Supplementary Material

Climate overshoot and irreversibility: Implications for the social cost of greenhouse gases and emission metrics

Daniel J.A. Johansson, Christian Azar, Jan S. Fuglestvedt, Peter H. Howard, Thomas Sterner, Katsumasa Tanaka

SM1. Estimation of potential damage irreversibility

SM1.1. What do we mean by irreversibility?

Scientists and economists use irreversibility in many ways, often imprecisely, leading to vagueness in the underlying concept. There is a substantive debate within the scientific literature over what are the definitions of irreversible, limited reversibility, and hysteresis. Definitions are often missing from scientific articles, such that meaning of irreversibility is often vague. This partly stems from differing definitions across scientific fields (Buhr et al., 2025). A related issue arises for tipping points – often discussed as a subset of irreversible phenomena – as the term has become a metaphor for boundary-spanning conditions that lacks precision in characterizing the relevant underlying systematic behavior(R. Kopp et al., 2025; R. E. Kopp et al., 2025). This is further complicated when academics infer the social implications from these non-linear state shifts (Kopp et al., 2016).

In economics, the term irreversible climate damage also lacks a consistent definition. Economists often invoke irreversibility as a characteristic of climate change rather than explicitly modeling it, with some notable exceptions. In several integrated assessment models, climate economists model tipping points as irreversible state shifts (Cai et al., 2016; Hope, 2013; Kikstra et al., 2021; Lemoine & Traeger, 2014; Lemoine & Traeger, 2016; Yumashev et al., 2019). Here crossing the thresholds results in a persistently higher damage regime or, in some cases, more rapid warming (from weakening of carbon sinks or an increase in equilibrium climate sensitivity parameter from feedback emissions). Unlike the damage tipping points, climate tipping points that trigger additional warming operate through the standard reversible damage functions of most integrated assessment models implying that the resulting economic impacts from their triggering are reversible with sufficient negative emission approaches.[1] The broader concept of irreversible impacts of climate change, including limited reversibility and hysteresis, are typically not discussed.

[1] In economics literature tipping points are typically modeled as irreversible once triggered, while their consequences may, in some cases, be partially or fully reversible. In particular, damage-related tipping points tend to represent direct, ongoing losses that cannot be undone. By contrast, tipping points that amplify warming often operate through damage functions that allow for reversibility, meaning their effects could, in principle, be mitigated or reversed with sufficiently large negative emissions.

The growth-damage literature often refers to permanent growth impacts as irreversible(Wang, 2024). This concept of irreversibility conflates persistence with irreversibility, as level- and growth-based climate damage functions allow damages to decline with temperature (with lags in some cases).[2] In these cases, past GDP losses are permanent in that they are sunk costs, even as contemporary damages decline as temperature changes reverse. Thus, the growth path is irreversibility alternated due to compound effects, though growth itself returns.

Relatedly, the application of the option value/pricing concept to the social cost of carbon links the irreversibility of damages to the irreversibility of the consequences of greenhouse gas emissions (Golub & Brody, 2017)(Golub et al, 2017). Thus, damages are only irreversible in this literature because the authors assume that temperature will not decline (Howard et al., 2020).

In our context, irreversibility means that social welfare, measured in consumption-equivalent dollars, does not fully recover when global average surface temperature decline. This implies an asymmetrical relationship between damages and temperature. Under a standard levels-based (asymmetric) damage function, some portion of annual consumption losses – measured as forgone goods and services – remain permanently lost even if global average surface temperature returns to 1.5ºC following an overshoot relative to a scenario in which temperatures never exceed a 1.5ºC increase.

This definition of damages can be simply written as

$$D\big(T(t)\big) = \begin{cases} \widehat{D}\big(T(\tau)\big) & \text{for } \tau < \tau_{peak} \\ (1-\alpha)\widehat{D}\big(T(\tau)\big) + \alpha\widehat{D}\big(T_{peak}\big) & \text{for } \tau \geq \tau_{peak} \end{cases}$$

where τ is calender year, τ_{peak} is the calendar year the peak occurs, $T(\tau)$ is the global mean surface temperature change compared to pre-industrial levels and $T_{peak}$the peak surface temperature. In this deterministic damage function, the history of temperature is captured only through the maximum temperature reached. As a result, this damage specification captures only threshold-type irreversibility. It does not represent hysteresis dynamics, which require additional state variables and potential interactions between those state variables and current temperature. Neither does it capture the fact that it may take time to trigger irreversible shifts, i.e. that is not solely dependent

[2] It should be noted that the existence of lags is not hysteresis, which requires the history of the state variables to matter (i.e., the history of climate exposure).

on the warming in one year that matters for the level of irreversibility. Hence, the damage function should be interpreted as simplified approximation. As such, we attempt to incorporate evidence on path dependence by calibrating to both the portion of damages that is highly sensitive to historical temperature exposure and the potion of damages that is effectively irreversible.

SM1.2. Which climate impacts and damages from overshoot scenarios could be irreversible?

While the natural sciences have begun to explore the impacts of overshoot on Earth systems, the corresponding literature in social sciences is virtually non-existent(Kruczkiewicz et al., 2025). However, a recent paper proposes a framework to think about the degree of reversibility (Al Khourdajie et al., 2026). It would depend on various physical dimensions of "overshoot" (magnitude, duration, rate of exceedance, and rate of decline) as well as the response (reversible vs. persistent change), and the socioeconomic outcome (reversible vs. irreversible impact). They propose a typology and show that whether temporary exceedance translates into permanent harm is determined primarily by socioeconomic factors. For communities with low adaptive capacity, overshoot may lead to irreversible effects even if temperatures subsequently decline.

We take different route and focus on the potential consequences of the peak as such, as that is the basis for the damage function we employ in the main paper. Here we surmise to what extent damages may be irreversible as the temperature decline. Thus, to describe possible irreversible economic impacts, we begin with the natural science literature on irreversible impacts from overshoot and translate them to economic terms.

Aggregated climate effect and climate impact drivers

As global average temperature decline after a peak, regional weather patterns may not fully return to pre-peak conditions, particularly due to persistent changes in large-scale climate systems, such as to the AMOC and in the Southern Ocean and intertropical convergence zones. Hydrological systems and land-surface water availability may shift along with these systems, including decreased from glaciers. Taken together, this implies that, as in the case of warming, some regions may benefit while others are likely harmed by persistent shifts in weather patterns and freshwater availability. The implication for the global damage function is unclear, although developing regions and regions reliant on glacial waters are more vulnerable to these regional irreversibilities(Kim et al., 2022; Reisinger et al., 2025; Reisinger & Geden, 2023; Schleussner et al., 2024; Schuster et al., 2025; Steinert et al., 2025).

