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One Earth

Commentary

Many risky feedback loops amplify the need for climate action

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Many feedback loops significantly increase warming due to greenhouse gas emissions. However, not all of these feedbacks are fully accounted for in climate models. Thus, associated mitigation pathways could fail to sufficiently limit temperatures. A targeted expansion of research and an accelerated reduction of emissions are needed to minimize risks.

As we increasingly understand climate change as a series of disasters in the short term and a major threat in the longer term, many governmental jurisdictions and world scientists have declared a climate emergency.[1] In addition, nearly all countries have signed on to the Paris Accord, which calls for limiting warming to 2°C, and ideally 1.5°C. One of the main factors making climate change especially dangerous is the risk of amplifying climatic feedback loops. An amplifying, or positive, feedback on global warming is a process whereby an initial change that causes warming brings about another change that results in even more warming (Figure 1). Thus, it amplifies the effects of climate forcings—outside influences on the climate system such as changes in greenhouse gas concentrations. In part because of positive climate feedbacks, a very rapid drawdown in emissions will be required to limit future warming.

Ultimately, even relatively modest warming is expected to increase the risk that various climatic tipping points will be crossed—causing large changes in the future state of Earth's climate system, thereby adding further amplifying feedbacks.[2] Despite major recent progress in incorporating a host of interacting feedbacks,[3,4] climate models may still be underestimating the acceleration in global temperature change that a large and interrelated set of amplifying feedback loops and tipping points could cause. In a likely short-term scenario, our lack of dramatic emission reductions could result in a future with ongoing and intensifying climate impacts. In the worst case long-term scenario, interactions among feedback loops could result in an irreversible drift away from the current state of Earth's climate to a state that threatens habitability for humans and other life forms.[5] In any case, the accuracy of climate models is of vital importance since they guide climate mitigation efforts by informing policymakers about the expected effects of anthropogenic emissions.

Here, we discuss feedback loops in the context of climate science, present an extensive list of diverse feedbacks, and consider implications for climate research and policy.

Feedback loops and the remaining carbon budget

The remaining carbon budget is defined as the permitted amount of future anthropogenic carbon dioxide (CO_2) emissions that are consistent with a given climate target and provides a direct link between climate science and climate policy, as it can guide emissions targets.[4,6] It is closely related to the transient climate response to cumulative emissions of carbon (TCRE), which characterizes the relationship between cumulative CO_2 emissions from the present day and warming due to CO_2 emissions relative to preindustrial levels.[6] Although highly uncertain, the remaining carbon budget associated with 1.5°C warming was recently estimated to be 260 Gt CO_2 relative to the start of 2023, which could be exhausted in just 6.5 years[7] If their combined effects are underestimated, the additional climate feedbacks could further reduce the remaining carbon budget.

Positive climate feedback loops lead to greater warming per unit of CO_2 emitted, thereby substantially increasing the TCRE and reducing the remaining carbon budget. However, it is often difficult to accurately model Earth system feedbacks. A recent major TCRE assessment[4] used expert judgment to account for limited coverage of Earth system components (e.g., certain biological feedbacks), arriving at a relatively wide "likely" interval of 1.0°C–2.3°C per 1,000 Gt C. Despite the clear importance of understanding positive feedbacks, the scientific understanding of the unrepresented Earth system positive feedbacks has been characterized as "very low."[6] Thus, better characterization of climate feedback loops is necessary to more accurately estimate the remaining carbon budget.

Many risky feedbacks

Here, we present, to the best of our knowledge, the most extensive list available of climate feedback loops (Tables 1, S1, S2, and Figure S1). In total, we have identified 41 biogeophysical feedback loops (20 physical and 21 biological), including 27

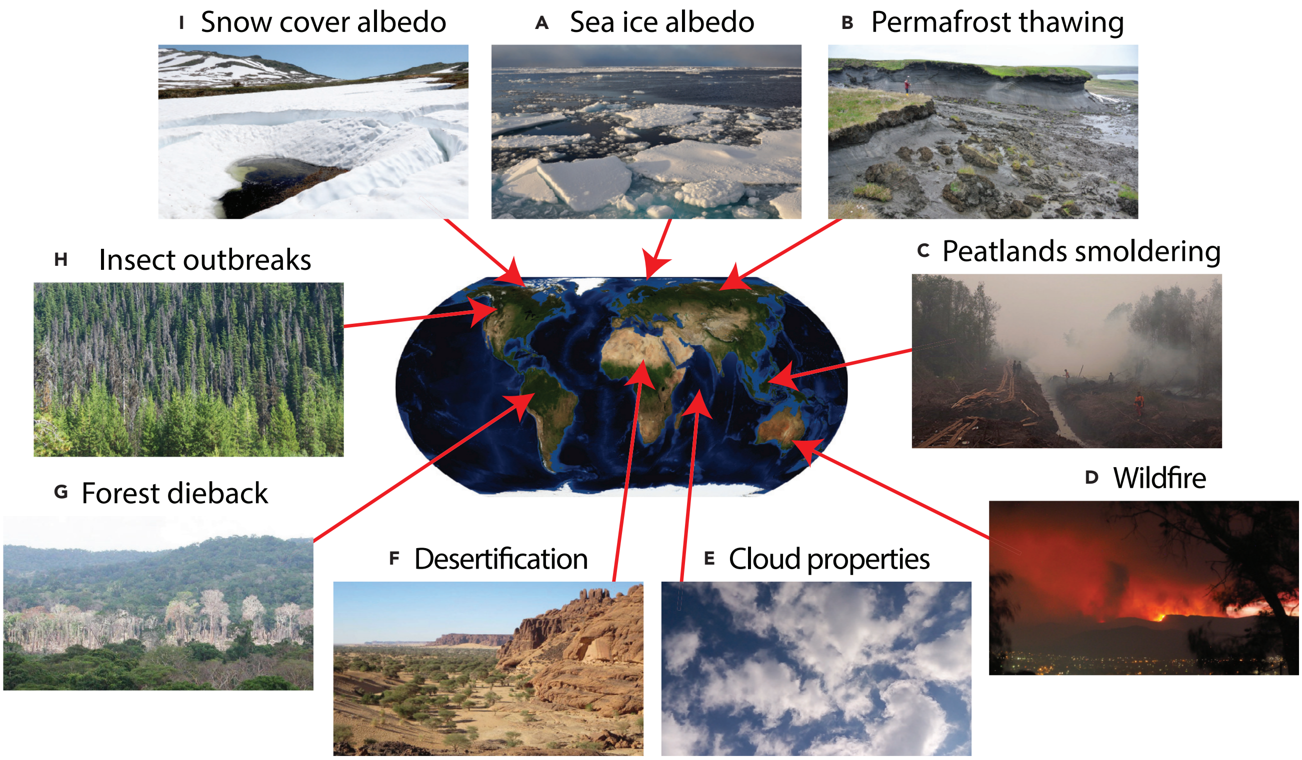

Figure 1. Map of feedback loops

(A–I) The map shows example locations where select positive feedback loops are likely operating. The full extent of the area and locations impacted by each feedback loop are not depicted. Feedback loop summaries: (A) sea ice melting or not forming → decreasing albedo; (B) increasing thawing and decomposition → increasing CO_2 and CH_4 emissions, loss of sequestration; (C) drying and increasing vulnerability to fire/smoldering, decreasing soil organic carbon → increasing release of CO_2 into the atmosphere and decreasing carbon sequestration; (D) increasing fire frequency and/or severity → increasing CO_2 emissions, loss of sequestration, change in albedo; (E) changing cloud distribution and optical properties → altered cloud albedo and greenhouse effect; (F) increasing chronic aridification and hotter drought stress extremes leading to expanding deserts → decreasing CO_2 sequestration, and increasing albedo; (G) dieback of Amazon, boreal, and other forests → loss of sequestration, change in albedo, decreasing evapotranspiration; (H) changing insect distributions and abundances, decreased host tree defense → loss of sequestration, change in albedo; (I) decreasing snow cover → decreasing albedo. See Table S1 for further feedback loop details. Photo credits (also given in Table S3): (A) Patrick Kelley, CC BY 2.0; (B) Boris Radosavljevic, CC BY 2.0; (C) NASA's Earth Observatory, CC BY 2.0; (D) Nick-D, CC BY-SA 4.0; (E) Doggo19292, Public Domain; (F) David Stanley, CC BY 2.0; (G) NASA/JPL-Caltech, (H) Jonhall, CC BY 3.0, (I) Natalia_Kollegova, Pixabay License.

positive (reinforcing) feedback loops, 7 negative (balancing) feedback loops, and 7 uncertain feedback loops (Tables 1 and S1). We obtained feedback strengths for 17 of these loops, including 13 strengths in standard units of $W/m^2/K$ (Table S1 and Figure S2). Physical feedback loops involve primarily abiotic systems. For example, warming in the Arctic leads to melting sea ice, which leads to further warming because water has lower albedo (reflectance) than ice (Figure S3). In contrast, biological loops involve the biosphere in some way. For instance, increasing temperatures lead to permafrost thawing, which produces CO_2 and methane (CH_4) emissions, which in turn leads to further increasing temperatures, and so on (Figure S3). Note that biological loops can also involve physical components. Because some loops were discovered relatively recently, we expect additional feedback loops to be described in the near future, especially in the biological category where many complex interactions are possible. Given that most of the feedback loops we identified are positive, it seems likely that many unknown feedbacks are also positive. Collectively, these additional loops could mean that the remaining carbon budget has been overestimated, in which case proposed mitigation pathways may be inadequate and net zero (human) emissions may need to be achieved more quickly than anticipated.[6] While climate feedbacks, the TCRE, and carbon budgets have been partially constrained using historical and paleo-climate data,[4] this does not diminish the importance of further research. In particular, we are now seeing greenhouse gas levels that have not occurred in several million years, and we lack the paleo data to understand carbon-climate and social feedbacks on a much warmer and more carbon-rich planet.[8]

Greenhouse gas emissions have been growing rapidly during the last century, despite several decades of warnings from scientists that emissions must be greatly reduced. Moreover, because climate feedbacks can interact with each other and exhibit temperature dependence[9,10] and non-linearities, currently weak feedbacks have the potential to become stronger, following warming driven by other feedback loops. In a grim scenario, interacting feedback loops could result in a sequence of climate tipping points being exceeded,[5,11] producing "climate cascades," whereby the net effect of reinforcing feedbacks is greater than the sum of their individual effects under current conditions.

Table 1. Summary list of feedback loops

Feedback	Effect of climate change	Effect on climate change	+/−
20 physical feedback loops			
1. Planck[†]	↑ Temperature	↑ Heat loss (radiation)	–
2. Water vapor[†]	↑ Increasing water vapor content	↑ Greenhouse effect	+
3. Sea ice albedo*[†]	↑ Sea ice melting or not forming	↓ Albedo	+
4. Ice sheets*[†‡]	↑ Glacier & ice sheet melting/ instability	↓ Albedo	+
5. Sea level rise[‡]	↑ Sea levels	↓ Albedo (↑ coastal submergence)	+
6. Snow cover[†]	↓ Snow cover	↓ Albedo	+
7. Clouds[†]	Δ Cloud distribution & optical properties	Δ Cloud albedo & greenhouse effect	+
8. Dust[†]	Δ Dust aerosol abundance	Δ Albedo & greenhouse effect	?
9. Other aerosols[†]	Δ Atmos. aerosol conc.	Δ Albedo & greenhouse effect	?
10. Ocean stratification	↑ Ocean stratification	↓ Carbon uptake by ocean	+
11. Ocean circ.*	↓ Ocean circ.	Δ Surface temperature	?
12. Solubility pump[†]	↑ Atmos. CO_2 levels	↓ CO_2 absorption by ocean	+
13. CH_4 hydrates*[‡]	↑ CH_4 hydrate dissociation rates	↑ Release of CH_4 into atmos.	+
14. Lapse rate[†]	Δ Temp.-altitude relationships	↓ Global mean temperature	–
15. Ice-elevation[‡]	↓ Ice sheet/glacier elevation	↑ Glacier & ice sheet melting, ↓ albedo	+
16. Antarctic rainfall[‡]	↓ Ice sheet extent, ↑ precipitation	↓ Albedo, ↑ deep ocean warming	+
17. Sea ice growth	↓ Sea ice thickness, ↓ insulation	↑ Thin ice growth rate	–
18. Ozone[†]	Δ Atmos. circ.	↓ Tropical lower stratospheric ozone	?
19. Atmos. reactions[†]	Δ Atmos. chem. reaction rates	Δ Greenhouse effect	?
20. Chem. weathering[‡]	↑ Chemical weathering rates	↑ CO_2 taken out of atmosphere	–
21 biological feedback loops			
21. Peatlands[†]	↑ Drying and fire, ↓ Soil carbon	↑ Release of CO_2 into atmos.	+
22. Wetlands[†]	↑ Wetlands area (↑ precipitation)	↑ CO_2 seq., ↑ CH_4 emissions	+
23. Freshwater	↑ Aquatic plant growth rates	↑ CH_4 emissions	+
24. Forest dieback*	↑ Amazon and other forest dieback	↓ CO_2 seq., Δ albedo	+
25. Northern greening	↑ Boreal forest area, Arctic vegetation	↑ CO_2 seq., ↓ albedo	+
26. Insects	Δ Insect ranges and abundances	↓ CO_2 seq., Δ albedo	+
27. Wildfire[†]	↑ Fire activity in some regions	↑ CO_2 emissions, Δ albedo	+
28. BVOCs[†]	Δ BVOC emission rates	↓ Greenhouse effect, ↑ tropospheric O_3	–
29. Soil carbon (other)	↑ Loss of soil carbon	↑ CO_2 emissions	+
30. Soil nitrous oxide[†]	Δ Soil microbial activity	↑ Nitrous oxide emissions	+
31. Permafrost*[†]	↑ Permafrost thawing	↑ CO_2 and CH_4 emissions	+
32. Soil and plant ET	↑ ET from soils and plants	↓ Latent heat flux	+
33. Microbes (other)	↑ Microbial respiration rates	↑ CO_2 and CH_4 emissions	+
34. Plant stress	↑ Thermal stress, ↑ droughts	↑ Plant mortality, ↓ CO_2 seq.	+
35. Desertification	↑ Desert area	↓ CO_2 seq., Δ albedo	+
36. Sahara/Sahel greening*	↑ Rainfall in Sahara and Sahel	↑ CO_2 seq. by vegetation	–
37. CO_2 fertilization	↑ CO_2 conc., ↑ NPP	↑ Carbon uptake by vegetation	–
38. Coastal productivity	↑ Coastal ecosystem degradation	↓ Coastal ecosystem carbon seq.	+

(*Continued on next page*)

Table 1. *Continued*

Feedback	Effect of climate change	Effect on climate change	+/−
39. Metabolic rates	↑ Phytoplankton respiration rates	↑ CO_2 released into atmos.	+
40. Ocean bio.	↑ Ocean CO_2, ↑ acidification, ↑ temp.	Δ Ocean carbon sink	?
41. Phytoplankton-DMS†	Δ Plankton DMS emissions	Δ Cloud albedo	?

Loops are divided into two categories: physical (loop numbers 1–20) and biological (loop numbers 21–41). The rightmost column shows the loop direction ("+": reinforcing, "-": balancing, "?": uncertain). Feedback loops that involve potential tipping elements are marked with asterisks (*; see supplemental experimental procedures). As a rough indicator of feedbacks that are more likely to be at least partly included in some climate models, loops that are covered in Figure TS.17 (feedbacks overview) or 5.29 (biogeochemical feedbacks) of IPCC[4] are marked with daggers (†). Many of these feedbacks will have significant effects on Earth's climate, but others are more speculative and possibly negligible. Feedback impacts operate on time scales ranging from short (e.g., months/years) to very long (e.g., millennia); feedbacks we believe to be exceptionally slow are marked with double daggers (‡). Symbols indicate increasing (↑), decreasing (↓), and changing (Δ), and abbreviations correspond to circulation (circ.), concentration (conc.), temperature (temp.), atmospheric (atmos.), chemical (chem.), sequestration (seq.), biogenic volatile organic compounds (BVOCs), ozone (O_3), evapotranspiration (ET), biological pump (bio.), and dimethyl sulfide (DMS). See supplemental experimental procedures and Table S1 for complete loop descriptions, grouping order, limitations (e.g., overlapping loops and uncertain tipping elements), and selected references.

