-sleep exposure and a measurable mortality burden, with pronounced geographic and demographic heterogeneity. These findings suggest that heat-health surveillance and adaptation should extend beyond daytime extremes and conventional heat-wave periods to include nighttime temperature as a health-relevant exposure, including persistently warmer nights occurring outside the hottest season. Adaptation strategies should also place greater emphasis on maintaining cooler sleeping environments through improved nighttime indoor cooling and access to effective cooling, particularly for populations projected to bear disproportionate future burdens.

Poster, Theme 6 Submission 101

Climate overshoot impacts on societies: A review of structures and trends in the academic literature

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Abstract

Global temperature rise is projected to exceed the Paris Agreement's 1.5C target limit, with projections indicating that humanity is on track to significantly exceed pre-

industrial global mean temperature levels before the 2050s under current national

commitments. Given insufficient emission reductions in recent years, it is now considered almost inevitable that warming will enter a period of climate overshoot. The scientific community is dedicating significant resources to understanding the consequences of different overshoot

trajectories, with a strong focus on understanding the likely biophysical and climatic impacts of

exceeding the 1.5C target. However, the eventual drawdown pathways will be heavily influenced

by mitigation and adaptation policies, which will be shaped by the impacts that societies

experience during overshoot. In this context, a comprehensive and data-backed understanding of the potential impacts of overshoot that includes the human and social impacts is critical for

informing policymakers and the humanitarian organizations tasked with responding to emergent

crises. This study presents a first attempt to understand the degree to which social and

humanitarian impacts are included in current literature on overshoot by presenting a bibliometric

analysis of studies related to overshoot. Our findings suggest that there is a significant

knowledge gap in the current literature regarding the likely social and humanitarian impacts of

climate overshoot. We advocate for advancing the global research agenda on overshoot by strengthening social science research into the impacts of overshoot.

Poster, Theme 7 Submission 38

Public expressed urban heat perception as a signal of adaptation strain in a warming climate

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Abstract

Urban heat is one of the most immediate ways in which communities experience a warming climate, and climate overshoot is likely to intensify not only physical heat exposure but also the social burdens and adaptation demands associated with it. Yet adaptation planning rarely captures how residents publicly interpret heat, which burdens they foreground, and when everyday discomfort becomes framed as a health, infrastructure, governance, or equity problem. We examine these dimensions through an attention–emotion framework for publicly expressed urban heat perception.

We analysed English-language Twitter/X posts from the 2022 warm season across 50 cities in Australia, Canada, the United Kingdom, and the United States. A validated large-language-model classifier assigned each post to one of three domains—exposure and lived experience, health impacts and burden, and systems and governance—and to one of seven expressed emotions. City-specific adjusted standardised residuals were then used to identify attention–emotion pairings that were enriched relative to each city's own discourse baseline, distinguishing recurrent cross-city signatures from context-sensitive framing differences.

Across cities, heat perception showed a consistent structure that may be relevant for anticipating adaptation strain under overshoot. Sleep disruption and work/commuting burdens were repeatedly associated with sadness, suggesting that cumulative heat impacts are often expressed as erosion of everyday functioning rather than as acute threat. Health consequences and preventive warnings were strongly associated with fear, while systems- and climate-related discourse showed recurrent neutral–fear signatures. Climate-justice discourse was more likely to be associated with anger in some cities, indicating that heat can become interpreted through questions of unequal burden, responsibility, and avoidability. Exploratory city-level analyses further suggested that accessibility, sociodemographic structure, governance, and environmental inequality co-varied with several attention–emotion patterns, often more consistently than climatic conditions alone.

These findings do not model overshoot pathways directly. Instead, they identify a social-perceptual layer of heat risk that is likely to become increasingly consequential as warming exceeds agreed thresholds. Public expressions of disrupted sleep, constrained mobility, health threat, inadequate urban systems, and unequal protection may provide early signals of where incremental adaptation is perceived as insufficient. Incorporating such experience-based indicators alongside physical and health metrics could help overshoot adaptation strategies better anticipate residual risk, distributional inequities, and emerging limits to urban coping.

Poster, Theme 7 Submission 47

Prolonged Nighttime Warming under Climate Overshoot May Amplify Sleep and Mental-Health Burdens in Urban Populations

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Abstract

Background: Climate overshoot is not only a question of peak global temperature. Its health consequences will unfold locally through the magnitude and duration of population exposure to elevated temperatures, and some resulting burdens may not decline synchronously with global temperature. Persistently warm nights are especially relevant because they can disrupt physiological recovery and sleep, potentially amplifying mental-health risks over the period during which temperature targets are exceeded. However, sleep remains largely absent from assessments of the health consequences of climate overshoot. We examined insufficient sleep as a potential population-level pathway linking nighttime heat to mental distress in urban populations.

Methods: We conducted an ecological pathway analysis using publicly available data for U.S. urban counties. Adjusted prevalences of short sleep duration and frequent mental distress were obtained from the 2024 and 2025 CDC PLACES releases. Heat exposure was characterized using mean June–August minimum temperature during 2022–2023 from NOAA Climate at a Glance. Urban counties were identified using the 2023 Rural–Urban Continuum Codes. Population-weighted linear models with state fixed effects and state-clustered standard errors estimated associations between nighttime heat, short sleep, and mental distress. We subsequently examined attenuation of the heat–mental-distress association after accounting for short sleep.

Results: The analysis included 1,147 urban counties in the 2024 release and 1,078 in the 2025 release. In 2025, each 5°F increase in summer minimum temperature was associated with a 1.43-percentage-point higher prevalence of short sleep (95% CI: 1.09–1.77) and a 0.41-percentage-point higher prevalence of frequent mental distress (95% CI: 0.05–0.77). After adjustment for short sleep, the heat coefficient was attenuated to 0.04 percentage points (95% CI: −0.24–0.33), while short sleep remained strongly associated with mental distress. The 2024 release showed the same directional pattern.

Conclusions: These findings identify sleep disruption as a plausible and underrecognized pathway through which sustained nighttime warming could translate into broader mental-health burdens during climate overshoot. Although the spatial associations estimated here should not be interpreted directly as projections of future temporal change, they provide an empirical basis for incorporating sleep-related

health outcomes into overshoot scenarios. Longer and higher overshoots would extend exposure to warm nights and could compound sleep and mental-health burdens, particularly among populations with limited access to household cooling, thermally adequate housing, and restorative urban environments. Moreover, these accumulated health burdens may not be automatically reversed when global temperature eventually declines. Overshoot health assessments should therefore consider nighttime thermal exposure, sleep, and mental health alongside conventional mortality outcomes, while adaptation strategies should prioritize nighttime cooling, housing retrofit, urban greening, and equitable access to thermal protection.

Poster, Theme 8 Submission 88

The effect of North–South economic convergence on the regional allocation of CDR

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Abstract

Mitigation pathways compatible with the Paris Agreement are typically built around a globally uniform carbon price. This is globally efficient, but imposes disproportionately high mitigation costs on developing regions. The same applies to the carbon dioxide removal (CDR) on which overshoot pathways depend: equity-based allocations of CDR responsibility have been shown to differ from the global cost-effective allocation. Moreover, the socio-economic assumptions underlying most scenario work imply slow international economic convergence. Based on this background, the integrated assessment community has called for frameworks that make equity and effort-sharing explicit. Rather than differentiating emission targets across regions, we introduce a new scenario where productive capital is redistributed towards developing regions, and examine how this changes the regional allocation of mitigation effort and CDR along an overshoot pathway.

Using AIM-Hub, a recursive dynamic computable general equilibrium model covering 17 regions to 2100, we impose a cumulative CO_2 budget of 400 $GtCO_2$ for 2021-2100, an overshoot pathway that turns net-negative in the second half of the century. In the International Convergence scenario, OECD regions stabilise GDP per capita, and the resulting surplus investment is transferred into capital formation in non-OECD regions.

Transfers average 7.9 trillion US$2010 per year over 2031-2100. Non-OECD GDP per capita converges to the OECD level by 2100, and the global Gini coefficient of GDP falls from 0.42 to 0.34 in 2050. Contrary to the expectation that scaling down affluent economies lowers CDR reliance, cumulative CDR over 2030-2100 is almost unchanged globally (970 against 1000 $GtCO_2$ in the reference scenario). Instead, transfer-driven shifts in exchange rates raise the carbon price faced by OECD regions in domestic terms, and OECD cumulative CDR rises to roughly 1.5 times its reference level.

Convergence achieved through capital transfer therefore does not reduce global reliance on CDR; it relocates the net-negative burden towards developed regions.

Wednesday, 25 November 2026

Plenary 2. Theme to Theme and Report back, Q&A

08:30 - 09:45, Harmony Hall (Plenary), 和合厅 Chair: Carl Schleussner

Theme 3: Technological solutions for decarbonization and negative emissions

10:00 - 11:00, Harmony Hall (Plenary), 和合厅 Chairs: Alessio Mastrucci, Dabo Guan

Time	Presenter	Title	Page
10:00 - 10:15	Giulio Pistolesi	A Spatially Explicit Roadmap for Agricultural Enhanced Weathering in China.	57
10:15 - 10:30	Soeren Lindner	From Overshoot Ambition to National Food-and-Land Action: A Global FABLE Scenathon for Rapid Methane Mitigation	57
10:30 - 10:45	Ron Milo	Eating the Overshoot: Microbes Eat CO_2; We Eat Microbes	58
10:45 - 11:00	Samuel Lovat	Replacing animal-based foods with microbial alternatives could reduce global greenhouse gas emissions by ≈10 $GtCO_2$-eq/year	58

10:00 - 10:15 Submission 59

A Spatially Explicit Roadmap for Agricultural Enhanced Weathering in China.

Giulio Pistolesi[1], Rui Wang[2], Wenjia Cai[1], Can Wang[3]

[1]School of Earth System Science, Tsinghua University, Beijing, China. [2]Copernicus Institute of Sustainable Development, Utrecht University, Utrecht, Netherlands. [3]School of Environment, Tsinghua University, Beijing, China

Abstract

Agricultural Enhanced Weathering (EW) involves applying crushed silicate rocks to croplands to sequester atmospheric CO2. Here, we model EW deployment across China from 2025 to 2060 using a spatially explicit optimization framework that integrates basalt deposit distributions, cropland locations, techno-economic dynamics, and climatic variables. Our results indicate an annual carbon removal potential of 70 to 110 MtCO2 by 2060, at a cost of $85–150 per tonne. A pronounced spatial mismatch between northern basalt reserves and warmer, high-precipitation croplands in the south necessitates either long-distance transport or the application of basalt to suboptimal sites. We show that slow electrification and continued reliance on fossil-fuel-based energy systems significantly reduce EW's efficacy and raise mitigation costs. Consequently, scenarios that rely heavily on CDR carry greater systemic risks, and EW should be viewed as a complement to—not a substitute for—emissions reductions.

10:15 - 10:30 Submission 25

From Overshoot Ambition to National Food-and-Land Action: A Global FABLE Scenathon for Rapid Methane Mitigation

Soeren Lindner, Federico Frank, Fernando Orduña-Cabrera, Alejandro Rios-Ochoa, Johannes Bednar

International Institute for Applied System Analysis, Laxenburg, Austria

Abstract

Temporary exceedance of 1.5°C heightens the need to limit peak warming and reduce future dependence on carbon dioxide removal (CDR) technologies (Lamb, 2026). Agriculture and land use is central to this challenge: methane and nitrous oxide from livestock, rice and managed soils remain among the most persistent residual emissions in integrated assessment pathways, while afforestation, reforestation and natural regrowth are frequently expected to compensate for these emissions (Humpenoeder et al, 2024; Edelenbosch et al. 2024). Because methane is short-lived, rapid cuts can lower peak warming and limit overshoot, complementing necessary CO_2 mitigation. While integrated assessment models provide aggregated detail on agriculture land-use emissions, they insufficiently account for national contextualised transformation pathways in agriculture and their impacts on food security, biodiversity targets and land constraints (Tavoni et al., 2026). In this study, we employ the FABLE model to identify regional portfolios capable of lowering agricultural residual emissions before mid-century, reducing the reliance on future CDR. We aim to operationalize the highest possible mitigation ambition under climate overshoot within a decentralized food and land-use model (Mosnier et al., 2023).

Methodologically, the FABLE Scenathon enables testing in how far and how rapidly agricultural methane emissions can be reduced through bottom-up pathways in 6 global regions. In the Scenathon, expert teams will start from the current trends of each region to develop three methane-action pathways (early, delayed and locally defined "high ambition") subject to common food and land guidelines. A set of emission targets compatible with 1.5°C trajectories will include FABLE's benchmark of limiting gross agricultural emissions in 2050 to 4 $GtCO_2e\ yr^{-1}$, a FABLE methane-reduction target, and a stringent 2030 methane stress test. Scenarios combine regionally appropriate portfolios of dietary change, reduced food loss and waste, livestock productivity, herd changes and enteric fermentation technologies. Additionally, FABLE distinguishes gross-emissions reductions from land-based CDR through afforestation, reforestation and natural regrowth. This enables assessing the pathways through CH_4, N_2O and CO_2 emissions, cumulative avoided methane-related emissions to 2050, achievements of agricultural GHG and land-CO_2 targets, implications for dietary adequacy, livestock and crop production, pasture and cropland, deforestation, biodiversity and land carbon removals.

Through its transparent accounting, participatory scenario design and explicit reconciliation of heterogeneous country pathways , the FABLE Scenathon makes an important contribution to studies assessing global mitigation in agricultural and land-use sectors otherwise predominantly conducted through partial-equilibrium models (Schmidt-Traub et al, 2019; Frank et al, 2019). While FABLE is limited by exogenous scenario choices, a 2050 time horizon of analysis and the lack of an explicit linkage with earth-system models – features that do not permit FABLE to classify outcomes as overshoot pathways, nor estimate peak temperature and overshoot duration -, it allows quantifying an overshoot-relevant agricultural mitigation frontier: the role of regional food system transformations in early methane reduction.