There are several important exceptions to the general reversibility of most climate drivers as global average surface temperature declines. First, sea-level rise is essentially irreversible on a human time scale once it occurs. Second, tropical cyclone intensity exhibits hysteresis, such that while intensity appears to reverse in the long-run as global temperatures decline – with regional variation similar to temperature and precipitation – the return to a stable intensity level is delayed due to ocean heat adjustments and circulation dynamics (Moon et al., 2025). Third, ocean acidification is only slowly reversible with net negative CO_2 emissions. Last, wildfires also demonstrate hysteresis, such that wildfire risk may decline more slowly than temperatures (Kim et al., 2024; Kim et al., 2026).

Market Impacts

It is difficult to identify the amount of irreversibility in the market sector. From a top down perspective, the panel data models are largely reversible by construction, while they only casually identify the market impacts of local temperature and precipitation. From a bottom-up sectoral perspective, global averages measurements of temperature and precipitation are generally reversible, suggesting that many warming and precipitation driven market impacts, like declines labor productivity, should be reversible. However, impacts from sea-level rise, storm intensity, ocean acidification, and wildfires are likely to suffer from irreversibility or path dependence. Of these, only sea-level rise is consistently included in damage estimates, and its impacts are often small due to assumptions of perfect adaptability, while only FUND includes increased storm intensity. Global climate-economic models currently exclude ocean acidification and wildfires.

Beyond these sectors, food and agriculture may exhibit partial irreversibility of impacts or hysteresis. As discussed further below, fishery habitat is likely to suffer from hysteresis, bordering on partial irreversibility on a human time scale if fisheries do not adapt (Morée et al., 2025). While we am not aware of studies directly studying the impact of overshoot on agricultural yields, there is evidence that climate change degrades soil through changes in temperature and precipitation (Kabato et al., 2025; Vindušková et al., 2025), and that degraded agricultural soils may take decades to recover to their original state (Jones et al., 2016). Also noted above, some regions may suffer from freshwater shortages. This suggests that hysteretic impacts in agriculture are possible, though not guaranteed, particularly as agricultural systems and consumers are likely to adapt.

More generally, climate change impacts on ecosystems and natural capital are characterized by irreversibilities and hysteresis (see discussion below). Because ecosystems contribute to the production of market goods and services, these impacts may reduce productive capacity in ways that do not immediately reverse when temperature declines. Even so, few damage functions explicitly capture these ecosystem service losses, and it remains unclear to what extent such effects are implicitly included. Like in agriculture, markets will adapt to minimize these impacts, through substitution of inputs and shifts in consumption patterns.

Non-Market - Health

There are subsets of health damages from climate change that are partially reversible. It may be tempting to discuss mortality and morbidity as irreversible more generally, as it is true on an individual scale and implies path-dependent welfare losses (Schleussner et al., 2024). However, the valuation methods used to estimate mortality, and morbidity impacts already account for this permanence.

The direct effect of warming on human health though cardiovascular and respiratory health – the primary health impacts captured by the social cost of carbon – are likely reversible. Heat, humidity, and overall precipitation decline with global average surface temperature (with some regional variation), and with them, these corresponding impacts.

Wildfires appear to demonstrate hysteresis, implying that health impacts from increased particulate matter exposure may decline more slowly than temperatures (Kim et al., 2024; Kim et al., 2026). Though not included in current climate damage estimates – including in meta-regressions of global climate damage estimates – recent estimates demonstrates that these health impacts could be quite significant (Qiu et al., 2026).

In terms of vector-borne diseases, the reversibility of climate-driven geographic expansion and associated risk under declining temperatures remains uncertain. While climatic suitability generally decreases as temperatures decline (Hoegh Guldberg et al., 2018), lagged ecosystem responses, regional climate changes, and climate variability imply that persistence in exposure risks to vector-borne diseases cannot be ruled out.

Given the current evidence, it is reasonable to err towards categorizing most human health impacts of climate change as reversible, at least within the scope of what is captured in existing damage estimates.

Beyond human health, there are issues of labor productivity and human capital formation. The former is likely reversible, as this loss is driven by higher temperatures and humidity which decline with temperature if we ignore the regional variation discussed earlier. It is less clear with the latter, which could have impacts that are both path dependent and characterized by hysteresis (i.e., through school disruptions, cognitive delay and impairment, and nutritional constraints affecting human capital formation), though we am unaware of any damage functions including impacts of climate change on human capital. Moreover, some of these human capital impacts are likely partially captured by morbidity impact estimates, which as discussed above, account for the present value of impacts.

Non-Market - Ecosystem

Ecosystems and biodiversity will clearly experience irreversible loss. Higher temperatures will cause biodiversity loss from increased extinction risk. Beyond initial extinction, many species will experience higher risks of extinction and loss, potentially for centuries in some cases. Of note, ocean ecosystems are slower to respond to temperature declines, partially due to the slower response of dissolved oxygen in the water, which limits the return of habitats for centuries. Peak habitat loss potentially occurs 150 years after peak temperature. Even if species do not go extinct, hysteresis implies that, in many cases, ecosystems will not return to their original state as the warming phase of overshoot will give some species – particularly invasive ones – a leg up in competition. In the extreme, species experiencing regional extinction may find it difficult to return to these areas. As ecosystems feed into market sector production, including fisheries into food production, these losses of natural capital will likely result in gross domestic production effects, as discussed earlier (Meyer et al., 2022; Meyer & Trisos, 2023; Morée et al., 2025).

Beyond shifting habitats and species loss, the loss of ecosystems and the extinction of species implies the loss of ecosystem services, non-use value, and relative price shifts. However, the way that the damage function should be adjusted for the permanent loss of this natural capital and its services depends on their valuation. If the loss of ecosystem services is valued in present value terms at the time of impact, such as valuing the loss of natural capital, then the irreversibility of the direct loss is captured in the valuation technique (similar to how the value of statistical life captures the mortality impact). For example, if the present value of species loss is used, then it cannot be counted annually unless multiple species are expected to be lost annually.[3] Instead, if species loss is treated like a hazard increasing in temperature, like tipping points, and/or ecosystems more generally are treated as a service loss (including non-use values like existence and bequest values), then annual damages are lost from climate change, such that damage function can be adjusted for irreversibility or hysteresis. The exception is option value, which is always treated in present value terms, as it is the discrete loss of the corresponding option at the time of extinction.

Beyond the direct loss of ecosystem services themselves, the general and climate-driven decline of ecosystems increases their relative scarcity. When ecosystem loss occurs and market consumption continues to growth, the relative prices of ecosystems rise over time. When this loss is irreversible – such that the growth rate of ecosystems is negative or equal to zero – the relative price increase from these permanent losses is also irreversible. Even though these welfare losses are partially mitigated by substitution to other goods, the economy will experience persistent price increases (Drupp et al., 2024).

