The risks of temperature overshoot

Submission to the first Global Stocktake

February 2023

Call for inputs from Parties and Observer States, UN Agencies and other international organisations and non-Party Stakeholders and observer organisations, to the first Global Stocktake:

Joint Submission by European Union Horizon 2020 Research and Innovation Programme Projects: CONSTRAIN (Grant Agreement No. 820829), PROVIDE (Grant Agreement No. 101003687), and ESM2025 (Grant Agreement No. 101003536) to the first Global Stocktake

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Efforts to enhance action on mitigation and adaptation in this critical decade must consider the implications of a potential temporary overshoot of global temperature limits, including on Loss and Damage, based on the best available science. Latest research from the projects CONSTRAIN, PROVIDE, and ESM2025 can inform these efforts in a number of areas.

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Executive summary

Mitigation

Stringent reductions of greenhouse gas (GHG) emissions before 2030 – roughly halving them by this date – are required to minimise the risk of overshooting the 1.5°C limit set out in the Paris Agreement.

A carbon budget can inform such stringent mitigation efforts, including requirements to get back within a 1.5°C-compatible budget after an overshoot. Important scientific uncertainties around the size of the remaining global carbon budget nonetheless imply that best estimates should be interpreted with caution. We estimate the remaining global carbon budget from the start of 2023 for a 50% chance of staying below 1.5°C to be around 260 $GtCO_2$ (*likely* range: 70 to 490 $GtCO_2$).

To meet the Paris Agreement, any potential overshoot above 1.5°C must still remain "well below 2°C". Achieving and sustaining net-zero GHG emissions as per Article 4 of the Agreement will, as a best estimate, lead to long-term declining temperatures, thereby ensuring that temperatures are eventually brought back down below 1.5°C. Paris Agreement-compatible emissions pathways therefore simultaneously keep 1.5°C within reach, limit any potential overshoot to "well below 2°C" with a *very likely* (90%) chance and achieve net zero GHGs.

Short-lived climate forcers will dominate the warming trend under 1.5°C-compatible emissions pathways until the 2030s. Stringent near-term mitigation of non-CO_2 GHGs like methane therefore has a critical role to play in limiting and delaying temperature overshoot, and contributing to a long-term decline in temperatures in line with the Paris Agreement. In a hypothetical situation where methane emissions are phased out completely, methane concentrations would decline below pre-industrial levels within 12 years and global surface ozone concentrations decrease to 1970 levels, reducing the annual rate at which the planet is increasing its temperature by up to 25% in the next decades.

Decreasing temperatures again after a potential overshoot will require the deployment of carbon dioxide removal (CDR) options. Substantial uncertainties in relation to climate and Earth system feedbacks remain that could make it both harder or easier to reverse global temperature increase, hence complicating the assessment of adaptation strategies. Large-scale deployment of land-based CDR needs to carefully consider the impact on climate-carbon cycle feedbacks in overshoot scenarios and their wider sustainability impacts.

Loss and Damage

Delaying stringent emission reductions until after 2030 will see continued warming until mid-century and beyond that would progress at virtually the same rate as over the past decade and have a high chance of overshooting the 1.5°C limit, further increasing Loss and Damage.

Focusing only on limiting temperature rise in the long run, or aiming to lower temperatures again after an initial overshoot, would do little to minimise Loss and Damage in the next 30 years.

This does not mean that bringing temperatures back down after overshoot will not help to reduce future climate risks. Taking stringent mitigation action that leads to long-term declining temperatures after an overshoot would lead to less Loss and Damage in the long-term compared to stabilising temperatures at the higher peak level of the overshoot.

However, some consequences of overshoot will be irreversible, including loss of biodiversity and loss of environmental habitability. Even if temperatures are brought back down, we will not return to where we were before. There is also the potential for crossing irreversible thresholds during an overshoot period, which could cause additional Loss and Damage. Pursuing every effort to avoid or minimise the magnitude and duration of overshoot through appropriate mitigation action is key.

Adaptation

Stringent mitigation in line with the 1.5°C limit – which would also limit any temporary temperature overshoot of 1.5°C – could slow down the pace of warming as early as the 2030s, thus buying time for adaptation efforts.

Every bit of warming avoided, including through limiting temperature overshoot, benefits adaptation efforts and lowers risks of human and natural systems reaching their adaptation limits.

Conversely, even a temporary temperature overshoot would put additional strains on human and natural systems and cause Loss and Damage. Approaches to adaptation must therefore consider these additional severe risks from temperature overshoot.

Introduction: why focus on overshoot?

Continuous delay of stringent climate mitigation increases the possibility of an at least temporary exceedance of the 1.5°C limit of the Paris Agreement. Even the majority of very low emissions scenarios assessed by the Intergovernmental Panel on Climate Change (IPCC) are projected to temporarily exceed the Paris Agreement's 1.5°C limit in their median temperature outcome – if "only" by up to 0.1°C and for 15 years on average – before returning back below that limit.[1] However, it is important to emphasise that substantial uncertainties remain regarding the exact temperature trajectories and potential reversibility of overshoots.

As part of international efforts to enhance action and increase ambition, we must therefore consider the implications of a temporary temperature overshoot for mitigation, adaptation, and Loss and Damage, based on the latest scientific evidence. This includes, for example, consequences of increased extreme events and associated damages. In the case of an overshoot above 1.5°C materialising, it is critical that temperatures are brought back down in the long run. Stabilising temperatures at higher levels is not an option to minimise adverse climate impacts and Loss and Damage and would also be at odds with the physical climate system response of eventually achieving Article 4.1 of the Paris Agreement.[2]

As illustrated in Figure 1 (next page), it is clear that only enhancing action now can minimise the wide range of risks from overshoot, including for adaptation and Loss and Damage.

