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Characterizing transient temperature trajectories for assessing the value of achieving alternative temperature targets

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Abstract Trajectories of policy-driven transient temperatures are reported here for four different maximum temperature targets through 2100 and a "no-policy" baseline because it is they, and their associated manifestations in other impact and risk dimensions, that natural and human and natural systems see in real time as their common future unfolds. It follows that it is they that inform both the reactive and (for human systems) anticipatory responses that embedded decision-makers would contemplate in the future. Median pathways as well as 5th and 95th percentile alternatives for each set of scenarios are reported in decadal increments from 2010 through 2100. Two illustrations (agricultural yields and Intergovernmental Panel on Climate Change "reasons for concern") are presented to provide provocative context within which to begin to see their potential value across a wide range of applications.

Analyses and assessments of key vulnerabilities to climate change (and opportunities) across the full range of sectors and regions are most effectively and appropriately cast in terms of risk—the products of likelihood and consequence. Limiting increases of global mean temperature to 1.5 or 2.0 °C or even 3.0 °C relative to preindustrial levels would change the likelihood of potential impacts relative to a no-policy world, but climate change is not the only factor that will influence our common future. Intergovernmental Panel on Climate Change (IPCC 2014a, p. 662) correctly noted that the consequence side of the risk calculation will depend on a litany of confounding factors: "population, age, (the distribution of) income, technology, relative prices, lifestyle, regulation, governance, and many other aspects of socioeconomic development" that will "have an impact on the supply and demand of

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economic goods and services …" These confounding factors are site-specific and (development) path dependent, and they affect the degree to which the consequences of observed and projected ranges of climate impacts can be attributed, year after year, to anthropogenic warming.

It follows that analyses and assessments of the potential effects of achieving various long-term temperature targets must create climate and socioeconomic context by tracking projected distributions of transient (contemporaneously observed) temperature change on the way to 2100; this is a challenge, but the actors on the consequence side will see and react to only transient temperatures. A small amount of work has, for example, been done that illustrates how mitigation could buy time for adaptation by postponing the time at which 2 °C of warming is reached (Meehl et al. 2012; Warren et al. 2013), but the forthcoming IPCC *Special Report on 1.5 Degrees* has widened the scope of these investigations considerably.

Researchers can sometimes use climate models whose outputs include time-specific local and regional scale changes to overcome this time and location challenge, but authors of assessments of the social value (economic and otherwise) of achieving any temperature target calibrated in whatever metric is appropriate have historically found literature to be little sparse. Some more recent publications of projected climate change impacts have, however, begun to use regional climate changes obtained by downscaling in time series and combined these with socioeconomic trends. For example, a growing collection of analyses is being produced by more than 100 modeling groups under the umbrella of the Inter-Sectoral Impact Model Inter-Comparison Program. This organized but decentralized initiative has been underway for several years under the auspices of the Potsdam Institute for Climate Impacts Research and the International Institute for Applied Systems Analysis. A special feature of the Proceedings of the National Academy of Sciences (PNAS 2014) published an early round of products from this initiative; nine in number, they are certainly representative of best practices for the next generation of impact analyses that will want to take time into account.

The wider impacts of literature, however, still contain many more contributions that do not typically indicate timing along a future path that may or may not limit temperature rise in the long term when they impose specific (and sometimes arbitrary) manifestations of climate change on a subject of interest. If they were armed with a coherent set of trajectories of transient temperature change that were attached to specific temperature targets, these authors, and/or the authors of assessments that include their work, could more effectively and more comprehensively infer timing and perhaps likelihood along the associated temperature pathways *and* visualize the socioeconomic structures that would help portray consequence taking account of possible adaptation responses. It is the point of this exercise to support these efforts to synthesize across the risk equation by producing such a set of target-specific, not-implausible, representative transient temperature trajectories for alternative mitigation targets based on the convenient truth that transient temperature at any point in time depends on cumulative emissions up to that point.