It is often unclear to what extent these estimates factor in impacts to environmental goods and services. Many climate damage studies exclude non-market impacts altogether, such as the top-down panel-data and CGE studies. Others include them implicitly – such as scientific based studies and expert elicitation estimates. Only authors of enumerative estimates make clear whether they include impacts to natural capital and how. A review of earlier enumerative assessments found that climate-driven ecosystem losses were often included imprecisely, with biodiversity values and relative prices clearly missing (Howard & Derek, 2016). For example, FUND includes only a "warm-glow effect", while DICE-1999 and DICE-2007 cite Nordhaus' "own unpublished estimates of the capital value of climate sensitive human settlements and natural ecosystems in each sub-region, and estimate that each sub-region has an annual WTP of 1% of the capital value of the vulnerable system for a 2.5 degrees increase." In contrast, the GIVE and DSIC models do not include loss of ecosystem services or natural capital (EPA, 2023). Though recently, Resources

[3] Even then, this does not seem to be the right dynamic, as there is a limit to species that will be impacted by a temperature change and species will adapt over time.

for the Future estimated the non-use value of biodiversity loss, though its contribution to the SCC is relatively small compared to health and labor productivity impacts(Wingenroth et al., 2024).

Climate Tipping Points

In contrast, non-linear tipping points and elements are often treated as effectively irreversible on human timescales, particularly in integrated assessment models. Some tipping points becoming increasingly likely as temperature increases approach and exceed 1.5ºC (Armstrong McKay et al., 2022). Other tipping points that are sensitive to interacting human pressures – such as the Amazon, boreal forests, and reefs – may remain more vulnerable to non-climate stressors (i.e., triggers). Some slower moving tipping elements may not become strictly irreversible, but their long adjustment times imply that they are practically irreversible from a human perspective (Armstrong McKay et al., 2022; Meyer et al., 2022; Reisinger et al., 2025).

Some tipping points involve carbon cycle feedbacks that amplify warming and/or weaken climate sinks, making returning to the 1.5ºC target more difficult and require increasing reliance on carbon removal, which in turn generate additional ecological impacts. However, IAMs often treat this warming as reversible, except to the extent that they capture the domino effect of tipping point reflected in earlier stochastic dynamic integrated assessment models(Cai et al., 2016; Lemoine & Traeger, 2016).

For aggregate damage functions, it is a reasonable starting point to treat the portion attributable to tipping points as effectively irreversible on the time scale relevant for human and policy decision-making.

Social Tipping Points

In contrast to climate tipping points, social tipping points are generally not explicitly included in the damage function of integrated assessment models or the wider set of global damage estimates. Social tipping dynamics and feedback effects include migration, violence and conflict, and social and political unrest and instability, as well as broader social feedback mechanisms (Howard & Livermore, 2019; Kopp et al., 2016). Irreversibility and hysteresis are likely to arise with these climate-driven social non-linearities.

Migration networks formed during climate-driven displacement can reduce information, transaction, and psychological costs of further migration creating persistence in migration flows, such that destination-specific pull factors and network effects even when temperature and climate-related push factors decline. Moreover, migrants do not necessarily return after temperatures stabilize following overshoot, as individuals and households establish economic and social ties to new locations. These ties may also reduce the psychological and economic costs associated with migration (Entwisle et al., 2020; Howard & Livermore, 2021).

Similarly, conflict and political or social instability are complex phenomena driven by many factors beyond climate stress. These disturbances triggered or amplified by climate shocks may persistent even after the climate trigger is reduced following peak warming. These disturbances may also generate additional social feedback effects – including governance disruptions, military intervention, or other social reinforcing dynamics –making it difficult to determine the ultimate magnitude and reversibility of their impacts (Howard & Livermore, 2019; Howard & Livermore, 2021).

At present, almost no global climate damage estimates explicitly incorporate social tipping point dynamics. One partial exception is migration in the FUND model, as it captures migration as an impact pathway, However, it does not capture the feedback dynamics associated with the establishment of migration networks and potential subsequent social responses.

Adaptation

It should be recognized that there are potential mitigating factors that may erode the persistence of impacts over time. Beyond changes in substitution possibilities, discussed above, generational turnover, adaptation, and technological innovation may reduce persistence and increase the reversibility of damages. Generational turnover could potentially diminish non-use values over time, as evidence suggests that willingness to pay for environmental services and their conservation is strongly reference dependent (Papworth et al., 2009; Sáenz-Arroyo et al., 2005; Soga & Gaston, 2018; Viscusi & Huber, 2012). Similarly, the psychological and economic costs associated with migration may decline over time, particularly across generations. Adaptation may reduce persistent costs, particularly if additional warming in overshoot scenarios induces additional adaptation responses (Reisinger et al., 2025). Likewise, technological innovation may relax constraints by enabling greater substitution or reducing welfare losses associated with irreversible changes, particularly if they enable reversibility of currently irreversible impacts. However, overshoot scenarios may also exceed adaptation limits or eliminate green adaptation options (Schleussner et al., 2024), thereby reinforcing or generating additional irreversiblities. Even so, current global damage estimates may omit adaptation effects or imply that adaptation costs are substantial, such that modeling these effects may not be possible or advisable for now (Howard & Sterner, 2025).

SM1.3. What is the potential approximate share of damages being irreversible?

To provide some rough estimate on plausible levels of damage irreversibility we need to simplify, and for example neglect the time dynamics of potential triggers. Weassume that the following impacts are irreversible, partially reversible, and reversible. Specifically,

- Reversible:
  - Health impacts
  - Labor productivity
  - Other market impacts (other than sea-level rise, fisheries, forestry, and agriculture)
- Irreversible
  - Sea-level rise
  - Climate tipping points
  - Ecosystem service losses
  - Fisheries
- Partially reversible:
  - Agriculture / Forestry
- Non-included: in current damages
  - Social tipping points
  - Adaptation
  - Wildfire smoke

Based on this classification and the above analysis, we can roughly break down specific damage estimates into reversible, irreversible, and partially reversible components. For example, based on the breakdown of the relative contribution of sectors to the SCC by the EPA(2023), we approximate that roughly 1% to 48% of GIVE's damage estimate is irreversible depending on the classification of agriculture(EPA, 2023). In contrast, in the DSCIM model, only 1% to 3% is irreversible. The breakdown of Howard and Sterner (2017) is much more complicated, as it requires the inclusion of additional structural control variables for health or biodiversity, sea-level rise, and agriculture. However, when we include these controls in Howard and Sterner (2025) – one by one or in groups – we find that the variables are highly collinear with existing controls, resulting in unstable coefficients and often incorrect coefficient signs. For Howard and Sterner (2025), we find similar – if not worse – identification issues. This indicates that sub-diving the Howard and Sterner regressions to a sector level is unadvisable.