[1] See Annex I: Kikstra et al. (2022). The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *Geosci. Model Dev.,* 15, 9075-9109.
[2] Mitigation Target (Article 4.1 of the Paris Agreement): "*Parties aim to reach global peaking of greenhouse gas emissions as soon as possible [....] so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century*." – commonly understood as achieving net zero GHG emissions." – commonly understood as achieving net zero GHG emissions. From: UNFCCC (2015). Paris Agreement.

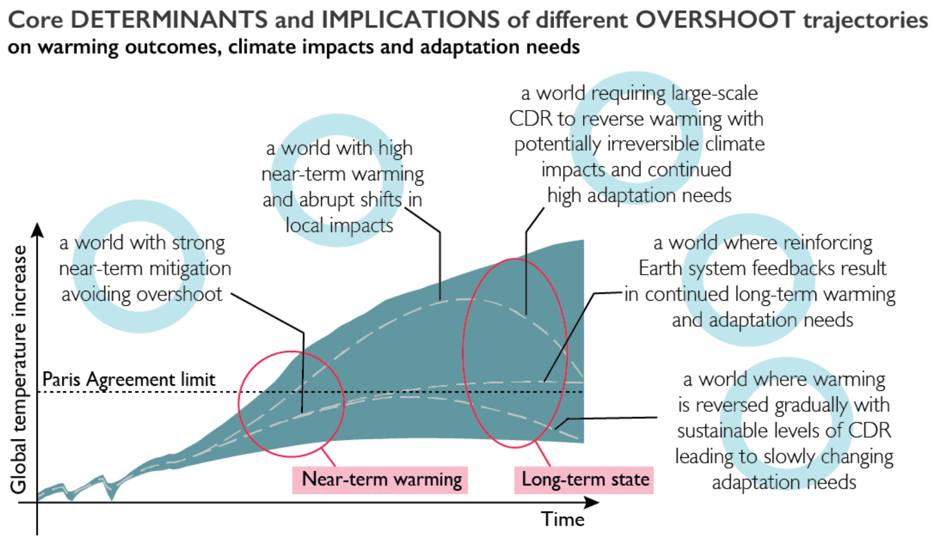

Figure 1. A summary of core determinants and implications of different overshoot trajectories on warming outcomes, climate impacts and adaptation needs. Adapted from [3].

The science-policy context on overshoot

The best available scientific information, as set out in the **IPCC Sixth Assessment Report (AR6) Working Group I, II, and III reports**, also formed the basis of the **UNFCCC's Second Periodic Review (PR2, 2020-2022)**. The PR2's **Structured Expert Dialogue (SED)** Synthesis Report[4] concludes with regards to "overshoot":

> *Box 3* [...] Avoiding overshoot of the 1.5 °C limit reduces the risk of crossing tipping points and triggering irreversible impacts.

> *28.* Achieving the long-term global goal without overshooting the 1.5 °C limit is imperative in order to avoid the most catastrophic impacts.

These findings are also reflected in the **PR2's decision at COP27**,[5] which explicitly acknowledges that limiting global warming to 1.5°C with no or limited overshoot would avoid increasingly severe impacts, while every increment of avoided warming reduces severity.

These science-based outcomes must be given due consideration, especially given the role of the First Periodic Review (2013-2015) in providing the scientific basis to inform the Long-Term Temperature Goal of the Paris Agreement, and the explicit mentioning in the PR2 COP27 decision that **SED outputs could serve as input to the GST** (paragraph 21).

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[3] PROVIDE, https://www.provide-h2020.eu/about/.
[4] UNFCCC (2022). Structured expert dialogue on the second periodic review of the long-term global goal under the Convention (2020–2022). Synthesis report by the co-facilitators of the structured expert dialogue.
[5] UNFCCC (2022). Second periodic review of the long-term global goal under the Convention and of overall progress towards achieving it. Advance unedited version.

Outlines by theme

Mitigation

Efforts to scale up mitigation in this critical decade and inform the next round of Nationally Determined Contributions (NDCs) must consider the implications of temporary temperature overshoot, based on the best available science.

Paris Agreement-compatible emissions pathways

IPCC AR6 insights

The IPCC AR6 assessment contains 50 emissions pathways that both limit global warming and achieve net zero GHG emissions in line with the Paris Agreement's temperature and mitigation goals (Articles 2 and 4)[6] – these are pathways that limit warming to 1.5°C (with an at least 50% probability) with no or limited overshoot (category "C1a").

In these pathways, "[g]lobal GHG emissions are projected to peak between 2020 and at the latest before 2025 [...]", while "[...] rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (*high confidence*)", "[...] with reductions of 43% [34–60%] by 2030 and 84% [73–98%] by 2050 [...] (*high confidence*)".[7]

We propose that the IPCC "C1a" pathways therefore set standards for how we can fully achieve the Paris Agreement temperature and mitigation goals, and can inform efforts for closing ambition and implementation gaps.[8, 9] Only stringent emission reductions before 2030 such as these can reduce the risk of overshooting the 1.5°C limit, while any less ambitious mitigation efforts risk failing the Paris Agreement temperature goal.