1 Creating the transient temperature trajectories

Figure 1 portrays four representative emission pathways that limit increases in transient temperature to 1.5, 2.0, 2.5, and 3.0 °C above preindustrial levels plus a "no-policy" baseline. Four targets are chosen to illustrate a policy choice as well as to offer insight into the possible consequences of trying to achieve a temperature-calibrated policy objective. These trajectories are derived relative to a baseline that mimics the median no-policy case reported in Fawcett et al. (2015), a pathway that sees

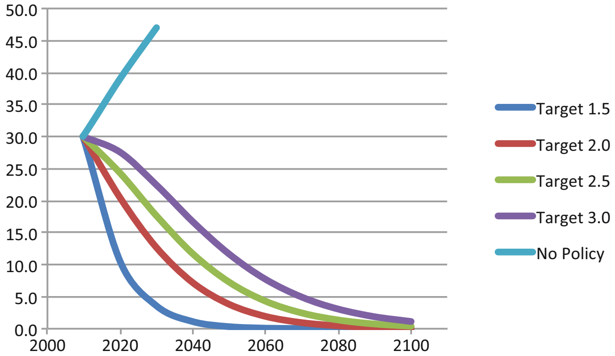

Fig. 1 "Ideal" emission trajectories for temperature targets of 1.5, 2.0, 2.5, and 3.0 °C by 2100 (calibrated in $GtCO_2$). Associated transient temperatures are uncertain, but their median estimates achieve these targets through 2100

global emissions soar above 100 $GtCO_2$ per year toward the end of the century.[1] They are "ideal" in the sense that they reduce emissions over time so as to maximize the discounted logarithmic utility generated by emissions through 2100. That is to say, they solve four parallel Hotelling-style exhaustible resource problems where median cumulative emission constraints serve as operating constraints on total emissions for each of the four temperature targets: 1715, 2571, 3229, and 4286 $GtCO_2$ through 2100 for the 1.5, 2.0, 2.5, and 3.0 °C targets, respectively (depicted in the upper panel of Figure S.2 in NRC (2010) and described in Sect. 3.4).

The effect of the applying the effective scarcity rents for each target on carbon emissions is implemented in terms of the utility discount rate required to guarantee that the chosen emission pathways in fact satisfy exactly their respective constraints.[2] It should also be noted that the 2.0 °C emission pathway conforms well to the lower range of the IPCC Fifth Assessment range of emissions that achieve that temperature target with a likelihood of 50% (see Fawcett et al. 2015).

NRC (2010) also reports an approximate reduced form "quasi-linear" relationship between contemporaneous cumulative emissions and transient temperature (in the caption of the NRC (2010) Figure 3.8, the relationship is given as 1.75 °C of warming for every 1000 GtC emitted). Uncertainty, here, is driven by uncertainty about the behavior of sinks in higher temperatures and by uncertainty about the sensitivity of the climate to external forcing. According to this relationship, the 95th percentile temperature for any emission total is 70% above the temperature associated with median, and the 5th percentile temperature is 40% below the median.

Table 1 reports temperature pathways in decadal intervals through 2100 for the four temperature targets along the ideal emission pathways. The table reports median, 5th, and 95th percentile values for decadal time increment beginning in 2010. Panel a of Fig. 2 depicts these results for 1.5 and 2.5 °C targets through 2100. Panel B shows comparable results for 2.0

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[1] Fawcett et al. (2015) examine a full range of emission scenarios reported in the Fifth Assessment of the IPCC for a variety of policy scenarios: a "no-policy case", a low policy case (the Paris Accord and little else), a continuation of the pace of emission reductions consistent with the Paris commitments, and an increase in the stringency of Paris Accord commitments to increase the likelihood of achieving a 2 °C warming cap. The authors report distributions (likelihoods) of ranges of temperature increases ranging from 1 to 1.5 °C to more than 4 °C in 2100. This paper works from a "no policy" baseline that they report as the median of the first cohort of emission scenarios. See Section 2 of the SM to view their figure (Figure SM-1).

[2] The implementation discount rates for the 1.5, 2.0, 2.5, and 3.0 °C targets are 15.4, 8.6, 6.9, and 5.7%, respectively.

Table 1 Ranges of increases in global mean temperature in decadal increments along emission pathways that achieve temperature targets of 1.5, 2.0, 2.5, and 3.0 °C by 2100 along the median temperature sensitivity trajectories (calibrated in °C)