Some feedback loops may be associated with key tipping points (Tables 1 and S1) that could profoundly disrupt the global climate system and biosphere once critical thresholds are crossed. Although it has been argued that most of these tipping points are not expected to drive large positive feedbacks, there is deep uncertainty associated with unlikely but extreme feedbacks and tipping points.[4] Specific concerns include slowing of ocean circulation and the large-scale loss of ice sheets, permafrost, and forests.[2] In the worst case, if positive feedbacks are sufficiently strong, this could result in tragic climate change outside the control of humans.[5]

Based on our compilation of numerous and potentially risky climate warming feedback loops, we call for immediate concurrent changes to both (1) climate research and (2) climate policy, which should strategically inform and guide each other.

Climate research

While we applaud the significant accomplishments of feedback researchers to date, we believe an immediate and massive international mobilization must occur to advance climate science with an increase in research priorities and funding to quickly get the impacts and interactions of feedbacks better assessed in the context of the remaining carbon budget. We call for a faster transition toward integrated Earth system science because the climate system can only be understood by integrating the functioning and state of all Earth system interactions.[12] For example, an Earth system science approach can provide information on both mitigation pathways that minimize risks associated with climate feedbacks and the societal transformations needed to pursue these trajectories. This will give policymakers better and more usable scientific information, which is needed to manage risks associated with the climate emergency.

More research is needed to incorporate the mechanisms and processes of diverse feedback loops into climate models, especially biological feedback loops. These have received comparatively little attention and are often grouped together as "unrepresented feedback mechanisms."[3,6,13] Therefore, we propose that feedback loops and tipping points as well as their possible combined severe consequences (e.g., potential runaway dynamics) receive more attention, for example, as an IPCC special report. Biological feedback loops involving forest dieback, loss of soil carbon, thawing permafrost, drying and smoldering peatlands, and the changing ocean biological pump are highly uncertain and may be large. Developing a better understanding of these and other feedbacks will require large-scale funding and collaboration to coordinate data collection and synthesis efforts.

As part of an Earth system approach, more research is also needed to identify, quantify, and integrate the myriad of human feedbacks (Table S2), which is complicated by the inherent uncertainty in the social system.[14] Because they involve complex social and economic systems, it is important that analyses of human feedbacks be conducted in an interdisciplinary fashion, including researchers from the social sciences in all stages of the process.[15] Overall, insight into the complex trajectories that tie physical, biological, and social feedbacks together may be gained through various methods. Promising approaches include simulations that can reflect the behavior of complex adaptive systems and artificial intelligence-based network analysis of the matrix of feedback loop interactions. Such insights will likely be needed to make progress on two major challenges facing Earth system science: assessing the stability and resiliency of the Earth system and fully integrating biophysical and human dynamics.[12]

Climate policy

Individual countries are not even close to being on track to achieve the Paris emissions reduction pledges that were not enough to meet the insufficient Paris 2.0°C upper limit warming target and are now distressingly inadequate to meet the later 1.5°C warming limit.[16] Worse still, researchers have recently raised the likely minimum equilibrium warming associated with atmospheric CO_2 doubling from 1.5°C (Stocker et al.[17]) to a more devastating 2.5°C (IPCC[4]). With these troubling developments in mind, we make two arguments for immediate and massive reductions in emissions. First, we suggest that further small increases in short-term warming are a big risk, considering the suffering that we are already experiencing from climate disasters of "unprecedented" wildfires, intense storms, coastal flooding, permafrost thaw, and extreme weather that have occurred with just 1.1°C to 1.2°C global average warming. Second, as part of a longer timeline, positive feedback loops and tipping points may pose a major threat. Given the potential for catastrophic climate change and the lack of complete scientific understanding to date, policymakers should strongly consider the potentially dangerous effects of feedback loops, tipping points, and climate cascades, even if all desired scientific data are not available at this time.

Transformative and socially just changes in global energy and transportation, short-lived air pollution, food production, nature preservation, and the international economy, together with population policies based on education and equality, are required to address this immense problem in both the short and the long term.[1] Many of these changes will require significant time, research, and political support to fully carry out. However, reductions in warming due to mitigating methane and other short-lived pollutant emissions can be achieved rapidly. Equitable policies and funding are also needed to support climate adaptations in less wealthy regions where knock-on effects of feedbacks or secondary feedback loop effects are particularly dangerous.

The remaining carbon budget is rapidly shrinking and waiting until 2050 to achieve net-zero carbon emissions might be far too late.[13] The gap between projected emissions (assuming 2030 mitigation pledges are met) and emissions consistent with 1.5°C is very large, and time is running out to avoid the worst effects of climate change.[16] Specifically, the gap is roughly 23 Gt CO_2e per year in 2030 for 1.5°C.[16] Therefore, shortened timelines for carbon neutrality (before 2050), and more ambitious emissions drawdown with near-term requirements should be swiftly implemented as a response to this emissions gap. Large natural carbon sinks are also critical, but they must be established strategically with relevant biological feedback loops in mind.

Summary

The first step in curbing the near-term climate impacts and minimizing the risk of an eventual catastrophic outcome is for us to expand our awareness of the severity of our predicament.[18] Thus, we have described an extensive set of potentially harmful feedback loops to increase our understanding, justify a more serious response, and motivate work into less probable but dangerously underexplored scenarios.[18]

It is too late to fully prevent the pain of climate change as severe impacts are already being felt, but if we can have a much better understanding of feedback loops and make the needed transformative changes soon while prioritizing basic human needs, there might still be time to limit the harm. Even if it turns out that feedbacks are already sufficiently characterized, these changes will provide enormous benefits to human well-being and the entire biosphere. Conversely, if the worst-case risks posed by feedback loops and tipping points have been underestimated, the future of a hospitable planet Earth may be at stake.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests should be directed to and will be fulfilled by the co-lead contacts, Christopher Wolf (wolfch@oregonstate.edu) and William Ripple (bill.ripple@oregonstate.edu).

Materials availability

This study did not generate new unique materials.

Data and code availability

All data associated with the paper are provided in the Supplemental Information. This paper does not report original code.

Summary of experimental procedures

Here, we provide a summary of the experimental procedures used to construct the tables of feedback loops (Table 1 and S1). Please see the Supplemental Experimental Procedure section for more detail, including limitations.

We compiled an initial set of climate feedback loops by performing a literature review using computerized searches. We considered standard research articles and also review papers dealing with feedback loops. We also examined references cited by these papers.

We grouped the feedback loops into three general categories: Physical (abiotic), Biological, and Human, and we identified feedback loop "types," which correspond to subcategories.

Because of the complexity of social systems, the human feedback loops may be speculative in nature and difficult to quantify. So, we present these possible feedback loops separately from the physical and biological loops. These human loops are intended as examples only, and this list is not intended to be exhaustive.

We only considered feedbacks to global temperature, excluding internal feedbacks. For each climate feedback loop, we identified two processes: the "effect of climate change" and the "effect on climate change." For example, warming in the Arctic causes ice to melt (effect of climate change) and melting ice in turn leads to further warming by decreasing albedo (effect on climate change). We also categorized each loop as positive, negative, or uncertain direction. Lastly, we determined estimates of feedback loop strengths where possible. Feedback strengths are quantified in a number of ways, although units of W/m^2/K are standard. When available, we included uncertainty estimates associated with strengths (e.g., standard errors).

Although each feedback loop differs from the others in either the "effect of climate change," or the "effect on climate change," there may be overlaps among some groups of feedback loops. Given that these feedback loops can involve many complex and interacting systems, we viewed some degree of overlap as unavoidable. We used footnotes to indicate occurrences of partial overlap (see Table S1). The strength estimates are generally separate and additive, except in cases of overlapping feedback loops. In our feedback loops tables, we included loops that vary in strength over time, many of which could eventually weaken. Likely examples include permafrost (limited capacity to emit greenhouse gases), sea ice (eventually, there may be no sea ice), and forest dieback (eventually, large forested areas could be fully converted to other ecosystem types, possibly halting this process).

The focus of our table is on feedback loops. However, climate tipping elements and tipping points are related concepts that are of major importance to the Earth system. Therefore, we identified the feedback loops in our table that might involve tipping elements.

After constructing the preliminary tables of feedback loops, we then had them reviewed by more than twenty climate feedback experts (see main paper acknowledgments section). These experts were typically authors of feedback loop papers that we cited. We invited them to propose modifications to our tables of feedback loops, such as adding or removing loops, improving loop descriptions, or proposing additional references to cite.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.01.004.

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Supplemental Tables

Table S1. Summary of 41 climate feedback loops. The first column indicates the primary system or process involved in the loop (e.g., clouds). "Effect of climate change" describes how climate change alters the system (an active process) and "Effect on climate change" describes how the response of the system contributes to climate change. Subsequent columns indicate overall/net feedback direction (positive loops shown are shown in red), strength, and type respectively. References for strength estimates are listed in the first column ("Feedback name") or in the footnotes (when the feedback has multiple references). Type refers only to the dominant type or types associated with the feedback loop. When the overall feedback direction is unknown, this is indicated with a "?" symbol. Loops are divided into two categories: physical (no significant biological or human component [aside from anthropogenic climate change]) and biological (includes a biological component but no human component). Feedback loops that involve potential tipping elements identified in Table 1 of Lenton et al.[1] are marked with asterisks (*) and feedback loops that are covered in Fig. TS.17 (feedbacks overview) or 5.29 (biogeochemical feedbacks) of IPCC[2] with daggers (†). Some feedback loops may be highly uncertain or speculative; especially, those for which feedback strength estimates (or confidence intervals, etc.) were unavailable. Thus, it should not be assumed that all loops in the table are equally important in any sense. Feedback impacts occur on various time scales ranging from short (e.g., months or years) to very long (e.g., millennia); feedbacks we believe to be exceptionally slow (i.e., millennia) are marked with double daggers (‡). There are some instances of overlap among feedback loops (e.g., "soil carbon (other)" and "permafrost"), which are identified with footnotes. In these cases, strength estimates are not necessarily additive (see Supplemental Experimental Procedures).

Feedback name	**Effect of climate change**	**Effect on climate change**	**+/-**	**Approximate strength**	**Type**
		20 physical (abiotic) feedback loops			
1. Planck (black body radiation)[†] [3,4]	Increasing mean surface and atmosphere temperature	Increasing heat loss due to emitted radiation	-	-3.22 (-3.4 to -3.0) $W/m^2/K$ [a]	Other
2. Water vapor[†] [5,6,3]	Increasing water vapor content due to warming	Increasing greenhouse effect (water vapor is a greenhouse gas)	+	2.04 $W/m^2/K$ [b]	Water vapor
3. Sea ice albedo*[†] [8–14] [c]	Sea ice melting[d] or not forming	Decreasing albedo	+[e]	0.31 $W/m^2/K$ [f]	Surface albedo[g]
4. Glacier and ice sheet albedo*[†‡] [21,22]	Increasing glacier & ice sheet melting and marine ice sheet instability[23–25]	Decreasing albedo	+		Surface albedo
5. Sea level rise[‡] [26,27]	Rising sea levels (caused by ice melting)	Decreasing albedo due to coastal regions being submerged	+		Surface albedo
6. Snow cover[†] [28–30]	Snow metamorphosis and decreasing snow cover	Decreasing albedo	+	0.03 to 0.16 $W/m^2/K$ [h]	Surface albedo

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
7. Clouds[†] [8,31–33,20,3,4]	Changing cloud distribution (extent and height) and optical properties	Changing cloud albedo and greenhouse effect	+	0.45 W/m^2/K (σ = 0.33 W/m^2/K) [i]	Cloud
8. Dust[†] [34–37]	Changing dust aerosol abundance[j]	Changing planetary albedo and greenhouse effect	?	-0.004 ± 0.007 W/m^2/K [k]	Aerosol
9. Other aerosols[†] [34,38,3,39,36,37]	Changing atmospheric aerosol (e.g., sulfate, sea salt) concentrations	Changing planetary albedo and greenhouse effect	?	[l]	Aerosol
10. Ocean stratification[40,41] [m]	Ocean warming resulting in increasing stratification	Decreasing carbon uptake by ocean[n]	+		Ocean
11. Ocean circulation* [42–47] [o]	Slowing of the Atlantic Meridional Overturning Circulation (AMOC)[p]	Changing surface temperature	?	Independent short term strength not applicable[q]	Ocean
12. Ocean solubility pump[49,50]	Increasing atmospheric CO_2 levels	Decreasing absorption of CO_2 by ocean[r]	+	0.16 W/m^2/K [s]	Ocean
13. Methane hydrates*[‡] [52–57]	Increasing methane hydrate dissociation rates	Increasing release of methane into the atmosphere[t]	+		Ocean
14. Lapse rate[†] [8,59,3,4]	Changing relationships between temperature and altitude	Increasing heat loss due to emitted radiation	-	-0.68 to -0.23 W/m^2/K [u]	Other
15. Glacier and ice sheet elevation[‡] [23,60–62] [v]	Decreasing glacier and ice sheet mass balance and elevation	Increasing glacier and ice sheet melting (due to increasing surface temperatures), decreasing albedo	+		Other
16. Antarctic rainfall[‡] [63]	Decreasing Antarctic ice sheet extent leading to increasing precipitation	Decreasing albedo, increasing deep ocean warming	+		Other
17. Sea ice growth[20,64] [w]	Decreasing sea ice thickness, increasing open-water fraction, decreasing insulation	Increasing growth rate of thin ice	-		Other
18. Ozone[66,67,20,3,37] [x]	Strengthening of the Brewer-Dobson circulation, increasing stratosphere-to-troposphere transport	Decreasing lower tropical stratospheric ozone, increasing middle and extratropical stratospheric ozone, changing tropospheric ozone concentration	?	-0.064 (-0.08 to 0.04) W/m^2/K [y]	Other

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
19. Atmospheric chemical reaction rates[† 20,36,37,68 z]	Changing chemical reaction rates in the atmosphere[aa]	Changing greenhouse effect	?	[bb]	Other
20. Chemical weathering[‡ 70]	Increasing carbonate and silicate weathering rates	Increasing CO_2 taken out of the atmosphere	-		Geological
		21 biological feedback loops			
21. Peatlands[71–73]	Decreasing soil organic carbon due to lowering of water table, increasing vulnerability to fire, increasing metabolization	Increasing release of CO_2 into the atmosphere, decreasing carbon sequestration, changing methane emissions	+		Wetlands
22. Wetlands (expansion)[† 36,74,75]	Increasing precipitation[74] and boreal near-surface soil moisture[75] potentially leading to expansion of wetlands[cc]	Increasing CO_2 sequestration (negative feedback) and methane emissions[75–77] (positive feedback)	+	0.16 ± 0.03 $W/m^2/K$ [dd]	Wetlands
23. Freshwater ecosystems[† 78,74,79–81 ee]	Increasing aquatic plant growth rates (negative feedback) and microbial methane production (positive feedback)	Increasing methane emissions	+		Freshwater
24. Forest dieback*[82,83,57,84]	Dieback of Amazon,[ff] boreal, and other forests[gg]	Loss of sequestration, change in albedo, decreasing evapotranspiration	+		Trees
25. Northern greening[93–99,20,100]	Potential expansion of high latitude/elevation forests & woody vegetation into tundra,[hh] increasing Arctic/ northern vegetation[ii] (warmer & longer growing seasons, nutrient fertilization)	Increasing CO_2 sequestration, decreasing albedo[jj]	+		Trees/ vegetation
26. Insect outbreaks (forests)[103–105 kk]	Changing insect distributions & abundances; decreased host tree defense	Loss of sequestration, change in albedo	+		Trees