It is important that, to meet the Paris Agreement (Article 2), any overshoot above 1.5°C is also constrained to "well below 2°C". Achieving net-zero GHG emissions (Article 4) will meanwhile, as a best estimate, lead to long-term declining temperatures, ensuring temperatures are brought below 1.5°C again. Paris Agreement-compatible pathways therefore simultaneously keep 1.5°C within reach, limit any potential overshoot to "well below 2°C" with a *very likely* (90%) chance, and achieve net zero GHGs.

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[6] Long-Term Temperature Goal (Article 2.1a of the Paris Agreement): "*Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change*"; *See note 2.*

[7] IPCC (2022). Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.001.

[8] See Annex A: The CONSTRAIN ZERO IN report series (2019-2022).

[9] See Annex E: Schleussner et al. (2022). An emission pathway classification reflecting the Paris Agreement climate objectives. Commun Earth Environment 3, 135.

Uncertainties in climate projections

With regards to these future scenarios, it is important to note that there is still incomplete understanding of physical climate processes, and uncertainties exist in climate projections. These uncertainties come from a number of sources, including the effect of aerosols or carbon released from thawing permafrost on temperatures, any variations in which can increase or decrease our chances of staying within 1.5°C of global warming[10] and change the magnitude and duration of any overshoot. This highlights how the temperature projections provided by climate models, whichever pathway they follow, encompass a range of possible outcomes and should not be reduced to a single number.[11]

We therefore argue that any communication around overshooting a temperature limit (or remaining below it) must include probabilities and ranges alongside best estimates to adequately inform decision-making.

The remaining global carbon budget

We argue that carbon budgets can be a useful tool for climate policy – provided best estimates are communicated alongside uncertainties especially as the 1.5°C carbon budget is very small – and that the carbon budget concept can inform stringent mitigation efforts to get us back within the 1.5°C budget after an overshoot.

If long-term temperatures reach or exceed 1.5°C, this would mean that the corresponding carbon budget had been exceeded. However, if temperatures then return back below 1.5°C with stringent mitigation, meaning only a temporary temperature overshoot, this would get us back within that carbon budget. Not all processes are reversible, however, and we would probably not return to the same climate and Earth system as before.

We argue that the remaining *global* carbon budget concept can inform climate policy, although budget estimates are subject to large uncertainties. These should be explicitly recognised in, for example, the setting of net zero CO_2 targets[12] in efforts to limit temperature rise and avoid an overshoot, and updated regularly as methods improve. It is important that net zero targets are clearly defined (e.g., whether they cover only CO_2 or all GHGs) and supported (e.g., whether set in law vs. only a political pledge).[13] We furthermore argue that considerations of equity and fairness in emissions reductions, net zero targets, and the remaining carbon budget are crucial in supporting the implementation of the Paris Agreement and enhancing action.[14]

As the remaining carbon budget decreases with ongoing emissions, central estimates of its size become increasingly small compared to the uncertainties. The IPCC AR6 Working

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[10] See note 8, Annex A.
[11] See Annex B: CONSTRAIN's initial submission to the first Global Stocktake (2022).
[12] See Annex H: Dickau et al. (2022). The Role of Remaining Carbon Budgets and Net-Zero CO_2 Targets in Climate Mitigation Policy. *Current Climate Change Reports* **8**, 91-103.
[13] See Annex J: Rogelj (2023). Net zero targets in science and policy. *Environ. Res. Lett.* **18** 021003.
[14] Ibid.

Group III report states that "[...] the current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C with a probability of 50% has been assessed as 500 $GtCO_2$ [...]", and that "[r]emaining carbon budgets depend on the amount of non-CO_2 mitigation"[15]. More recently, we have estimated a remaining carbon budget from the start of 2023 for a 50% chance of staying below 1.5°C of 260 $GtCO_2$ (likely range: 70 to 490 $GtCO_2$).[16]

Carbon dioxide removal (CDR)

IPCC AR6 insights

Bringing temperatures back down below 1.5°C after an overshoot raises questions around CDR,[17] as some form of CDR is unavoidable for achieving the required net negative CO_2 or GHG emissions. Still, CDR deployment comes with feasibility and sustainability constraints.[18]

We emphasise that Paris-compatible mitigation strategies must reflect the understanding of CDR as an *addition* to stringent near-term emissions cuts – one which supports drawing down temperatures after an overshoot – rather than a means of delaying or avoiding them.

Drawing temperatures back down after an overshoot must take the potential trade-offs of such measures into account, and careful design is needed so as not to introduce any additional risks.

Large-scale deployment of land-based CDR needs to carefully consider the impact on climate-carbon cycle feedbacks[19] in overshoot scenarios and its wider sustainability impacts, for example on food production.

The role of non-CO_2 mitigation

IPCC AR6 insights

Reducing non-CO_2 emissions, especially of methane (CH_4) and nitrous oxide (N_2O), is a key characteristic in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot: "CH_4 is reduced by 45% [25–70%]; N_2O is reduced by 20% [–5 to +55%]; and F-gases are reduced by 85% [20–90%]".

"Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead

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[15] See note 7.

[16] See Annex O: CONSTRAIN (2022). Guest post: What the tiny remaining 1.5C carbon budget means for climate policy. *Carbon Brief.*

[17] See note 1, Annex I.

[18] See note 7.