Year	5th %ile 1.5	Median 1.5	95th %ile 1.5
2010	0.85	0.85	0.85
2020	0.99	1.02	1.03
2030	1.09	1.17	1.21
2040	1.15	1.28	1.36
2050	1.18	1.36	1.50
2060	1.18	1.42	1.63
2070	1.16	1.45	1.75
2080	1.13	1.48	1.86
2090	1.09	1.49	1.98
2100	1.05	1.50	2.10
Year	5th %ile 2.0	Median 2.0	95th %ile 2.0
2010	0.85	0.85	0.85
2020	1.01	1.04	1.06
2030	1.16	1.24	1.29
2040	1.28	1.43	1.52
2050	1.37	1.59	1.75
2060	1.43	1.72	1.97
2070	1.46	1.82	2.18
2080	1.46	1.90	2.39
2090	1.44	1.96	2.60
2100	1.40	2.00	2.80
Year	5th %ile 2.5	Median 2.5	95th %ile 2.5
2010	0.85	0.85	0.85
2020	1.02	1.05	1.07
2030	1.20	1.29	1.33
2040	1.37	1.52	1.63
2050	1.52	1.75	1.93
2060	1.63	1.96	2.25
2070	1.71	2.13	2.56
2080	1.75	2.28	2.87
2090	1.76	2.40	3.19
2100	1.75	2.50	3.50
Year	5th %ile 3.0	Median 3.0	95th %ile 3.0
2010	0.85	0.85	0.85
2020	1.03	1.06	1.08
2030	1.23	1.32	1.37
2040	1.44	1.60	1.71
2050	1.64	1.89	2.08
2060	1.80	2.16	2.48
2070	1.93	2.41	2.90
2080	2.02	2.64	3.32
2090	2.08	2.83	3.76
2100	2.10	3.00	4.20
Year	No policy 5th %ile	No policy Median	No policy 95th %ile
2010	0.85	0.85	0.85
2020	1.03	1.07	1.09
2030	1.27	1.36	1.41
2040	1.55	1.72	1.84
2050	1.87	2.15	2.38
2060	2.20	2.64	3.03
2070	2.53	3.17	3.80
2080	2.85	3.72	4.68
2090	3.14	4.28	5.67
2100	3.38	4.83	6.76

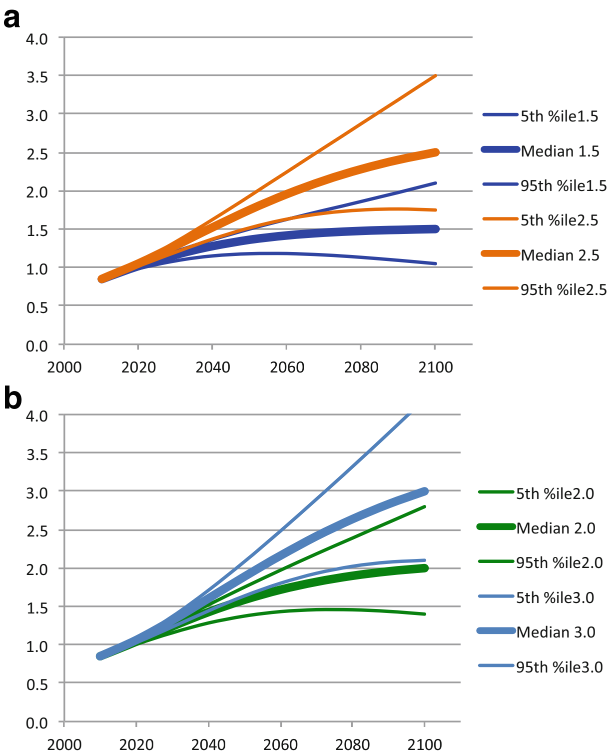


Fig. 2 Temperature pathways in decadal intervals through 2100 for the four temperature targets along the ideal emission pathways. For each temperature target, the two panels depict median, 5th, and 95th percentile values for decadal time increments beginning in 2010 (calibrated in °C). The median pathways do not exceed the indicated targets through 2100. **a** Temperature trajectories for achieving 1.5 and 2.5 °C targets by 2100. **b** Temperature trajectories for achieving 2.0 and 3.0 °C targets by 2100

and 3.0 °C. These are targets of interest for researchers and assessment authors considering the value of lowering the temperature target from 2.0 C to 1.5 °C (e.g., the forthcoming *Special Report on 1.5 Degrees* currently being prepared by the IPCC).

For reference in reading the following illustrative applications, recall that the four temperature targets are met exactly for only the median associations of cumulative emissions and temperature, and notice that uncertainty persists and grows as the future unfolds in both cases. Notice, as well, that the three trajectories for the 2.0 °C target diverge more significantly than those for the 1.5 °C; it would seem that moving toward the lower target produces not only less warming but also smaller variance in the projected future. In addition, the lowest trajectory for the 1.5 °C target actually peaks around 2040 or so. Thereafter, adaptors could count on stable or lower temperature climate from 1 year to the next if there is lower sensitivity of temperature to cumulative emissions—a fortunate but not guaranteed (for even the 1.5 °C target runs) new normal climate for which rules of adaptive thumb might suffice. The fifth percentile temperature pathways for the 2.0 and 2.5 °C target emission trajectories also peak, but not until much later than before—around 2080 or so. If no peak occurs even under strenuous mitigation policies, then it becomes clear that temperature manifestations of the lowest imaginable emission trajectories could still present high likelihoods that transient temperatures could climb well above 2.0 °C shortly after mid-century and continue past 2100.