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
27. Wildfire[†] 34,106–109 ll	Increasing fire frequency and/or severity and/or extent in some regions	Increasing CO_2 emissions, loss of sequestration,[mm] change in albedo	+	-0.10 to 0.44 W/m^2 by 2100 [nn]	Trees/ aerosol
28. Biogenic volatile organic compounds (BVOCs)[†] 34,20,112,36,37	Changing BVOC emission rates	Decreasing greenhouse effect, increasing tropospheric ozone	-	-0.05 (-0.22 to 0.12) $W/m^2/K$ [oo]	Aerosol
29. Soil carbon (other)[113–117] pp	Increasing loss of soil carbon to the atmosphere[qq]	Increasing CO_2 emissions	+		Soil
30. Soil nitrous oxide[†] 118–120,108 rr	Accelerated decomposition and changing soil microbial activity affecting substrate availability for denitrification	Increasing N_2O emissions	+	1 Tg N/yr/K [ss]	Soil
31. Perma-frost*[†] 123–130,57,131–133,108	Increasing thawing and decomposition[tt]	Increasing GHG (CO_2 and methane) emissions	+	0.03 to 0.29 $W/m^2/K$ [uu]	Soil
32. Evapotrans-piration from soils and plants[20]	Increasing evaporation from soils, plants open stomata less widely[vv]	Decreasing latent heat flux (leading to warming)	+		Soil/ vegetation
33. Microbial respiration (other)[134,135] ww	Increasing respiration rates for many prokaryotic microbes	Increasing net CO_2 and CH_4 emissions due to microbes	+		Microbes
34. Plant stress[136]	Increasing chronic & extreme thermal and moisture stress	Increasing plant[xx] mortality leading to decreasing CO_2 sequestration	+		Vegetation
35. Desertifica-tion[137,138] yy	Increasing chronic aridification & hotter drought stress extremes leading to expanding deserts	Decreasing CO_2 sequestration, increasing CO_2 emissions,[zz] and increasing albedo	+		Vegetation
36. Sahara and Sahel greening* 140,139 aaa	Possibly increasing rainfall in Sahara and Sahel[bbb]	Increasing CO_2 sequestration by vegetation, decreasing albedo	-		Vegetation
37. CO_2 fertilization 141,83,142,20,108	Increasing CO_2 concentration possibly leading to increasing net primary productivity (NPP)[ccc]	Possibly increasing carbon uptake by vegetation[ddd]	-	approx. 23% increase in forest NPP at 550 ppm CO_2 eee	Vegetation

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
38. Coastal productivity[148–152]	Increasing degradation of coastal ecosystems (e.g., mangroves, seagrass beds, salt marshes) due to heat stress and loss of coral reef protection	Decreasing carbon sequestration by coastal ecosystems	+		Coastal
39. Ocean metabolic rates[57,153]	Potentially increasing phytoplankton[fff]/bact-erial respiration rates	Increasing CO_2 released into the atmosphere	+	approx. 0.02 °C by 2100 [ggg]	Ocean
40. Ocean biological pump [155–158,108]	Increasing CO_2 in ocean, ocean acidification, warming, decreasing upwelling	Changing effectiveness of ocean as a carbon sink, decreasing CO_2 uptake due to reduced primary productivity in upper layers of ocean[hhh]	?[iii]		Ocean
41. Phyto-plankton dimethyl sulfide (DMS) [† 160–163]	Changing DMS emissions from plankton (due to ocean acidification,[jjj] increasing stratification, etc.)	Changing cloud longevity and albedo (leading to changing radiative forcing)	? [kkk]	0.005 (0.0 to 0.01) W/m^2/K [lll]	Ocean/ aerosol/ albedo

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[a] Central estimate and "very likely" interval from Table 7.10 of Forster et al.[4]

[b] Average feedback strength between 2003 and 2008 estimated by Dessler et al.[5] Note that there is a positive feedback associated with stratospheric water vapor in particular (approximate strength 0.3 W/m^2/K according to Dessler et al.[7]).

[c] We have flagged this loop as being associated with a potential tipping point following Lenton et al.[1], although evidence may be limited.[9,15]

[d] Both Arctic sea ice and Greenland ice sheet melting could potentially be accelerated by the jet stream slowing and becoming wavier due to climate change[16–18] – another possible feedback loop (but see Blackport and Screen[19])

[e] However, this positive feedback may be countered by negative sea ice feedbacks – see "sea ice growth rate" feedback loop and Heinze et al.[20]

[f] Estimate for the entire globe obtained from Cao et al. 2015[12]

[g] Total surface albedo feedback strength estimated to be 0.30 W/m^2/K (σ = 0.015 W/m^2/K) by Sherwood et al.[3]

[h] Strength estimate from Qu and Hall[29]

[i] Estimate from Table 1 of Sherwood et al.[3] While most models show a net positive feedback for clouds, some models exhibit a net negative cloud feedback. The net cloud feedback can be decomposed[3] – in short, increasing cloudiness means that high altitude clouds will trap more heat (positive feedback) while low altitude clouds will reflect more sunlight (negative feedback). For reference, the AR6 assessed range central estimate is 0.42 W/m^2/K and the "very likely" interval is (-0.10 to 0.60) W/m^2/K.[4]

[j] This feedback may include a small biological component[34]

[k] Dust aerosol optical depth (AOD) feedback strength estimate taken from Thornhill et al.[36] Naik et al.[37] also list a central estimate of -0.004 W/m^2/K, but with "very likely range" (-0.02 to 0.01) W/m^2/K.

[l] The feedback strength associated with sea-salt emissions alone was estimated by Paulot et al.[39] to be -0.08 W/m^2/K and, more recently, by Naik et al.[37] to be -0.049 W/m^2/K with a "very likely range" of (-0.13 to 0.03) W/m^2/K.

[m] Ocean stratification feedbacks involve both abiotic and biological processes. Here, we consider only the abiotic aspects. The biological components are treated separately in the "ocean biological pump" feedback.

[n] Decreasing carbon uptake by the ocean occurs due to at least two abiotic processes. First, increasing ocean stratification means that water near the surface stays warm, reducing CO_2 absorption (see also "solubility pump" loop). Second, reduced ocean mixing results in less CO_2 from the atmosphere being buried under the ocean's surface. See Mann[41] for a non-technical overview.

[o] We have not classified this feedback loop as being exceptionally "slow" (in its entirety), although some aspects – notably, potential AMOC collapse and recovery – operate on very long time scales. Note that large-scale overturning circulation together with ocean heat uptake can be viewed as a significant negative feedback.[48,20]

[p] Other climate feedbacks involving ocean circulation are also possible.[20] For example, the Walker circulation could intensify, leading to a negative feedback (due to the ocean thermostat mechanism) or weaken, leading to a positive feedback – see section 3.4.2 of Heinze et al. for details.[20]

[q] In terms of radiative change per degree of warming ($W/m^2/K$), the effect of changing surface temperatures due to the slowdown of the AMOC falls under the Planck, water vapor, lapse rate, surface albedo (sea ice, etc.), and cloud feedbacks, depending on how it alters the pattern of warming. So the short-term changes in the AMOC are already included in these other feedbacks from this perspective.

[r] There may also be a feedback involving abiotic carbonate precipitation.[51]

[s] Ciais et al.[50] estimated this feedback strength in terms of CO_2 concentration at 4%/K. We converted this estimate to units of $W/m^2/K$ by multiplying it by the CO_2 forcing for a 1% rise, 0.04 $W/m^2/\%$, yielding 0.16 $W/m^2/K$.

[t] Current evidence for methane derived from hydrates entering the atmosphere is limited and there may be mitigating factors in terms of a potential feedback loop[55,58]

[u] Range of estimates for net feedback strength presented in Table 1 of Klocke et al.[59]

[v] Although this feedback loop appears similar to the "glacier and ice sheet albedo" feedback loop, it differs in that the underlying mechanism is the lapse rate (elevation-temperature) relationship, which causes decreasing glacier and ice sheet elevations to result in increasing surface warming rates.[23,60–62]

[w] This is actually a set of three potential negative feedbacks that collectively act to increase the growth rate of thin ice – see Heinze et al.[20] for details. In addition, there are two other ice-ocean feedbacks in the Southern Ocean: the ice production–entrainment feedback (negative) and the ice-production-ocean–ocean-heat-storage feedback (positive). [20,65]

[x] The climate-ozone feedback involves many different processes that are difficult to cover in a simple table; for a detailed overview, see the "Climate-ozone feedback" subsection in section 6.4.5 of Naik et al.[37]

[y] Net ozone feedback and "very likely range of feedback parameter" estimated by Naik et al.[37] Note that changing lightning NO_x emissions – sometimes treated as a separate feedback loop – can affect ozone production.[36] The lightning feedback loop strength was estimated by Naik et al.[37] to be -0.010 $W/m^2/K$ with a "very likely range" of -0.04 $W/m^2/K$ to 0.02 $W/m^2/K$.

[z] We have flagged this loop with a dagger because it includes "climate CH_4 lifetime," which is listed in Fig. 6.20 of Stocker et al.[69] (2013)

[aa] This feedback loop primarily involves water vapor, CH_4, and O_3.[20] Although we have classified it as "physical" (abiotic), it can be indirectly linked to biological processes (e.g., wetlands methane emissions). Methane lifetime may also be affected by changing lightning NO_x emissions – sometimes treated as a separate feedback loop.[36]

[bb] The methane lifetime component of this feedback loop has an estimated strength of -0.010 $W/m^2/K$ with "very likely range" (-0.12 to 0.06) $W/m^2/K$ – see Table 6.8 of Naik et al.[37]

[cc] Climate change could also lead to an increase in methane emissions from wetlands due to other mechanisms[76]

[dd] Estimate from Table 15 of Thornhill et al.[36]

[ee] This feedback may be primarily associated with northern (temperate/boreal) lakes because they contain most of Earth's ice-free freshwater.[79]

[ff] There is some uncertainty regarding the existence of a possible tipping point associated with Amazon (and other) forest dieback.[1,85–91] This uncertainty is partly due to the complexity of the system and how multiple anthropogenic pressures (including climate change and deforestation) are co-occurring. While many climate models suggest a tipping point may not exist,[87] even the latest generation of models (CMIP6) do not include all relevant processes that could create climate-vegetation feedbacks.[92] See section 5.4.9.1.1 of IPCC[2] for a recent overview of the literature. For reference, IPCC[2] estimated a maximum release of tropical land carbon of 200 GtC over the course of this century.

[gg] We use “dieback” to refer to a transition from forest to a new ecosystem state (e.g., grassland). In contrast, wildfires and insect outbreaks may have only temporary effects on forests, so these are treated as different feedback loops.
[hh] The effects of climate change on boreal forests and other woody vegetation are complex; for example, forested area in boreal regions could increase in response to moderate warming, but shrink in response to extreme warming[99]
[ii] But, see Phoenix and Bjerke[101] for a discussion of possible “Arctic browning.”
[jj] There is also be a negative feedback due to surface roughness changes affecting evapotranspiration (see also “evapotranspiration” loop) and heat fluxes.[20,102] However, the positive albedo feedback likely dominates.[20]
[kk] In some cases, this feedback loop may be viewed as a subset of the “plant stress” feedback loop.
[ll] Wildfires and smouldering combustion in peatlands are addressed in the “peatlands” feedback loop
[mm] Over longer time scales, this effect may be partially offset by the production of pyrogenic carbon (charcoal), which is relatively stable.[110,111]
[nn] This is only the direct radiative perturbation[34]
[oo] Estimate with very likely range of feedback parameter based on Naik et al.[37]
[pp] Because of its importance, permafrost treated separately as the “permafrost” feedback loop
[qq] Numerous mechanisms are involved, including soil organic matter decomposition and microbial respiration[113–117]
[rr] This loop may have a human or social component since agricultural nitrogen fertilizer use is a primary source of N_2O. Increasing N_2O losses with a warming climate may leads to increasing demand for nitrogen fertilizer, which further increases N_2O loss. Note that there are also several cooling effects related to nitrogen.[121,122]
[ss] Estimate from Xu-Ri et al.[118]; may be highly uncertain. More generally, Canadell et al.[108] estimated the total land N_2O feedback strength is estimated to be 0.02 ± 0.01 W/m^2/K and the total ocean N_2O feedback strength is estimated to be -0.008 ± 0.002 W/m^2/K.
[tt] Multiple permafrost-related mechanisms are likely involved. For example, in addition to methane produced by microbial decay, permafrost thaw can lead to the release of natural gas (thermogenic methane).[133]
[uu] This is the 5th-95th percentile range from Burke et al.[125]; this estimate is emissions scenario dependent.[125] Note that this loop is contained within the “soil carbon (other)” loop, and thus the feedback strengths of these loops are not independent. According to Canadell et al.[108], there is “low confidence” associated with the permafrost feedback with regard to timing, magnitude, and the relative roles of carbon dioxide and methane.
[vv] This occurs in response to rising atmospheric CO_2 concentration, but the effect is at least partly offset by CO_2 fertilization (see “CO_2 fertilization” feedback loop).[20]
[ww] This feedback loop covers microbes that are not included in the “ocean metabolic rates,” “freshwater ecosystems,” “soil carbon (other),” or “permafrost” feedback loops.
[xx] Unlike the “forest dieback” feedback loop, this includes terrestrial plants of all types. Unlike the “desertification” loop, plant stress need not involve a shift to arid/desert land cover.
[yy] One possible driver of desertification is a potential northward shift of the West African Monsoon (WAM) (which is also relevant to Sahara-Sahel greening[139]). Specifically, if the WAM moves northward, likely so will the subtropical high pressure that creates the Sahara, further shifting northward over the Mediterranean basin and amplifying desertification there. Similar effects could occur in places like northern New Mexico (if the Chihuahuan and Sonoran deserts shift northward).
[zz] A pulse of CO_2 emissions associated with plant community die-off is likely to occur along the desertification front.
[aaa] This feedback loop is related to the more general “terrestrial net primary productivity (NPP)” loop through potentially enhanced water-use efficiency of photosynthesis due to atmospheric CO_2 enrichment (except during extreme hotter drought episodes).
[bbb] However, if the West African monsoon moves northward, desertification in the Mediterranean basin could result – see “desertification” feedback loop footnote for details.
[ccc] The effects of rising CO_2 on productivity may be partly (or fully) countered by effects of increasing temperature, etc. (see “plant stress” feedback loop); thus, the overall effect of climate change on NPP may be uncertain.[83]
[ddd] However, climate change could reduce the rates at which plants can absorb carbon from the atmosphere due to triose phosphate utilization (TPU)-limited photosynthesis.[143] Similarly, climate change could lead to increasing

plant respiration rates[144] (although this effect might be relatively weak[145]) and to increasing CH_4 and N_2O emissions by cryptogamic covers.[146] Other effects such as increasing heat wave occurrence are also possible.[147]

[eee] This estimate is from Norby et al.[141]

[fff] Arctic phytoplankton may also contribute substantially to Arctic warming through direct warming – another potential positive feedback loop[154]

[ggg] Estimate is for ocean bacterial respiration[57]

[hhh] The ocean biological pump involves many interrelated processes and factors that may be sensitive to climate change, including phytoplankton growth, deoxygenation, seawater viscosity, and calcification.[156,158] Climate change driven coral bleaching[159] may also affect the ocean biological pump. Ocean metabolic rates are handled separately in the "ocean metabolic rates" feedback loop, although they may be considered part of the ocean biological pump.