[19] See Annex G: Melnikova et al. (2022). Impact of bioenergy crop expansion on climate–carbon cycle feedbacks in overshoot scenarios. *Earth Syst. Dynam.*, 13, 779-794.

to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*)"[20]

Stringent mitigation of non-CO_2 GHGs thus has a critical role to play in limiting temperature overshoot, and contributing to a long-term decline in temperatures in line with the Paris Agreement.

To test the implications of cutting or removing methane emissions, a novel generation of Earth System Models (ESMs) fitted to assess mitigation strategies has been applied.[21] We find that each effective petagram of methane removed causes a mean global surface temperature reduction of 0.21 ± 0.04°C and a mean global surface ozone reduction of 1.0 ± 0.2 parts per billion. This relationship supports the establishment of a novel metric, the effective cumulative removal, that can complement the portfolio of geophysical tools such as the carbon budgets.[22]

If anthropogenic methane emissions were phased out completely, we find that methane concentrations decline to below pre-industrial levels within 12 years and global surface ozone concentrations decrease to 1970 levels.[23]

Decadal warming rates

Our research finds that if stringent mitigation scenarios in line with limiting warming to 1.5°C with no or limited overshoot are followed, the effects on temperatures will be seen in the next decade (see Figure 2). Such strong action could well halve the current warming rate of around 0.2°C per decade, and halt or even begin to reverse warming by the middle of the century. These reductions can be achieved by a range of different mitigation options, including a focus on renewable energies, low energy demand, and a broader shift towards sustainable development – called "illustrative mitigation pathways" by the IPCC Working Group III. These relatively small differences in warming rates over the coming decades, and in absolute warming by 2050, still have significant implications for climate impacts[24] (see next section on "Loss and Damage"), highlighting how every fraction of a degree – including overshoot – matters.

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[20] See note 7.
[21] See Annex L: Folberth et al. (2022). Description and evaluation of an emission-driven and fully coupled methane cycle in UKESM.1 *Journal of Advances in Modeling Earth Systems*, 14(7).
[22] See Annex M: Abernethy et al. (2021). Methane removal and the proportional reductions in surface temperature and ozone. *Philosophical Transactions of the Royal Society: A: Mathematical, Physical and Engineering Sciences* 379, no. 2210.
[23] See Annex N: Staniaszek et al. (2022). The role of future anthropogenic methane emissions in air quality and climate. *Clim Atmos. Sci.,* 5 21.
[24] See note 8, Annex A.

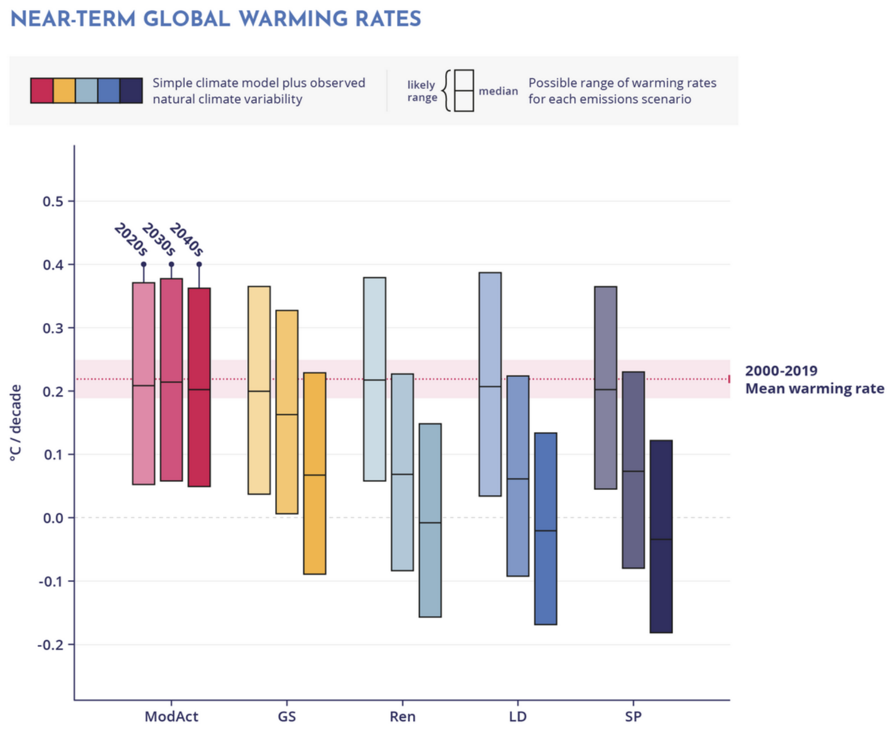

Figure 2. Warming per decade up to 2050 of selected illustrative pathways (sustainable development – SP; low energy demand – LD; renewable energy – Ren; gradual strengthening of current policies – GS; and the reference pathway for moderate action – ModAct), based on FaIR model projections.[25]

In conclusion, efforts for scaling up mitigation action in this critical decade to advance the implementation of the Paris Agreement must take the possibilities and implications of temporary temperature overshoot into consideration, as exceeding 1.5°C cannot be ruled out even under the most stringent mitigation pathways assessed by the IPCC.

In doing so, these efforts must be based on the best available science, taking into account our collective knowledge of Paris Agreement-compatible emissions pathways, uncertainties in climate projections, the remaining global carbon budget, the role of non-CO_2 mitigation, and decadal warming rates. Efforts must also recognise that even with this knowledge there remains a range of possibilities regarding, for example, the point in time when overshoot is projected. This range must be accounted for in decision-making.