O’Neill et al. (2017) highlighted their aspiration eventually to create “burning ember” diagrams that are development pathway specific. This illustrative application of transient temperature pathways is, perhaps, one way to approach this challenge. Risk levels associated with various increases in temperature could be taken from their work, but their superimposition over transient temperature trajectories offers a potential link to concomitant socioeconomic development pathways along which dynamic vulnerability cum adaptation could be described as time evolves; see Sect. 3 below. The derivative challenges, here, would be two (1) correlating changes in global mean temperature to changes in more regional temperatures and other climate-related drivers of those vulnerabilities and (2) correlating time frames to the exercise of evolving adaptive capacity (Sect. 3).

2 An illustrative example—aggregate economic damages to the USA (Hsiang et al. 2017)

Aggregate economic damages from warming, calibrated in terms of the percentage loss of GDP, have recently been updated by Hsiang et al. (2017). Along with coverage of enormous collection of supporting sectoral and micro-scale regional analyses, they displayed median, 5th percentile, and 95th percentile damage estimates for temperature increases up to 8 °C in panel c of Fig. 5. Table SM-2 in the Supplementary Material reports the details of these reaction functions and offers a graphical representation in Figure SM-2.

Panel a of Fig. 3 displays transient trajectories of aggregate economic damages (real GDP) from climate change in decadal increments for the USA through the year 2100 along the no-policy baseline described above. Panel b shows the avoided damages along a trajectory whose median outcome achieves a 1.5 °C temperature limit through 2100. Panel c shows the avoided damages along a trajectory whose median outcome achieves a 2.0 °C temperature limit through 2100. Panel d compares the avoided damages along a trajectory whose median outcome achieves a 1.5 °C temperature limit through 2100 against a trajectory whose median outcome achieves the higher 2.0 °C temperature limit through 2100; i.e., it reflects the value of extending mitigation efforts to achieve the lower temperature target (with the median trajectory).

The results for the no policy show that economic damages along the “median-median” case (median temperature change and median damages) reach 4.5% of GDP by 2100 surrounded by a range (different combinations of temperature change and damages) between 8.5 and 2.5%. The value of achieving a 1.5 °C temperature limit calibrated in damages avoided along the median-median case is nearly 4% by 2100 surrounded by a range of 7.0 and 2.0%. The value of achieving a 2.0 °C temperature limit along the median-median case is lower as should be expected: 3.5% by 2100 surrounded by a range of 6.5 and 1.8%. The value of achieving a 1.5 °C temperature limit rather than a 2.0 °C is modest; along the median-median case, it is around 0.35% by 2100 surrounded a range of 0.20 and 0.65%.

Even though the no-policy baseline shows significant damage diversity across temperature and damage trajectories almost immediately, the values of achieving either temperature limit do not diverge significantly until roughly 2040 when their difference tracks between 0.05 and 0.13%. Thereafter, the differences between the two temperature targets do, however, begin to diverge substantially in the second half of the century. This means that patience will be required to notice potentially value in proceeding toward the more aggressive 1.5 °C mitigation temperature target.