[iii] As noted by Pörtner et al.[157], it is difficult to determine whether the ocean biological pump will act as a net positive or negative climate feedback. Moreover, there is "low confidence" with regard to how the changing biological pump will affect the magnitude and sign of the ocean carbon feedback.[108]

[jjj] Ocean acidification could also increase N_2O production rates, representing another potential feedback loop.[164] However, this might be restricted to certain regions, and the opposite effect is also possible.[165,164]

[kkk] The sign of this feedback appears to be uncertain. For example, a negative sign is reported in Ciais et al.[50] based on HadGEM2-ES[166], whereas the simulations of Wang et al.[163] suggest there is a small positive feedback associated with DMS globally. More recently, the DMS feedback strength was given as 0.005 ± 0.006 $W/m^2/K$ by Thornhill et al.[36] So, we have opted to list the sign as uncertain, although we provide a positive central estimate for the strength based on Naik et al.[37]

[lll] Assessed central estimate and very likely range of the feedback parameter as given in Table 6.8 of Naik et al.[37]

Table S2. Summary of 15 potential human climate feedback loops. The first column indicates the primary system or process involved in the loop. "Effect of climate change" describes how climate change alters the system (an active process) and "Effect on climate change" describes how the response of the system contributes to climate change. Subsequent columns indicate overall/net feedback direction, strength, and type respectively. References for strength estimates are listed in the first column ("Feedback name") or in the footnotes (when the feedback has multiple references). When a complete feedback loop has (to the best of our knowledge) not been presented before it, is shown in blue. Sub-category refers only to the dominant type or types associated with the feedback loop. When the overall feedback direction is unknown, this is indicated with a "?" symbol. Note that these human loops may include biological and physical aspects. Some feedback loops may be highly uncertain or speculative; especially, those for which feedback strength estimates (or confidence intervals, etc.) were unavailable. This is a list of example human feedback loops and is therefore not intended to be exhaustive.

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
1. Climate-related disasters	Increasing forest fire[106], tropical storm[167], flood[168], and coastal erosion frequency or intensity in some regions	Increasing carbon costs associated with rebuilding[mmm], but may be offset by more energy-efficient replacements and negative impacts on economic growth	?		Natural disasters
2. Human migration	Increasing uninhabitable area due to extreme heat[169], sea level rise[170], permafrost thaw[171], coastal flooding[170], and potential soil degradation[172]	Increasing migration and construction carbon costs, movement to more carbon-intensive areas; conversely, potentially smaller carbon footprints (increasing poverty), energy efficient construction	?		Movement
3. Human mobility[173]	Potentially increasing movement (vehicle miles travelled) due to warming	Increasing CO_2 emissions	+		Movement
4. Transport routes[174–176]	Changing transport routes (e.g., due to decreasing Arctic sea ice)	Changing CO_2 emissions	?		Movement
5. Energy demand[177] [nnn]	Increasing global mean temperature	Changing GHG emissions due to changing energy demand (e.g., increasing energy needed to cool buildings but decreasing energy needed for heating)	? [ooo]	Heating and cooling CO_2 emissions projected to rise from 0.8 Gt C (2000) to 2.2 Gt C (2100)	Energy

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
6. Agriculture[178–180] [ppp]	Changing crop yields overall,[qqq] changing agricultural suitability, water supply and demand	Changing GHG emissions due to agriculture, deforestation-related emissions due to migration of agricultural areas[rrr]	?		Food/water
7. Coral reefs[181–183]	Increasing coral die-off, loss of associated fisheries and other ecosystem services	Potentially increasing carbon costs due to alternative food production or migration[sss]	+	Roughly 850 million people likely derive benefits from coral reef ecosystem services[ttt]	Food/water
8. Freshwater	Declining freshwater availability in certain regions[184,185]	Increasing CO_2 emissions due to increasing migration or desalination[186] [uuu]	+		Food/water
9. Mitigation[188,189]	Increasing sense of urgency as climate change intensifies and damages increase[vvv]	Increasing mitigation (climate action) efforts[www] (e.g., increasing renewables[xxx], carbon prices, natural climate solutions such as reforestation or afforestation, bio-energy)[yyy]	-	Collectively, mitigation may be the largest human feedback loop	Psycho-logical
10. Policy paralysis[193]	Climate change becomes an increasingly large policy issue	Larger policy issues can be more or less difficult to address[zzz]	+		Psycho-logical
11. Economic growth[188,194]	Decreasing macroeconomic production and human consumption[aaaa]	Decreasing emissions, but potentially decreasing investments in capital-intensive renewables and other mitigation strategies	?		Political/ economic
12. Economic disruption[188]	Increasing frequency of economic disruptions (natural disasters, crop failures, etc.)	Decreasing investment in climate mitigation and associated technologies (due to focusing on immediate concerns)	+		Political/ economic
13. Political disruption[188]	Increasing political upheaval (e.g., due to mass migrations)	Increasing nationalism leading to decreasing international cooperation on climate mitigation	+		Political/ economic

Feedback name	Effect of climate change	Effect on climate change	+/-	Approximate strength	Type
14. Geopolitics[193] [bbbb]	Increasing large and unequal climate impacts on countries	Increasing difficulty of global cooperation (leading to decreasing mitigation)	+		Political/ economic
15. Human conflict[195]	Increasing conflict (declining resources)	Increasing GHG emissions associated with militaries	+		Political/ economic

[mmm] However, the carbon costs of rebuilding are likely small relative to those associated with new construction due to rising global demand.

[nnn] Although we refer primarily to energy demand for heating and cooling, this feedback loop is much broader. For example, energy is also required to produce green technologies such as batteries.

[ooo] With respect to heating and cooling, increasing need for air conditioning and decreasing need for heating roughly cancel each other out – feedback loop is slightly negative in the short term (demand for heating is the dominant factor) and slightly positive in the long term (demand for air conditioning is the dominant factor)[177]

[ppp] Other feedback loops involving land use change are also possible. For example, climate change could lead to additional forestry at high latitudes, with consequences for surface albedo, carbon sequestration, and so on.

[qqq] This could occur due to multiple factors, including crop failures as a result of extreme extents such as drought, extreme heat, and insect outbreaks.

[rrr] Shifting agricultural areas (especially due to soil degradation) can also lead to human migration – see "human migration" feedback loop

[sss] Coastal ecosystem damage (loss of CO_2 sequestration) as a result of losing coastal protection is also possible, but this is addressed under the "coastal productivity" biological feedback loop.

[ttt] See Burke et al.[181] for details

[uuu] In addition, large-scale desalination produces concentrated brine, which can have negative impacts on the environment and wildlife[187]

[vvv] Conversely, there may be an increasing sense of hopelessness as climate change intensifies (leading to decreasing mitigation efforts), but this effect may be relatively weak. The public's response to climate change may be partly dependent on whether fear-inducing representations are employed.[190] Additionally, the public's sense of urgency may be limited due to shifting baselines with respect to "normal" conditions.[191]

[www] Note that climate policy and air pollution policies are often connected and may involve complex, non-linear feedback loops[189]

[xxx] The physical impacts of climate change can also impact renewable energy potential, resulting in other potential feedback loops[192]

[yyy] These mitigation efforts can have many climate-related effects such as changing CO_2 and short-lived pollutant emissions and changing surface albedo.[189] Other mitigation efforts are also possible; for example, increasing funding to develop new techonologies for decarbonization.

[zzz] But, this need not necessarily be the case – see "mitigation" feedback loop for details

[aaaa] Although not addressed separately, human population growth could be relevant to this and other human feedback loops.

[bbbb] This loop is closely linked to the "mitigation" loop in that climate mitigation efforts are often a geopolitical challenge

Table S3. Credits for feedback loop pictures (Figures 1, S1). Columns indicate the loop name and number (see Tables 1, S1), source/credit, license (Public Domain or Creative Commons), approximate location, and image URL (as of May 25, 2021).

Name	#	Credit	License	Location	URL
Sea ice albedo	3	Patrick Kelley	CC BY 2.0	The Arctic	https://en.wikipedia.org/wiki/Sea_ice#/media/File:Arctic_ice.jpg
Ice sheets	4	Hannes Grobe	CC BY-SA 2.5	Greenland's east coast	https://en.wikipedia.org/wiki/Ice_sheet#/media/File:Greenland-ice_sheet_hg.jpg
Snow cover	6	Natalia_Kollegova	Pixabay License	Unknown	https://pixabay.com/photos/mountains-tundra-summer-snow-5359560/
Clouds	7	Doggo19292	Public Domain	Monterrey, Mexico	https://en.wikipedia.org/wiki/Cloud#/media/File:Monterrey_Mexico_Clouds.jpg
Dust	8	Advanstra	CC BY-SA 3.0	Surfers Paradise Beach	https://en.wikipedia.org/wiki/2009_Australian_dust_storm#/media/File:20090923_-_Dust_Storm_-_Surfers_Paradise_(looking_south).JPG
CH_4 hydrates	13	USGS	Public Domain	Seafloor of the northern Gulf of Mexico	https://en.wikipedia.org/wiki/Methane_clathrate#/media/File:Gas_hydrate_under_carbonate_rock.jpg
Chem. weathering	20	Bernard Spragg. NZ	Public Domain	Waipu Caves, Northland, New Zealand	https://www.flickr.com/photos/volvob12b/20125209969
Peatlands	21	NASA's Earth Observatory	CC BY 2.0	Indonesia	https://commons.wikimedia.org/wiki/File:Seeing_Through_the_Smoky_Pall-_Observations_from_a_Grim_Indonesian_Fire_Season_%2823451153146%29.jpg
Wetlands	22	Abrget47j	CC BY-SA 3.0	Viru Bog, Estonia	https://en.wikipedia.org/wiki/Viru_Bog#/media/File:Sunrise_at_viru_bog.jpg
Freshwater	23	Aaron Rees	CC BY-SA 4.0	West Coast region of New Zealand	https://en.wikipedia.org/wiki/Lake#/media/File:Lake_Kaniere.jpg
Forest dieback	24	NASA/JPL-Caltech		Western Brazil	https://www.nasa.gov/feature/jpl/nasa-finds-amazon-drought-leaves-long-legacy-of-damage
Northern greening	25	Logan Berner/ Northern Arizona University		Arctic tundra	https://climate.nasa.gov/news/3025/warming-temperatures-are-driving-arctic-greening/
Insects	26	Jonhall	CC BY 3.0	E. C. Manning Provincial Park, British Columbia, Canada	https://en.wikipedia.org/wiki/Mountain_pine_beetle#/media/File:Pine_Beetle_in_Manning_Park.jpg
Wildfire	27	Nick-D	CC BY-SA 4.0	Viewed from Tuggeranong in southern Canberra, Australia	https://en.wikipedia.org/wiki/2019%E2%80%9320_Australian_bushfire_season#/media/File:Orroral_Valley_Fire_viewed_from_Tuggeranong_January_2020.jpg
Permafrost	31	Boris Radosavljevic	CC BY 2.0	Herschel Island, Canada	https://en.wikipedia.org/wiki/Permafrost#/media/File:Permafrost_in_Herschel_Island_001.jpg
Desert-ification	35	David Stanley	CC BY 2.0	Ennedi Mountains, Chad, Central Africa	https://en.wikipedia.org/wiki/Sahel#/media/File:Acacia_Trees_(24227057806).jpg
Coastal productivity	38	Kino Obusan	CC BY-SA 4.0	Puerto Princesa, Palawan, Philippines	https://en.wikipedia.org/wiki/Mangrove#/media/File:Mangroves_in_Puerto_Princesa_City.jpg
Ocean bio.	40	Alexander Vasenin	CC BY-SA 3.0	Manta Alley (near Komodo, Indonesia)	https://en.wikipedia.org/wiki/Bluestripe_snapper#/media/File:A_school_of_blue-striped_snappers_at_Manta_Alley.JPG

Supplemental Figures

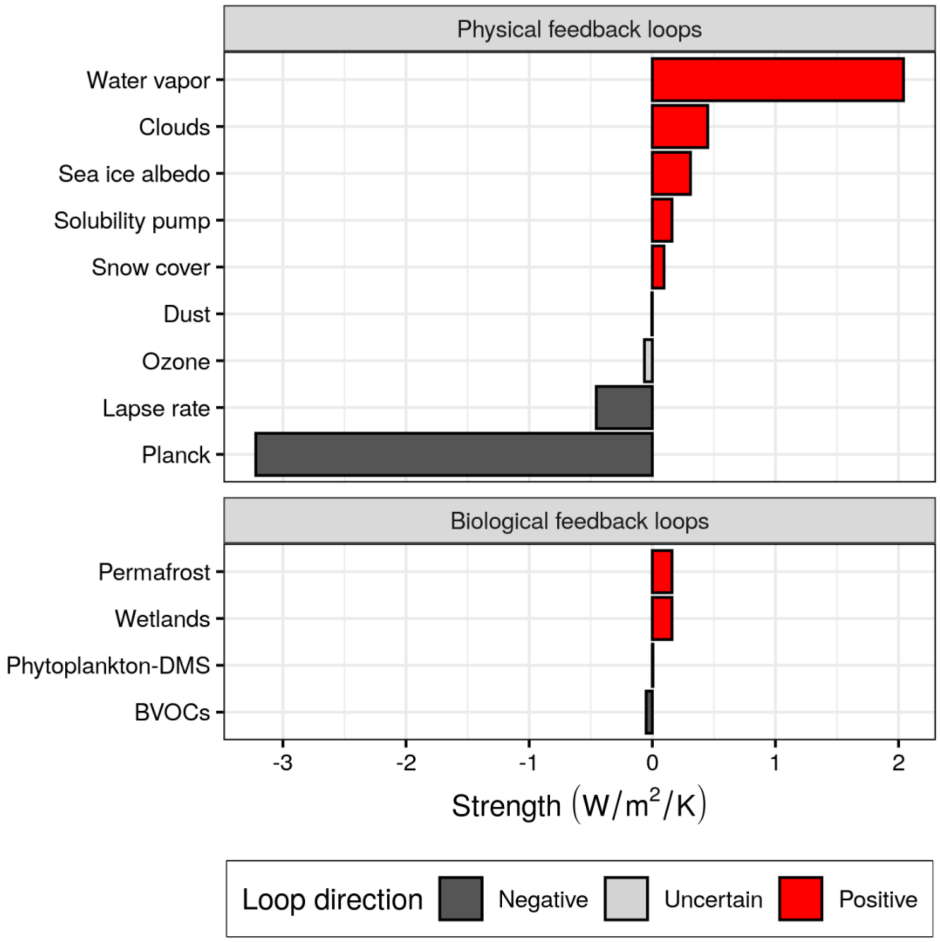


Figure S1. Approximate feedback strengths. Estimated strengths are shown for select physical and biological feedback loops. See Table S1 for details and uncertainty estimates (where available).