10:30 - 10:45 Submission 16

Eating the Overshoot: Microbes Eat CO_2; We Eat Microbes

ron milo

Weizmann Institute, Rehovot, Israel

Abstract

Transforming food production is essential to help with food security, land and water stress, climate and ecological stability etc. I will present our integrative analysis on how we evolved a microbe to change its diet from sugar to CO2 and the potential of using such microbes as a promising alternative to feed humanity in place of animal-based foods. Using simplified-by-design techno-economic analysis, I will illustrate that microbial production could become cheap enough to compete with existing animal-based foods, following further industrial maturation. I will then show with coarse-grained life-cycle assessments that microbial foods could have a greenhouse gas footprint more than 10-fold smaller than current animal-based products, offering major potential reductions in the ≈10 GtCO2-eq/year currently driven by animal-based foods. Microbial-based food production also requires 10- to 100-fold less land than animal-based products, with large-scale shifts to microbial foods unlocking massive rewilding potential. Following vegetative regrowth, a complete transition to microbial-based foods in place of animal-based foods could store as much as 500-1000 GtCO2. Microbial-based foods therefore have great potential to reduce future climate overshoot. Going forward, I will discuss what we can do to galvanize this essential transformation by driving key catalytic elements: lower production prices, better taste and improved health outcomes.

10:45 - 11:00 Submission 27

Replacing animal-based foods with microbial alternatives could reduce global greenhouse gas emissions by ≈10 $GtCO_2$-eq/year

Samuel J Lovat, Ron Milo

Weizmann Institute of Science, Rehovot, Israel

Abstract

We need new ways of producing food to feed a growing population amid mounting environmental pressures. Using quantitative arguments, I will illustrate the potential of producing alternatives to animal-based foods with microbes (e.g. yeast, bacteria etc.). We constructed a transparent and robust model that is simplified-

by-design to explore the environmental implications of producing alternatives to meat, dairy and egg products using microbes. We quantify a range of scenarios, including different feedstocks and electricity mixes for microbial growth. Across most scenarios, we estimate that a complete transition from animal-based foods to microbial alternatives could substantially reduce greenhouse gas emissions. In the most promising scenario, where microbes are grown on green hydrogen, greenhouse gas emissions could be reduced by one order of magnitude, or ≈10 $GtCO_2$-eq/year. We further find across all scenarios that a microbial transition could reduce land use by a few tens of million km^2 (largely corresponding to pasture land). Completely rewilding this area could store up to 500-1000 $GtCO_2$, or ≈5-10 $GtCO_2$/year when linearised across a ≈100 year time period for vegetative regrowth. Finally, we show a microbial-food transition could behave in a non-linear manner, with smaller shifts offering large benefits. Going forward, the desirability and cost of microbial foods must be improved to catalyse wide-scale adoption and help reduce global environmental burdens.

Theme 4: Climate impact (ir)reversibility

10:00 - 11:00, Cloud Room, 云岚厅 Chairs: Debra Roberts, Adriano Vinca

Time	Presenter	Title	Page
10:00 - 10:12	Nico Bauer	Biodiversity impacts of transformation scenarios compatible with the Paris Agreement	60
10:12 - 10:24	X Wong	A Dynamical System Theory of Climate Overshoot	61
10:24 - 10:36	Malon Muronzi	Irreversible Climate Impacts and Adaptation Limits in Southern Africa: Pathways, Tipping Points, and Policy Responses under Overshoot	61
10:36 - 10:48	Bryony Worthington	What does the Earth's Energy imbalance tell us about the next two decades of warming and expected level of overshoot?	62

10:00 - 10:12 Submission 58

Biodiversity impacts of transformation scenarios compatible with the Paris Agreement

Nico Bauer[1], Shradda Gupta[2], Patrick José v. Jeetze[1], Leon Merfort[1], Andreas Schwarz Meyer[3], Paul Miller[4], Dánnell Quesada-Chacón[1], Pascal Sauer[1], Raffaele Bernadello[5], Timothée Bourgois[6], Momme Butenschön[7], Chiara Ciscato[7], Jan Philipp Dietrich[1], Chiara De Falco[8], Ana Franco[5], Florian Humpenöder[1], David Klein[1], Tomas Lovato[1], Lars Nieradzik[4], Julia Pongratz[2,9], Robert Salzwedel[1], Alexander Popp[1], Jörg Schwinger[6], Christopher Trisos[3], Michael Windisch[10]

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Abstract

Biodiversity conservation and climate change stabilization are two interrelated global policy challenges. The international treaties of Paris and Kunming formulate objectives for temperature stabilization and reduction of biodiversity threats. Reverting global warming below 1.5°C above pre-industrial levels by 2100 calls the degree of temperature overshoot into question. Varying the magnitude of overshoot leads to vastly different pathways for emissions and land-use. While the emission pathway drives range- and vegetation shifts, changes of land-use directly affect habitat availability. Moreover, emissions and removals are partially linked to land-use changes. These factors may threaten biodiversity. Thus, climate change mitigation and biodiversity protection are interrelated in multiple ways. We investigate the interrelationship to test for potential synergies and trade-offs between both policy objectives. For this purpose we set up a quantitative framework that integrates these various drivers.

We use the REMIND-MAgPIE integrated assessmen model to derive global emission and land-use scenarios for the 21st century that meet exogenous carbon budgets with varying degrees of overshoot (Bauer et al. 2023, Merfort et al. 2023). The emissions and land-use information drives five different Earth System Models (FOCI, MPI-ESM, EC-Earth, CMCC, NorESM) to cover the uncertainties of future climate. We analyze threats to biodiversity, considering three layers. First, we analyze the exposure of species to climate change using monthly data on temperatures and precipitation (Trisos et al. 2020; Meyer et al. 2022). Second, we add the effect of land-use change on habitat availability. Therefore, we link projected land-use changes to species-specific habitat preferences across both managed and unmanaged land cover types (von Jeetze et al. 2025). Third, we add changes of habitats due to vegetation shifts driven by climate change. The three layers are represented on a global 0.25° grid and we highlight near, mid- and long-term impacts on biodiversity change, and identify the regions where the greatest changes are expected to occur. The analysis is based on range maps for a set of 25,000 vertebrate species from the IUCN Red List, which well-represents patterns of biodiversity across global biomes (Lumbierres et al., 2022; IUCN Red List, 2020).

Our study analyzes the dynamic threat patterns for biodiversity. We will compare the importance of the three layers across major world regions and time periods that characterize the scenarios. We aim to identify major trade-offs that are related to the overshoot and its dynamics of land-use changes and temperature. In particular, we will investigate the near-term threat from land-use changes necessary to limit the

temperature overshoot and the double-thread from higher temperature and larger terrestrial carbon removals required for the temperature draw down.

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10:12 - 10:24 Submission 110

A Dynamical System Theory of Climate Overshoot

Xiaoming Wang[1], Shiwei Liu[2]

Presented by **X Wong**

[1]Monash University, Melbourne, Australia. [2]Changsha University of Science & Technology, Changsha, China

Abstract

Assessments of climate overshoot can no longer treat temporary exceedance of global warming targets as a reversible detour, to evaluate impacts through static warming levels. Here, we formulate a continuous-time differential dynamical system that resolves the simultaneity between risk accumulation and vulnerability evolution. By linking incremental risk to dynamic adaptive capacity erosion, we prove analytically that vulnerability expands exponentially as a function of cumulative exposure history. Closed-form solutions demonstrate profound path hysteresis during post-peak cooling, proving that system state recovery is non-symmetrical and generates a persistent, unrecoverable legacy. This theoretical framework demonstrates that overshoot impacts cannot be inferred from endpoint temperatures alone. More importantly, it illustrates that temporary climate overshooting likely lock in permanent socioeconomic and ecological degradation regardless of late-century carbon removal.

10:24 - 10:36 Submission 11

Irreversible Climate Impacts and Adaptation Limits in Southern Africa: Pathways, Tipping Points, and Policy Responses under Overshoot

Malon Muronzi

Environment and Climate Action Zimbabwe, Harare, Zimbabwe

Abstract

Background

Climate overshoot pathways assume global warming will temporarily exceed 1.5°C and potentially 2°C before declining. A central but under-examined feature of these pathways is irreversibility impacts that cannot be undone even if temperatures return to lower levels. In the Earth system, examples include ice sheet loss, species extinction, and permanent ecosystem shifts. For human systems, irreversibility appears as lost livelihoods, abandoned land, cultural loss, and locked-in development deficits. Southern Africa is particularly exposed because it is a climate hotspot for warming above the global average, relies heavily on rain-fed agriculture, and has high levels of poverty and inequality.

Introduction

This paper examines how climate impact irreversibility manifests in Southern Africa under overshoot scenarios, and what it means for adaptation limits and governance. We focus on 3 transboundary systems: 1) water resources in the Zambezi River Basin, 2) rangeland and food systems in Zimbabwe and Botswana, and 3) coastal communities in Mozambique facing sea-level rise.

Methodology

We use a mixed-methods, place-based approach. First, climate and hydrological modeling outputs from CMIP6 and CORDEX-Africa for 1.5°C, 2°C, and overshoot scenarios to 2100 are used to identify biophysical

tipping points. Second, document analysis of NDCs, National Adaptation Plans, and SADC regional strategies to assess how irreversibility is framed in policy. Third, qualitative fieldwork: 45 semi-structured interviews and 6 focus groups in Zimbabwe, Zambia, and Mozambique between Feb–June 2026 with farmers, traditional leaders, and local officials. Fourth, analysis of disaster loss databases and satellite data 2015–2025 to track permanent land use change and infrastructure loss.

Data Presentation
Data are presented in 3 parts. 1) *Biophysical data: maps and timeseries showing projected permanent drying in the Zambezi basin, probability of savanna-to-shrubland transition, and coastal inundation under 0.5m and 1.0m sea-level rise. 2) Policy data: coding of how often terms like "irreversible", "loss and damage", and "limits to adaptation" appear in national documents.

Research Findings
Four key findings emerge. 1) Thresholds crossed: Multiple systems show early signs of irreversibility. Groundwater recharge in parts of Zimbabwe and Botswana is projected to decline by >30% even under net-negative emissions, and coral reefs in Mozambique are unlikely to recover under any overshoot scenario. 2) Adaptation limits reached: Soft limits are evident in agriculture where farmers can no longer adjust planting dates. Hard limits appear in coastal areas where relocation is the only option after Cyclone Freddy-type events. 3) Policy gap: National plans treat adaptation as incremental. Irreversibility is rarely mentioned, and no mechanism exists to compensate for permanent loss.

Conclusion
Southern Africa is already entering a regime of partially irreversible climate impacts. Under overshoot pathways, these legacies will intensify and create permanent development setbacks. We argue that policy must shift from "avoid and adapt" to "anticipate, acknowledge, and address irreversible loss.

Keywords
Climate Irreversibility, Southern Africa, Overshoot, Adaptation Limits, Loss and Damage, Tipping Points

10:36 - 10:48 Submission 106

What does the Earth's Energy imbalance tell us about the next two decades of warming and expected level of overshoot?

Piers Forster[1], **Bryony Worthington**[2]

[1]University of Leeds, Leeds, United Kingdom. [2]Worthington Associates, London, United Kingdom

Abstract
The latest Indicators of Global Climate Change publication from June 2026 headlined three numbers that were all at all-time highs: greenhouse gas emissions of 56.8 $GtCO_2e$; human induced warming of 1.37°C; earth's energy imbalance of 1.12 Wm^{-2}. The Earth's energy imbalance tracks the overall warming of the climate system and it is trending higher than expected. We will discuss the implications of this related to the current El Niño and expected near term warming, climate sensitivity estimates and the possibility of having to revise the range of future warming levels and impacts upwards for a given emission scenario. The presentation will discuss both what we know and what we don't know and consider ways to mitigate risk.

Theme 6: Health implications of overshoot pathways

10:00 - 11:00, River Room, 江河厅 Chairs: Marina Andrijevic, Kristie L. Ebi

Time	Presenter	Title	Page
10:15 - 10:25	Shuiqing Yin	Nonlinear amplification of heatstroke risk during climate overshoot reversal: evidence from Jiangsu province, China	63
10:25 - 10:35	Yuanchao Fan	Beyond Peak Temperature: Humidity and Radiation Shape Human Heat-Stress Impacts Along Climate Overshoot Pathways	63
10:35 - 10:45	John Ji	Residential greenness as adaptation buffer against heat extremes under climate overshoot: evidence from Chinese older adults	64

10:15 - 10:25 Submission 97

Nonlinear amplification of heatstroke risk during climate overshoot reversal: evidence from Jiangsu province, China

Shuiqing Yin, Tianyue Zhang

Beijing Normal University, Beijing, China

Abstract

Climate overshoot pathways involve a temporary exceedance of a warming target followed by a decline in global mean temperature. Whether such global temperature reversal leads to a corresponding recovery of regional heat-related health risks remains poorly understood. Here, we investigate how residual changes in compound heat exposure during overshoot reversal translate into heatstroke risk and whether this translation is amplified by nonlinear exposure–response relationships. Using historical meteorological observations and heatstroke cases in Jiangsu Province, China, we first establish a locally derived nonlinear relationship between compound heat exposure and heatstroke risk. This relationship is then combined with bias-corrected daily climate projections from multiple CMIP6 models under the SSP5-3.4-OS overshoot scenario. By comparing the warming and cooling branches at matched global warming levels, we separate regional compound-heat residuals from changes in global mean temperature and quantify their subsequent amplification into health risk.

Preliminary results show that returning to the same global warming level does not fully restore compound heat exposure in Jiangsu to its warming-branch state. More importantly, relatively small residual differences in compound heat exposure translate into disproportionately larger differences in heatstroke risk because of the nonlinear exposure–response relationship. The magnitude of this amplification varies substantially across southern, central, and northern Jiangsu, indicating pronounced spatial heterogeneity in the translation of climate residuals into health risks. These findings reveal a previously underexplored pathway of post-overshoot risk: even when global temperature declines, regional heat-health risks may not recover proportionally because residual compound heat exposure is amplified through nonlinear health responses. Our results highlight the need to assess climate overshoot not only in terms of global temperature reversibility, but also through the regional and nonlinear translation of residual climate hazards into human-health risks.