An alternative approach is to analyze sector impacts across several enumerative and CGE models for which damage estimates are available at this scale. Tol (2024) breaks down five enumerative damage estimates and four CGE damages estimates corresponding to a 2.5°C increase. He sub-divides these estimates into multiple market sectors – agriculture, forestry, energy, water tourism, other market / labor productivity, and sea level rise (coastal defense, dryland, wetland) – non-market sectors (ecosystems, health, air pollution, time use, settlements, migration, and amenities) – and catastrophic impacts. As sector coverage is incomplete, Tol imputes the missing sectoral impact estimates using the average across all studies that value this impact. Using these estimates, we classify sectors into reversible (energy, water, tourism, other market / labor productivity, health, air pollution, time use, and amenity), irreversible (sea-level rise, ecosystem, settlements, migration, and catastrophic), and potentially irreversible (agriculture and forestry). Accounting for only non-catastrophic impacts and only including potentially irreversible in the upper bound estimate of irreversible, we find that on average 28% to 38% of climate damage estimates are irreversible, with the lowest estimate at 21% and the highest estimate at 53%. If we include catastrophic impacts, this range shifts to 34% to 42% with low and high estimates of 26% and 65%, respectively. These estimates are rough approximations, as every market and non-market impact is only partially reversible and partially reversible, but to varying extents.

Table S1. Estimate of potentially irreversible component of damages based on Tol (2024)

Sector Paper	Fankhauser	Berz	Tol	Nordhaus	Bosello	Dellink	Sartori	Kompas	Takakura	Average
Non-Cat Irriversibility- Lower	27%	26%	29%	40%	34%	21%	40%	26%	20%	28%
Non-Cat Irriversibility - Upper	36%	34%	34%	47%	53%	43%	47%	35%	20%	38%
Total Irriversibility- Lower	27%	26%	29%	61%	40%	26%	47%	31%	20%	34%
Total Irriversibility - Upper	36%	35%	34%	65%	58%	46%	53%	39%	20%	42%

Using Table 3 in Tol (2024), we can use the average sector breakdown of damages by sector for enumerative and CGE estimates to allocate impacts market and non-market impacts in Howard and Sterner (2017) and Howard and Sterner (2025) to reversible and irreversible (see table 1). According to the average Tol (2024) estimates, 18% of market damage estimates correspond to irreversible sea-level rise impacts and 16% to potentially irreversible impacts to agriculture and forestry. In contrast, 42% of non-market impacts are irreversible. Finally, 100% of climate tipping points are irreversible impacts. Weighing only market and non-market impacts from the Howard and Sterner (2017) meta-regression, we find that the range of damages impacts that are irreversible is between 38% to 41%, while the range is 21% to 36% in Howard and Sterner (Howard & Sterner, 2025). Accounting for catastrophic impacts, these ranges increase to 54% to 56% in Howard and Sterner (2017) and 61% to 68% in Howard and Sterner (2025). As noted above, these approximations are very rough and should only be used to provide a rough guide on the approximate value.

SM2: Detailed analytical derivations

Section SM2 provides additional details on the analytical derivations presented in the main paper.

Let *X* denote a climate forcer emitted as a marginal pulse in calendar year τ_0. The social cost of this pulse, $SCX(\tau_0)$, is the present value of the incremental damages caused by the pulse. We denote by $T(\tau)$ the global mean background temperature pathway in calendar year τ, and by $\Delta T_X(t)$ the incremental temperature response *t* years after the pulse. Thus, the calendar year corresponding to time *t* after the pulse is $\tau = \tau_0 + t$.

For the analytical derivation, we assume that $\Delta T_X(t)$ is independent of the calendar year in which the pulse occurs and independent of the climate state. This abstracts from nonlinearities in perturbation lifetimes and concentration-forcing relationships. These nonlinearities are included in the numerical model, but they are not needed for the conceptual mechanisms illustrated here.

The general expression for the social cost can be written as:

$$SCX(\tau_0) = \int_0^{\infty} \Big(D\big(T(\tau_0 + t) + \Delta T_X(t)\big) - D\big(T(\tau_0 + t)\big) \Big) \cdot B(\tau_0, t)\, dt \qquad \text{(S1)}$$

where $D\big(T(\tau_0 + t) + \Delta T_X(t)\big) - D\big(T(\tau_0 + t)\big)$ is the incremental damage in year $\tau_0 + t$ caused by the pulse emitted in year τ_0, and $B(\tau_0, t)$ is the discount factor from year τ_0 to year $\tau_0 + t$, which is

$$B(\tau_0, t) = e^{-\int_{\tau_0}^{\tau_0 + t} r(s)\, ds} \qquad \text{(S1a)}$$

where $r(s)$ is the discount rate in calendar year *s*.

We next insert the asymmetric damage formulation used in the main text (equation 1). τ_{peak} denote the calendar year in which the background temperature pathway reaches its peak, and let $T_{peak} = T(\tau_{peak})$ denote the peak temperature. For a pulse emitted before the peak, we define $t_{peak} = \tau_{peak}$ - τ_0, i.e., the number of years from the emission pulse to the temperature peak. We assume that the pulse is marginal and therefore does not affect the timing of the peak year, τ_{peak}. With a quadratic damage share and an irreversible damage fraction *α*, the social cost can be decomposed into three components:

$$SCX(\tau_0) = I_{\text{pre}} + (1-\alpha)\cdot I_{\text{rev}} + \alpha \cdot I_{\text{irr}} \tag{S2}$$

The pre-peak component is:

$$I_{\text{pre}} = \int_0^{t_{peak}} \varphi \cdot \left(\left(T(\tau_0+t) + \Delta T_X(t)\right)^2 - T(\tau_0+t)^2\right) \cdot Y(\tau_0+t) \cdot e^{-\int_{\tau_0}^{\tau_0+t} r(s)\,ds}\, dt \tag{S2a}$$

The reversible post-peak component is:

$$I_{\text{rev}} = \int_{t_{peak}}^{\infty} \varphi \cdot \left(\left(T(\tau_0+t) + \Delta T_X(t)\right)^2 - T(\tau_0+t)^2\right) \cdot Y(\tau_0+t) \cdot e^{-\int_{\tau_0}^{\tau_0+t} r(s)\,ds}\, dt \tag{S2b}$$

The irreversible post-peak component is:

$$I_{\text{irr}} = \int_{t_{peak}}^{\infty} \varphi \cdot \left(\left(T_{peak} + \Delta T_X\left(t_{peak}\right)\right)^2 - T_{peak}^2\right) \cdot Y(\tau_0+t) \cdot e^{-\int_{\tau_0}^{\tau_0+t} r(s)\,ds}\, dt \tag{S2c}$$

The key distinction is that the reversible post-peak component, i.e. equation 7b, depends on the temperature response of the pulse in each future year, $\Delta T_X(t)$, whereas the irreversible component, equation 7c, depends on the effect of the pulse on the peak temperature, $\Delta T_X\left(t_{peak}\right)$. This follows directly from the assumption that irreversible damages remain tied to the damage level reached at the peak.