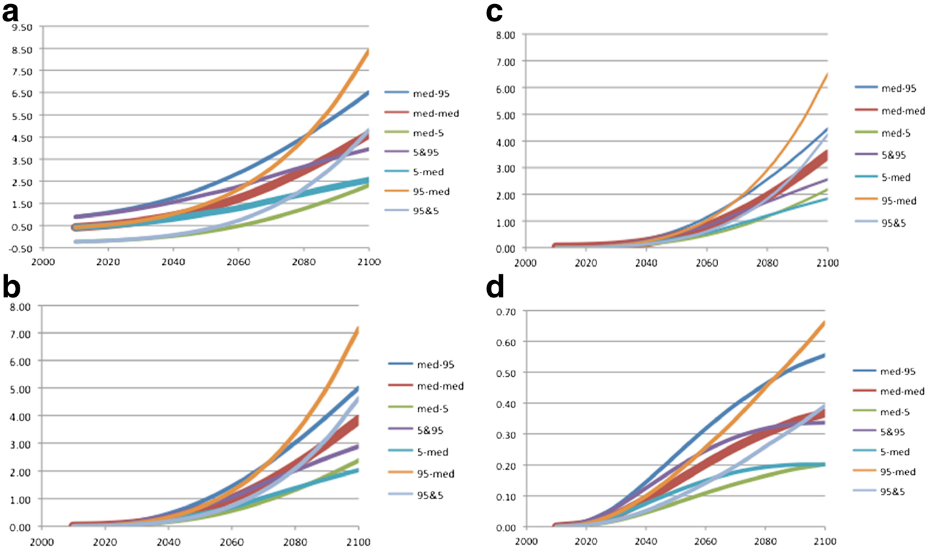


Fig. 3 Trajectories of the economic value of estimated economic damages to the USA along selected policy emission trajectories. Damages are calibrated along the vertical axis in terms of percentage loss to the US GDP through 2100. As noted by the asterisk footnote, the labels indicate the combination of median, 5th, and 95th percentile scenarios for temperature and estimated damage, in that order. **a** The economic value of damages along the "no-policy" baseline emission trajectory (difference in percentage of average US GDP loss per year). **b** The economic value, compared to no-policy baseline, of moving along the emission trajectory that achieves a 1.5 °C temperature target with the median temperature sensitivity (difference in percentage of average US GDP loss per year). **c** The economic value, compared to no-policy baseline, of moving along the emission trajectory that achieves a 2.0 °C temperature target with the median temperature sensitivity (difference in percentage of average US GDP loss per year). **d** The economic value of moving along the emission trajectory that achieves a 1.5 °C temperature target with the median temperature sensitivity instead of the 2.0 °C target (difference in percentage of average US GDP loss per year). In the legend, "med-95" signifies the combination of the median emissions trajectory and the 95th percentile damage function; "med-med" signifies the combination of the median emissions trajectory with the median damage function, etc

3 A second illustrative example from the Fifth Assessment of the IPCC—updated reasons for concern

Reasons for concern were designed by the authors of Chapter 19 of the Third Assessment Report (TAR) of the IPCC (2001a) to calibrate impacts in something other than currency. Two reasons did, though, target economic distribution and aggregate economic values (using current names from O'Neill et al. (2017)): risks associated with the distribution of impacts (RFC3) and risks associated with global aggregate impacts (RFC4). Others were drawn from other literatures: risks to unique and threatened systems (RFC1), risks associated with extreme weather events (RFC2), and risks associated with large-scale singular events (RFC5). Insights drawn from this qualitative and subjective expansion of broad potential vulnerabilities were elevated to the Synthesis Report of the TAR (IPCC 2001b) (Figure SPM-3, Figure TS-12, and the supporting text on pages 284–289); the corresponding visual, the so-called burner ember diagram, is replicated as the left panel of Figure SM-3 in the supplementary material.

As noted in Yohe (2010), reasons for concern evolved in Chapter 18 of the Fourth Assessment Report of the IPCC so that each category was expanded (IPCC 2007a). For example, concern about unique and threatened systems was no longer derived exclusively from natural systems; communities and other human systems that were threatened by climate change were included in RFC1. Distributions of impacts that were calibrated in metrics other than currency that could be aggregated across nations (e.g., human lives at risk) were included in both RFC3 and RFC4.

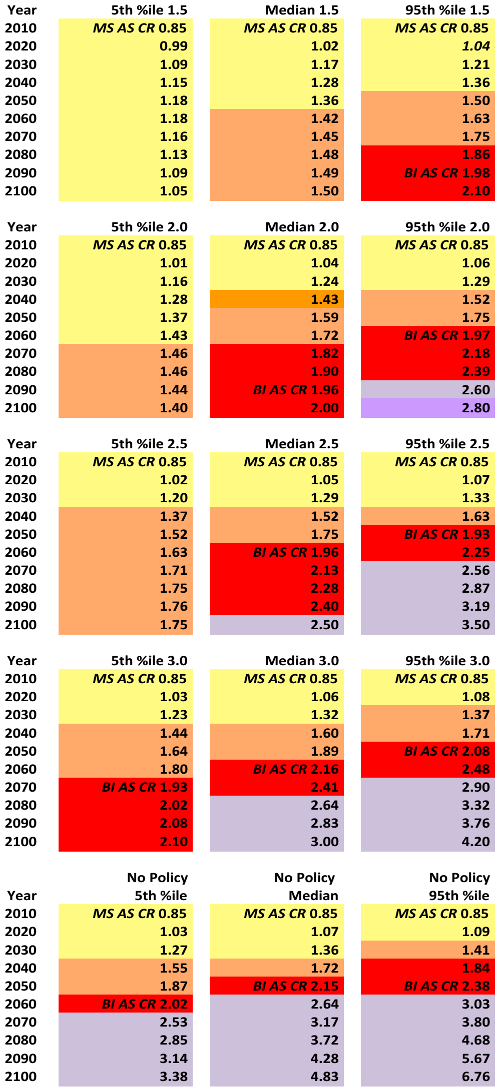
Given the emphasis across the AR4 to support risk management approaches to adaptation and mitigation, the concept of the RFCs was now supported by parallel application of "key vulnerabilities" (calibrated in terms of magnitude, timing, persistence/irreversibility, the potential for adaptation, distributional aspects, likelihood, and importance) in Chapter 19 (IPCC 2007a). The Synthesis Report of the IPCC (2007b) again highlighted in the text (pages 18–19), but the illuminating visual did not appear. That image, displayed in their Fig. 1, is the focal point of Smith et al. (2009); for reference, see the right panel of Figure SM-3.