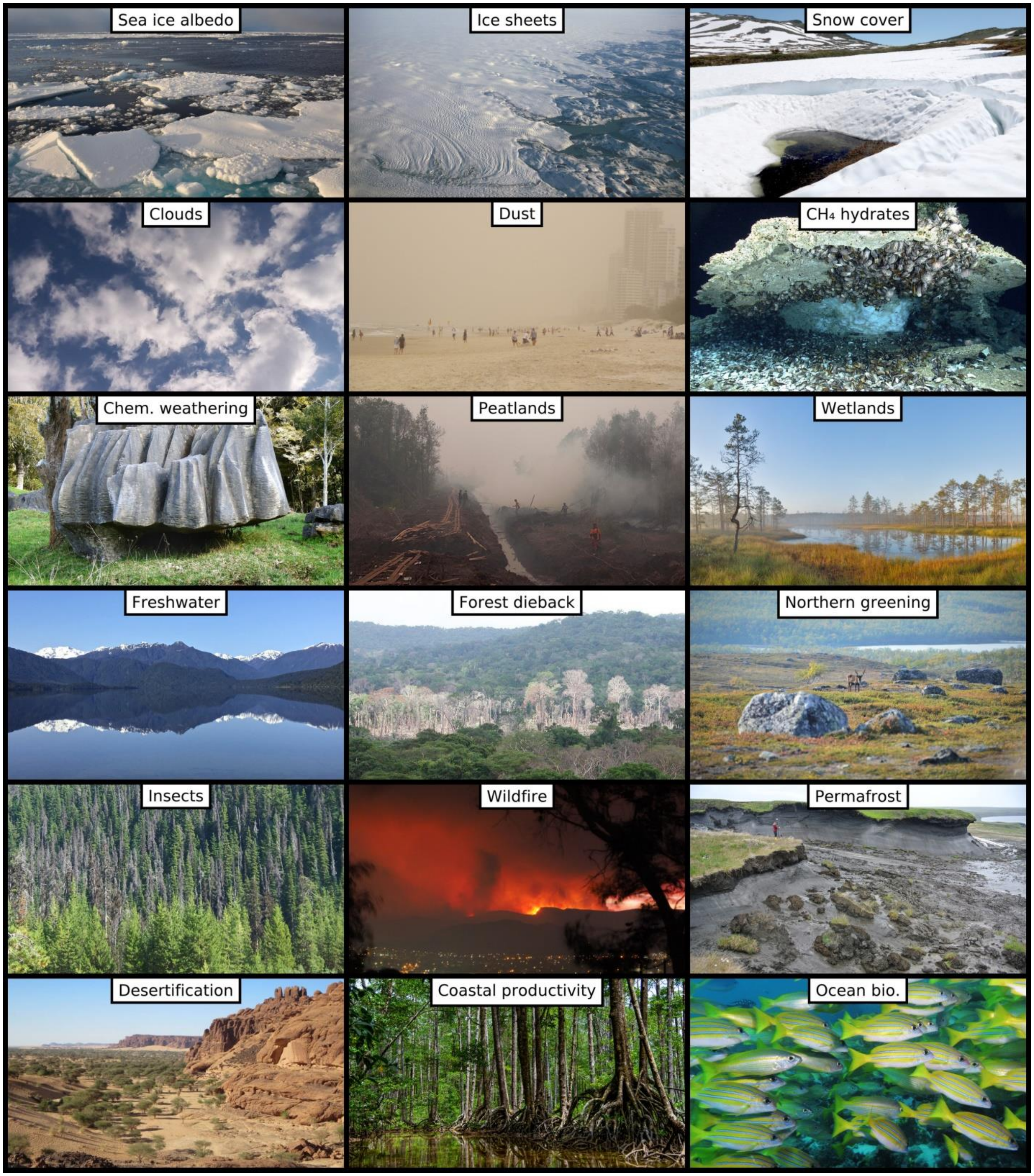


Figure S2. Feedback loop pictures. Loop descriptions and photo credits are as follows: Sea ice albedo - Sea ice melting or not forming ⟶ Decreasing albedo [Patrick Kelley, CC BY 2.0]; Ice sheets - Increasing glacier & ice sheet melting ⟶ Decreasing albedo [Hannes Grobe, CC BY-SA 2.5]; Snow cover - Snow metamorphosis and decreasing snow cover ⟶ Decreasing albedo [Natalia_Kollegova, Pixabay License]; Clouds - Changing cloud distribution and optical properties ⟶ Changing cloud albedo and greenhouse effect [Doggo19292, Public Domain]; Dust - Changing dust aerosol abundance ⟶ Changing planetary albedo and greenhouse effect [Advanstra, CC BY-SA 3.0]; CH_4 hydrates - Increasing methane hydrate dissociation rates → Increasing release of methane into the atmosphere [USGS, Public Domain]; Chem. Weathering - Increasing carbonate and silicate weathering rates ⟶ Increasing CO_2 taken out of the atmosphere [Bernard Spragg. NZ, Public Domain]; Peatlands - Decreasing soil organic carbon due to lowering of water table, increasing vulnerability to fire/smoldering ⟶ Increasing release of CO_2 into the atmosphere, decreasing carbon sequestration [NASA's Earth Observatory, CC BY 2.0]; Wetlands - Increasing precipitation and boreal near-surface soil moisture potentially leading to expansion of wetlands ⟶ Increasing CO_2 sequestration and methane emissions [Abrget47j, CC BY-SA 3.0]; Freshwater - Increasing aquatic plant growth rates and microbial methane production ⟶ Increasing methane emissions [Aaron Rees, CC BY-SA 4.0]; Forest dieback - Dieback of Amazon, boreal, and other forests ⟶ Loss of sequestration, change in albedo, decreasing evapotranspiration [NASA/JPL-Caltech]; Northern greening - Potential expansion of high latitude/elevation forests & woody vegetation into tundra ⟶ Increasing CO_2 sequestration, decreasing albedo [Logan Berner/ Northern Arizona University]; Insects - Changing insect distributions & abundances ⟶ Loss of sequestration, change in albedo [Jonhall, CC BY 3.0]; Wildfire - Increasing fire frequency and/or severity and/or extent ⟶ Increasing CO_2 emissions, loss of sequestration, change in albedo [Nick-D, CC BY-SA 4.0]; Permafrost - Increasing CO_2 and methane release ⟶ Increasing GHG emissions [Boris Radosavljevic, CC BY 2.0]; Desertification - Increasing chronic aridification & hotter drought stress extremes leading to expanding deserts ⟶ Decreasing CO_2 sequestration, increasing CO_2 emissions, and increasing albedo [David Stanley, CC BY 2.0]; Coastal productivity - Increasing degradation of coastal ecosystems and loss of coral reef protection ⟶ Decreasing carbon sequestration by coastal ecosystems [Kino Obusan, CC BY-SA 4.0]; Ocean bio. - Increasing CO_2 in ocean, ocean acidification, warming, decreasing upwelling ⟶ Changing effectiveness of ocean as a carbon sink, decreasing CO_2 uptake [Alexander Vasenin, CC BY-SA 3.0]. See Table S1 and S3 for more information on the feedback loops and photos respectively.

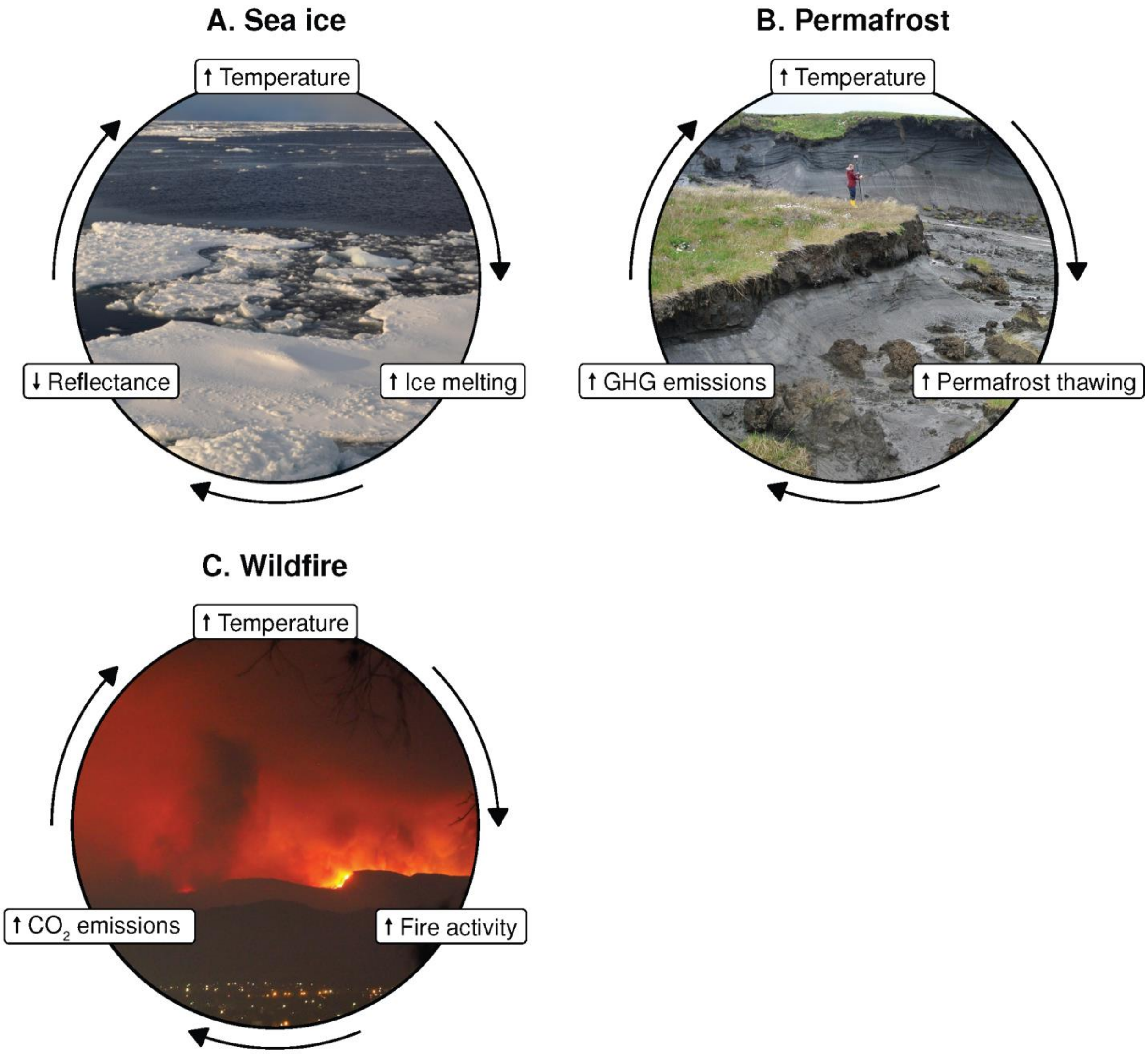


Figure S3. Feedback loop diagrams. The feedback loops operate as follows: (A) Arctic warming leads to melting sea ice, which leads to further warming because water has lower albedo (reflectance) than ice; (B) Increasing temperatures lead to permafrost thawing, which produces CO_2 and methane emissions, which in turn leads to further increasing temperatures; (C) Rising temperatures lead to increasing fire frequency or severity causing increasing CO_2 emissions, loss of sequestration, and changes in albedo, which causing more warming. See Table S1 for details. Photo credits: (A) Patrick Kelley, CC BY 2.0; (B) Boris Radosavljevic , CC BY 2.0; (C) Nick-D, CC BY-SA 4.0.

Supplemental Experimental Procedures

Feedback loops

Here, we describe the methods used to construct our comprehensive list of feedback loops.

We compiled an initial list of climate feedback loops by conducting a literature review using computerized searches of the Google Scholar and Web of Science databases. We considered both synthesis papers dealing with multiple feedback loops (e.g., Bony et al.[8], Steffen et al.[57], Sherwood et al.[3]) and papers concerned with single loops. We also selectively looked at references cited by these papers.

We grouped the feedback loops into three general categories: Physical (abiotic), Biological, and Human. Physical feedback loops (e.g., water vapor[3]) primarily involve abiotic systems, biological loops involve the biosphere in some way (e.g., forest dieback[83]), and human loops involve human or social systems (e.g., agriculture[179]). Note that biological loops may also involve physical components and human loops can involve (non-human) biological or physical components. We also identified feedback loop "types," which correspond to subcategories. For example, physical feedback loops were divided into types including "surface albedo" and "ocean." We used this "type" variable to group the feedback loops in our list (within the general categories).

Because of the complexity of human systems, the human feedback loops may be more speculative in nature and difficult to quantify. So, we present these potential feedback loops separately from the physical and biological loops. These human loops are examples only, and this list is not intended to be exhaustive. While not recognized in our categorization system, all loops are "Human" in the sense that they involve anthropogenic climate change.

The term "climate feedback" has been defined in a number of different ways (for details, see Bates et al.[196]). For our project, we were motivated by the definition of Stocker et al.[197]: "*An interaction mechanism between processes in the climate system is called a climate feedback when the result of an initial process triggers changes in a second process that in turn influence the initial one. A positive feedback intensifies the initial process and a negative feedback reduces it.*" However, we only considered feedbacks to global temperature, excluding internal feedbacks that may be covered under this definition (e.g., grass cover increasing fires, which increases grass cover). According to this definition, each feedback loop can be partitioned into two interacting processes. For example, warming in the Arctic causes ice to melt (the initial process) and melting ice in turn leads to further warming by decreasing albedo (the second process).[8] For each climate feedback loop, we identified these two processes, which we termed as the "effect of climate change" and the "effect on climate change." We also categorized each feedback loop as positive, negative, or unknown/uncertain direction. Finally, we determined approximate estimates of feedback loop strengths where possible. Feedback strengths are quantified in a variety of ways, although units of $W/m^2/K$ are commonly used. In some cases, only a rough proxy indicator of strength was available – for example, the number of people who likely benefit from coral-related ecosystem services. When available, we included uncertainty estimates associated with feedback strengths (e.g., standard errors or confidence intervals).

While each feedback loop differs from the others in either the “effect of climate change,” or the “effect on climate change,” there may be overlaps among some of the feedback loops. Given that these feedback loops can involve many highly complex and interacting systems, we viewed some overlap as unavoidable. We used footnotes to indicate occurrences of partial overlap (e.g., between “forest dieback” and “plant stress” feedback loops). Our strength estimates are generally separate and additive, except in cases of overlapping feedback loops (e.g., permafrost and general soil carbon loop strengths are not additive because of overlap). In practice, combined strengths (e.g., for water vapor and lapse rate feedbacks together) may be preferable for modeling since they can be easier to estimate.[59]

In our feedback loops table, we included loops that vary in strength over time, many of which could eventually weaken. Likely examples include permafrost (finite capacity to emit greenhouse gases), sea ice (eventually there may be little or no sea ice), and forest dieback (eventually large forested areas could be converted to other ecosystem types, possibly halting this process).

The focus of our table is on feedback loops. However, climate tipping elements and tipping points are related concepts of major importance to the biosphere.[1,198,199,46,200] In particular, tipping elements (biophysical systems with multiple stable states that contribute to regulate the state of the planet) in the current Earth system are inherently (at least since we left the last Ice Age some 12,000 years ago) in a state dominated by negative feedbacks, i.e., which dampen warming. But, if tipping points are crossed, as far as we know today, some feedbacks will likely shift from negative to positive, acting to amplify warming. Consequently, we identified the feedback loops in our table that might involve tipping elements. We followed the framework of Lenton et al.[1,46], and considered only the 15 “policy-relevant potential future tipping elements in the climate system” in Table 1 of Lenton et al.[1]

After constructing the preliminary tables of feedback loops, we had them reviewed by more than twenty climate feedback specialists (see main paper acknowledgments section). These specialists were typically authors of feedback loop papers that we cited. We invited them to propose modifications to our tables of feedback loops, including adding or removing loops, improving loop descriptions, or suggesting additional references to cite.

Remaining carbon budget

We present information on the remaining carbon budget framework for context.[201,202] Specifically, we provide the estimate of Forster et al.[203] that the remaining carbon budget (relative to the start of 2023) associated with 1.5 °C warming is roughly 260 Gt CO_2. This budget could be exhausted in just 6.5 years.[203] Note that this is lower than the associated estimate of 380 Gt CO_2 provided by the Global Carbon Project.[204]

Limitations

We took an inclusive approach to identifying potential feedback loops, and thus some of the loops in our table may be speculative and potentially negligible. We have classified these loops as having uncertain or unknown direction in our table. For example, the dust feedback loop has an estimated strength ranging from -0.2 to 0.2 W/m^2 by 2100, making it potentially negligible.[34] In particular, feedback loops for which we could not obtain strength estimates or strength uncertainty estimates (e.g., confidence intervals) may be highly uncertain.

Some feedback loops (e.g., chemical weathering[70]) may have major impacts only on very long time scales. Where applicable, we have identified these loops in our table. Some tipping elements may be uncertain since tipping elements can be challenging to identify; see feedback loop footnotes for details.

Our table of feedback loops is intended to be a general, simplified overview of Earth's many climate feedback loops. Therefore, providing an accurate strength estimate, associated time scale (and time of occurrence), and level of uncertainty for each feedback loop is beyond the scope of our work. Most likely, some of the feedback loops in our table are already occurring whereas others are not yet occurring and may ultimately be relatively weak.

The references for each feedback loop that we provide are intended as a selection from the literature, rather than an exhaustive list. We have generally prioritized citing work that is relatively recent and comprehensive in nature. Thus, these references may be useful to readers looking for more information on specific feedback loops. In cases where some aspects of a feedback loop are controversial and actively being debated in the literature, our selection of references is not intended as an endorsement of any particular point of view.