We now impose the additional simplifications used to obtain the expression in the main text. In the analytical model, global population is assumed to be constant, global GDP grows at a constant annual rate *g*, and the savings rate in the economy is fixed. These assumptions imply that per capita consumption grows at the same rate as economic output. With Ramsey discounting, $r(t) = \eta \cdot g(t) + \delta$, and with $\eta = 1$, the growth term in future output exactly offsets the consumption-growth component of the discount rate. Hence:

$$Y(\tau_0+t) \cdot e^{-\int_{\tau_0}^{\tau_0+t} r(s)\,ds} = Y(\tau_0) \cdot e^{gt} \cdot e^{-(g+\delta)\cdot t} = Y(\tau_0) \cdot e^{-\delta t} \tag{S3}$$

We also linearize the damage share around the background temperature pathway. For a small temperature perturbation, the marginal change in the quadratic damage share is:

$$\left(\varphi \cdot \left(T(\tau_0+t) + \Delta T_X(t)\right)^2 - \varphi \cdot T(\tau_0+t)^2\right) \approx \left(2 \cdot \varphi \cdot T(\tau_0+t) \cdot \Delta T_X(t)\right) \tag{S4}$$

and equivalently for the irreversible part of the damage function.

Applying equations (S3), and (S4) to equation (S2) yields the analytical expression for a pulse emitted before the temperature peak:

$$SCX(\tau_0) = 2 \cdot \varphi \cdot Y(\tau_0) \cdot \left(J_{\text{pre}} + (1-\alpha) \cdot J_{\text{rev}} + \alpha \cdot J_{\text{irr}}\right) \tag{S5}$$

where:

$$J_{\text{pre}} = \int_0^{t_{peak}} T\,(\tau_0 + t) \cdot \Delta T_X(t) \cdot e^{-\delta t}\, dt \tag{S5a}$$

$$J_{\text{rev}} = \int_{t_{peak}}^{\infty} T\,(\tau_0 + t) \cdot \Delta T_X(t) \cdot e^{-\delta t}\, dt \tag{S5b}$$

$$J_{\text{irr}} = T_{peak} \cdot \Delta T_X(p) \cdot \int_{t_{peak}}^{\infty} e^{-\delta t}\, dt \tag{S5c}$$

Equation (S5) corresponds to equation 2 in the main text for emissions occurring before the temperature peak. It shows that irreversibility adds a post-peak damage term that is proportional to the effect of the pulse on peak temperature, rather than to its subsequent temperature response.

For comparison, if damages are fully reversible, $\alpha = 0$, the social cost is:

$$SCX(\tau_0) \approx 2 \cdot \varphi \cdot Y(\tau_0) \cdot \int_0^{\infty} T\,(\tau_0 + t) \cdot \Delta T_X(t) \cdot e^{-\delta t}\, dt \tag{S6}$$

This corresponds to the reversible-damages expression, equation 3, presented in the main text.

Finally, consider a marginal pulse emitted after the temperature peak, in calendar year $\tau_0 > \tau_{peak}$. A fraction of the damages are locked into and determined by peak temperature so an additional pulse after the peak does not affect the irreversible damage component. The social cost is therefore determined only by the reversible damage component:

$$SCX(\tau_0) \approx 2 \cdot \varphi \cdot Y(\tau_0) \cdot (1-\alpha) \cdot \int_0^{\infty} T\,(\hat{\tau} + t) \cdot \Delta T_X(t) \cdot e^{-\delta t}\, dt \tag{S7}$$

This corresponds to the post-peak expression, equation 4, presented in the main text.

SM3: Background information regarding the temperature impulse response for different GHGs and forcers

The temperature response $\Delta T_X(t)$ to an emission pulse of a GHG (or forcing pulse) X is critical for its social cost. Both the magnitude and the temporal dynamics of the response matter.

Based on the model used for calculating GWP and GTP values in the sixth assessment report of the IPCC (Forster et al., 2021) as implement in Persson & Johansson (2022) we calculate, for illustrative purposes, the temperature impulse response for an emission pulse of CO_2 and CH_4 as well as for a one year forcing pulse for contrail cirrus. For the contrail cirrus forcing, expressed in gigajoules (GJ) of efficacy-adjusted energy forcing, where energy forcing is the cumulative radiative effect (Johansson et al., 2025), the temperature response increases during the year the pulse occurs and then declines according to the time scales of the two-box energy balance model (EBM), see figure S1. The time scales in the EBM include a rapid component, associated with the mixing time of the well-mixed upper ocean, typically less than a decade, and a slower, smaller response linked to deep-ocean mixing, which operates on century-long time scales.

In the case of a CH_4 emission pulse, the temperature response is more prolonged than that of contrail cirrus, since the atmospheric concentration of CH_4 decays with a response time of roughly 12 years rather than the annual forcing step that was applied adopted for contrail cirrus. As for contrails cirrus, the thermal inertia of the climate system prolongs the temperature impacts of a CH_4 emissions pulse, see figure S1. As long as the radiative forcing generated by the emission pulse exceeds the increase in outgoing longwave radiation caused by the induced temperature impact, the global temperature will continue to rise. However, once the forcing diminishes below that value, the temperature begins to decline. By contrast, a CO_2 emission pulse produces a largely irreversible temperature response due to its very long perturbation lifetime and the slow time scales associated with the CO_2 sink and the deep-ocean heat exchange, see figure S1.

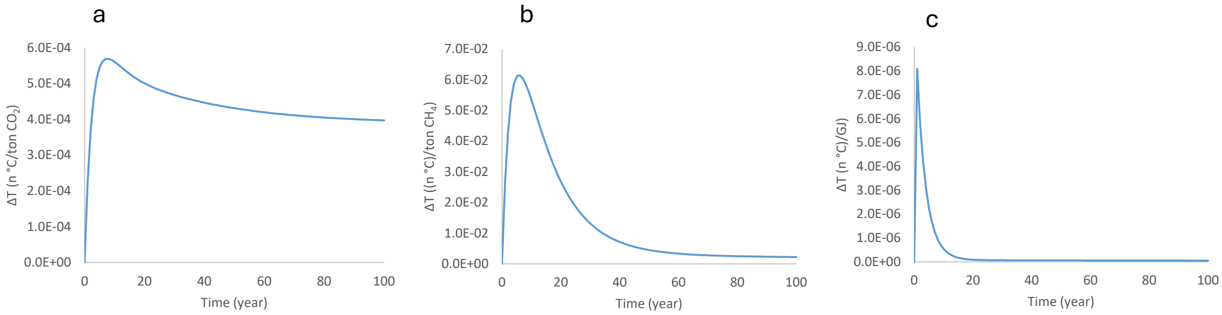

Figure S1. *Illustration of temperature response of CO_2 (panel a) and CH_4 (panel b) emission pulses as well as an annual averaged contrail cirrus forcing pulse (panel c).*

SM4: Sensitivity analysis with respect to choice of discount rate

As found in previous studies on the ratio of SCM and SC-contrail to SCC, its value is sensitivity to the choice of discount rate (Azar et al., 2023; Johansson et al., 2025). For this reason, we analyze the ratio of SCM and SC-contrail to SCC, respectively under a set of different discount rate. We use the original Ramsey discount rate approach in the original version of DICE-2016R2 (Nordhaus, 2018), using $\eta = 1.45$ and $\delta = 1.5\%/$ yr, which implies an average discount rate of approximately 4.3%/yr on average from 2020 to 2100, but it varies over time depending on the consumption growth rate. For comparison, we include also results for three different constant discount rates being 2%/yr, 4%/yr and 6%/yr. Note that the discount rates are only applied when estimating the social cost values, the emission pathways as such remain the same.

