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ESD Ideas: Climate tipping is not instantaneous – the duration of an overshoot matters

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Abstract. Climate Tipping Points are not instantaneous upon crossing critical thresholds in global warming, as is often assumed. Instead, it is possible to temporarily overshoot a threshold without causing tipping, provided the duration of the overshoot is short. In this Idea, we demonstrate that restricting the time over 1.5^{o}C would considerably reduce tipping point risks.

Many elements of the climate system are susceptible to undergoing large and abrupt changes often referred to as tipping points (Lenton et al., 2008). Exceeding a critical threshold for a sufficiently long period of time will cause tipping and may lead to damaging impacts both regionally and globally (Lenton et al., 2019; Ritchie et al., 2020; Armstrong McKay et al., 2022).

Panel (a) of Figure 1 shows the different elements of the climate system that would undergo tipping for each level of stabilised global warming, based on the warming thresholds provided in a recent assessment of climate tipping points (Armstrong McKay et al., 2022). Die-off of low latitude coral reefs, abrupt thaw of boreal permafrost, and collapse of the West Antarctic and Greenland ice sheets all have a best estimate for their thresholds at the lower end of the Paris Climate Agreement (2015) – 1.5^{o}C warming. A fifth element, the loss of the Barents sea ice, has been estimated to have a threshold at 1.6^{o}C. As a result, all five of these components are considered likely to tip if warming is stabilised at, say, 1.75^{o}C (see range 1.5-2.0^{o}C of Figure 1a). Stabilising warming at the upper end of the Paris Climate Agreement (2015) (2^{o}C) could additionally risk subpolar gyre collapse. Current climate commitments have been estimated to lead to global warming at 2.7 $\pm$ 0.2^{o}C (Climate Action Tracker, 2021), which in addition puts many more mountain glaciers at risk. If climate was only eventually stabilised near to 4^{o}C, around ten major Earth system elements could tip, while a final warming level over 4^{o}C raises the total to fourteen (Figure 1a). Only the collapse of the Arctic Winter sea ice and East Antarctic ice sheet are estimated to have even higher warming thresholds.

However, tipping is not instantaneous upon crossing the tipping threshold. In fact, tipping can still be avoided if the exceedance of a threshold has a short duration compared to the characteristic timescale of the tipping element. Previously, Ritchie et al. (2019) showed that tipping point risk depends on both the threshold temperature and the timescale of the tipping element. Broadly, tipping elements with slow timescales allow overshoots that avoid tipping, whereas, fast tipping elements

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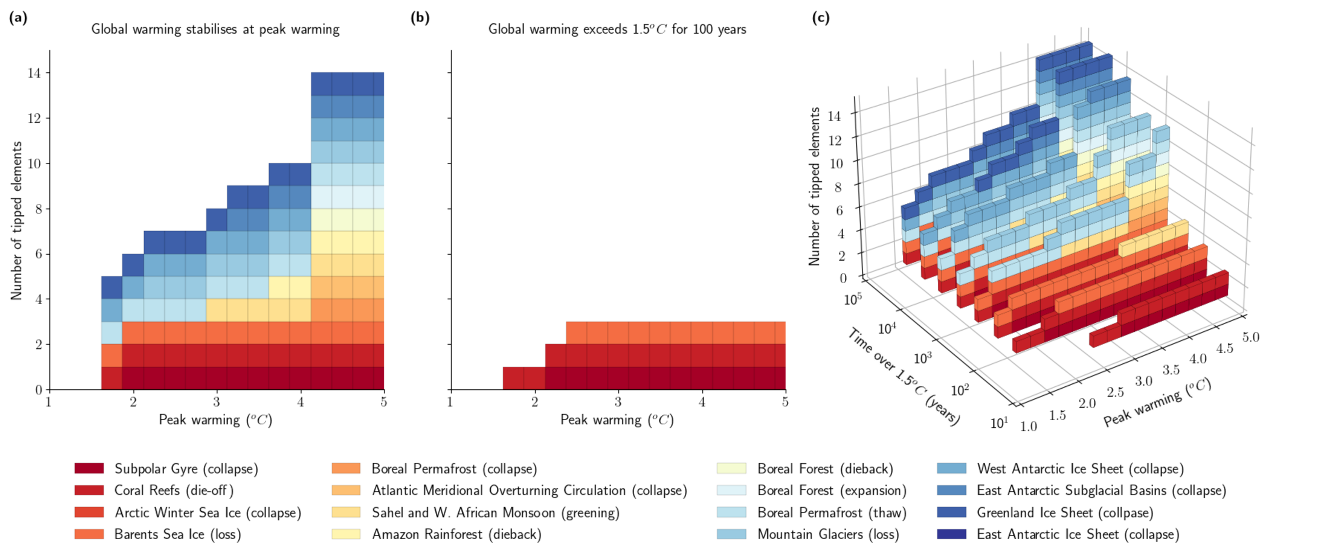