[25] Ibid.

Loss and Damage

Long-term declining temperatures after an overshoot – in line with fulfilling the Paris Agreement's Article 4.1 – are always preferable to stabilising temperatures at higher levels due to the likelihood of additional impacts, risks, and Loss and Damage occurring. If temperatures are brought back below 1.5°C after a temporary overshoot, the overshoot period would still have consequences which cannot be simply reversed, including for Loss and Damage. Mitigation plans and strategies such as NDCs must thus strive to at least minimise the magnitude and duration of overshoot.

IPCC AR6 insights

The IPCC AR6 Working Group II finds that Loss and Damage[26] is already occurring which cannot all be prevented by adaptation. Increasing global warming will worsen Loss and Damage and make it increasingly difficult to avoid. Limiting global warming to 1.5°C cannot eliminate all Loss and Damage but would substantially reduce it, while Loss and Damage would escalate with every further increment of warming.[27]

On risks specifically related to overshooting 1.5°C, the IPCC finds: "If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot), then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts [...] will be irreversible, even if global warming is reduced (*high confidence*)."[28]

These findings make clear that even pathways with no or low overshoot will not avoid all Loss and Damage, and some will still occur before mid-century. Loss and Damage from sea level rise is one such example, as sea level rise will occur irrespective of future emission mitigation. However, the shorter the overshoot and the lower the level, the less severe the Loss and Damage will be.

For example, recent research finds substantial differences in climate impacts from "only" incremental differences in global warming: for instance, if temperatures rose by 1.7°C rather than 1.5°C by 2050, the additional 0.2°C warming could increase the number of people exposed to heatwaves by around one third in a number of different countries across the

[26] Definitions: "The concept of Loss and Damage (with capitalised letters, L&D) refers to the discussion point under the UNFCCC [...] Lowercase letters of losses and damages refer broadly to harm from (observed) impacts and (projected) risks". From: Ara Begum et al. (2022). Point of Departure and Key Concepts. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 121-196, doi:10.1017/9781009325844.003.
[27] IPCC (2022). Summary for Policymakers [H.-O. Pörtner et al. (eds.)]. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3-33, doi:10.1017/9781009325844.001.
[28] Ibid.

world; and if warming reached 1.8°C in 2050, the additional 0.1°C temperature rise could increase these numbers by a further 10% or more.[29]

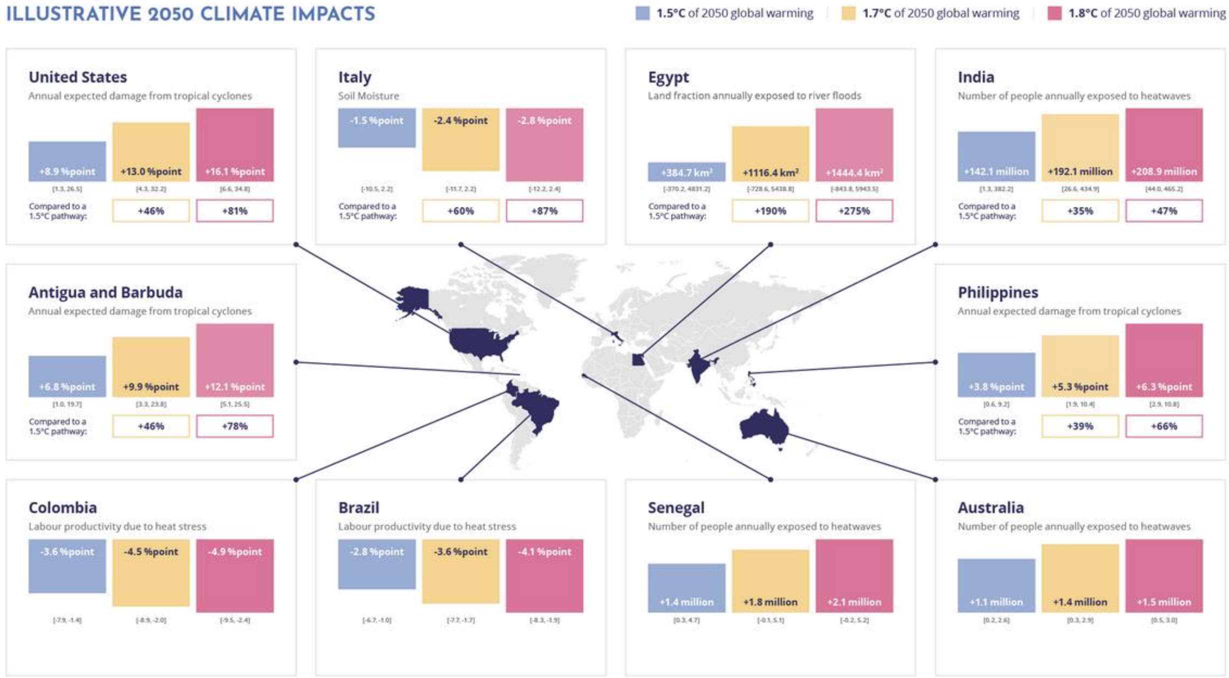

Figure 3. Examples of climate impacts in 2050 as a result of three different global warming levels (blue: 1.5°C; orange: 1.7°C; magenta: 1.8°C) in different countries. Results are presented in either absolute terms or changes in percentage points relative to the 1986-2005 reference period (median; 90% uncertainty range in square brackets).[30]

Research also suggests that there is the potential of crossing irreversible thresholds during an overshoot period,[31] which could introduce additional risks and Loss and Damage. Recent research exploring irreversible impacts due to temperature overshoot finds, for instance, lesser water availability in the Upper Indus Basin because of glacial loss, which would result in catastrophic events for billions of people in the region such as droughts, crop failure, food security, migration, and heat waves.[32]

While an improved understanding of the implications of overshoot for impacts, Loss and Damage, and risk of crossing irreversible thresholds is needed[33], we conclude that efforts to enhance action for the implementation of the Paris Agreement must at least minimise the magnitude and duration of overshoot due to the substantial differences in impacts, risks, and Loss and Damage from only incremental differences in global warming levels and the benefits in drawing temperatures back down vs. stabilising temperatures at higher levels.