10:25 - 10:35 Submission 95

Beyond Peak Temperature: Humidity and Radiation Shape Human Heat-Stress Impacts Along Climate Overshoot Pathways

Yuanchao Fan, Lei Sheng

Tsinghua Shenzhen International Graduate School, Shenzhen, China

Abstract

Overshoot pathways, in which global warming temporarily exceeds 1.5 °C before declining through net-negative carbon-dioxide removal, raise a pressing question for public health: do heat-related risks rise and fall in step with temperature, or do they behave asymmetrically across the peak and decline phases? Most assessments of overshoot health impacts rely on air temperature or empirical heat indices such as wet-

bulb temperature and WBGT, which ignore the net radiation, wind speed, metabolic heat and sweating limits that together determine whether the human body can actually dissipate heat. This temperature-only lens can mis-estimate the magnitude, timing and reversibility of health burdens along an overshoot trajectory.

Here we present a biophysical framework that resolves these drivers explicitly. Building on our human energy-balance model — which computes the net rate of heat storage (G) and defines uncompensable heat stress (UHS) as G > 0, validated against the PSU-HEAT chamber trials — we project UHS hours and population exposure under increasing warming and alternative climate pathways. At fixed warming levels the model indicates that 2 °C of global warming could expose roughly 24 million outdoor workers to about eight days per year of uncompensable heat stress, rising to about 145 million workers and 14 days at 4 °C, underscoring the health stakes of even a transient overshoot peak.

A single-factor attribution of heat-stress change then reveals why the decline phase need not mirror the peak. Temperature is the dominant first-order driver of relief, with reduced shortwave and longwave radiation providing a secondary benefit. Humidity, however, acts as a hidden offset: higher relative humidity suppresses sweat evaporation and can add heat-stress hours even as temperatures fall, partly cancelling the cooling relief. Because humidity and temperature co-evolve non-monotonically and interact nonlinearly, post-peak heat-stress risk can lag behind — or depart from — the temperature trajectory.

These results argue that a multi-factor, biophysical assessment, rather than a temperature-only or empirical-index metric, is required to project the health consequences of overshoot pathways, to judge their reversibility, and to time adaptation and carbon-removal efforts so as to minimise both peak and legacy heat-stress burdens.

10:35 - 10:45 Submission 36

Residential greenness as adaptation buffer against heat extremes under climate overshoot: evidence from Chinese older adults

John Ji

Tsinghua University, Beijing, China

Abstract

Climate overshoot pathways, characterised by temporary exceedance of the 1.5 °C threshold followed by decline, will expose populations to prolonged periods of elevated heat extremes. Older adults are among the most vulnerable due to physiological decline, comorbidities, and limited adaptive capacity. Nature-based solutions such as residential greenness may offer feasible adaptation, yet their protective role under overshoot conditions remains under-examined.

Drawing on prior analyses of the Chinese Longitudinal Healthy Longevity Survey (CLHLS), a nationally representative prospective cohort of older adults, we synthesise evidence on residential greenness (measured by satellite-derived Normalised Difference Vegetation Index, NDVI) as a modifier of temperature- and heatwave-related mortality. In a 2019 study of 23 754 oldest-old participants (mean baseline age 93 years), individuals in the highest quartile of contemporaneous NDVI experienced 27–30 % lower mortality compared with the lowest quartile. Subsequent work demonstrated clear interaction: each additional three heatwave days increased mortality risk, while higher greenness attenuated this effect and conferred greater marginal protection in urban settings. Case-crossover analyses further showed that greenness reduces the mortality risk associated with extreme heat (and, to a lesser extent, extreme cold), with regional variation across climatic zones. Complementary findings highlight functional and cognitive impairments as climate-sensitive risk factors that amplify cold- and heat-related mortality.

These results indicate that residential greenness acts as a measurable buffer against heat extremes—precisely the intensified hazard expected during the peak phase of overshoot pathways. The protective association is strongest among the oldest-old and urban residents, underscoring both the potential and the equity challenges of nature-based adaptation. Under prolonged or high-magnitude overshoot, the feasibility of scaling greenness, its interaction with residual air pollution, and its limits for functionally impaired older adults become critical questions for health impact assessment and adaptation planning.

By linking established longitudinal evidence from China to the health implications of peak-and-decline trajectories, this work supports the integration of green infrastructure into overshoot-informed adaptation strategies, particularly in rapidly ageing Asian societies. It also aligns with ongoing efforts to extend Shared Socioeconomic Pathways with health dimensions, emphasising that adaptation limits are already visible in the most vulnerable cohorts.

Theme 8: Governance and equity of overshoot pathways

10:00 - 11:00, Bamboo Room, 竹韵厅 Chair: Xianchun Tan

Time	Presenter	Title	Page
10:00 - 10:12	Tianpeng Wang	Greater temperature overshoot amplifies asymmetric post-net-zero obligations across countries	66
10:12 - 10:24	Xin Lin	Adaptive governance for climate–social systems facing overshoot risk: A deep reinforcement learning framework	66
10:24 - 10:36	Chen Huang	Modeling Critical Mineral Access to Inform Equitable Climate Governance under Overshoot	67
10:36 - 10:48	Lucas Snaije	Governing Cities to Manage Climate Overshoot: Risks, Impacts and Responses	68

10:00 - 10:12 Submission 64

Greater temperature overshoot amplifies asymmetric post-net-zero obligations across countries

Tianpeng Wang, Fei Teng

Tsinghua University, Beijing, China

Abstract

Meeting the Paris Agreement's 1.5°C target now entails temperature overshoot and subsequent return, with 90% of viable pathways peaking above 1.6°C. Overshoot depth is an unacknowledged distributional decision. As overshoot deepens, the net-negative removal requirement expands, but how the resulting burden falls across countries and whether this pattern holds across equity principles has not been quantified. Applying a warming-excess equity framework across 1.5°C-consistent scenarios, we quantify how overshoot depth shapes national net-negative obligations. For historical high emitters, each additional 0.1°C of peak warming raises cumulative net-negative requirements by up to 7.8 Gt CO_2 and attributed global damages by approximately USD 0.5 trillion, while low emitters face near-zero additional obligations regardless of overshoot depth. This asymmetric amplification persists across equity frameworks incorporating historical warming responsibility and disappears only when historical responsibility is excluded entirely, establishing it as the necessary condition for equitable post-net-zero burden sharing and a basis for future nationally determined contributions.

10:12 - 10:24 Submission 81

Adaptive governance for climate–social systems facing overshoot risk: A deep reinforcement learning framework

Xin Lin[1], Yi Lu[2], Donghai Zheng[3], Erhu Du[4], Zhen Meng[5], Ziyong Sun[2], Shiwei Yuan[3], Xin Li[3]

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Abstract

The evolution of climate overshoot pathways and their potential impacts are highly uncertain, increasing the complexity of future climate risk management and governance decision-making. This requires governance strategies that can adapt to the continuous evolution of climate–social systems while balancing environmental goals and socioeconomic development needs over the long term. However, for conventional policy simulation models like integrated assessment models (IAMs), their reliance on predetermined scenarios makes it challenging to adequately address the substantial uncertainties inherent in climate-social system evolution. Building on our recently published work (Lin et al., 2026), this study presents an adaptive decision-making framework integrating deep reinforcement learning (DRL) with a climate–social system model. The framework identifies governance strategies to reduce the risk of transgressing planetary boundaries and, more broadly, to manage overshoot risks. In this framework, we operationalize Social Tipping Elements (STEs) as targeted actions. A reward function provides feedback to optimize these

interventions, ensuring that the system remains within critical planetary boundaries. Our results demonstrate that, compared to conventional static models, the framework discovers adaptive policies through dynamic learning, enabling real-time responses to evolving climate-social conditions. These adaptive policies exhibit an "early-stage intensive intervention, mid-term moderation, and late-stage reinforcement" pattern, reducing planetary-boundary overshoot time by 55 years while stabilizing global warming below 1.5 °C by 2100. Across alternative governance objectives, we further identify trade-offs between climate protection and socioeconomic performance. Notably, a multi-objective reward structure achieves the strongest overall balance, producing the shortest planetary-boundary overshoot duration—15 years—among the evaluated scenarios. The results offer a governance perspective directly relevant to overshoot-prone climate pathways: effective responses need not be fixed ex ante but can be designed as adaptive, state-dependent strategies that respond to changing risks and competing objectives. The proposed framework provides a new methodological approach for investigating adaptive governance in complex climate–social systems, enabling exploration of how to reduce the risks and impacts associated with threshold transgression while achieving long-term climate goals. It also extends the potential for future analyses of governance strategies under explicit peak-and-decline temperature overshoot pathways.

Reference: Lin, X., Lu, Y., Zheng, D., Du, E., Meng, Z., Sun, Z., Yuan, S., & Li, X. (2026). Realizing adaptive governance of coupled climate-social systems: A deep reinforcement learning framework. Geography and Sustainability, 7(4), 100519.

10:24 - 10:36 Submission 87

Modeling Critical Mineral Access to Inform Equitable Climate Governance under Overshoot

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Abstract

Fueling the energy transition, critical minerals are becoming central to climate stabilization, particularly when delayed mitigation must be recovered under climate overshoot. Yet physical scarcity, supply-chain disruptions, and unequal access to minerals can slow technology deployment, prolong fossil-fuel dependence, and ultimately translate material constraints into additional emissions and warming. We still lack a systematic framework for tracing this chain from mineral access to unrealized mitigation. Here, we introduce the MIneRAl analysis in CLimatE actions (MIRACLE) model, developed within the IIASA Energy, Climate, Environment (ECE) Program to quantify and optimize the role of transition minerals in climate action. MIRACLE connects climate pathways, technology deployment, mineral demand and supply, and climate outcomes within a unified framework. It identifies where and when material constraints emerge, estimates the supply expansion required to alleviate them, and evaluates how trade, recycling, substitution, and shifts in technology portfolios can improve the use of scarce resources. By allocating available minerals toward technologies and regions where they enable the greatest mitigation, the framework makes it possible to examine not only how much mineral supply is required, but also how access to scarce materials shapes the distribution of mitigation opportunities. Applications to IAM scenarios show that mineral constraints can delay the deployment of low-carbon technologies and sustain fossil-fuel use, with these effects more pronounced in rapidly industrializing yet resource-poor regions. We further find that minerals frequently act as co-limiting groups rather than independent constraints: expanding supply across individually binding minerals can close only part of the emissions gap when complementary materials remain scarce. This complementarity substantially changes the effectiveness of supply-side interventions and highlights the need to govern mineral access across materials, technologies, and regions rather than mineral by mineral. MIRACLE therefore reframes critical minerals from an input constraint into a climate-governance problem of access, allocation, and coordination. Our results suggest that equitable access to transition minerals may be a prerequisite for limiting the duration and consequences of climate overshoot.

10:36 - 10:48 Submission 31

Governing Cities to Manage Climate Overshoot: Risks, Impacts and Responses

David Dodman[1], Debra Roberts[2,3], **Lucas Snaije**[1]

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Abstract

As global temperatures continue to rise, understanding the implications of climate overshoot in cities is essential to prepare for the challenges that this will present. Temperature overshoot beyond 1.5°C will exacerbate risks to infrastructure especially for low-lying coastal settlements, low-income cities, and socioeconomically disadvantaged neighbourhoods within wealthier cities. Urban impacts will worsen in particular through increased frequency, duration, and intensity of heatwaves; altered spatial and temporal distribution of vector-borne disease risks; flooding; and increased morbidity and mortality from extreme events. These impacts will affect labour productivity and local economies, drive substantial growth in energy demand and associated household costs, and undermine urban development gains and objectives.

Even in pathways where temperature reaches a plateau and subsequently declines, non-linear, uncertain effects will still be generated, complicating infrastructure planning and investment, posing significant challenges to achieving equity and justice. At the same time, cities will need to play a central role in mitigation, through changes in economic activities, transportation and the built environment. This preparation and response must take place in a context of ongoing rapid urbanization, where the scale and nature of towns and cities is also changing rapidly: by the end of the century 84 per cent of the global population is projected to live in urban areas, with the most rapid growth occurring in smaller settlements across Asia and Africa.

The paper argues that key urban stakeholders will need to navigate a period of “overshoot, peak and decline” that involves coping with severe impacts and irreversible impacts, rapidly reducing emissions and moving towards net-negative emissions, and planning for a period of long-term resilience. The multifaceted challenges presented by exceedance, peak and decline will exacerbate existing vulnerabilities and create new ones, and drive new levels of loss and damage – thereby fundamentally shifting the assumptions underlying traditional thinking about city form and function. Assessing the implications of this as early as possible is essential, and we therefore propose a policy localisation perspective that centres local institutional awareness, capabilities, and financing. This will require flexible, adaptive, and responsive approaches to urban decision-making and governance, supported by institutional literacy, resourcing and capacity for strategic and integrated responses to plan and manage urban service provision under overshoot conditions, with a renewed commitment to enhancing adaptation grounded in urban climate justice.