Note S1. Feedback Loop Descriptions

For each feedback loop, we provide a brief overview, typically using excerpts (at most 200 words) from the associated references (Tables S1, S2). Aside from citations, modifications to the quoted text (deletions or insertions) are indicated with square brackets. For consistency, citations within excerpts have been reformatted according to our numbering system. Feedback loops that, to the best of our knowledge, have never before been presented in their entirety are shown in blue. Loop names are followed by directions: positive (+), negative (-), uncertain (?). When available, pictures are provided below the loop names; the associated credits are given in Table S3. Explanatory notes are provided in purple text.

Physical and biological feedback loops (Table S1)

1. Planck (black body radiation) (-)

"The Planck feedback represents the extra emission to space of [longwave] radiation arising from a vertically uniform warming of the surface and the atmosphere with no change in composition. Physical expectation for this feedback is that $\lambda_{Planck} \approx -4\varepsilon\sigma T^3 \approx -3.3$ W m^{-2} K^{-1} for present-day conditions, and the values shown in […] from [general circulation models] of −3.2 ± 0.04 W m^{-2} K^{-1} (1-sigma)[205–207] and those from observations of interannual variability[208] are both in general agreement with this physical expectation."[3]

2. Water vapor (+)

"Water vapor absorption is strong across much of the longwave spectrum, generally with a logarithmic dependence on concentration. Additionally, the Clausius–Clapeyron equation describes a quasi-exponential increase in the water vapor–holding capacity of the atmosphere as temperature rises. Combined, these facts predict a strongly positive water vapor feedback providing that the water vapor concentration remains at roughly the same fraction of the saturation specific humidity (i.e., unchanged relative humidity). Indeed, the global warming associated with a carbon dioxide doubling is amplified by nearly a factor of 2 by the water vapor feedback considered in isolation from other feedbacks[209], and possibly by as much as a factor of 3 or more when interactions with other feedbacks are considered.[210]"[8]

"[A] warmer climate increases stratospheric water vapor, and because stratospheric water vapor is itself a greenhouse gas, this leads to further warming. An estimate of its magnitude from a climate model yields a value of +0.3 W/(m^2·K), suggesting that this feedback plays an important role in our climate system."[7]

3. Sea ice (+)

"There are a number of important feedbacks associated with sea ice that influence projected climate sensitivity. The net effect is such that changes in sea ice contribute to a projected amplification of climate warming in the Arctic region (e.g., Holland and Bitz[211]; Rind et al.[212]). They also contribute to the global mean warming. For example, Rind et al. (1995) showed that 20%–40% of the simulated global surface air temperature increase at 2xCO_2 conditions was associated with changes in the ice cover."[8]

"Arguably the most important sea ice feedback is the influence of the ice area and surface state on the surface albedo. As sea ice melts under a climate-warming scenario, the highly reflective surface is lost, allowing increased solar absorption. This enhances the initial warming perturbation, resulting in a positive feedback."[8]

"Sea ice also affects the surface energy budget by insulating the overlying atmosphere from the relatively warm ocean. As such, the extent and thickness of sea ice modifies the turbulent heat fluxes at the surface."[8]

4. Greenland and ice sheet albedo (+)

"On longer timescales […], a tipping point (when the ice sheet enters a state of irreversible mass loss and complete melting is initiated) exists as part of the coupled ice sheet–atmospheric system. This consists of two interrelated feedback mechanisms: the [surface mass balance]–elevation feedback, as described above, and the melt–albedo feedback.[213–215] The latter acts on the surface energy balance, by allowing more absorption of solar radiation from a melting and darkening snow surface, or removal of all snow leading to a darker ice surface. This feedback may be enhanced by ice-based biological processes, such as the growth of algae.[216] Thus, the activation of these feedbacks can lead to self-sustained melting of the entire ice sheet, even if the anomalous climatic forcing is removed."[22]

5. Sea level rise (+)

"Apart from the cryosphere, a small positive surface albedo feedback comes from the inundation of coastal lands by sea level rise which thus replaces land with a less reflective ocean surface. For the Last Glacial Maximum (LGM), the estimated radiative effect is of order 1 W m^{-2} (Köhler et al.[217], see section 5.1). But because sea-level rise realized during 150 years and several K of warming would be limited to at most a few meters compared to the LGM change of over 100 meters, the resulting effective feedback is only of order 0.01 W m^{-2} K^{-1}."[3]

6. Snow cover (+)

"Snow-albedo feedback (SAF) enhances climatic anomalies in Northern Hemisphere […] land masses because of two changes in the snowpack as surface air temperature […] increases.[8,28,218–228] First, snow cover shrinks, and where it does it generally reveals a land surface that is much less reflective of solar radiation. Second, the remaining snow generally has a lower albedo due to snow metamorphosis. For example, wet melting snow, more common in a warmer climate, has a lower surface albedo than dry frozen snow[229]."[29]

7. Clouds (+)

“The inferred positive total cloud feedback arises from several contributions. These include (1) a lifting of high cloud tops in warmer climates, as indicated by detailed numerical cloud simulations, observed trends since the 1980s, climate models and expected from theory; (2) a dissipation of tropical and midlatitude marine low cloud, probably due to increased mixing of environmental air into clouds as the climate warms, as indicated by observed cloud variability, and detailed numerical cloud simulations; and (3) a dissipation of warm-season low cloud over land due to decreasing boundary layer relative humidity, as expected because land warms faster than oceans, and as seen in observed humidity trends since the 1970s and in [general circulation model] simulations of warming. Meanwhile, a sizable negative feedback from clouds in tropical deep convection regions is inferred from observations of interannual variability but does not overwhelm the combined positive feedbacks from rising high cloud tops and reduced low-cloud cover. […] Interannual fluctuations in [top-of-atmosphere] energy balance, which reflect the net effect of all cloud types, also point to a positive total feedback, suggesting that we have not missed any major feedbacks by assessing only a finite set of individual cloud types.”[3]

8. Dust (?)

“Atmospheric dust is also changing partly due to climate effects. For example, dust concentrations at Barbados show a four-fold increase since the 1960s driven by meteorological changes in the African source region.[230„34]

"Changes in global dust deposition predicted by models are also highly variable, as are estimates of future changes in dust emissions, which may be positive or negative"[34]

"Wind speed, soil moisture and vegetation cover are climate-driven variables that strongly affect dust emission fluxes, size distribution and mineralogical composition and hence, indirectly, control dust transport, deposition and radiative effects. Transport is also controlled by the atmospheric circulation and wet deposition by precipitation. There is, consequently, clear potential for feedbacks involving dust associated with a changing climate. However, as in the case of emissions of biomass burning aerosols from wildfires, there are both natural and anthropogenic factors governing dust emissions.[231] The attribution of changing dust emissions to natural or human causes is very uncertain for this reason and also because, unlike for purely anthropogenic species, the choice of a base time to define natural emissions is essentially arbitrary."[34]

9. Other aerosols (?)

"A warmer climate could also affect the production and/or lifetime of aerosols, in particular, dust, sea salt, natural sources of SO_2/SO_4 and reactive nitrogen species, and natural fires. Besides changes to the direct aerosol radiative effect,[39] this could lead to additional indirect aerosol effects on clouds[32,232] and fire-induced effects on surface albedo."[3]

10. Ocean stratification (+)

"In this study, we analysed changes in ocean stratification (using N^2) in multiple datasets, finding consistent evidence for overall enhanced stratification in most regions of the world oceans, down to depths of 2,000 m."[40]

"Increasing stratification has important climate implications. The expected decrease in ocean ventilation[233,234] could affect ocean heat and carbon uptake,[235,236] water mass formation[233] and tropical storm formation and strength.[237] The associated decrease in ocean mixing, moreover, is consistent with a decline in ocean oxygen concentration,[234,238] reduced nutrient flux[239] and alteration of marine productivity and biodiversity,[236,239,240] as observed."[40]

"Warmer waters absorb less atmospheric carbon dioxide […] Less ocean mixing also means that less of the atmospheric carbon dioxide gets buried beneath the ocean surface. So carbon pollution accumulates even faster in the atmosphere, causing yet more warming."[41]

11. Ocean circulation (?)

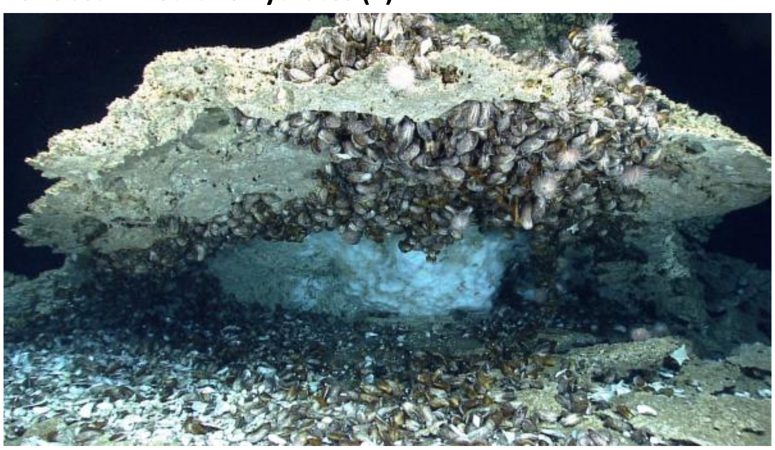
"While the Atlantic Meridional Overturning Circulation (AMOC) is projected to slow down under anthropogenic warming, the exact role of the AMOC in future climate change has not been fully quantified. […] Our results show that a weakened AMOC can explain ocean cooling south of Greenland that resembles the North Atlantic warming hole and a reduced Arctic sea ice loss in all seasons with a delay of about 6 years in the emergence of an ice-free Arctic in boreal summer. In the troposphere, a weakened AMOC causes an anomalous cooling band stretching from the lower levels in high latitudes to the upper levels in the tropics and […].”[47]

“By […], we can isolate the pattern of surface temperature change due to a weakened AMOC. We find that surface air temperature shows a ‘bipolar seesaw’ response,[241–243] with cooling in the Northern Hemisphere (NH) and warming in the Southern Hemisphere (SH)[…]. The largest cooling occurs south of Greenland in the North Atlantic and exceeds 3°C. This cooling seems related to a decreased northward heat transport induced by the weakened AMOC […]. On a global scale, the weakened AMOC causes a 0.2°C cooling in global mean surface temperature by 2061–2080 […].”[47]

12. Ocean solubility pump (+)

“The surface dissolution and equilibration of CO_2 with the atmosphere is well understood and quantified. It varies with the surface ocean conditions, in particular with temperature (solubility effect) and alkalinity. The capacity of the ocean to take up additional CO_2 for a given alkalinity decreases at higher temperature.”[50]

13. Ocean methane hydrates (+)



“Gas hydrate, a frozen, naturally-occurring, and highly-concentrated form of methane, sequesters significant carbon in the global system and is stable only over a range of low-temperature and moderate-pressure conditions. Gas hydrate is widespread in the sediments of marine continental margins and permafrost areas, locations where ocean and atmospheric warming may perturb the hydrate stability field and lead to release of the sequestered methane into the overlying sediments and soils. Methane and methane-derived carbon that escape from sediments and soils and reach the atmosphere could exacerbate greenhouse warming. The synergy between warming climate and gas hydrate dissociation feeds a popular perception that global warming could drive catastrophic methane releases […] Methane hydrate is likely undergoing dissociation now on global upper continental slopes and on continental shelves that ring the Arctic Ocean. Many factors […] mitigate the impact of gas hydrate dissociation on atmospheric greenhouse gas concentrations though. There is no conclusive proof that hydrate-derived methane is reaching the atmosphere now, but more observational data and improved numerical models will better characterize the climate-hydrate synergy in the future."[55]

14. Lapse rate (+)

"Variation with height of the temperature changes induced by an external climate forcing can also constitute a radiative feedback […]. The tropospheric temperature lapse rate is controlled by radiative, convective, and dynamical processes. At extratropical latitudes, the lapse rate is constrained by baroclinic adjustment.[244] The temperature profile of deep convective atmospheres is nearly moist adiabatic,[245] and dynamical processes prevent the tropical atmosphere from maintaining substantial horizontal temperature gradients in the free troposphere. As a result, the temperature profile of the free troposphere is close to a moist adiabat throughout low latitudes."[8]

"In response to global warming, at low latitudes [general circulation models] predict a larger tropospheric warming at altitudes than near the surface (consistent with the moist adiabatic stratification of the atmosphere), and thus a negative lapse rate feedback. At mid- and high latitudes, on the other hand, they predict a larger warming near the surface than at altitude (i.e., a positive lapse rate feedback). On average over the globe, the tropical lapse rate response dominates over the extratropical response, and the climate change lapse rate feedback is negative in most or all the [general circulation models] […]."[8]

15. Glacier and ice sheet elevation (+)

"The next most well-characterized geometry/SMB [surface mass balance] positive feedback is the temperature-based elevation/SMB feedback[246] that depends on the presence of ablation areas and atmospheric temperature change with elevation (i.e., lapse rates). As a result of these factors, an initial externally forced increase in ablation—for example, due to increased summer temperature—will lower ablation area elevation. This in turn causes additional melting as the ice surface experiences warmer low-elevation temperatures. The same mechanism also operates in reverse (as with all feedback processes). The impact of this feedback increases with greater levels of elevation change: using idealized ice loss geometries in an atmospheric model, Hakuba et al.[247] estimated a ∼2°C increase in GrIS-averaged [Greenland ice sheet-averaged] surface temperatures for each 25% GrIS volume loss increment, which is similar to earlier studies (e.g., Ridley et al.[248]), with the majority of this temperature increase arising from temperature lapse rate considerations. The importance of the temperature-based height/SMB feedback may have played a critical role in glacial climates characterized by ice sheets with large ablation zones, by triggering rapid deglaciation as thresholds in ice sheet geometry initiated the height/SMB feedback across a massive ice sheet area.[249]"[61]

16. Antarctic rainfall (+)

"While we do not propose the [Miocene Climatic Optimum] Antarctica was ever completely ice-free, our results demonstrate any spatial retreat of the [Antarctic ice sheet] can increase precipitation, causing associated warming of the deep ocean—changes perhaps having the ability both to accelerate ice melt of ice shelves and glaciers through hydrofracturing from increased precipitation falling into crevasses[250,251] and to accelerate ice melt of marine-based subglacial basins.[251,252] Although the temperature changes resulting from changing ice-sheet extent are similar to those resulting from CO_2 changes, our study does not include feedbacks to the carbon cycle or to the ice sheet itself, and therefore the significance of our results could be greater than indicated here. Our non-realistic sensitivity studies using only a skin thickness of ice demonstrate the importance of both surface albedo and roughness for a hydrologic control on [deep water temperature] evolution."[63]

17. Sea ice growth rate (-)

"The fact that sea ice decrease is not self-accelerating[253] in the presence of the ice albedo feedback leads to the conclusion that negative sea ice feedbacks must exist. There are at least three potential mechanisms which lead to sea ice negative feedbacks. First, thinner ice is warmer and has a higher winter open-water fraction, which induces more [long-wave] emission. Second, thinner ice is less insulating. Third, thinner ice has less snow,[254] further decreasing the insulation power of the sea ice cover. Overall, these three mechanisms drastically (and non-linearly) increase the growth rate for thin ice[64] contributing to rapidly bringing sea ice back to its equilibrium thickness in response to a perturbation[255]. In the Southern Ocean, where the stratification of the water column is weaker than in the Arctic, two competing ice–ocean feedbacks have been documented.[65] The first feedback is negative and is termed ice production–entrainment feedback. […] The second feedback is positive and termed ice-production–ocean-heat-storage feedback. […]"[20]

18. Ozone (?)

"State-of-the-art climate models now include more climate processes which are simulated at higher spatial resolution than ever.[256] Nevertheless, some processes, such as atmospheric chemical feedbacks, are still computationally expensive and are often ignored in climate simulations.[256,257] […] [We] find an increase in global mean surface warming of around 1°C (~20%) after 75 years when ozone is prescribed at pre-industrial levels compared with when it is allowed to evolve self-consistently in response to an abrupt $4\times CO_2$ forcing. […] This has important implications for global model intercomparison studies[256,257] in which participating models often use simplified treatments of atmospheric composition changes that are neither consistent with the specified greenhouse gas forcing scenario nor with the associated atmospheric circulation feedbacks[258–260]."[66]