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[29] See note 8, Annex A.
[30] Ibid.
[31] See Annex C: Kloenne et al. (2023). Only halving emissions by 2030 can minimize risks of crossing cryosphere thresholds. *Nat. Clim. Chang*. **13**, 9–11 (2023). https://doi.org/10.1038/s41558-022-01566-4
[32] See Annex D: PROVIDE (2022). Deliverable 4.1: Four review reports on key overshoot adaptation challenges in Iconic Regions and Cities.
[33] See note 1, Annex I.

Adaptation

Successful adaptation requires warming to be limited in line with the Paris Agreement. However, adaptation efforts must plan for the effect of incremental warming including any temperature overshoot, the risk of reaching adaptation limits, the role of the pace of warming for adaptation, and the effect of different social and environmental factors.

IPCC AR6 insights

The IPCC AR6 Working Group II explains the relationship between adaptation and warming levels, and in particular the relevance of the 1.5°C limit as well as incremental temperature changes. The report is clear that the "effectiveness of adaptation to reduce climate risk [...] will decrease with increasing warming (*high confidence*)" and that "[c]limate resilient development pathways are progressively constrained by every increment of warming, in particular beyond 1.5°C [...] (*very high confidence*)". Not only will adaptation become more difficult with increasing warming, but "additional human and natural systems will reach adaptation limits (*high confidence*)."[34]

We find that following stringent mitigation pathways in line with limiting warming to 1.5°C and minimising overshoot will slow the rate of global warming in the next decade, thereby allowing more time for adaptation and climate resilient development.[35] Our research suggests, for example, that a slower pace of warming may allow certain systems time to adapt, for example coral reefs.[36] A slower pace of warming may also allow more time for the reduction of "soft" limits[37] to adaptation.

A range of social and environmental factors affect climate adaptation across global regions, affecting limits to adaptation and managing emission scenario potentials that overshoot the Paris Agreement. Lack of finance, information availability, human capacity or local expertise, and governance are relevant adaptation constraints, shown to be of particular relevance for Caribbean Small Island Developing States (SIDS).[38] Diverse regions see constraints to adaptation from socio-economic factors such as inequalities, urbanisation pressure, and lack of adequate adaptation governance incentives which can all be described as "soft" limits to adaptation.[39]

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[34] See note 27.
[35] See note 8, Annex A.
[36] See Annex K: Dixon et al. (2022). Future loss of local-scale thermal refugia in coral reef ecosystems. *PLOS Clim* 1(2): e0000004.
[37] Adaptation Limits: "The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions." In hard adaptation limits, no adaptive actions are possible to avoid intolerable risks while in soft adaptation limits, options may exist but are currently not available to avoid intolerable risks through adaptive action. From: IPCC (2022): Annex II: Glossary [Möller, V, et al. (eds.)]. In: Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, et al. (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 2897-2930, doi:10.1017/9781009325844.029.
[38] See Annex P: Theokritoff et al. (2023). Interacting adaptation constraints in the Caribbean highlight the importance of sustained adaptation finance. *Climate Risk management.* 39.
[39] Ibid.

At the same time, stringent mitigation pathways must be inclusive and sustainable, avoiding less inclusive or fossil fuel-driven development, so as to allow for effective climate resilient development in this century, and also deliver benefits starting in this critical decade.[40]

We furthermore put forward that adaptation approaches must also integrate the additional severe risks from temperature overshoot that human and natural systems would face even if temperatures were brought back below 1.5°C. For example, trees may be added in urban areas in order to adapt to increased urban heat, but be unable to survive decreased water availability in the case of a temperature overshoot.[41]

Recent research into the regions of the Arctic Fennoscandia, Upper Indus Basin, Iberian Mediterranean, and Caribbean has shown that all report examples of where temperature overshoot impacts will negatively affect adaptive capacity, including impacts related to migrations and to impacts on key economic sectors.[42]

Our findings show that the slowing rate of warming as a result of stringent 1.5°C-aligned mitigation in this critical decade would significantly reduce climate impacts and "buy time" for adaptation. We argue that better understanding adaptation options and limits in the context of different global warming levels, incremental temperature change, and overshoot can be an important leverage for enhanced mitigation ambition and implementation that is in line with the 1.5°C limit.

[40] See Annex F: Schleussner et al. (2021). Pathways of climate resilience over the 21st century. *Environ. Res. Lett.* 16 054058.
[41] Ibid.
[42] See note 32, Annex D.

Project summaries

Below are short descriptions of the three European Union Horizon 2020 Research and Innovation Programme Projects that prepared this joint submission.

CONSTRAIN aims to improve understanding of natural and human factors affecting multi-decadal global and regional climate change and deliver improved climate projections for the next 20 to 50 years.