Theme 3: Technological solutions for decarbonization and negative emissions

11:30 - 12:30, Harmony Hall (Plenary), 和合厅 Chairs: Alessio Mastrucci, Dabo Guan

Time	Presenter	Title	Page
11:30 - 11:45	Honglin Dai	Fine-grained technology deployment for plant-level deep decarbonization of China's iron and steel sector	69
11:45 - 12:00	Deyue Chen	Tracking Divergent City–Industry Decarbonization under Subsector-Specific Mitigation across China's Major Urban Agglomerations	70
12:00 - 12:15	Xiangyuan Meng	How Do Low-Carbon Policies Affect Firms' Carbon Total Factor Productivity? Evidence from China's Manufacturing Companies	70
12:15 - 12:30	Sam Krevor	Geophysical and techno-economic growth limits to the global scale-up of geological CO_2 storage	71

11:30 - 11:45 Submission 32

Fine-grained technology deployment for plant-level deep decarbonization of China's iron and steel sector

Honglin Dai[1], Shaohui Zhang[2], Hui Yue[1,3], Jiashuo Li[4], Ernst Worrell[3], Qi Zhang[5,6], Wina Crijns-Graus[3]

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Abstract

The iron and steel sector is a hard-to-abate industry, and its deep decarbonization is constrained by resource endowments, existing assets, regional disparities, and infrastructure conditions. A substantial body of research has examined decarbonization pathways, but the spatial distribution of steel plants and production units, equipment lifetimes, and constraints associated with raw material logistics are still difficult to represent in sufficient detail. This study develops a spatiotemporal transition assessment framework for China's steel production capacity based on plant- and unit-level data. Under the Shared Socioeconomic Pathway 2 (SSP2) demand pathway, the framework incorporates provincial steel demand, scrap availability, iron ore resources, electricity emission factors, water stress, and CO2 storage conditions to evaluate costs, carbon emissions, and air pollutant emissions under different technology pathways and spatial configurations from 2026 to 2060. The available data include approximately 700 records of steel plant sites or capacity and around 200 iron ore assets or mining sites in China. Four scenarios are considered: baseline continuation, spatial lock-in, spatiotemporal reconfiguration, and accelerated decarbonization. The analysis examines four technology pathways, namely BF-BOF, EAF-SCRAP, DRI-H2-EAF, and BF-BOF+CCS, and represents capacity-transition states including natural retirement, on-site retrofitting, new low-carbon capacity additions, and interregional capacity reallocation. An intertemporal least-cost optimization model compares capacity structures and technology deployment pathways across scenarios, identifies the timing and regional patterns of deployment and the conditions under which different technology pathways are suitable across regions, and quantifies changes in demand for scrap, iron ore, electricity, hydrogen, and coal to assess pressures on resources and infrastructure. These resource-demand estimates are further used to assess whether regional resource availability and supporting infrastructure may constrain the deployment of individual technology pathways. The optimized outputs are converted into activity data required by the air quality model to quantify and compare CO2, SO2, NOx, and PM emissions across scenarios. The results provide quantitative evidence for existing capacity retirement, the spatial deployment of low-carbon production capacity, and the allocation of key resources.

11:45 - 12:00 Submission 53

Tracking Divergent City–Industry Decarbonization under Subsector-Specific Mitigation across China's Major Urban Agglomerations

Deyue Chen[1], Wina Crijns-Graus[2], Shaohui Zhang[3], Fei Guo[4], Ernst Worrell[2], Hui Yue[2,1]

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Abstract

Cities are central to long-term climate mitigation, but industrial decarbonization within urban agglomerations remains poorly understood because mitigation opportunities and remaining emissions vary across cities and subsectors. We develop an integrated framework combining high-resolution emission characterization, driver decomposition, scenario-based decarbonization modeling, and regional emission-to-sink assessment. Applied to 77 cities and seven industrial subsectors across four major Chinese urban agglomerations using historical data for 2011–2023 and scenarios through 2060, the framework examines historical emission changes, spatial concentration, and regional decarbonization pathways. Historical trajectories diverge, with emissions declining in Beijing–Tianjin–Hebei and the Pearl River Delta but continuing to grow in the Yangtze River Delta and the Central Plains. Industrial output expansion dominates historical emission growth, whereas declining energy intensity provides the largest mitigation contribution. Changes in the energy mix remain limited, particularly in heavy industries. Emissions are concentrated in a small number of persistent and expanding city–subsector hotspots associated mainly with steel and chemical industries. Under deep mitigation, industrial emissions decline by more than 85% overall by 2060, with regional reductions ranging from 61% to 96%. Efficiency improvement alone is insufficient to achieve these reductions. The contributions and deployment timing of electrification, fuel substitution, process restructuring, and carbon capture, utilization, and storage differ across regions. Remaining emissions become increasingly concentrated in hard-to-abate sectors, especially coastal chemical industries, which account for 81% and 90% of remaining industrial emissions in the Yangtze River Delta and Pearl River Delta, respectively. By 2060, emission-to-sink ratios are highest in the Yangtze River Delta and Pearl River Delta, but substantially lower in Beijing–Tianjin–Hebei and the Central Plains. These results show that deep industrial decarbonization substantially reduces overall emissions but does not eliminate spatial and subsectoral heterogeneity in remaining emissions and mitigation requirements. As decarbonization advances, mitigation priorities therefore need to shift toward geographically concentrated, hard-to-abate sources and technology portfolios tailored to the dominant industrial sources of each urban agglomeration.

12:00 - 12:15 Submission 83

How Do Low-Carbon Policies Affect Firms' Carbon Total Factor Productivity? Evidence from China's Manufacturing Companies

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Abstract

Abstract: As global warming breaches the 1.5°C threshold, the window for achieving the temperature goal is rapidly closing, making mitigation pathways ever more urgent. China has elevated climate response to a national strategy, put forward the "dual carbon" goals (the "30·60" pledge), and has implemented a series of low-carbon policies combining command-and-control with economic instruments since 2007 to steer enterprises toward low-carbon transition. As the main source of energy consumption and carbon emissions, manufacturing is the core target of low-carbon policies. Through what mechanisms do low-carbon policies improve the carbon emission reduction efficiency of Chinese manufacturing firms?

Using data on Chinese A-share listed manufacturing firms from 2013 to 2022, this study measures carbon total factor productivity (CTFP) via the SBM-GML model and employs a city-level low-carbon policy intensity index based on natural language processing to examine the effect of low-carbon policies on firms' CTFP and its underlying mechanisms. The results show that low-carbon policies boost firms' CTFP by promoting green technology innovation, which reduces energy consumption and carbon emissions per unit of output and thus improves CTFP. It implies that regulatory pressure can be transformed into endogenous momentum for

green upgrading. In addition, the higher the media attention, the stronger the policy effect, as media coverage raises firms' reputation risk and pushes them to respond more actively. Similarly, the stronger executives' green cognition, the stronger the policy effect, as green-cognizant executives treat regulation as a strategic opportunity and channel resources toward green R&D. External public scrutiny and internal governance cognition thus form synergistic amplifiers of the policy effect.

Heterogeneity analysis further shows that the policy effect varies across policy instruments, policy objectives, firm characteristics, and regions. Command-and-control and combined policies significantly improve CTFP, while market-based policies show no significant effect, as China's carbon trading remains at an early stage with insufficient price-signal transmission. Energy-conservation policies are effective, while carbon-reduction and capacity-utilization policies are not, because energy conservation directly affects production costs and is more readily converted into efficiency gains. The effect is more pronounced among high-carbon firms, which face stronger regulatory pressure and thus invest more in green R&D. And in eastern China, where stronger economic strength and better policy implementation amplify policy transmission.

This study provides Chinese empirical evidence for testing the carbon-reduction effectiveness of low-carbon policies. China offers valuable insights for other economies facing the dual pressure of development and emission reduction. The findings suggest prioritizing combined policy instruments, improving carbon market price signals, and adopting differentiated policies across regions and firm types. For manufacturing firms, green technological investment serves as the core driver of improved carbon total factor productivity. Meanwhile, enhancing executives' green cognition, standardizing environmental disclosure and utilizing media supervision help convert policy pressure into endogenous green upgrading momentum.

Keywords: low-carbon policy intensity; carbon total factor productivity; green technology innovation; media attention; executives' green cognition;

12:15 - 12:30 Submission 33

Geophysical and techno-economic growth limits to the global scale-up of geological CO_2 storage

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Abstract

Climate overshoot pathways defer a growing share of mitigation to the second half of the century, when up to several hundred gigatonnes of atmospheric CO_2 removals may be needed to draw temperatures down after peak warming [1].

Whether and when geophysical constraints in sedimentary basins, or techno-economic growth constraints on infrastructure development can permit this pace of deployment is an open question. Assessments of geological CO_2 storage resources report large storage potential worldwide, 10^3-10^4 $GtCO_2$ [1]. Those resources are not immediately usable. Pressure buildup, plume migration, and injectivity mean that storage deployment is governed by how fast each basin can sustainably accept CO_2 [2]. Regarding techno-economic growth, models parameterised by rates of development in historical industrial analogues also suggest limits, with an upper feasible rate of ~16 $GtCO_2$ yr^{-1} by 2050 [1]. The growth models include the geological resource base but treat it as a static parameter rather than a temporal rate limit. Similarly, pressure-limited analyses rarely test deployment trajectories projected from techno-economic models.

We further this analysis by coupling geophysical and techno-economic growth models of the deployment of CO_2 storage at the country and basin scale. For ten jurisdictions dominating present day activity in developing CO_2 storage capacity, we build probabilistic storage-demand ensembles by Monte Carlo spanning two growth forms (logistic and Gompertz) and eight scenario families from technical to policy-anchored and IPCC-derived demand. Growth caps follow historical energy-technology precedent [1]. Supply of CO_2 storage is then modelled by simulating pressure-limited deliverability of 132 sedimentary basins worldwide, computed with a simplified physics model which estimates basin scale pressurisation from injection sites [2]. Pathways constructed to exhaust each jurisdiction's scenario resource are

temporally tested against its basin portfolio over 150 years, and every shortfall is reconstructed into a geologically feasible counterpart.

Summed across the basins, pressure-limited deliverability sustains about 49 $GtCO_2$ yr^{-1} by 2050, 1.6 times the top of the AR6 range. Delivery falls short in none of the 150 admissible country-scenario-growth-form cases before 2050, and the earliest arrives in 2059. Until mid-century, delivered storage tracks targeted storage, so the sixteen-fold spread in 2050 outcomes (0.5-8.2 GtCO2 yr^{-1}) reflects scenario ambition and growth form, not limits from the subsurface. Despite this headroom, thirty of the 150 cases reach pressure-limited ceilings after mid-century, concentrated in jurisdictions whose resource bases are small relative to ambition, and in those cases the feasible long-run commitment falls to a median of 23% of the scenario resource. Raising ambition brings the onset earlier, from the 2110s to 2059. The net-negative commitments that overshoot recovery adds after mid-century thus fall in the very decades when pressure limits begin to cap what national subsurface resources can accept.

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Theme 2: Earth System responses to net negative emissions and CDR

11:30 - 12:30, Cloud Room, 云岚厅 Chairs: Biqing Zhu, June-Yi Lee

Time	Presenter	Title	Page
11:30 - 11:45	Jingtao Ding	Path-Dependent Climate-Mode Responses to CO_2 Reversal Revealed by AI-Discovered Dynamics	73
11:45 - 12:00	Daniele Visioni	Solar Radiation Modification in the context of Overshoot Pathways	74
12:00 - 12:15	Di Sheng	Towards sustainability-aware carbon dioxide removal deployment	74
12:15 - 12:32	Yue He	Temporary carbon dioxide removal to offset short-lived climate forcers	75

11:30 - 11:45 Submission 103

Path-Dependent Climate-Mode Responses to CO_2 Reversal Revealed by AI-Discovered Dynamics

Jingtao Ding, Zihan Yu, Yong Li, Deliang Chen

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Abstract

Climate overshoot pathways require the Earth system to evolve first under increasing and subsequently under declining anthropogenic forcing [1]. While coupled climate-model experiments have revealed asymmetric responses to CO_2 reversal [2,3], it remains unclear whether dynamical relationships identified during the warming phase remain valid once the direction of forcing reverses, and which internal processes encode such path dependence.

Here we use an AI-guided conjecture–refutation framework to discover an explicit reduced-order dynamical system for the coupled evolution of sea-surface temperature (SST) and upper-ocean heat content (OHC) across major Pacific, Indian, and Atlantic climate modes. The discovered equations integrate local mode evolution, cross-basin teleconnections, subsurface heat-content memory, and an explicit logarithmic dependence on atmospheric CO_2. To test whether these dynamics generalize across forcing reversal, we apply their fixed symbolic structure to paired CMIP6 1pctCO2 and 1pctCO2-cdr experiments [4]. Model-specific coefficients are calibrated exclusively on the increasing-CO_2 branch, while the decreasing-CO_2 branch is withheld from equation discovery, coefficient estimation, residual calibration, model selection, and diagnostic tuning.

Despite this withholding, the discovered dynamics recover key ramp-up–ramp-down asymmetries simulated by coupled climate models, including enhanced ENSO variance, increased occurrence of extreme El Niño events, and a shortened dominant ENSO period during CO_2 decline. These responses are reproduced more consistently than by an expert-designed conceptual model and by an ablated version of the discovered system without explicit CO_2 forcing. Mechanistic interventions and phase-space analysis further indicate that the response to changing CO_2 is transmitted through coupled SST–OHC dynamics and a slow, forcing-sensitive direction dominated by Pacific and Indian Ocean heat-content variability. Holding CO_2 fixed at its 1979 level suppresses this forced displacement by approximately 83%, highlighting the role of subsurface ocean memory in shaping the system's response to changing forcing pathways.

Our results show that reduced-order climate dynamics learned under increasing forcing can retain predictive and explanatory power under forcing reversal, while revealing why declining CO_2 does not necessarily cause climate variability to retrace its warming trajectory. More broadly, the results suggest a route toward mechanism-aware overshoot emulators that combine explicit external forcing with internal memory states and dynamical interactions, enabling generalization across warming and declining-forcing branches rather than treating climate response as an instantaneous function of forcing.