"Tropospheric ozone shows a range of responses to climate with models generally agreeing that warmer climate will lead to decreases in the tropical lower troposphere owing to increased water vapour and increases in the sub-tropical to mid-latitude upper troposphere due to increases in lightning and stratosphere-to-troposphere transport.[261] A small positive feedback is estimated from climate-induced changes in global mean tropospheric ozone[262] while a small negative feedback is estimated by Heinze et al.[20] based on the model results of Stevenson et al.[261]"[37]

19. Chemical reaction rates (?)

"Changing reaction rates in atmospheric chemistry involving the dynamics of CH_4, O_3, and water vapour can lead to both positive and negative climate feedbacks […]. The major removal process for CH_4 is reaction with the OH radical, but OH is in turn removed by CH_4. This self-feedback has the effect of amplifying any changes to CH_4 production or removal by a factor *f*.[263] Parameter *f* depends on the change in the lifetime of CH_4 with changing CH_4 concentration."[20]

"Increased water vapour leads to increased O_3 destruction. Model simulations show that globally the effect of enhanced O_3 loss due to increased water vapour dominates, so that O_3 concentrations in the free troposphere decrease in a warmer and wetter climate.[264,265] Stevenson et al.[261] found varying responses to climate change in different chemistry models. They all showed decreased O_3 over the oceans, but some showed increased O_3 over the tropical continents where NO_x emissions from lightning increased, and some showed increased O_3 in the upper troposphere around the subtropical jets due to increased stratosphere–troposphere exchange."[20]

20. Chemical weathering (-)

"On geologic time scales, the amount of CO_2 in the atmosphere is determined by processes such as organic-carbon and carbonate-carbon sedimentation and burial, carbonate, organic carbon, and silicate weathering on land, and volcanic and metamorphic release of CO_2 […].[266] Many of these processes are sensitive to the state of the surface environment, including its temperature and the intensity of the hydrologic cycle. These environmental variables, in turn, are sensitive to atmospheric pCO_2 through the greenhouse effect. Thus, it is reasonable to assume that there are negative feedback mechanisms at work over geologic time that stabilize atmospheric pCO_2 and climate."[70]

21. Peatlands (+)

"Globally, the amount of carbon stored in peats exceeds that stored in vegetation and is similar in size to the current atmospheric carbon pool. Fire is a threat to many peat-rich biomes and has the potential to disturb these carbon stocks. Peat fires are dominated by smouldering combustion […]. In undisturbed peatlands, most of the peat carbon stock typically is protected from smouldering, and resistance to fire has led to a build-up of peat carbon storage in boreal and tropical regions over long timescales. But drying as a result of climate change and human activity lowers the water table in peatlands and increases the frequency and extent of peat fires. The combustion of deep peat affects older soil carbon that has not been part of the active carbon cycle for centuries to millennia, and thus will dictate the importance of peat fire emissions to the carbon cycle and feedbacks to the climate."[72]

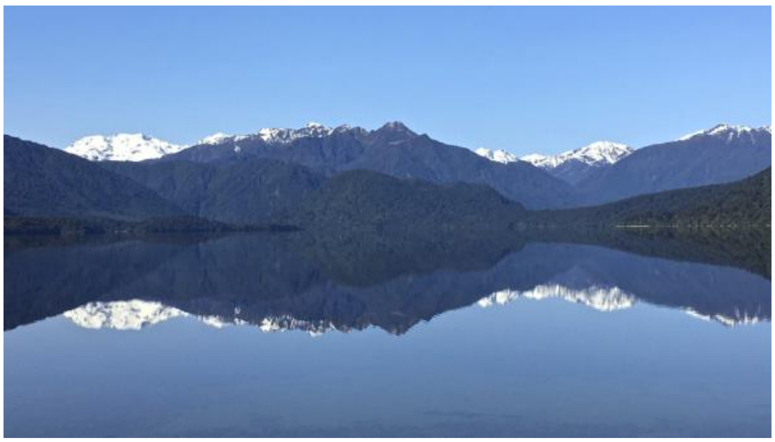
"Drying in peatlands also increases the depth of belowground fuel combustion, releasing carbon to the atmosphere that has been stored in soils for centuries to millennia, thus creating a positive feedback to the climate system."[72]

22. Wetlands (precipitation) (+)

"The influence of temperature on CH_4 emissions, however, is also strongly dependent on hydrologic conditions.[267] Mean precipitation in already dry midlatitude and subtropical regions is predicted to decline under warming scenarios, whereas in the wet midlatitudes and northern wetland regions it is predicted to increase.[268] Extended droughts will lower water tables in wetlands and decrease CH_4

emissions but increase CO_2 emissions.[269] Increased precipitation will raise water tables and even expand wetland areas thereby promoting C sequestration and also CH_4 emission. The balance between these two processes is critical in determining whether changes in wetlands are contributing to a positive or negative climate feedback. A rise in precipitation can also increase the rate of organic substrate leaching to deeper parts of the peat profile, leading to increased methanogenesis. CH_4 production rates at depth can be 2–4 times higher than in the top 1 m of peat, and this effect has been observed on decadal timescales.[270] Increased methanogenesis will put greater pressure on the oxidative capacity along the export pathway of this CH_4 whether vertically or laterally when dissolved in groundwater."[74]

23. Freshwater ecosystems (+)



"Net emissions of the potent GHG methane from ecosystems represent the balance between microbial methane production (methanogenesis) and oxidation (methanotrophy), each with different sensitivities to temperature. How this balance will be altered by long-term global warming, especially in freshwaters that are major methane sources, remains unknown. Here we show that the experimental warming of artificial ponds over 11 years drives a disproportionate increase in methanogenesis over methanotrophy that increases the warming potential of the gases they emit. The increased methane emissions far exceed temperature-based predictions, driven by shifts in the methanogen community under warming, while the methanotroph community was conserved. Our experimentally induced increase in methane emissions from artificial ponds is, in part, reflected globally as a disproportionate increase in the capacity of naturally warmer ecosystems to emit more methane. Our findings indicate that as Earth warms, natural ecosystems will emit disproportionately more methane in a positive feedback warming loop."[80]

24. Forest dieback (+)

Here, we focus on the effects of extreme heat and drought. Although wildfires and insect damage can also impact forests, we treated these as separate feedback loops because they often represent transient disturbances. We also distinguish "plant stress" (can include non-forest vegetation) from the overlapping "forest dieback" feedback loop.

"Greenhouse gas emissions have significantly altered global climate, and will continue to do so in the future. Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate change could fundamentally alter the composition, structure, and biogeography of forests in many regions. Of particular concern are potential increases in tree mortality associated with climate-induced physiological stress and interactions with other climate-mediated processes such as insect outbreaks and wildfire. […] Here we present the first global assessment of recent tree mortality attributed to drought and heat stress. Although episodic mortality occurs in the absence of climate change, studies compiled here suggest that at least some of the world's forested ecosystems already may be responding to climate change and raise concern that forests may become increasingly vulnerable to higher background tree mortality rates and die-off in response to future warming and drought, even in environments that are not normally considered water-limited. This further suggests risks to ecosystem services, including the loss of sequestered forest carbon and associated atmospheric feedbacks. […] Overall, our review reveals the potential for amplified tree mortality due to drought and heat in forests worldwide."[82]

25. Northern greening (+)

"Northern high latitude ecosystems are experiencing amplified climate warming[271] that will be exacerbated by a series of positive feedbacks,[272] the relative magnitudes of which remain uncertain. A terrestrial albedo feedback to climate is underway in these ecosystems and being driven by two processes: densification and northward expansion of woody vegetation[273–275] and changes in the extent and duration of snow cover[272,276]. Currently, snow melt advance exerts the strongest feedback on regional warming,[272] however, continued increases in tree and shrub cover will likely diminish its role[272,277]."[95]

26. Insect outbreaks (forests) (+)

"The mountain pine beetle […] is a native insect of the pine forests of western North America, and its populations periodically erupt into large-scale outbreaks.[278–280] During outbreaks, the resulting widespread tree mortality reduces forest carbon uptake and increases future emissions from the decay of killed trees. […] Here we estimate that the cumulative impact of the beetle outbreak in the affected region during 2000–2020 will be 270 [Mt] carbon […] Climate change has contributed to the unprecedented extent and severity of this outbreak6. Insect outbreaks such as this represent an important mechanism by which climate change may undermine the ability of northern forests to take up and store atmospheric carbon […]."[103]

“Warming-induced [Siberian silkmoth (SSM)] outbreaks are one of the major driving factors of successions within the taiga zone. […] We analyzed the migration of alpine and northerly SSM outbreak boundaries in Siberia and the impact of […] climate variables and topography on the outbreak dynamics. […] outbreak onset was promoted by increased dryness and active temperatures and decreased root zone moisture content in the spring-early summer period. [...] Climate warming contributes to SSM migration into former outbreak free conifer stands located in highlands and at northern latitudes.”[104]

27. Wildfire (+)

“Although certain biomes are sensitive to constraints on biomass productivity and others to atmospheric conditions promoting combustion, substantial and rapid shifts are projected for future fire activity across vast portions of the globe. In the near term, the most consistent increases in fire activity occur in biomes with already somewhat warm climates; decreases are less pronounced and concentrated primarily in a few tropical and subtropical biomes. However, models do not agree on the direction of near-term changes across more than 50% of terrestrial lands, highlighting major uncertainties in the next few decades. By the end of the century, the magnitude and the agreement in direction of change are projected to increase substantially. Most far-term model agreement on increasing fire probabilities (~62%) occurs at mid- to high-latitudes, while agreement on decreasing probabilities (~20%) is mainly in the tropics. Although our global models demonstrate that long-term environmental norms are very successful at capturing chronic fire probability patterns, future work is necessary to assess how much more explanatory power would be added through interannual variation in climate variables.”[106]

28. Biogenic volatile organic compounds (BVOCs) (+)

“[…] shows the possible climate feedbacks associated with biogenic [secondary organic aerosol (SOA)]. The main driver of the feedback is that climate exerts a strong control over the emission of BVOCs […]. Increases in temperature are likely to lead to increased BVOC emissions and aerosol concentrations, resulting in increased aerosol radiative cooling and a potential negative feedback mechanism.[281]”[34]

“Increased temperature causes increased BVOC emissions (e.g., Guenther et al.[282]) but may also reduce the partitioning of semi-volatile compounds to the particles. Increased temperature also modifies vegetation resulting in either further increased or decreased BVOC emissions.”[34]

"Increased CO_2 concentrations may directly inhibit leaf-level isoprene emission[283,284] but the fertilization effect of the CO_2 on plant growth can increase emission rates."[34]

"The observational evidence for large-scale climate-driven changes in BVOC emissions and SOA formation is limited, unlike for wildfires […]. In a good example of such a study, Palmer et al.[285] used a 6 year record of satellite-observed formaldehyde column to infer a 20–30% interannual variability in isoprene emission over the south-eastern United States driven primarily by variations in surface air temperature."[34]

29. Soil carbon (other) (+)

"The majority of the Earth's terrestrial carbon is stored in the soil. If anthropogenic warming stimulates the loss of this carbon to the atmosphere, it could drive further planetary warming.[286–289] [...] By extrapolating […] to the global scale, we provide estimates of soil carbon sensitivity to warming that may help to constrain Earth system model projections. Our empirical relationship suggests that global soil carbon stocks in the upper soil horizons will fall by 30 ± 30 petagrams of carbon to 203 ± 161 petagrams of carbon under one degree of warming, depending on the rate at which the effects of warming are realized. Under the conservative assumption that the response of soil carbon to warming occurs within a year, a business-as-usual climate scenario would drive the loss of 55 ± 50 petagrams of carbon from the upper soil horizons by 2050. […] Despite the considerable uncertainty in our estimates, the direction of the global soil carbon response is consistent across all scenarios. This provides strong empirical support for the idea that rising temperatures will stimulate the net loss of soil carbon to the atmosphere, driving a positive land carbon–climate feedback that could accelerate climate change."[116]

30. Soil nitrous oxide (+)

"Although fertilizer use is presumed to have greatly stimulated global N_2O emission, nonagricultural (especially tropical) soils still represent a source of N_2O equal to all of the anthropogenic sources combined.[290] This natural N_2O source must be influenced by climate, as can be deduced from both field observations and manipulative experiments.[291] In particular, widespread enhancement of soil N_2O emission by warming is to be expected, because both nitrification and denitrification are highly temperature-dependent processes with estimated optima as high as 38°C.[292–295] It has been proposed that the global soil source of N_2O should increase as the atmosphere warms,[296] and that this climate-induced increase could even become as important for the global N_2O budget as projected increases in the anthropogenic sources of N_2O.[296]"[118]

"The modelled temperature dependence of N_2O emission (c. 1 Tg N yr^{-1} K^{-1}) implies a positive climate feedback which, over the lifetime of N_2O (114 yr), could become as important as the climate–carbon cycle feedback caused by soil CO_2 release."[118]

31. Permafrost (+)

Dissociation of methane hydrates, which can occur in permafrost, is treated separately under "methane hydrates."

"Large quantities of organic carbon are stored in frozen soils (permafrost) within Arctic and sub-Arctic regions. A warming climate can induce environmental changes that accelerate the microbial breakdown of organic carbon and the release of the greenhouse gases carbon dioxide and methane. This feedback can accelerate climate change, but the magnitude and timing of greenhouse gas emission from these regions and their impact on climate change remain uncertain."[128]

32. Evapotranspiration (+)

"Warming leads to an increase in evaporation from soils. This negative soil moisture anomaly leads to a positive surface temperature anomaly through the reduction in latent heat flux.[297] The result is a positive feedback. In addition to this physical feedback, there is a chemically forced feedback. Under rising atmospheric CO_2 concentrations, plants open their stomata (plant stomata; […]) less widely […].[298,299] This leads to a reduction in evapotranspiration over land, a decrease in latent heat flux, and respective warming. This overall positive feedback is somewhat reduced by a secondary negative feedback: CO_2 fertilization […]will lead to an increase in carbon assimilation and a respective increase in LAI (leaf area index – area covered by leaf canopy in relation to ground area) and a slight increase in surface albedo.[300] An uncertainty associated with this feedback is the original underlying surface albedo (if this were high, then the feedback could even become reversed)."

33. Microbial respiration (other) (+)

"Understanding how the metabolic rates of prokaryotes respond to temperature is fundamental to our understanding of how ecosystem functioning will be altered by climate change, as these micro-organisms are major contributors to global carbon efflux. Ecological metabolic theory suggests that species living at higher temperatures evolve higher growth rates than those in cooler niches due to thermodynamic constraints. Here, using a global prokaryotic dataset, we find that maximal growth rate at thermal optimum increases with temperature for mesophiles (temperature optima ≲45 °C), but not thermophiles (≳45 °C). Furthermore, short-term (within-day) thermal responses of prokaryotic metabolic rates are typically more sensitive to warming than those of eukaryotes. Because climatic warming will mostly impact ecosystems in the mesophilic temperature range, we conclude that as microbial communities adapt to higher temperatures, their metabolic rates and therefore, biomass-specific CO_2 production, will inevitably rise. Using a mathematical model, we illustrate the potential global impacts of these findings."[134]

34. Plant stress (+)

We treated "plant stress" as different from "forest dieback" because plant stress can apply to non-forest vegetation.