As shown in Figures S2 and S3, a higher discount rate increases the ratios SCM/SCC and SC-contrail/SCC, since the net presentation valuation of long-term climate damages decreases with an increasing discount rate. Hence, we value the short-lived climate damages relatively more the higher the discount rate is. This holds for both pathways and for all the three assumptions on the level of damage irreversibility.

This dependence on the discount rate is particularly pronounced (in relative terms) when damages are either fully reversible or when the emission pulse or contrail forcing pulse occurs well before the temperature peak in cases with damage irreversibility. By contrast, for pulses occurring close to the peak and when damages are irreversible, the discount rate has a more limited influence on these relative social cost measures. If the damage irreversibility fraction is large the social cost ratios are related to their relative peaks in the temperature impulse response functions.

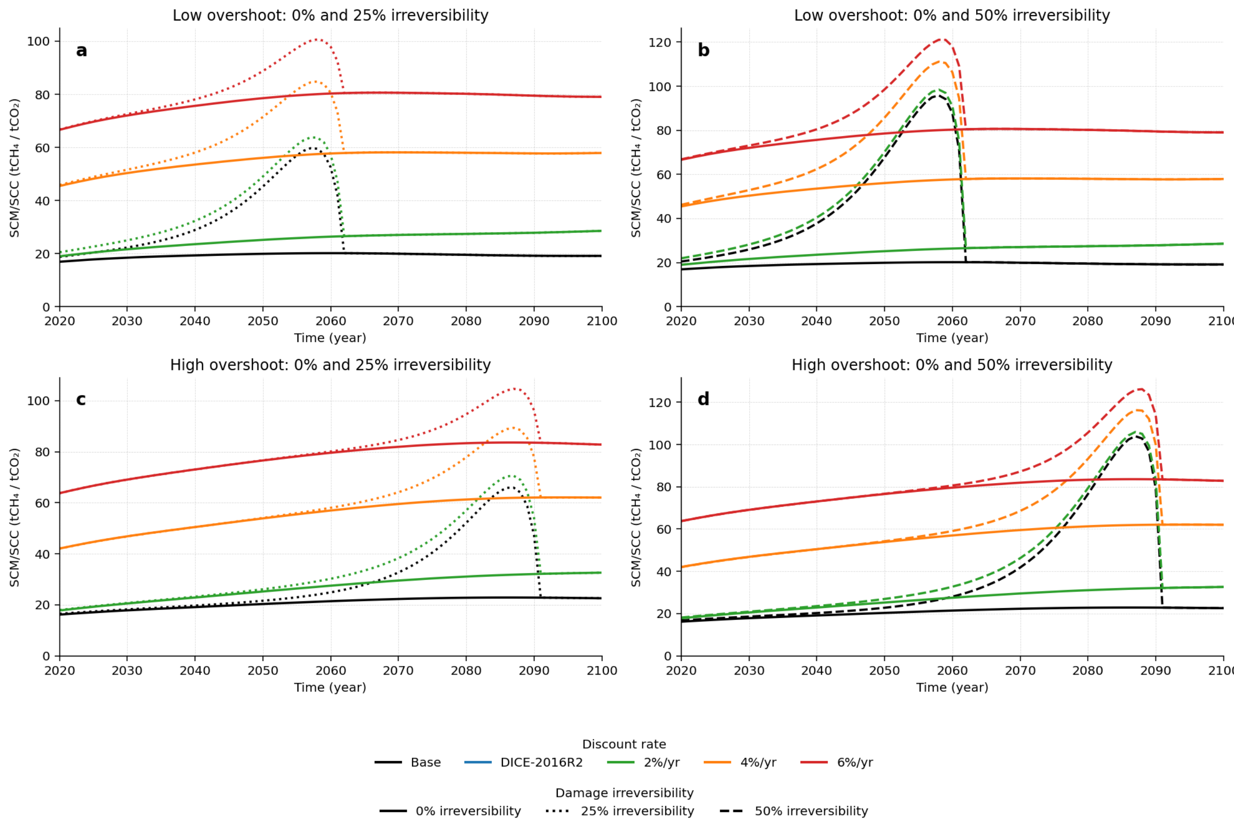

Figure S2. *Ratio of SCM to SCC across temperature pathways and discounting assumptions. The top row (a–b) shows low-overshoot pathways and the bottom row (c–d) large-overshoot pathways. Columns vary the degree of damage irreversibility (0% and 25% in a, c; 0% and 50% in b, d). Colored lines indicate discount rate schemes, and line styles denote irreversibility assumptions.*