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11:45 - 12:00 Submission 117

Solar Radiation Modification in the context of Overshoot Pathways

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Abstract

In the context of growing interest in overshoot pathways, discussions around the topic of Solar Radiation Modification (SRM) approaches are growing. SRM approaches would be attempts to avoid further increases in Earth's Energy Imbalance by increasing the amount of reflected solar radiation, rather than avoiding warming by reducing the greenhouse effect. If temperatures will inevitably peak higher than 1.5ºC, even if temporarily, SRM could potentially be used to avoid that warming and "shave" that peak while decarbonization and carbon dioxide removal (CDR) scale. SRM raises many thorny questions, ranging from technical feasibility, to uncertainties in physical and ecological responses to such approaches, to issues with how it might be governed and by whom and with mitigation displacement. Here I will focus on two specific aspects. 1) What would be the implied commitment if one where to deploy SRM, even in the context of a limited overshoot pathway, in terms of length of deployment, cumulative impacts, and risks of termination, and how do they connect with and impact mitigation commitment and potential CDR? and 2) What kind of modeling and assessment framework is necessary to understand the potential impact of SRM? What is the counterfactual or rather set of counterfactuals that we need to compare one or more modeled SRM deployment pathways against to understand what those possible deployments would entail, both in the short and the long term, in order to properly identify potential benefits and risks?

12:00 - 12:15 Submission 96

Towards sustainability-aware carbon dioxide removal deployment

Di Sheng[1], Yoga Pratama[1], Jan Dietrich[2], Keywan Riahi[1], Florian Maczek[1], Elina Brutschin[1], Jan Steinhauser[1], Oliver Fricko[1], Kristine Karstens[2], Isabelle Weindl[2], Volker Krey[1], Jan Minx[2], Alex Popp[2]

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Abstract

Meeting the Paris climate targets will require large-scale carbon dioxide removal (CDR). Yet estimates of CDR potential are often constrained primarily by techno-economic factors, with limited consideration of the trade-offs that deployment may create across land, energy, water, biodiversity, and human health. Because CDR technologies have distinct resource and environmental footprints, a critical question is not simply how much CDR is technically feasible, but what scale and portfolio can be deployed sustainably, and what this implies for the magnitude and duration of temperature overshoot.

We assess these questions using an integrated assessment framework that links the energy-system model MESSAGEix with the land-use model MAgPIE. Under a stringent carbon budget, we assess CDR deployment across three portfolios: nature-based, technology-intensive, and a full portfolio combining both. We compare scenarios with and without sustainability considerations, including biodiversity conservation, environmental-flow protection, sustainable diets, decent living standards, and constraints related to geological storage and toxicity. We then use MAGICC to translate the resulting emissions pathways into peak warming and the magnitude and duration of overshoot.

Three findings emerge from our preliminary results. First, sustainability constraints reduce biomass availability but increase the mitigation potential of land-use change, shifting deployment away from biochar

and bioenergy with carbon capture and storage toward other land-based removals. Second, adding technology-intensive options substantially increases total CDR, while synergies between sustainable diets and biodiversity conservation facilitate the achievement of land-system sustainability targets. Third, sustainability considerations and geological storage constraints strongly influence not only the achievable scale of CDR but also the composition of the resulting portfolio.

These results demonstrate that explicitly integrating sustainability constraints is essential for developing credible CDR deployment pathway and understanding their implications for temperature overshoot.

12:15 - 12:32 Submission 108

Temporary carbon dioxide removal to offset short-lived climate forcers

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Abstract

Carbon dioxide removal (CDR) is considered for achieving the long-term temperature objectives of the Paris Agreement and national net-zero emission targets The durability of these CDR methods varies widely, ranging from decades to theoretically permanent. Temporary CDR dominates present deployment, whereas permanent solutions face further feasibility and cost challenges at scale. However, efforts to integrate temporary CDR into climate policies have relied on equivalency assumptions between temporary and permanent CDR that contradict physical climate science: temporary CDR cannot fully offset CO_2 emissions as permanent CDR can. Here we show that temporary CDR can serve as compensation for non-CO_2 climate forcers, particularly for short-lived species whose compensation ratios are fairly insensitive to the choice of time horizon. For instance, offsetting 1 kg CH_4 requires 498 kg CO_2 with 20-year temporary storage (such as bioplastics) or 101 kg CO_2 with 100-year storage (such as durable wood products). We suggest a critical lifetime threshold separating short-lived and long-lived species for temporary CDR applications, with implementation requiring differentiated reporting of these categories. This framework can provide a physical basis for crediting temporary CDR activities in sectors such as agriculture, in which non-CO_2 emissions dominate and direct emission reductions remain challenging.

Theme 5: Overshoot pathway legacy, tipping dynamics and other abrupt changes

11:30 - 12:30, River Room, 江河厅 Chairs: Jingfang Fang, Alexander Nauels

Time	Presenter	Title	Page
11:35 - 11:45	Yixuan Li	Confronting Compound Temporal Mismatches Under Temperature Overshoot	76
11:50 - 12:00	Bo Su	The Cryosphere Beyond a Planetary Safe Operating Space	77
12:05 - 12:15	Nico Wunderling	Climate Tipping Risks under Paris Target Overshoots: Towards an Emulator for Tipping Elements	77

11:35 - 11:45 Submission 89

Confronting Compound Temporal Mismatches Under Temperature Overshoot

Le Yu[1,2], **Yixuan Li**[1], Yue Cao[3,4]

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Abstract

Climate overshoot means global temperatures temporarily exceed the 1.5°C threshold before an eventual decline. Global mean temperature in 2024 already reached about 1.55°C above pre-industrial levels (WMO, 2025), and current emission trajectories make sustained overshoot increasingly likely (Reisinger et al., 2025). A recent UNEP report reinforces this concern (UNEP, 2026). It shows that Earth system and ecological components have very different reversibility timescales, and that peak biodiversity impacts generally lag behind peak temperature.

Building on Gaston and Pettorelli's call for a mission-oriented ecology (2025), we argue that this vision needs more explicit attention to the temporal structure of ecological risk. Evidence from terrestrial and marine systems shows that ecological impacts accumulate quickly during warming. Recovery is slower and often stays incomplete even after temperatures stabilize or decline (Anderson et al., 2020; Munday et al., 2025; Albrich et al., 2020; Wunderling et al., 2023; Meyer et al., 2022). Meanwhile, governance and monitoring frameworks remain organized around near-term targets. This echoes the IPCC's finding that adaptation actions are widely delayed (IPCC, 2022). These delays cascade across biological scales, from individuals to ecosystems (Ellis et al., 2025).

We propose that ecological risk under overshoot is shaped by three interacting trajectories. Climate, ecological recovery, and governance response each unfold on a different timescale. This compound mismatch means declining temperatures do not guarantee ecological recovery. Vulnerability can persist through demographic lags, structural ecosystem change, and accumulated ecological debt. Current biodiversity governance, including the Kunming-Montreal Global Biodiversity Framework, has not yet systematically included recovery trajectories after overshoot. This gap matters given the upcoming 2026 CBD and UNCCD summits (Convention on Biological Diversity, 2025; UNCCD, 2025), which offer a chance to align biodiversity governance with post-overshoot ecological realities. We propose a conceptual framework that classifies overshoot-driven ecological risks by timescale and reversibility. This framework offers a basis for embedding temporal structure into ecological targets, monitoring, and adaptive governance.

11:50 - 12:00 Submission 82

The Cryosphere Beyond a Planetary Safe Operating Space

Bo Su

Stockholm University, Stockholm, Sweden. Beijing Normal University, Beijing, China

Abstract

The cryosphere plays a vital role in regulating Earth system dynamics and habitability, yet it remains unclear whether its essential functions remain within a safe operating space (SOS) amid Anthropocene change. Here, we propose a cryosphere SOS and systematically evaluate its contributions to Earth system resilience using the planetary boundaries framework. Multiple lines of evidence indicate an accelerating and partly irreversible loss of cryospheric integrity, driven by amplifying feedbacks. Key cryospheric control variables are departing from Holocene-like conditions. We conclude that the cryosphere has breached its SOS and is on a trajectory that locks in long-term risks for human societies and ecosystems. Safeguarding Earth system resilience therefore requires explicit consideration of cryosphere change and its interactions across the Earth system.

12:05 - 12:15 Submission 29

Climate Tipping Risks under Paris Target Overshoots: Towards an Emulator for Tipping Elements

Nico Wunderling[1,2,3], Niki Lohmann[1,2], Paul Ritchie[4], Norman Steinert[5]

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Abstract

Due to insufficient emission reductions in recent years, limiting global warming to 1.5°C without an at least temporary overshoot has become increasingly infeasible [1,2]. Such a temperature overshoot poses substantial risks to crossing critical thresholds and triggering vital components of the Earth system, so-called climate tipping elements, including the Greenland and West Antarctic Ice Sheets, the Atlantic Meridional Overturning Circulation, or the Amazon rainforest [3].

This presentation will review the latest literature on tipping risks under global warming overshoots, building on recent advances in the Global Tipping Points Reports 2025 (GTPR 2025) and preparations of GTPR 2027 [3,4]. In many of these risk assessments, tipping element dynamics are still largely based on phenomenological representations. However, a growing body of process-based evidence is now emerging from comprehensive Earth system models and coordinated community efforts (such as TIPMIP, ClimTip, TIPESM and further initiatives). Building on these advances, we present a process-informed and updatable framework that translates tipping point assessments across comprehensive Earth system models into a transparent low-order emulator for several high-impact tipping elements as well as their interactions and timescales [5,6,7]. By combining process-based knowledge with computationally efficient representations of tipping dynamics, this framework enables systematic assessments of tipping risks across a wide range of uncertainties in global warming and overshoot pathways, particularly those that temporarily exceed and subsequently return to at or below 1.5-2.0°C of global warming.

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Theme 8: Governance and equity of overshoot pathways

11:30 - 12:30, Bamboo Room, 竹韵厅 Chair: Xianchun Tan

Time	Presenter	Title	Page
11:30 - 11:42	Yonglong Cheng	Individual carbon inequality and equitable mitigation burden-sharing in China: Implications for climate overshoot governance	79
11:42 - 11:54	Nariswari Nurjaman	Beyond Carbon Accounting: Governing Social Forestry, Carbon Trading and Food Security under Climate Overshoot in Indonesia	80
11:54 - 12:06	Aijun Yan	Surface Albedo Modification: A Relatively Equitable Climate Governance Option Combining Local Adaptation with Global Peak-Shaving Benefits	81

11:30 - 11:42 Submission 69

Individual carbon inequality and equitable mitigation burden-sharing in China: Implications for climate overshoot governance

Yonglong Cheng[1,2,3], Xianchun Tan[2], Deliang Chen[4], Jarmo Kikstra[3,5], Setu Pelz[3], Hongshuo Yan[6], Chen Huang[3], Shonali Pachauri[3]

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Abstract

Climate overshoot would increase pressure for rapid and potentially more stringent emissions reductions, making the distribution of mitigation burdens a central governance and equity challenge. Yet national climate targets are commonly translated into subnational responsibilities using regional averages, with limited consideration of inequalities among individuals within regions. This can obscure whether emissions are concentrated among high emitters or associated with basic needs among low emitters, leading to very different equity implications for mitigation.

Here, we examine how individual carbon inequality can inform more equitable mitigation burden-sharing across Chinese provinces. We estimate comprehensive individual carbon footprints by combining provincial household microdata on income and wealth with an environmentally extended multiregional input-output model. Unlike conventional household-consumption-based assessments, our accounting includes household consumption, government consumption and capital formation, while distinguishing public from private investment-related emissions according to their different ownership and benefit structures. We then develop an individual-centred effort-sharing framework based on two distributional principles: safeguarding a province-specific emissions floor required for decent living standards (DLS), while assigning additional mitigation responsibility to individuals above a high-emitter threshold. Provincial mitigation responsibilities are obtained by aggregating these individual-level adjustments while ensuring consistency with the national mitigation target. This framework explicitly links within-province carbon inequality to subnational burden-sharing.

We find substantial carbon inequality both within and across provinces, although including investment-related emissions moderates measured inequality relative to household-consumption-only accounting because public investment emissions are more broadly distributed than private capital emissions. Nationally, the top 10% of income earners account for 20% of total emissions, while the bottom 50% account for 32%. Under a pathway consistent with China's 2030 climate target, 4.6% of the population falls below province-specific DLS emissions floors. Raising these individuals to the DLS threshold requires only 0.3% of national business-as-usual emissions. By contrast, meeting the national target implies an individual carbon-footprint ceiling of approximately 10.3 tCO_2 yr^{-1}, requiring substantial reductions from high emitters, corresponding roughly to the upper 40% of the income distribution.

The resulting provincial mitigation burdens vary strongly with both average emissions and the shape of within-province carbon-footprint distributions. Northern and northwestern provinces face particularly high mitigation intensity because high per-capita emissions often coincide with pronounced individual

inequality. Moreover, as national mitigation stringency increases, provincial reduction burdens respond differently depending on these distributional profiles, showing that equity cannot be captured by regional averages alone.

Our results show that protecting essential emissions for low emitters can remain compatible with ambitious mitigation, while progressively greater responsibility can be assigned to carbon-affluent groups. As climate overshoot increases the likelihood of tighter mitigation constraints and increasingly scarce emissions space, incorporating within-region inequality into burden-sharing can help prevent stronger climate action from disproportionately constraining basic needs. This provides an equity-oriented governance framework for distributing mitigation responsibilities under increasingly stringent climate pathways.

11:42 - 11:54 Submission 46

Beyond Carbon Accounting: Governing Social Forestry, Carbon Trading and Food Security under Climate Overshoot in Indonesia

Nariswari Nurjaman

University of Cambridge, Cambridge, United Kingdom

Abstract

Climate-overshoot pathways increasingly rely on land-based mitigation and carbon finance. However, forests risk being governed primarily as carbon assets before their livelihood and distributive functions are understood. This is especially crucial in Indonesia, home to the world's third-largest tropical rainforest, where about 63% of national land is legally designated as forest estate. Indonesia's social forestry programme provides or recognises community access, management or tenure rights through five schemes. It covers 8.41 million hectares and involves 1.4 million families, against a national target of 12.7 million hectares. Its effects vary across biophysical and institutional contexts.