"While higher CO_2 concentrations may boost plant growth and simultaneously help plants conserve water, the co-occurrence of hot conditions during drought could exacerbate plant stress, and potentially lead to increased damage to tissues and higher rates of mortality.[301–303] This increase in plant stress could occur even if drought frequency remains constant and have major impacts on forest structure and functioning in a hotter world.[83]"[136]

"Higher rates of mortality during drought could dramatically alter forest structure. The timescales associated with forest growth are significantly longer than those associated with death, such that increased mortality will reduce forest cover much faster than it can regenerate. […] Loss of forest cover due to mortality increases the surface albedo and simultaneously decreases evapotranspiration rates and increases sensible heating.[304] […] The relatively longer timescale of recovery from mortality could also lead to less plant cover, and thus less regulation by stomata of surface to atmosphere water flux. The mortality response to the hotter droughts expected in the future is a critical uncertainty in determining the impact of future droughts on forests, and is likely to be a major impact independent of any increase in drought frequency."[136]

35. Desertification (+)

This feedback loop deals with climate change potentially leading to expanding deserts. However, the effects of climate change can also cause deserts to shrink in some cases (e.g., see "Sahara and Sahel greening").

"[Desertification] typically results from the compound effect of climate change and land use. Changes in the global and regional patterns of precipitation can be major drivers of desertification and have historically led to the expansion and contraction of major deserts on Earth. In fact, while many of the existing deserts are very old and formed millions of years ago, most of them were affected by Pleistocene climatic changes and expanded at some point into areas that are currently much wetter (500–800 mm/yr). In those areas the temporary loss of vegetation cover can explain the formation of some of the sand seas that are currently stabilized by vegetation [74], including the Kalahari, southern Sahara, the High Plains (US), the Mega-Thar (India), the Kimberlies (Australia), and the Llanos and the Pampas (S. America). Thus, in the course of Earth's history, several regions around the world experienced the alternation of wet and dry periods. It is interesting to analyze how climate has been changing in more recent times and whether climate change studies predict an expansion or contraction of arid lands on Earth."[137]

36. Sahara and Sahel greening (+)

"In the future, the Sahara and Sahelian regions could experience more rainfall than today as a result of climate change. Wetter periods, termed African humid periods, occurred in the past and witnessed a mesic landscape in place of today's hyperarid and semiarid environment. Such large past changes raise the question of whether the near future might hold in store similar environmental transformations, particularly in view of the growing human-induced climate, land-use, and land-cover changes."[139]

37. CO_2 fertilization (+)

"One critical feedback occurs if C uptake by the biosphere increases in response to the fossil-fuel driven increase in atmospheric [CO_2] ("CO_2 fertilization"), thereby slowing the rate of increase in atmospheric

[CO_2]. Carbon exchanges between the terrestrial biosphere and atmosphere are often first represented in models as net primary productivity (NPP). However, the contribution of CO_2 fertilization to the future global C cycle has been uncertain, especially in forest ecosystems that dominate global NPP, and models that include a feedback between terrestrial biosphere metabolism and atmospheric [CO_2] are poorly constrained by experimental evidence. We analyzed the response of NPP to elevated CO_2 (≈550 ppm) in four free-air CO_2 enrichment experiments in forest stands. We show that the response of forest NPP to elevated [CO_2] is highly conserved across a broad range of productivity, with a stimulation at the median of 23 ± 2%. At low leaf area indices, a large portion of the response was attributable to increased light absorption, but as leaf area indices increased, the response to elevated [CO_2] was wholly caused by increased light-use efficiency."[141]

38. Coastal productivity (+)

"Mangroves will survive into the future but there have already been, and will continue to be, more negative than positive impacts due to climate change."[151]

"As the world begins its transition to a low-carbon economy, removing atmospheric carbon dioxide (CO_2) through biosequestration will be necessary to keep global warming under 2°C. Among the most efficient systems that provide biosequestration services are vegetated coastal habitats (VCHs), which include seagrasses, tidal marshes, and mangroves […] and are known as 'blue carbon' ecosystems.[149] VCHs occupy only 0.2% of the ocean surface, yet contribute 50% of the total amount of carbon buried in marine sediments.[150] They have the ability to accumulate carbon without reaching saturation, and can store it in sediments over millennial timescales.[149] As with important terrestrial carbon sinks (eg Amazonian forests, permafrost regions), ecosystem degradation can shift blue carbon ecosystems from carbon sinks to carbon sources.[305]"[152]

39. Ocean metabolic rates (+)

The ocean represents a major sink for atmospheric carbon, partly through the 'biological carbon pump' in which sinking organic matter is exported from the surface to the deep sea.[156] The efficiency of the pump relies on a fine balance between the counteracting metabolic processes of carbon fixation into organic matter by photosynthesis and remineralization back to CO_2 by respiration.[156] When organic carbon is moved to the deep ocean and/or buried, it creates a return flux from the atmosphere to the surface ocean. As the global ocean changes temperature, the balance between the two processes is likely to shift. If global temperatures increase, the efficiency of the ocean as a carbon sink should decline, and vice versa in a cooling world. This is potentially a very important positive feedback on global climate and atmospheric CO_2 levels.

40. Ocean biological pump (?)

"Two ocean pumps play key roles in removing carbon from the surface ocean—the solubility pump is physico-chemically mediated whereas the biological pump is driven primarily by the interactions of marine biota from microbes to metazoa.[306] In brief, in the euphotic zone (Ez) photosynthetic carbon fixation by autotrophs, and heterotrophic bacterial production, inputs POC [particulate organic carbon] (and dissolved organic carbon […]) to the biological pump. This POC supply to the upper ocean is subsequently modified and attenuated by a wide range of grazing activities which transform most of the phytoplankton and bacterial carbon into heterogeneous particles which eventually settle out of the surface ocean after a residence time of days to weeks.[307]"[158]

"Pörtner et al.[157] in the Working Group 2 Fifth Assessment Report of the Intergovernmental Panel on Climate Change […] concluded that due to the many "moving parts" it was not possible state with confidence how the sign or magnitude of the pump would alter in the coming decades. Instead they put forward a first assessment of the integrated knowledge platform (see Table 6.1, Pörtner et al.[157]) required to project how the biological pump will function in a future ocean."[158]

41. Phyto-plankton dimethyl sulfide (DMS) (+)

"Dimethyl sulfide (DMS) is a significant source of marine sulfate aerosol and plays an important role in modifying cloud properties. Fully coupled climate simulations using dynamic marine ecosystem and DMS calculations are conducted to estimate DMS fluxes under various climate scenarios and to examine the sign and strength of phytoplankton-DMS-climate feedbacks for the first time. Simulation results show small differences in the DMS production and emissions between pre-industrial and present climate scenarios, except for some areas in the Southern Ocean. There are clear changes in surface ocean DMS concentrations moving into the future, and they are attributable to changes in phytoplankton production and competition driven by complex spatially varying mechanisms. Comparisons between parallel simulations with and without DMS fluxes into the atmosphere show significant differences in marine ecosystems and physical fields. Without DMS, the missing subsequent aerosol indirect effects on clouds and radiative forcing lead to fewer clouds, more solar radiation, and a much warmer climate."[163]

Human feedback loops (Table S2)

1. Climate-related disasters (?)

In many regions of the world, climate change is projected to increase the frequency and severity of several types of climate-related disasters including forest fires[106], tropical storms[167], and floods[168]. These disasters can result in damages to buildings and infrastructure, which must be repaired or rebuilt. Since repairing and rebuilding have associated carbon costs, this constitutes a potential positive feedback loop wherein increasingly frequent or severe disasters results in increasing repairing and rebuilding carbon costs, which in turn contributes to further increasing disaster frequency or severity (through climate change). In 2009, 5.7 Gt of CO_2 emissions were associated with the global construction sector, representing 23% of all CO_2 emissions attributable to global economic activities[308]. Thus, rebuilding on a massive scale could have a substantial carbon footprint.

2. Human migration (?)

In contrast to short-term disasters like hurricanes (see "climate-related disasters") where in-place rebuilding may be an option, climate change can also render regions uninhabitable on a long-term basis. For example, sea level rise,[170,309] extreme mean annual temperatures,[169] and desertification[137] can all result in land becoming relatively unsuitable for human habitation. In such cases, humans may be forced to move and build new housing and infrastructure elsewhere. Given that both migration[310,311] and construction[308] can have significant carbon footprints, this could represent a significant positive feedback loop. Notably, sea level rise alone could force hundreds of millions of people to move by 2100.[309]

3. Human mobility (+)

"Human behaviours alter—and are altered by—climate. Might the impacts of warming on human behaviours amplify anthropogenic contributions to climate change? Here, we show that warmer temperatures substantially increase transportation use in the USA. To do so, we combine meteorological data with data on vehicle miles travelled (VMT) and public transit trips (PTT) between 2002 and 2018. Moving from freezing temperatures up to 30°C increases VMT by over 10% and amplifies use of public transit by nearly 15%. Temperatures beyond 30°C exert little influence on either outcome. We then examine climate model projections to highlight the possible transportation impacts of future climatic changes. We project that warming over the coming century may add over one trillion cumulative VMT and six billion PTT in the USA alone, presenting the risk of a novel feedback loop in the human–environmental system."[173]

4. Transport routes (?)

"Rapid loss of sea ice is opening up the Arctic Ocean to shipping, a practice that is forecasted to increase rapidly by 2050 when many models predict that the Arctic Ocean will largely be free of ice toward the end of summer. These forecasts carry considerable uncertainty because Arctic shipping was previously considered too sparse to allow for adequate validation. Here, we provide quantitative evidence that the extent of Arctic shipping in the period 2011–2014 is already significant and that it is concentrated (i) in the Norwegian and Barents Seas, and (ii) predominantly accessed via the Northeast and Northwest Passages. Thick ice along the forecasted direct trans-Arctic route was still present in 2014, preventing transit. Although Arctic shipping remains constrained by the extent of ice coverage, during every September, this coverage is at a minimum, allowing the highest levels of shipping activity. Access to Arctic resources, particularly fisheries, is the most important driver of Arctic shipping thus far."[176]

5. Energy demand (?)

"In this article, we assess the potential development of energy use for future residential heating and air conditioning in the context of climate change. In a reference scenario, global energy demand for heating is projected to increase until 2030 and then stabilize. In contrast, energy demand for air conditioning is projected to increase rapidly over the whole 2000–2100 period, mostly driven by income growth. The associated CO_2 emissions for both heating and cooling increase from 0.8 Gt C in 2000 to 2.2 Gt C in 2100, i.e. about 12% of total CO_2 emissions from energy use (the strongest increase occurs in Asia). The net effect of climate change on global energy use and emissions is relatively small as decreases in heating are compensated for by increases in cooling. However, impacts on heating and cooling individually are considerable in this scenario, with heating energy demand decreased by 34% worldwide by 2100 as a result of climate change, and air-conditioning energy demand increased by 72%. At the regional scale considerable impacts can be seen, particularly in South Asia, where energy demand for residential air conditioning could increase by around 50% due to climate change, compared with the situation without climate change."[177]

6. Agriculture (?)

There may also be climate feedbacks related to nitrous oxide emissions from fertilizer use.

"Change in yields, followed by a change in the area needed to supply the same amount of food. As discussed above, yields are projected to be affected from mildly positively to severely negatively, meaning that overall cropland will have to expand further into natural vegetation to compensate for somewhat lower average yields."[179]

"Shifts in agricultural suitability, followed by relocation of agriculture. Cropping will follow agricultural suitability into higher latitudes, sometimes higher altitudes, causing deforestation of previously uncultivated areas and some reforestation on abandoned land."[179]

"Changes in water demand for irrigated agriculture. In crop yield models, areas equipped with irrigation are 'protected' from any changes in precipitation and optimal evapotranspiration. That is, the models assume that enough water will be available for optimum irrigation. In reality, yields of irrigated agriculture can be affected if climate change alters the balance between the water available for irrigation and irrigation water demand (it can influence both the supply and demand sides). This again would result in cropland expansion as compensation for lower yields."[179]

7. Coral reefs (+)

While coral reefs provide a number of important ecosystem services, especially with regard to food, income (e.g., from tourism), and storm protection, they are increasingly at risk due to climate change[181–183]. Thus, climate-related coral die-off could cause major problems for the approximately 850 million people who are likely to benefit from ecosystem services provided by coral reefs.[181] Many of these people may be forced to respond by migrating (with associated CO_2 emissions) and/or shifting to alternative means of food production that may have significant carbon costs. Because coral die-off could impact hundreds of million people, it is possible that this may be a significant positive feedback loop.

8. Freshwater (+)

Climate change is projected to result in decreasing freshwater availability in some regions. [184,185] In these regions, humans may need to adapt by migrating (moving elsewhere),[310,311] scaling up desalination technology, [186] or importing freshwater. All of these options have associated carbon costs. Thus, declining freshwater availability could be part of a positive feedback loop where decreasing freshwater availability results in increasing greenhouse gas emissions.

9. Mitigation (-)

Psychologically and behaviorally, there are two general ways in which humans might react to climate change becoming increasingly severe. Humans may respond by increasing mitigation efforts at the individual level (and higher levels). For example, by reducing air travel or shifting to plant-rich diets.[312,313] Conversely, some people may feel an increasing sense of hopelessness, apathy, or powerlessness,[314] leading them to decide that climate mitigation is futile and not worth pursuing. Depending on the relative strengths of these reactions, which could be affected by how climate change is represented,[190] "mitigation" could constitute a positive or negative feedback loop.

10. Policy paralysis (+)

"Unlike most policy challenges, climate change gets worse the longer we take to address it.

How it works: The longer we wait to address climate change with major government action, the bigger the policy needed and the bigger economic impact that policy will have.

But the bigger the policy and economic hit get, the harder the politics get.

So we wait longer still, making the required policy and economic impact ever bigger, which makes the politics even more difficult."[193]

11. Economic growth (?)

Note that climate-related effects on human population growth are also possible; this could form a related feedback loop.

"Empirical analysis of economic production trends generally finds a negative relationship between temperature and income.[315] Climate-related reduction in macroeconomic production will negatively affect human consumption, but may reduce emissions as well. The feedbacks associated with climate damages and growth are likely negative for the climate system, meaning that they lead to less severe climate change. This is because extreme climate outcomes become less probable as future emissions are dampened by the effects of current emissions on economic growth. But as noted by economist Martin Weitzman and others, this effect nevertheless would have profoundly harmful consequences for human well-being as future generations suffer substantial consumption losses compared to currently modeled damages.[316]"[188]

12. Economic disruption (+)

"The first pathway involves economic disruption caused by climate damages. Such disruptions are relatively easy to imagine: a sudden fall in agricultural productivity, the failure of critical infrastructure, or a string of high-impact natural disasters could all lead to severe economic disruptions that would result in a decline of national productivity. Given the interconnectedness of the global economic system, even if these harms did not befall the country in question, they could generate effects that propagated through the system, resulting in widespread costs. In the face of economic crisis, the attention of national leaders could turn from long-term global issues such as climate change to more pressing matters of economic stabilization. Investments in mitigation or adaption might find themselves sacrificed for the needs of the day."[188]

13. Political disruption (+)

"The second pathway involves political disruption caused by climate damages. For example, climate change–related events could lead to a wave of out migration from Bangladesh to nearby countries, causing political upheaval through an already unstable region. This climate change damage would turn into a positive self-reinforcing feedback if political leaders in India or China responded by embracing nationalist or isolationist positions or simply focused on the immediate crisis at hand, rather than long-term problems such as climate change. The basic relationships in these scenarios are between greenhouse gases, climate damages, economic or political disruption, and policy change."[188]

14. Geopolitics (+)

"It takes global cooperation to address climate change, given its global nature. But climate change impacts different countries differently, so they're more likely to act on their own, and in their own self-interest.

But if there's no global cooperation, climate change continues to get worse — prolonging the adverse impacts on different countries, and giving them even less incentive to cooperate with other countries and more incentive to act on their own."[193]

15. Human conflict (+)

"According to Dr. Neta C. Crawford, Department Chair of Boston University's Department of Political Science and the co-director of the study group Costs of War, military aggression and preparation exacerbates environmental problems that could lead to greater security risks and more war in the future as natural resources are depleted, causing a global refugee crisis.

'The Pentagon is very worried about the stresses of climate change leading to displacement... and they're concerned about climate war,' Crawford tells Big Think in an interview. 'They believe that it's coming to a neighborhood near you.'

The problem, she notes, is that the Pentagon is a huge emitter of greenhouse gases and perpetrator of environmental destruction that increases the probability of war."[195]

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