PROVIDE focuses on the impacts of exceeding a 1.5°C warming level, including questions of impact (ir)reversibility to identify risk thresholds as starting points for adaptation planning.

ESM2025 builds new Earth System Models (ESMs) to support the development of mitigation and adaptation strategies in line with Paris Agreement commitments, aiming to deliver the next generation of European 'mitigation-oriented' ESMs.

Annex summaries

A. The CONSTRAIN Zero In Report series (2019-2022)

The annual ZERO IN reports by the CONSTRAIN project provide information on scientific topics that are central to the Paris Agreement, as well as background and context on new developments at the climate science-policy interface. This includes new insights into the complex processes represented in climate models and what they mean for temperature change and other climate impacts over the coming decades. The reports also include supporting information on the climate science set out in the latest IPCC reports, increasing understanding of the scale of mitigation needed in this critical decade for climate.
https://constrain-eu.org/publications/type/reports/

B. CONSTRAIN's initial submission to the first Global Stocktake (2022)

CONSTRAIN's initial submission drew on the first three ZERO IN Reports referred to above. Topics covered include the Paris Agreement Long-Term Temperature Goal; near-term warming, warming rates and greenhouse gas emissions; uncertainties in the climate system that could affect our chances of staying within 1.5°C warming; and remaining global carbon budgets. The submission also speaks to cross-cutting issues including methodologies for taking stock of the implementation of the Paris Agreement, and knowledge gaps regarding the information necessary to support a robust global stocktake.
https://constrain-eu.org/wp-content/uploads/2022/08/CONSTRAIN-Submission-to-the-first-Global-Stocktake.pdf

C. Kloenne et al. (2023). Only halving emissions by 2030 can minimize risks of crossing cryosphere thresholds

Considering cryosphere and warming uncertainties together implies drastically increased risk of threshold crossing in the cryosphere, even under lower-emission pathways, and underscores the need to halve emissions by 2030 in line with the 1.5 °C limit of the Paris Agreement.
https://www.nature.com/articles/s41558-022-01566-4

D. PROVIDE (2022). Deliverable 4.1: Four review reports on key overshoot adaptation challenges in Iconic Regions and Cities

The PROVIDE project deliverable offers a review of key adaptation challenges in four iconic case study regions and urban areas: Arctic Fennoscandia, and the city of Bodø, Norway; Iberian Mediterranean, and the Lisbon Metropolitan Area, Portugal; Upper Indus Basin and the city of Islamabad, Pakistan; and The Bahamas, with a focus on Nassau according to relevant literature review, stakeholder workshops undertaken by in-region experts, and analyses of the urban environment structural profiles. Despite their regional differences, climate change impacts are heavily exacerbated by socio-economic factors, such as inequalities and lack of financial and human capital and adaptation challenges including discontinuity of green-blue structures, intensity of the built-up space, land ownership and governance regimes without sufficient spatial coherence, among others.
https://www.provide-h2020.eu/wp-content/uploads/PROVIDE_NRI_D4.1_Review-Reports.pdf

E. Schleussner et al. (2022). An emission pathway classification reflecting the Paris Agreement climate objectives

A fully consistent interpretation of the Paris Agreement needs to be based on an emission pathway classification that comprehensively reflects the climate criteria set out in the Paris Agreement. An pathway classification that aims to comprehensively reflect the climate criteria set out in the Paris Agreement is proposed, which can allow for a fully consistent interpretation of the Agreement. For

Paris Agreement compatible pathways, net zero CO2 and greenhouse gas emissions around 2050 and 2065 are reported, while it is illustrated that pathway design criteria not rooted in the Paris Agreement, such as the 2100 temperature level, result in scenario outcomes wherein about 6 - 24% higher deployment (interquartile range) of CO2 removal is observed.
https://www.nature.com/articles/s43247-022-00467-w

F. Schleussner et al. (2021). Pathways of climate resilience over the 21st century

Assessing trajectories of adaptation readiness, in comparison with the continued emergence of hot days as a proxy for climate change hazards for different emission and socio-economic pathways over the 21st century, provides insight into the prospects of future climate resilience building beyond what has been experienced to date. Findings indicate that only an inclusive and sustainable stringent mitigation pathway allows for effective climate resilient development over the 21st century. Less inclusive or fossil-fuel driven development will not allow for improvements in resilience building beyond the recent past.
https://iopscience.iop.org/article/10.1088/1748-9326/abed79

G. Melnikova et al. (2022). Impact of bioenergy crop expansion on climate–carbon cycle feedbacks in overshoot scenarios

Consequences of large-scale Bioenergy with Carbon Capture and Storage (BECCS) deployment on the climate-carbon cycle feedbacks under CMIP6 SSP5-3.4-OS overshoot scenario are explored using five state-of-the-art ESMs, keeping in mind that all these models use generic crop vegetation to simulate BECCS. The land cover representation by ESMs is evaluated and highlights the inconsistencies that emerge during translation of the data from Integrated Assessment Models (IAMs) then land-use change (LUC) emissions of ESMs are evaluated against bookkeeping models. This finally shows that an extensive cropland expansion for BECCS causes ecosystem carbon loss that drives the acceleration of carbon turnover and affects the CO2 fertilisation effect- and climate-change-driven land carbon uptake.
https://esd.copernicus.org/articles/13/779/2022/