Figure 1. Number of elements of the climate system, binned by increments of 0.25^{o}C, that would undergo tipping for: (a) temperature stabilising; and (b) exceeding 1.5^{o}C for 100 years, for different levels of peak global warming. (c) 3-D projection of number of tipped elements based on the peak global warming and the time over 1.5^{o}C (note, on a logarithmic scale). Tipping elements are colour coded according to their tipping timescale, starting with the fastest tipping elements in red and ending with the slowest in blue. Tipping timescale and threshold values from Armstrong McKay et al. (2022).

leave very little margin for overshoot without tipping Ritchie et al. (2021). Given that the recent comprehensive study of Armstrong McKay et al. (2022) provides estimates of both timescales and critical warming thresholds for a broad set of Earth system components, we can now combine the analyses of Armstrong McKay et al. (2022) and Ritchie et al. (2021), to show the dependency of tipping point risks on both peak global warming and also the duration of exceedance of 1.5^{o}C Our Supplementary Material (Ritchie et al., 2024) details how the theory has been advanced to accommodate both the tipping timescale and exceedence of a predefined temperature (here 1.5^{o}C). Ideally there would also be information about the curvature of the equilibrium branch on the approach to tipping. As this is not yet available, we have assumed this to be identical across tipping elements. Future extensions of Armstrong McKay et al. (2022) may consider deriving the curvature parameter.

Panel (b) of Figure 1 is of identical format to panel (a), except that now warming only remains above 1.5^{o}C for 100 years. Comparing panel (b) to (a), the number of elements that undergo tipping is considerably reduced, and as expected, those that remain have the shortest timescales (coloured red). Three of the five elements with the lowest equilibrium warming thresholds have tipping timescales of order centuries or millennia, which we project to avoid tipping with a 100 year overshoot, even if peak warming reached 5^{o}C. In contrast, the coral reefs and subpolar gyre would still undergo tipping at almost all levels of equilibrium warming or peak warming with overshoot (common, panel (a) and (b)), due to their fast tipping timescales and low temperature thresholds. Tipping of the Barents sea ice, would likely occur if warming is stabilised at 1.75^{o}C (panel (a)). However, if the time over 1.5^{o}C is limited to 100 years, then tipping of the same element would only occur at 2.5^{o}C and above

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(panel (b)). Of the fourteen elements that would tip if warming is stabilised in excess of 4^{o}C, we estimate that only three are likely to tip if overshoot of 1.5^{o}C is limited to 100 years.

Panel (c) provides a 3-D picture of the estimated number of tipped elements for overshoot profiles characterised by both peak warming and time over 1.5^{o}C (panel animation provided as a supplement) Panels (a) and (b) are cross sections of panel (c), namely the left-hand "back wall" and the third row from the right-hand front respectively. Panel (c) demonstrates that the fast tipping elements (red blocks) tip shortly after their thresholds are crossed. These fast tipping elements would only be avoided if overshoot duration is extremely short (only decades over 1.5^{o}C) combined with a small peak overshoot. For example, if the duration of exceedance of 1.5^{o}C is less than 30 years and the peak warming is less than 2.5^{o}C it may be possible to avoid all the tipping elements considered here (shown by the incomplete red bar at the front of panel (c)). In contrast, the slowest tipping elements (blue blocks), are not committed to tip until the time over 1.5^{o}C approaches a thousand years, despite these elements possessing some of the lowest warming thresholds. The accumulation of tipped elements in the back corner of panel (c) is because this is where both peak warming and time over 1.5^{o}C are large.

Our study challenges the conventional wisdom that the commitment to tip occurs as soon as a critical threshold is crossed. Instead, the number of elements that would undergo tipping is severely reduced if the duration of exceedance of the Paris 1.5^{o}C can be kept below a century. Furthermore, this analysis suggests all tipping elements would be avoided if global warming over 1.5^{o}C is restricted to 30 years and peak warming is kept below 2.5^{o}C.

Video supplement. Animation of Figure 1c provided as a supplement.

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