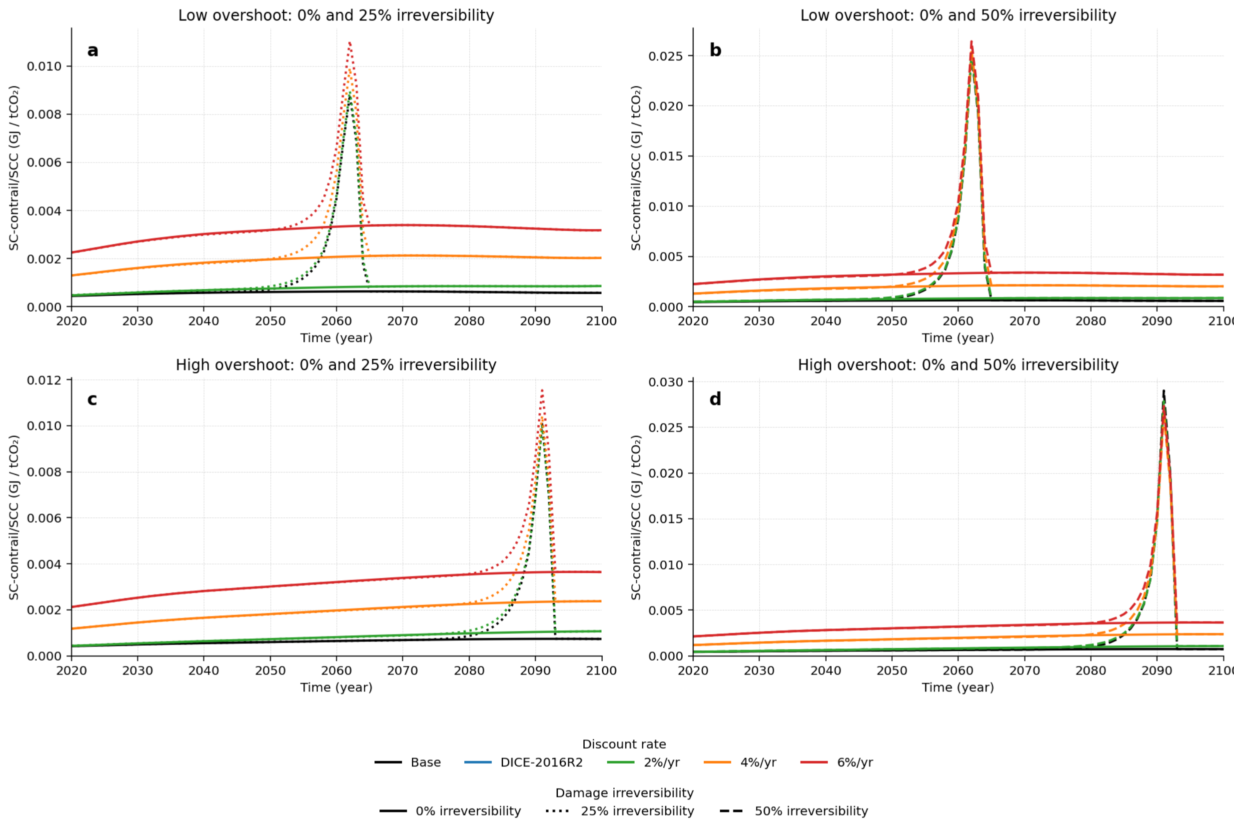

Figure S3. *Ratio of SC-contrail to SCC across temperature pathways and discounting assumptions. The top row (a–b) shows low-overshoot pathways and the bottom row (c–d) large-overshoot pathways. Columns vary the degree of damage irreversibility (0% and 25% in a, c; 0% and 50% in b, d). Colored lines indicate discount rate schemes, and line styles denote irreversibility assumptions.*

References

Al Khourdajie, A., Andrijevic, M., Byers, E., Pathak, M., Pirani, A., Schleussner, C.-F., & Stuart-Smith, R. (2026). Overshoot pathways of 1.5 C: reversible biophysical change, irreversible socioeconomic impacts.

Armstrong McKay, D. I., Staal, A., Abrams, J. F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S. E., Rockström, J., & Lenton, T. M. (2022). Exceeding 1.5 C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), eabn7950.

Azar, C., Martín, J. G., Johansson, D. J., & Sterner, T. (2023). The social cost of methane. *Climatic Change*, *176*(6), 71.

Buhr, L., Lenzi, D. S., Pols, A. J., Brunner, C. E., Fischer, A., Staal, A., Hofbauer, B. P., & Bovenkerk, B. (2025). The concepts of irreversibility and reversibility in research on anthropogenic environmental changes. *PNAS nexus*, *4*(1), pgae577.

Cai, Y., Lenton, T. M., & Lontzek, T. S. (2016). Risk of multiple interacting tipping points should encourage rapid CO2 emission reduction. *Nature Climate Change*, *6*(5), 520-525.

Drupp, M., Hänsel, M. C., Fenichel, E., Freeman, M., Gollier, C., Groom, B., Heal, G., Howard, P., Millner, A., & Moore, F. (2024). Accounting for the increasing benefits from scarce ecosystems. *Science*, *383*(6687), 1062-1064.

Entwisle, B., Verdery, A., & Williams, N. (2020). Climate change and migration: New insights from a dynamic model of out-migration and return migration. *American Journal of Sociology*, *125*(6), 1469-1512.

EPA, U. (2023). Epa report on the social cost of greenhouse gases: Estimates incorporating recent scientific advances. In: US Environmental Protection Agency Washington DC.

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D. J., Mauritsen, T., Palmer, M. D., Watanabe, M., Wild, M., & Zhang, H. (2021). The Earth's Energy Budget, Climate Feedbacks, and Climate Sensitivity. In V. Masson-

Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 923-1054). Cambridge University Press. https://doi.org/10.1017/9781009157896.009

Golub, A., & Brody, M. (2017). Uncertainty, climate change, and irreversible environmental effects: application of real options to environmental benefit-cost analysis. *Journal of Environmental Studies and Sciences*, *7*(4), 519-526. https://doi.org/10.1007/s13412-017-0436-7

Hoegh Guldberg, O., Jacob, D., Taylor, M., Bindi, M., Brown, S., Camilloni, I. A., Diedhiou, A., Djalante, R., Ebi, K. L., & Engelbrecht, F. (2018). Impacts of 1.5 C global warming on natural and human systems.

Hope, C. (2013). Critical issues for the calculation of the social cost of CO2: why the estimates from PAGE09 are higher than those from PAGE2002. *Climatic Change*, *117*(3), 531-543.

Howard, P., Golub, A., & Lugovoy, O. (2020). *Option Value and the Social Cost of Carbon: What Are We Waiting For?* [Working Paper]. https://policyintegrity.org/publications/detail/option-value-and-the-social-cost-of-carbon-what-are-we-waiting-for

Howard, P., & Livermore, M. A. (2019). Sociopolitical feedbacks and climate change. *Harv. Envtl. L. Rev.*, *43*, 119.

Howard, P. H., & Derek, S. (2016). The Wisdom of the Economic Crowd: Calibrating Integrated Assessment Models Using Consensus.

Howard, P. H., & Livermore, M. A. (2021). Climate 聃 Society Feedback Effects: Be Wary of Unidentified Connections. *International Review of Environmental and Resource Economics*, *15*(1-2), 33-93.

Howard, P. H., & Sterner, T. (2017). Few and not so far between: a meta-analysis of climate damage estimates. *Environmental and Resource Economics*, *68*(1), 197-225.

Howard, P. H., & Sterner, T. (2025). Methodology matters: A careful meta-analysis of climate damages. *Environmental and Resource Economics*, 1-39.

Johansson, D. J., Azar, C., Pettersson, S., Sterner, T., Stettler, M. E., & Teoh, R. (2025). The social costs of aviation CO2 and contrail cirrus. *Nature Communications*, *16*(1), 8558.

Jones, A. R., Orton, T. G., & Dalal, R. C. (2016). The legacy of cropping history reduces the recovery of soil carbon and nitrogen after conversion from continuous cropping to permanent pasture. *Agriculture, Ecosystems & Environment*, *216*, 166-176.

Kabato, W., Hailegnaw, N., Mutum, L., & Molnar, Z. (2025). Managing soil health for climate resilience and crop productivity in a changing environment. *Science of The Total Environment*, *1000*, 180460.

Kikstra, J. S., Waidelich, P., Rising, J., Yumashev, D., Hope, C., & Brierley, C. M. (2021). The social cost of carbon dioxide under climate-economy feedbacks and temperature variability. *Environmental Research Letters*, *16*(9), 094037.

Kim, H.-J., Kim, J.-S., An, S.-I., Shin, J., Oh, J.-H., & Kug, J.-S. (2024). Pervasive fire danger continued under a negative emission scenario. *Nature Communications*, *15*(1), 10010.