Indonesia has also begun integrating social forestry into carbon trading. In July 2026, Forestry Minister Regulation No. 6/2026 and the Indonesia Forestry Carbon Hub opened participation beyond corporate concession holders. Initial approvals included three corporate projects and community-based carbon trading in Bujang Raba, Jambi. This transition may provide new finance for community forest management, but it raises questions about carbon rights, participation, monitoring and transaction costs, intermediary dependence, and the distribution of benefits and restrictions. These questions intensify as overshoot strategies increase demand for forest-based mitigation.

This research asks: under what institutional conditions does social forestry support food-security pathways, and how can this evidence inform the governance of community participation in carbon markets under climate overshoot? It draws on Elinor Ostrom's theory of common-pool-resource governance, emphasising locally appropriate rules, collective action, monitoring and coordination (Ostrom 1990). Schlager and Ostrom distinguish formal access from rights of withdrawal, management, exclusion and alienation (Schlager and Ostrom 1992), while access theory distinguishes legal rights from the effective ability to benefit (Ribot and Peluso 2003).

The research presents a systematic review of 44 publications, disaggregated into 68 social-forestry cases. Cases were coded for land-use context, rights and tenure, coordination and finance, inclusion and distribution, food-security pathways, research design and evidential proximity. Only 11 cases (16.2%) directly measured food-security outcomes; 30 (44.1%) used livelihood proxies, while 27 (39.7%) reported enabling institutional or biophysical conditions. Qualitative designs accounted for 39 cases (57.4%), mixed methods for 28 (41.2%) and strictly quantitative analysis for one. The literature therefore identifies plausible mechanisms more readily than average causal effects.

Across cases, food security operated through direct provisioning, income and markets, ecosystem services, tenure and collective action, and services or infrastructure. These pathways depended on usable rights, manageable coordination costs, post-permit support, inclusive participation and equitable benefit distribution. The paper argues that equitable governance under climate overshoot must move beyond carbon accounting. In that regard, social forestry is not an automatic carbon solution because its

contribution depends on whether institutions can translate formal recognition and carbon value into effective and inclusive capabilities while safeguarding food availability, access, utilisation and stability.

11:54 - 12:06 Submission 80

Surface Albedo Modification: A Relatively Equitable Climate Governance Option Combining Local Adaptation with Global Peak-Shaving Benefits

Aijun Yan[1], Yuanchao Fan[2], Hashem Akbari[3], Yan Li[4], Yong Liu[5], Hang Su[6], Yupeng Wang[7], Yuxuan He[6]

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Abstract

As the Paris Agreement's 1.5°C limit approaches the brink of being crossed, solar radiation modification (SRM) is gaining international attention as a temporary, supplementary mitigation measure. However, atmospheric SRM approaches—represented by stratospheric aerosol injection (SAI) and marine cloud brightening (MCB)—face significant disagreements over outcome uncertainty, transboundary climate impacts and global governance, making near-term international consensus unlikely. In contrast, surface albedo modification (SAM) is often regarded as strongly regional in effect and, when deployed alone, incapable of substantially reducing global mean temperature; it thus occupies a marginal position in SRM debates.

This study argues that such spatial heterogeneity—commonly treated as SAM's limitation—in fact constitutes its core advantage in governance and equity. Unlike atmospheric approaches such as SAI, SAM is land-based: it can be deployed incrementally, tested locally and reversed locally; its sphere of action largely coincides with spaces of human activity, and its benefits are realized fairly where it is implemented. Deployed at small scales, SAM serves as an adaptation measure that effectively mitigates regional heat extremes, protects public health and reduces cooling energy demand; deployed at global scales, it offers supplementary "peak-shaving" mitigation potential. SAM is therefore a comparatively equitable climate governance option, particularly for heat-vulnerable populations that lack a voice in global SRM discussions. Recent research further substantiates this dual local-adaptation and global supplementary-mitigation temperature benefit. Locally, raising urban and cropland albedo markedly lowers ambient and surface temperatures and reduces heat-related morbidity and mortality during heatwaves. Globally, assessments of reflective-surface potential indicate that large-scale deployment over managed lands and the built environment can generate non-negligible negative radiative forcing, and several reviews confirm SAM's clear adaptation benefits and potential peak-shaving contribution. It must be stressed that SAM remains a complement to—never a substitute for—deep mitigation and carbon dioxide removal.

Accordingly, we propose a three-stage deployment strategy of "habitat adaptation—ecological integration—climate mitigation." Stage one prioritizes albedo enhancement of human-habitat infrastructure—including cool roofs and cool cities—to directly reduce heat stress and population heat exposure. Stage two reverses the adverse albedo changes caused by human activities, deeply integrating albedo enhancement with ecological restoration, agricultural production, and energy development; this can provide robust support for current mainstream climate pathways and shift surface reflectivity in a favorable direction. Stage three advances global-scale deployment and explores the incorporation of solar trading into the international climate framework to deliver supplementary mitigation benefits. Progressing sequentially, the three stages couple local adaptation benefits with global "peak-shaving" effects within a single, locally governable instrument.

In sum, SAM deserves explicit consideration in climate-overshoot governance frameworks as an equitable, supplementary climate-governance measure. We recommend prioritizing the scale-up of habitat-adaptation applications and systematically assessing the mitigation effects of deployment at different

spatial scales, thereby providing scientific support and an institutional option for temperature-control pathways under overshoot scenarios.

Keywords: surface albedo modification (SAM); climate overshoot; climate equity; peak-shaving; habitat adaptation; ecological integration; climate mitigation

Joint Session. Theme 1 and Theme 3

14:00 - 15:30, Harmony Hall (Plenary), 和合厅 Chairs: Joeri Rogelj, Alessio Mastrucci, Dabo Guan

Time	Presenter	Title	Page
	Søren Lütken	Countering the Overshoot - Retaining Atmospheric and Biogenic Carbon in the Global Materials Economy	83
	Fan Wu	Persistent Effects of Climate Policy Rollback under Delayed Recovery Pathways	84
	Michiel Schaeffer	High climate sensitivity deepens key failures of solar radiation modification	85
	Roberta Quadrelli	Tracking Mitigation and Technology Deployment: Measurement Foundations for Energy Transitions	86
	Pete Smith	Additional Risks of Using Nature-based CDR in Overshoot Scenarios	86
	Richard Catlow	De-fossilising Chemicals and Fuels	87

Submission 23

Countering the Overshoot - Retaining Atmospheric and Biogenic Carbon in the Global Materials Economy

Søren Lütken

UNEP, Copenhagen, Denmark

Abstract

As the world now faces an overshoot of the 1.5°C limit, deep and sustained emission reductions will no longer suffice to keep the global environment within safe operating space. Large-scale carbon drawdown will ultimately determine if temperatures can later be brought back down.

About 1200 gigatons of carbon dioxide waste is accumulated in the atmosphere compared to pre-industrialization – a larger waste problem by mass than any other. It must be solved due to the environmental hazards it causes.

Most CDR approaches extract CO_2 from the atmosphere and store it geologically, but large-scale drawdown of atmospheric and biogenic carbon requires a diversified portfolio of CDR approaches that maximize industrial utilisation of carbon dioxide as a resource for productive purposes. As carbon remains a fundamental feedstock in chemicals, plastics, construction materials, fuels, and advanced industrial manufacturing (12% of global oil demand in 2018 (IEA)) demand for carbon-based molecules is projected to remain substantial through mid-century (Energy Transitions Commission, 2021). The question is not whether carbon remains within the economy, but rather which carbon, from which source, circulating through which systems.

There are two necessary and parallel areas of carbon dioxide commoditization:

substituting fossil carbon used as a feedstock in existing industrial processes and products with carbon removed from the atmosphere;

substituting conventional materials with alternatives designed to retain atmospheric carbon.

Replacing fossil carbon atoms with atmospheric and biogenic carbon in current products holds the shortest-term tangible drawdown potential; the replacement of traditional materials with carbon-based materials and products, primarily in construction and infrastructure, holds the largest. Both require adapting existing value chains or developing entirely new ones for new products and production systems.

Evolving the materials economy from using fossil carbon as a feedstock into becoming a systemic carbon sink requires the linking of atmospheric and marine carbon drawdown with industrial production systems, material value chains, and infrastructure development rather than treating carbon removal and industrial production as separate domains.

Reframing the carbon value chain as other materials flows attributes an intrinsic commercial value to non-fossil carbon and avoids the overlaps inherent in current phrasing. It must include Carbon Dioxide

Extraction, Carbon Dioxide Transport, Carbon Dioxide Processing, and Carbon Dioxide Commoditization, in addition to Carbon Dioxide Storage. However, extracting and processing the 'free' atmospheric carbon is currently not competitive with its fossil alternative and without coherent global guidance, adequate scale-up of CDR may well be foregone. A comprehensive framework for encouraging the development of new CDR approaches – technologically, environmentally, socio-economically and financially – is required.

A high-level, shared reference framework must provide governments, private actors, and international institutions with a common point of orientation for investment decisions and policy design and address these challenges in parallel:

Fragmented awareness and understanding among policymakers;

Absence of coherent governance principles;

Insufficient monitoring, reporting, and verification (MRV) and transparency systems;

Limited integration of CDR considerations into buildings and construction, materials industries, and national planning processes.

Risks of mitigation deterrence;

Weak international coordination and inconsistent standards, and

High costs and insufficient market incentives to push technology innovation.

Submission 24

Persistent Effects of Climate Policy Rollback under Delayed Recovery Pathways

Fan Wu[1], Ryna Cui[2], Russell Horowitz[3], Zebedee Nicholls[4,5,6], Dirk-Jan van de Ven[3], Rongqi Zhu[1], Haewon McJeon[7], Yang Ou[1,8]

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Abstract

Article 4.3 of the Paris Agreement requires each successive Nationally Determined Contribution (NDC) to represent a progression and reflect a country's highest possible ambition. Accordingly, climate ambition is usually assessed through target stringency and progressive strengthening. In practice, however, climate policy implementation is not necessarily monotonic, as political turnover and shifts in domestic priorities can reverse measures that may later be restored. The United States illustrates this. It withdrew from the Paris Agreement, rejoined, and withdrew again in 2026. Yet studies have largely examined continuous policy implementation, delayed mitigation, or rollback as separate pathway types, whereas rollback followed by recovery within the same pathway remains largely unexplored. This gap becomes consequential under overshoot, when emissions accumulated during rollback may raise peak warming and reshape the subsequent decline pathway even after commitments are restored. We therefore ask whether delayed recovery can fully compensate for rollback under overshoot.

We construct an NDC scenario covering 197 Parties and three rounds of NDC submissions. For major economies, we represent 332 sectoral policy records across 16 countries and regions to capture implemented policy measures underlying national commitments. We then construct a dynamic rollback and recovery scenario matrix along three dimensions: the geographic scope of rollback, from the US alone to progressively broader groups of countries; the onset of policy correction, in 2035, 2040, or 2045; and the recovery duration, 10, 20, or 30 years. We use the Global Change Analysis Model (GCAM) to assess emissions, energy system transformation, and mitigation costs, and couple it with the MAGICC simple climate model to derive peak warming and end-of-century temperature outcomes.

Rollback generates excess cumulative emissions and persistent energy-system lock in even when annual emissions later return to NDC consistent levels. In a representative case involving the US and ten additional

countries, with policy correction beginning in 2040 and a 20-year recovery, cumulative CO_2 emissions increase by 244 $GtCO_2$ relative to the NDC pathway. By 2050, electrification is 3 percentage points lower, coal-fired capacity remains 118 GW higher, and combined wind and solar capacity is 1,228 GW lower. At convergence, emissions-weighted marginal carbon prices across rollback regions remain 11% higher than under the NDC pathway. Earlier correction and faster recovery reduce these effects. However, even the fastest recovery cases retain a cumulative emissions gap of 98 $GtCO_2$.

The climate consequences therefore become harder to reverse as rollback expands, corrective action is delayed, or recovery slows. Across pathways, peak warming rises from approximately 1.80°C to as much as 1.93°C, while broader rollback shifts pathways toward higher end-of-century warming. Thus, returning annual emissions to an NDC-consistent level does not restore the climate outcome of continuous implementation. Under overshoot, highest possible ambition should therefore be assessed not only by target stringency and formal progression, but also by implementation continuity and the speed of corrective action. Preventing broader rollback and accelerating recovery are integral to limiting cumulative emissions, energy-system lock in, and the magnitude and duration of overshoot.

Submission 52

High climate sensitivity deepens key failures of solar radiation modification

Michiel Schaeffer, Alicia Hou, Fahad Saeed, Zarrar Khan, Uta Kloenne, Bill Hare

Climate Analytics, Berlin, Germany

Abstract

Climate action to date is failing to limit warming to 1.5°C, and an at least temporary exceedance of 1.5°C is now very likely. Solar Radiation Modification (SRM) – in particular Stratospheric Aerosol Injection (SAI) – is proposed by some as an option to address the lack of timely mitigation action. Here, we study potential SAI deployment in two distinct framings: as a complement to ambitious mitigation, including to close the gap widened by high climate sensitivity, or as a substitute for inadequate mitigation. Using a reduced-complexity climate model under default and high-sensitivity transient climate response distributions, we show that both framings fail — and that higher climate sensitivity deepens failure of the "substitution" framing. In the "complementary" framing, SRM offers no peak protection: owing to deployment lag, peak warming around the 2040s is essentially unchanged, while the use of SRM commits the world to sustained SRM in the longer term, so that termination risks a second overshoot in a world that has adapted to post-peak warming. In the "substitution" framing, compensating decades of excess GHG emissions could require significantly more forcing from SRM, and termination could produce a shock potentially even exceeding the current human-induced decadal warming rate. Under high climate sensitivity, the probability of post-termination warming could significantly exceed 1.5°C by 2100. An additional analysis based on GeoMIP simulations with Earth System Models indicates that an SRM-induced cooling signal may emerge later than in a lower-emissions pathway with near-term mitigation, with substantial variation across regions and models, reinforcing the importance of deployment timing and uncertainty. The analysis of GeoMIPsimulations carries the additional caveat that these can only be considered idealised as they do not account for real-world socio-political dynamics. Our findings show that SRM neither reliably protects against near-term peak warming nor provides a substitute for mitigation, underscoring rapid, deep, and sustained emissions reductions complemented by the sustainable deployment of carbon dioxide removal as the only robust pathway for limiting the magnitude and duration of overshoot of 1.5°C, and limiting climate risk.