H. Dickau et al. (2022). The Role of Remaining Carbon Budgets and Net-Zero CO2 Targets in Climate Mitigation Policy

Recent analyses offer a range of estimates of remaining allowable CO2 emissions for the 1.5 °C and well-below 2 °C climate targets, though the treatment and coverage of key sources of uncertainty vary considerably among studies. A review of recent estimates of the remaining carbon budget, with a focus on characterising key uncertainties and assessing the implications for net-zero CO2 targets and climate policy, recommends that net-zero CO2 targets be set with explicit recognition of the uncertainty associated with carbon budget estimates and be updated regularly as this uncertainty is better constrained.
https://link.springer.com/article/10.1007/s40641-022-00184-8

I. Kikstra et al. (2022). The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures

We discuss the implied overshoot severity of the mitigation pathways using overshoot degree years and look at emissions and temperature characteristics of scenarios compatible with one possible interpretation of the Paris Agreement. We find that the lowest class of emissions scenarios that limit global warming to “1.5 °C (with a probability of greater than 50 %) with no or limited overshoot” includes 97 scenarios for MAGICCv7.5.3 and 203 for FaIRv1.6.2, but “limited overshoot” typically implies exceedance of median temperature projections of up to about 0.1 °C for up to a few decades before returning to below 1.5 °C by or before the year 2100 for MAGICCv7.5.3 results.
https://gmd.copernicus.org/articles/15/9075/2022/

J. Rogelj (2023). Net zero targets in science and policy

Since the adoption of the 2015 Paris Agreement and the publication of the 2018 Special Report on Global Warming of 1.5°C of the IPCC, net zero targets have become a central feature in climate policy. This Perspective looks back at the scientific foundations of this recent policy development, the current state of play, and next frontiers for research on this topic.
https://iopscience.iop.org/article/10.1088/1748-9326/acb4ae

K. Dixon et al. (2022). Future loss of local-scale thermal refugia in coral reef ecosystems

Statistical downscaling is carried out to provide the highest resolution thermal stress projections (0.01°/1 km, >230,000 reef pixels) currently available for coral reefs and identify future refugia on locally manageable scales. Results show that climate change will overwhelm current local-scale refugia, with declines in global thermal refugia from 84% of global coral reef pixels in the present-day climate to 0.2% at 1.5°C, and 0% at 2.0°C of global warming and confirm that warming of 1.5°C relative to pre-industrial levels will be catastrophic for coral reefs.
https://journals.plos.org/climate/article?id=10.1371/journal.pclm.0000004

L. Folberth et al. (2022). Description and evaluation of an emission-driven and fully coupled methane cycle in UKESM1

The observed increase in methane concentration from 729 ppb in 1750 to 1866 ppb in 2019 has contributed 0.5°C to the observed global mean temperature rise since the pre-industrial period (IPCC AR6 WGI, 2021), making it second only to CO2 as a greenhouse gas. Methane's impact on climate extends beyond its direct radiative effect due to indirect effects on tropospheric ozone and stratospheric water vapour - so-called chemical adjustments. The latest IPCC AR6 WGI report relied on a generation of Earth system model driven by concentrations, meaning that potential feedbacks on natural methane emissions and/or methane lifetime are not explicitly included and any climate and/or air quality benefits cannot be directly attributable to changes in methane emissions.
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021MS002982

M. Abernethy et al. (2021). Methane removal and the proportional reductions in surface temperature and ozone

Global mean temperature and global mean surface ozone changes are assessed resulting from idealised methane emissions reductions that varied in both magnitude and timing. By defining a new metric, the effective cumulative removal of methane, they find that the global mean surface temperature and the global mean surface ozone concentration reduce by 0.21 ± 0.04°C and 1.0 ± 0.2 parts ppb per effective petagram of methane removed, respectively. They conclude that methane emission reductions and/or methane removal is effective in delaying warming thresholds and reducing peak temperatures.
https://royalsocietypublishing.org/doi/10.1098/rsta.2021.0104

N. Staniaszek et al. (2022). The role of future anthropogenic methane emissions in air quality and climate

A deep, rapid, and sustained cut in anthropogenic methane emissions is analysed, by implementing an idealised instantaneous reduction in anthropogenic methane emissions to zero. This reveals that methane concentrations decline to below pre-industrial levels within 12 years and global surface ozone concentrations decrease to 1970 levels.
https://www.nature.com/articles/s41612-022-00247-5

O. CONSTRAIN (2022). Guest post: What the tiny remaining 1.5C carbon budget means for climate policy

With latest insights from the Intergovernmental Panel on Climate Change (IPCC) and GCP data, it is estimated that the remaining 1.5C carbon budget could be just 260GtCO2. This carbon budget is

around 120GtCO2 smaller than what is currently expected and would imply that the budget will be reached in around six and a half years if emissions continue at current levels.
https://www.carbonbrief.org/guest-post-what-the-tiny-remaining-1-5c-carbon-budget-means-for-climate-policy/

P. Theokritoff et al. (2023). Interacting adaptation constraints in the Caribbean highlight the importance of sustained adaptation finance

Regional perceptions of adaptation constraints and avenues to overcome them are assessed based on a mixed-method approach with adaptation experts from Caribbean Small Island Developing States. We find that finance is the largest constraint being faced which closely interacts with information, human capacity and governance constraints throughout the entire adaptation process. Such interacting constraints can lead to vicious cycles profoundly hindering adaptation and therefore need to be addressed in parallel.
https://www.sciencedirect.com/science/article/pii/S2212096323000098