Kim, S.-K., Shin, J., An, S.-I., Kim, H.-J., Im, N., Xie, S.-P., Kug, J.-S., & Yeh, S.-W. (2022). Widespread irreversible changes in surface temperature and precipitation in response to CO2 forcing. *Nature Climate Change*, *12*(9), 834-840.

Kim, Y., Min, S.-K., An, S.-I., Paik, S., & Mondal, S. K. (2026). Responses of extreme fire weather to CO2 emission reductions and underlying mechanisms. *Science Advances*, *12*(2), eadw4705.

Kopp, R., Gilmore, E., & Shwom, R. (2025). Climate change will surprise us, but so-called ‘tipping points’ may lead us astray. *Bulletin of the Atomic Scientists*, *81*(2), 121-125.

Kopp, R. E., Gilmore, E. A., Shwom, R. L., Adams, H., Adler, C., Oppenheimer, M., Patwardhan, A., Russill, C., Schmidt, D. N., & York, R. (2025). ‘Tipping points’ confuse and can distract from urgent climate action. *Nature Climate Change*, *15*(1), 29-36.

Kopp, R. E., Shwom, R. L., Wagner, G., & Yuan, J. (2016). Tipping elements and climate–economic shocks: Pathways toward integrated assessment. *Earth's Future*, *4*(8), 346-372.

Kruczkiewicz, A., Zommers, Z., Kimutai, J., Garschagen, M., Fisher, J., & Severnini, E. (2025). The human and social impacts of climate overshoot. *PNAS nexus*, *4*(11), pgaf332.

Lemoine, D., & Traeger, C. (2014). Watch Your Step: Optimal Policy in a Tipping Climate. *American Economic Journal: Economic Policy*, *6*(1), 137-166. https://doi.org/10.1257/pol.6.1.137

Lemoine, D., & Traeger, C. P. (2016). Economics of tipping the climate dominoes. *Nature Climate Change*, *6*(5), 514-519. https://doi.org/10.1038/nclimate2902

Meyer, A. L., Bentley, J., Odoulami, R. C., Pigot, A. L., & Trisos, C. H. (2022). Risks to biodiversity from temperature overshoot pathways. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *377*(1857).

Meyer, A. L., & Trisos, C. H. (2023). Ecological impacts of temperature overshoot: the journey and the destination. *One Earth*, *6*(12), 1614-1617.

Moon, M., Min, S.-K., Chu, J.-E., An, S.-I., Son, S.-W., Ramsay, H., & Wang, Z. (2025). Tropical cyclone response to ambitious decarbonization scenarios. *NPJ climate and atmospheric science*, *8*(1), 228.

Morée, A. L., Lacroix, F., Cheung, W. W., & Frölicher, T. L. (2025). Long-term impacts of global temperature stabilization and overshoot on exploited marine species. *Biogeosciences*, *22*(4), 1115-1133.

Nordhaus, W. (2018). Projections and uncertainties about climate change in an era of minimal climate policies. *American Economic Journal: Economic Policy*, *10*(3), 333-360.

Papworth, S. K., Rist, J., Coad, L., & Milner-Gulland, E. J. (2009). Evidence for shifting baseline syndrome in conservation. *Conservation letters*, *2*(2), 93-100.

Persson, U. M., & Johansson, D. J. A. (2022). Simple climate model (2.0). In: Zenodo.

Qiu, M., Callahan, C. W., Higuera-Mendieta, I., Rennels, L., Parthum, B., Diffenbaugh, N. S., & Burke, M. (2026). Valuing wildfire smoke–related mortality benefits from climate mitigation. *Proceedings of the National Academy of Sciences*, *123*(8), e2533772123.

Reisinger, A., Fuglestvedt, J. S., Pirani, A., Geden, O., Jones, C. D., Maharaj, S., Poloczanska, E. S., Morelli, A., Johansen, T. G., & Adler, C. (2025). Overshoot: A Conceptual Review of Exceeding and Returning to Global Warming of 1.5° C. *Annual Review of Environment and Resources*, *50*.

Reisinger, A., & Geden, O. (2023). Temporary overshoot: origins, prospects, and a long path ahead. *One Earth*, *6*(12), 1631-1637.

Sáenz-Arroyo, A., Roberts, C. M., Torre, J., Cariño-Olvera, M., & Enríquez-Andrade, R. R. (2005). Rapidly shifting environmental baselines among fishers of the Gulf of California. *Proceedings of the Royal Society B: Biological Sciences*, *272*(1575), 1957.

Schleussner, C.-F., Ganti, G., Lejeune, Q., Zhu, B., Pfleiderer, P., Prütz, R., Ciais, P., Frölicher, T. L., Fuss, S., & Gasser, T. (2024). Overconfidence in climate overshoot. *Nature*, *634*(8033), 366-373.

Schuster, L., Maussion, F., Rounce, D. R., Ultee, L., Schmitt, P., Lacroix, F., Frölicher, T. L., & Schleussner, C.-F. (2025). Irreversible glacier change and trough water for centuries after overshooting 1.5° C. *Nature Climate Change*, 1-8.

Soga, M., & Gaston, K. J. (2018). Shifting baseline syndrome: causes, consequences, and implications. *Frontiers in Ecology and the Environment*, *16*(4), 222-230.

Steinert, N. J., Schwinger, J., Chadwick, R., Kug, J. S., & Lee, H. (2025). Irreversible land water availability changes from a potential ITCZ shift during temperature overshoot. *Earth's Future*, *13*(5), e2024EF005787.

Tol, R. S. (2024). A meta-analysis of the total economic impact of climate change. *Energy Policy*, *185*, 113922.

Vindušková, O., Deckmyn, G., Reynaert, S., Vancampenhout, K., Schlüter, S., Frouz, J., De Boeck, H., Portillo-Estrada, M., Verbruggen, E., & Asard, H. (2025). More persistent precipitation regimes induce soil degradation. *Geoderma*, *455*, 117230.

Viscusi, W. K., & Huber, J. (2012). Reference-dependent valuations of risk: Why willingness-to-accept exceeds willingness-to-pay. *Journal of Risk and Uncertainty*, *44*(1), 19-44.

Wang, T. (2024). Distinguishing short-term and long-term climate impacts in damage functions. *Environmental Research: Climate*, *3*(4), 041007.

Wingenroth, J., Prest, B. C., Rennels, L., Rennert, K., Errickson, F., & Anthoff, D. (2024). *Accounting for Biodiversity Loss Raises the Social Cost of CO2*.

Yumashev, D., Hope, C., Schaefer, K., Riemann-Campe, K., Iglesias-Suarez, F., Jafarov, E., Burke, E. J., Young, P. J., Elshorbany, Y., & Whiteman, G. (2019). Climate policy implications of nonlinear decline of Arctic land permafrost and other cryosphere elements. *Nature Communications*, *10*(1), 1900.