Submission 118

Tracking Mitigation and Technology Deployment: Measurement Foundations for Energy Transitions

Roberta Quadrelli

International Energy Agency, Paris, France

Abstract

The ability to assess whether countries are achieving their mitigation ambitions, and whether decarbonization technologies are scaling at the required pace, depends on the quality of the data used to track them. This presentation discusses national and international monitoring of energy transitions, based on the IEA experience.

Monitoring international trajectories requires a comparable statistical baseline across countries — built on harmonised energy balances and emissions estimation methodologies. However, energy systems are evolving rapidly, and recent findings from IEA reports demonstrate how quickly global trajectories can change.

Electrification trends are shifting the focus towards the energy demand side, up to the useful energy level, where data and methodologies remain considerably weaker than for the supply side. Several rapidly expanding elements of the energy system also remain poorly captured in conventional statistics — including distributed and behind-the-meter solar PV, data centre and AI-driven electricity demand, distributed energy resources, critical mineral supply chains, and carbon dioxide removal. Tracking the social dimension of transitions is equally important: the impacts of policies on people, such as for energy affordability, require dedicated, interdisciplinary monitoring.

The presentation discusses international progress towards closing these gaps. Analytically, this includes integrating real-time electricity and emissions data, spatially granular data, high-frequency microdata of different nature; and developing common methodologies in new areas of monitoring. In parallel, countries are reinforcing the institutional foundations for reliable energy data, and the IEA collaborates with governments worldwide, such as in the case of the recently developed Brazil national energy data strategy. Together, these efforts illustrate that credible global tracking of energy transitions requires sustained investment in both measurement science and statistical capacity, and closer collaboration with the research community.

Submission 119

Additional Risks of Using Nature-based CDR in Overshoot Scenarios

Pete Smith

University of Aberdeen, Aberdeen, United Kingdom

Abstract

Nature-based CDR is currently by far the largest form of CDR applied globally, and forms a significant wedge in mitigation scenarios with, or without, overshoot. Nature-based CDR has significant potential — it has higher TRL and is less costly than most engineered CDR solutions, but the carbon storage is less durable and more prone to risk of reversal. Overshoot entails temperatures that exceed 1.5°C for a period of time, with each 0.1°C increment each year presenting a greater climate risk of reversal of CDR sinks. In this short overview, I present the potential of various options for nature-based CDR, present the advantages of each option, including co-benefits and trade-offs, and then go on to present the risks of nature-based CDR now, and under future climates during periods of overshoot.

Submission 120

De-fossilising Chemicals and Fuels

Richard Catlow

University College London, London, United Kingdom

Abstract

Our societies and economies currently depend on carbon based chemicals and fuels sourced from fossil carbon. The transition to sustainability and net zero will require their replacement by other sources of carbon. We will discuss the key challenges and opportunities in this transition and show how a range of alternative carbon sources will be needed, including biomass, waste plastics and carbon dioxide. We emphasise the key role of developments in catalytic science and will highlight the findings of a policy briefing from the Royal Society (the UK Academy of Science)1. We will describe briefly a range of UK initiatives aimed at developing sustainable chemicals and fuels.

Joint Session. Theme 2, Theme 4, and Theme 5

14:00 - 15:30, Cloud Room, 云岚厅 Chairs: Debra Roberts, June-Yi Lee

Time	Presenter	Title	Page
	Xia Qu	Asymmetric climate responses to declining CO_2 concentration: from ocean heat exchange to regional monsoons	88
	Annika Högner	Overshoot pathway fingerprints persist after global temperature stabilization	89
	Niklas Schwind	Cascaded emulation of Earth system models for impact evaluation with SCALES-MESH	89
	Thomas Gasser	Exploring the effect of overshoot magnitude and reversal rate on climate and impact reversibility with a probabilistic reduced-complexity Earth system model	90

Submission 72

Asymmetric climate responses to declining CO_2 concentration: from ocean heat exchange to regional monsoons

Xia Qu, Gang Huang

Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

Abstract

Understanding the climate system's behavior during the declining phase of CO_2 concentration is critical for assessing the feasibility and consequences of overshoot scenarios. While much research has focused on warming under increasing CO_2, the pathways and mechanisms of recovery during the decline phase remain less explored. This study systematically investigates the hysteresis effects, regional asymmetries, and potential irreversible changes in global and regional climates when CO_2 follows a ramp-up and ramp-down trajectory.

First, we quantify the global-scale hysteresis in surface temperature and monsoon precipitation. Using a simplified energy balance framework, we isolate the contributions of climate sensitivity, ocean vertical heat exchange efficiency, and effective radiative forcing to the delayed temperature response. Our results demonstrate that ocean vertical heat exchange is the dominant factor governing the temperature evolution during the CO_2 decline, causing a significant lag in cooling relative to the forcing reduction. This residual warming, in turn, maintains a higher atmospheric water vapor content via the Clausius–Clapeyron relationship, leading to enhanced global monsoon precipitation during the declining phase compared to the ascending phase at the same CO_2 level.

Second, we identify distinct regional disparities in this hysteresis. For the South Asian monsoon, we find a rapid transition from wet to dry conditions, where precipitation not only recovers to its initial state but can drop significantly below it. This is driven by residual warm sea surface temperature (SST) anomalies in the central-eastern Pacific and the Southern Ocean, which suppress the large-scale circulation and moisture convergence. In East Asia, these residual SST anomalies excite an “East Asia–Pacific” teleconnection pattern, exacerbating the “southern flooding and northern drought” risk over China. For the Amazon, we demonstrate an “irreversible reduction” in rainy-season precipitation. The persistent El Niño-like warming in the Pacific suppresses local vertical motion and excites poleward-propagating Rossby wave trains, collectively weakening the climatological ascending branch and reducing rainfall.

Third, we examine the response of the Tibetan Plateau. We find that cryospheric elements, such as snow/ice cover and the Tibetan High, exhibit pronounced hysteresis. Their recovery is primarily controlled by the slow evolution of global mean surface temperature rather than the direct radiative effect of CO_2, leading to a delayed recovery. Conversely, summer precipitation over the plateau responds rapidly and synchronously to CO_2 forcing changes, as it is directly modulated by the direct radiative effect of CO2 forcing.

Collectively, our findings highlight that the declining phase of CO_2 is not a simple reversal of the warming phase. The interplay between ocean thermal inertia, residual SST anomalies, and regionally specific dynamic and thermodynamic processes can generate unexpected hydroclimatic outcomes, including

persistent droughts and irreversible regional drying. These results underscore the necessity of incorporating transient hysteresis and regional dynamics into climate risk assessments for overshoot scenarios.

Submission 35

Overshoot pathway fingerprints persist after global temperature stabilization

Assaf Shmuel[1,2], **Annika Högner**[1,3], Niklas Schwind[1,3], Vassili Kitsios[4,5], Carl-Friedrich Schleussner[1,3]

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Abstract

Exceedance of global warming thresholds under overshoot, peak and decline pathways may leave regional climate legacies that persist even after global temperature stabilization. This study examines whether such overshoot pathway fingerprints remain detectable after stabilization at similar global warming levels by comparing two multi-century CMIP6 simulations with different magnitudes and characteristics of temperature exceedance. Using machine learning classifiers and statistical tests on regional multivariate climate data, we show that overshoot pathways leave detectable regional fingerprints. Regional climate states remain distinguishable between pathways, even when global temperatures stabilize. Comparisons with transient pre-overshoot periods at similar global warming levels further indicate that some regional differences will not reverse to their transient pre-exceedance state. These findings underline that the consequences of overshoot pathways cannot be assessed from global mean temperature trajectories alone. Evaluating possible impacts and risks from temporary exceedance of global warming of 1.5 °C requires attention to persistent regional fingerprints, including changes in the distribution and spatial structure of climate variables after stabilization.

Submission 39

Cascaded emulation of Earth system models for impact evaluation with SCALES-MESH

Verena Kain[1,2], **Niklas Schwind**[1,3], Annika Högner[1,3], Raffaela Langer[1,3], Tessa Möller[1,3], Alexander Nauels[1,4], Zebedee Nicholls[1,5,4], Sarah Schöngart[6], Marco Zecchetto[1], Carl-Friedrich Schleussner[1,3]

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Abstract

Today's climate adaptation and mitigation planning tasks require rapid access to large ensembles of climate projections for a wide range of emissions scenarios, including overshoot scenarios. While Earth system models (ESMs) provide physically consistent projections, their high computational cost limits scenario exploration at scale. Climate emulators—statistical or machine-learning-based models trained on ESM data to replicate ESM behavior across a multitude of emissions scenarios—are therefore proposed to deliver these projections efficiently. Here we present the novel modular and hierarchical SCALES–MESH emulator framework, which combines AI-based regional projections with local downscaling. The SCALES module translates global mean surface air temperature trajectories into regional climate variable projections aggregated over the AR6-IPCC regions, while the MESH module performs spatial downscaling to gridded fields at 2.5 degree resolution. We reframe regional emulation as a conditional diffusion task: a diffusion transformer generates 20-year blocks of monthly regional temperature and precipitation fields, conditioned on a transformer embedding of the global mean temperature trajectory together with a latent state encoding path dependency, scenario diagnostics, and a target-model embedding that enables a single network to emulate multiple ESMs. Arbitrarily long, temporally consistent trajectories are produced through autoregressive rollout via partial outpainting, in which each new 20-year block is conditioned on the preceding one. This formulation avoids explicit distributional assumptions while learning realistic spatial and temporal correlation structure directly from data. The model is trained on multiple ESM datasets and evaluated against parent ESMs using spatial, temporal, and distributional diagnostics. Results show that the emulator reproduces regional patterns, spatial and temporal correlations, trends, and path-dependent responses, including during the warming and cooling phases of overshoot scenarios, with accuracy

approaching that of simulation-versus-simulation comparisons on held-out test data. The approach generalizes across multiple climate models within a single model and generates hundreds of emulated realizations in under a minute. Together, SCALES–MESH enables rapid, flexible, and physically grounded exploration of climate futures, supporting decision-relevant climate risk assessment at unprecedented scope.

Submission 94

Exploring the effect of overshoot magnitude and reversal rate on climate and impact reversibility with a probabilistic reduced-complexity Earth system model

Thomas Gasser[1,2], Yuqin Lai[3], Biqing Zhu[4,1]

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Abstract

Returning global temperatures below 1.5°C after overshoot has become the only realistic long-term climate strategy. Yet the benefits of such reversal, relative to stabilisation at peak warming, remain poorly quantified, in part because the cost of running large ensembles with comprehensive Earth system models limits the exploration of the relevant scenario space. Reduced-complexity models offer a path forward, but most lack the process depth needed to capture the biogeochemical feedbacks and regional climate dynamics that govern impact (ir)reversibility.

We present a probabilistic overshoot assessment framework built around OSCAR v4, a compact but process-rich Earth system model that explicitly represents the coupled climate–carbon–chemistry system, including permafrost thaw, wetland methane dynamics, and wildfire. We follow the TIPMIP protocol (Jones et al., 2026, GMD), which prescribes idealised ramp-up, stabilisation, and ramp-down CO_2 emission pathways reaching global warming levels (GWLs) of 2°C and 4°C, and further extend the experimental design to cover additional GWLs (1.5°C, 1.8°C, 2.5°C, 3°C) and a range of negative emission rates, exploiting OSCAR's low computational cost to run large probabilistic ensembles where full ESMs cannot. This allows us to characterise not just the mean climate response under overshoot but its full uncertainty range across warming trajectories.

Beyond the physical climate system, we connect OSCAR v4 to a suite of impact emulators spanning multiple sectors and timescales: permafrost thaw, wildfire intensity, crop yields, sea level rise, and economic damages. By driving these emulators with OSCAR's probabilistic output across the TIPMIP-extended scenario space, we assess the reversibility — or lack thereof — of both climatic and socioeconomic impacts as a function of overshoot magnitude, duration, and the rate of subsequent temperature decline. This framing directly addresses questions central to overshoot pathways: how does a world after overshoot differ from one that never exceeded the threshold, for which systems and at what timescales, and what is the added value of long-term temperature reversal compared to stabilisation at peak warming?

Recent results from our contribution to RCMIP phase 3 (Romero-Prieto et al., 2026, GMD) show that, contrarily to most simple climate models, OSCAR’s biogeochemical feedbacks produce a slightly positive committed warming after net-zero emissions, which suggests that the effective benefit of overshoot reversal may be systematically underestimated by tools that omit these processes. The extended TIPMIP ensemble will allow us to quantify this effect across GWLs and connect it directly to impact outcomes, providing a probabilistic, multi-sector picture of what climate reversal can and cannot undo.

Joint Session. Theme 6, Theme 7, and Theme 8

14:00 - 15:30, River Room, 江河厅 Chairs: Marina Andrijevic, Annika Högner, Sindra Sharma-Khushal

Roundtable on Trade-offs in Overshoot

Overshoot creates interdependencies between governance, adaptation and health decisions because the way we draw temperatures back down shapes the impacts people must adapt to and the health outcomes they may face. This is especially pertinent in the context of (large-scale) CDR needed to return to the temperature limit of 1.5oC, and the competition it creates for land, water, energy and finance. At the same time, years spent above the temperature thresholds generate impacts that may push societies to adapt in ways that can be maladaptive, such as raise energy demand or generate additional emissions by powering adaptation with non-renewable energies, or lock-in vulnerabilities if not considering equity when designing adaptation plans. These issues are usually treated in separate research communities, and in this session we bring experts together to identify research questions that we need to ask, that would address these cross-cutting issues.

Time	Presenter	Title	Page
	Adriano Vinca	Mitigation consequences of maladaptation in buildings, power, and water systems under climate overshoot.	91

Submission 62

Mitigation consequences of maladaptation in buildings, power, and water systems under climate overshoot.

Adriano Vinca, Vignesh Raghnathan, Edward Byers

International Institute for Applied Systems Analysis, Laxenburg, Austria

Abstract

Mitigation scenarios in line with the Paris Agreement in the IPCC AR6 and in recent intercomparison projects like ScenarioMIP rely on decarbonization solutions in multiple sectors, but often do not include sectoral climate impact drivers. Impacts from heatwaves and water scarcity could drive energy-intensive adaptation solutions that, depending on the energy production system, could result in undesired additional carbon emissions, potentially undermining mitigation goals. This creates a blind spot for adaptation planning as well: where adaptation relies on energy-intensive technologies, its costs, effectiveness, and limits cannot be assessed separately from the mitigation pathway with which it interacts.

This study aims to assess, in 1.5°C and 2°C scenarios with different levels of climate overshoot, the extent to which maladaptive responses in the use of air conditioning in the building sector, water desalination, and thermal power generation impact overall GHG emissions.

While some existing studies have attempted to assess the maximum emissions associated with AC and desalination individually, we use the MESSAGEix Integrated Assessment Model with coverage of the water and energy sectors to explore the maladaptive effect of such technologies within a portfolio of possible options for different climate scenarios. In addition, we take into account responses to water scarcity impacts on thermal power plants and assess whether that could lead to an increase in installed capacity, with consequences for emissions. To our knowledge, this is the first study to represent these three maladaptation channels jointly and endogenously within a process-based IAM, where adaptation-driven energy demand competes with mitigation options for low-carbon energy, rather than being assessed as isolated bounding estimates. Beyond GHG emissions and energy needs, we also quantify implications for system costs and investments, comparing against adaptation scenarios with limited deployment of AC, desalination, and thermal capacity expansion.

We expect the maladaptive impact on emissions to scale with the level of overshoot; the analysis will quantify whether it remains marginal or materially undermines mitigation goals, and at what additional cost to the energy transition. Because cooling stock, desalination plants, and thermal capacity are long-lived assets, we also discuss how adaptation-driven investments made during an overshoot may lock in emissions and infrastructure that persist even after temperatures decline.

Plenary 3.Theme report back on central Science and Policy Insights

16:30 - 16:45, Harmony Hall (Plenary), 和合厅 Chair: Inga Menke

Eight science and policy insights
Panel: Relevance of overshoot in Asian context

Panel: Relevance of overshoot in Asian context

16:45 - 17:35, Harmony Hall (Plenary), 和合厅 Chair: Inga Menke

Closing Remarks

17:35 - 18:00, Harmony Hall (Plenary), 和合厅

Author index

Page numbers in bold: presenting author. Click a page number to go to the abstract.

A

Akbari, Hashem ... 81
Alaux, Nicolas ... 46
Alléon, Julien ... 16
An, Soon-Il ... **14**, 18
Asayama, Shinichiro ... 27

B

Bauer, Nico ... **60**
Bednar, Johannes ... 39, 57
Benmarhnia, Tarik ... 22
Bernadello, Raffaele ... 60
Bernard, Juliette ... 16
Bertram, Christoph ... 10
Bistričić, Petra ... **39**
Bodirsky, Benjamin ... 41
Bonserio, Teresa ... 11, **33**
Bourgois, Timothée ... 60
Brutschin, Elina ... 74
Butenschön, Momme ... 60
Buyana, Kareem ... **37**
Byers, Edward ... 51, 91

C

Cai, Wenjia ... 57
Cao, Long ... **15**
Cao, Yue ... 76
Carril, Luis Fernandez ... **40**
Casamassima, Luca ... 28
Catlow, Richard ... **87**
Chen, David ... 41
Chen, Deliang ... 21, 73, 79
Chen, Deyue ... **70**
Chen, Song ... 29
Cheng, Yonglong ... **79**
Ciscato, Chiara ... 60
Colligan, Tom ... 16
Creutzig, Felix ... 46
Crijns-Graus, Wina ... 27, 48, 69, 70
Cui, Ryna ... **10**, 84

D

Dai, Aiguo ... 50
Dai, Honglin ... **69**
Daly, Hannah ... **12**, 49
Deane, Paul ... 49
Debnath, Ramit ... 46
De Falco, Chiara ... 60
Dekker, Mark ... 9
Dietrich, Jan ... 74
Dietrich, Jan Philipp ... 60
Ding, Jingtao ... **73**
Dittus, Andrea ... 19
Dodman, David ... 68
Dong, Jinchi ... 48
Donges, Jonathan ... 32
Dorndorf, Tabea ... 41
Du, Erhu ... 66
Duke, Rick ... 10

E

Ebi, Kristie ... **22**
Elizarev, Maksim ... 71

F

Fan, Limeng ... **55**
Fan, Yuanchao ... **63**, 81
Fisher, Joshua ... 53
Fisher, Rosie ... 34
Forster, Piers ... 62
Franco, Ana ... 60
Frank, Federico ... 57
Fricko, Oliver ... 23, 74
Fujimori, Shinichiro ... 26, 27, 49, 55

G

Gao, Xiaowei ... 71
Gao, Yang ... **21**
Gasser, Thomas ... 16, 50, 75, **90**
Gidden, Matthew ... 75
Gidden, Matthew J. ... 46
Goll, Daniel ... 16
Gong, Junxi ... **37**
Goris, Nadine ... 34
Grant, Neil ... 11, 33
Gu, Vincent ... 10
Guo, Fei ... 27, 48, 70
Guo, Xiaojie ... 21
Guo, Xiuwen ... 21
Gupta, Shradda ... 60

H

Hara, Takuya ... **47**
Hare, Bill ... 11, 33, 85
Hasegawa, Tomoko ... 26, **27**
Hasse, Robin ... 41
He, Xiaojia ... 20
He, Yue ... **75**
He, Yuxuan ... 81
Hess, Jeremy ... 22
Högner, Annika ... 51, **89**
Hooke, Daniel ... 50
Horowitz, Russell ... 84
Hou, Alicia ... **11**, 33, 85
Huang, Chen ... **67**, 79
Huang, Gang ... 88
Huang, Yuying ... **52**
Hultman, Nate ... 10
Humpenöder, Florian ... 60

J

Jaggeshar, Neha ... 12
Janick, Dorothy ... 53
Jeetze, Patrick José V. ... 60
Ji, John ... **64**
Ji, John S. ... 53
Jiang, Kejun ... **43**
Joshi, Siddharth ... 28
Ju, Yiyi ... **28**

K

Kain, Verena ... 89
Kanduth, Anna ... 11
Karstens, Kristine ... 74
Khan, Zarrar ... 11, 33, 85
Kiesewetter, Gregor ... 23
Kikstra, Jarmo ... 55, 79
Kitsios, Vassili ... 89
Kivi, Iman ... 71
Klein, David ... 60
Klimont, Zbigniew ... 23
Kloenne, Uta ... 85
Koch, Johannes ... 41
Krevor, Samuel ... **71**

Krey, Volker 23, 28, 74
Kriegler, Elmar 41
Kruczkiewicz, Andrew **53**

L

Lai, Yuqin 90
Langer, Raffaela 89
Lecuyer, Fabrice 33
Lee, Huiji 34
Lee, June-Yi 18
Li, Chao **15**
Li, Hongmei 15
Li, Jiashuo 69
Li, Mingyu **9**
Li, Sibo **54**
Li, Xin 66
Li, Yan 81
Li, Yixuan **76**
Li, Yong 54, 73
Lin, Xin **66**
Lindner, Soeren **57**
Liu, Laibao 19, 45
Liu, Shiwei 61
Liu, Xinrui **16**
Liu, Yong 81
Lohmann, Niki **32**, 77
Loriani, Sina 32
Lovat, Samuel J **58**
Lovato, Tomas 60
Lu, Yi 66
Lu, Yixiong 12
Luderer, Gunnar 33
Luo, Haiming **46**
Lütken, Søren **83**
Lyngfelt, Anders 39

M

Maczek, Florian 46, 74
Mashayek, Ali 46
Mastrucci, Alessio **46**
Mathison, Camilla 19, 50
McJeon, Haewon 9, 84
Mei, Wei 50
Melnikova, Irina 50
Meng, Jing 42
Meng, Xiangyuan **70**
Meng, Zhen 66
Merfort, Anne 41
Merfort, Leon 41, 60
Meyer, Andreas Schwarz 60
Milkoreit, Manjana 32
Miller, Paul 60
Milo, Ron **58**
Minx, Jan 74
Missbach, Leonard 41
Möller, Tessa 89
Moretti, Christian 27
Mori, Shotaro 49
Moriarty, Roisin 12
Mu, Xinyue 29
Muronzi, Malon **61**

N

Nauels, Alexander 89
Nicholls, Zebedee 84, 89
Nieradzik, Lars 60
Nishiura, Osamu 26, 27
Nurjaman, Nariswari **80**

O

Obersteiner, Michael 39
O'Donnell, Carissa 53
Olivié, Dirk 34
Orduña-Cabrera, Fernando 57
Oshiro, Ken 49
Ou, Yang 9, 84

P

Pachauri, Shonali 79
Pan, Hao 19, **45**
Panda, Architesh **36**
Park, Kyungmin **19**, 51
Pathak, Anuj **49**
Peeters, Benjamin 41
Pelz, Setu 12, 79
Piao, Shilong 75
Piontek, Franziska 20, 41
Pistolesi, Giulio **57**
Pongratz, Julia 60
Popp, Alex 74
Popp, Alexander 60
Poulter, Ben 16
Pratama, Yoga 74

Q

Qu, Xia **88**
Quade, Merle 46
Quadrelli, Roberta **86**
Quesada-Chacón, Dánnell 60

R

Raghnathan, Vignesh 91
Reisinger, Andy 39
Reynard, Nick 46
Riahi, Keywan **12**, 74, 75
Rios-Ochoa, Alejandro 57
Ritchie, Paul 77
Roberts, Debra 68
Rochberg, Daniel 10
Röck, Martin 46
Rodriguez-Pardo, Carlos 9
Rogelj, Joeri 9
Rynne, Nina **32**

S

Saeed, Fahad 33, 85
Salzwedel, Robert 60
Sauer, Pascal 60
Schaeffer, Michiel 11, 33, **85**
Schlesier, Hauke **31**
Schleussner, Carl-Friedrich 9, 12, 19, 51, 89
Schöngart, Sarah 89
Schwind, Niklas **51**, 89
Schwinger, Jörg 34, 60
Séférian, Roland 19, 51
Shang, Yilin **27**, 48
Sheng, Di 46, **74**
Sheng, Lei 63
Shi, Zheng 42, **45**
Shmuel, Assaf 51, 89
Shrivastav, Gaurav 51
Shrivastav, Gaurav P. 50
Smith, Chris 50
Smith, Pete **86**
Smith, Steven 10
Snaije, Lucas **68**
Springmann, Marco **24**
Steinberger-Maierhofer, Dominik 46
Steinert, Norman 34, 77

Steinhauser, Jan 74
Su, Bo **77**
Su, Hang 81
Sukuman, Thanakon **26**
Sun, Ziyong 66
Sundvor, Ingrid 39

T

Takahashi, Kiyoshi 27
Takakura, Junya 26
Tan, Xianchun 79
Tanaka, Katsumasa 50
Teng, Fei **25**, 66
Tiong, Ying Ying 37
Tjiputra, Jerry **34**
Totake, Ryo 26
Trisos, Christopher 60
Tsuchiya, Kazuaki 27

V

Van De Ven, Dirk-Jan 84
Van Ruijven, Bas 46
Vinca, Adriano **91**
Vishwanathan, Saritha 49
Visioni, Daniele **74**

W

Wang, Can 57
Wang, Rui 57
Wang, Tao 75
Wang, Tianpeng 12, **66**
Wang, Xiaoming 61
Wang, Yupeng 81
Wang, Zeyu 25
Wang, Zhi 20
Warner, Koko **35**
Weindl, Isabelle 74
Weisberg, Michael 35
Welder, Lara 11, 33
Wen, Qin **51**
Werning, Michaela 51
Windisch, Michael 60
Woon, Kok Sin **44**
Worrell, Ernst 27, 48, 69, 70
Worthington, Bryony **62**
Wu, Fan 9, **84**
Wunderling, Nico 32, **77**

X

Xia, Tong 52, 54
Xie, Weipeng **49**
Xiong, Weiwei **50**
Xochil, Alexandra 53

Y

Yan, Aijun **81**
Yan, Hongshuo 79
Yang, Hongxuan 37
Yang, Young-Min **18**
Yao, Sheng 70
Yi, Bowen 48
Yin, Shuiqing **63**
You, Meizi **53**
Yu, Le 76
Yu, Zihan 73
Yuan, Shiwei 66
Yue, Hui 27, **48**, 69, 70

Z

Zecchetto, Marco 89
Zekollari, Harry 19
Zhang, Da 12
Zhang, Danni 16
Zhang, Jing 29
Zhang, Junting 12
Zhang, Kaiwen **50**
Zhang, Lujia **19**, 45
Zhang, Qi 69
Zhang, Renhe 50
Zhang, Shaohui **23**, 27, 48, 69, 70
Zhang, Tianyue 63
Zhang, Wendan **20**
Zhang, Xian **42**
Zhang, Xiaoye 12
Zhang, Xifeng **16**
Zhang, Xudong 9
Zhang, Yunke 54
Zhang, Zhen 16
Zheng, Donghai 66
Zhong, Jiarui **41**
Zhong, Xiaoyang 46
Zhou, Peijie 9
Zhou, Zhengxu **29**
Zhu, Biqing 16, 50, 90
Zhu, Rongqi 9, 84
Zhu, Yanlei 67
Zommers, Zinta 35
Zuo, Zhiyan 50