The Fifth Assessment Report of the IPCC (IPCC 2014a, b) further advanced the application of RFCs with better support on detection and attribution (Chapter 18) as well as increased global coverage in the impacts, adaptation, and vulnerability literature (Chapter 2). IPCC (2014a—Chapter 19) and IPCC (2014b—pages 72–73) as well as O'Neill et al. (2017) reported these updated and extended versions that explicitly incorporated a list of "key risks" that is included in the SOM. O'Neill et al. (2017) also illustrated the sensitivity of the RFCs to two RCP emission scenarios, but it did not provide corresponding portraits of risk over time. It is also important to note that RFC3 considers lives at risk in different parts of the world while RFC4 now includes the non-currency aggregation of impacts on biodiversity and ecosystems and human life, because these cannot easily be monetized and included in economic models without sparking enormous controversy; this follows a trend that began with the very inception of the RFCs in the TAR. Figure SM-4 replicates the IPCC (2014b) version of what is now the third generation of the burning ember visualization.

This section displays as much of the O'Neill et al. information as possible along transient temperature trajectories tied to achieving temperature targets as well as a no-policy baseline. Table 2, for example, indicates decadal levels of concern for risks to unique and threatened systems (RFC1) along transient temperature trajectories whose medians achieve four different temperature targets by 2100 as well as a no-policy baseline that mimics Fawcett et al. (2015). Cells in the table are color-coded to indicate changes in levels of concern that mirror O'Neill et al. (2017): pale white indicates undetectable risk, yellow for moderate concern, dark orange and red for growing high concern, and purple for very high concern; Table SM-3 reports the comparable results for the other four RFCs. It must be noted that demarcations of levels of concern are not as sharp in the O'Neill et al. paper as those depicted in this table. While it is nonetheless possible to infer the qualitative degree to which increasingly ambitious temperature targets delay crossing thresholds of concern, Fig. 4 is perhaps a bit more illustrative because it blurs the demarcations more in accordance with their source. There, for example, the median and 95th percentile trajectories are displayed for RFC1 with the same color-coding for 1.5 and 2.0 °C targets as well as the no-policy baseline for comparison; Fig. SM-5 does the same for the other for RFCs, as well.

In Fig. 4, it is clear that the no-policy baseline produces high levels of concern late in the first half of this century and very high concern around 2080; only the 95th percentile pathway reaches the very high concern threshold at the end of the century for the 2 °C target, but high concern is apparent in mid-century despite aggressive mitigation. More aggressive mitigation along the 1.5 °C target trajectories only reaches high concern late in the century. Comparable, but decidedly different timing results are depicted for the other four RFCs in Table SM-2 and Fig. SM-3.

Table 2 Visual calibration of five "reasons for concern (RFCs)" along policy-driven transient temperature pathways. The various panels reflect ranges of increases in global mean temperature in decadal increments along pathways that are aimed at achieving temperature limits of 1.5, 2.0, 2.5, and 3.0 °C through 2100 (along the median temperature trajectory—so values above or below the target are possible and portrayed for 5th and 95th percentile runs). A "no-policy" case is also portrayed for emissions that were calibrated to the median no-policy case in Fawcett et al. (2015). Colors correspond roughly to the visual portrayal of intensity in concern across the five RFCs as depicted in Fig. 1 in O'Neill et al. (2017): "undetectable" (white) indicates no associated impacts that are detectible and attributable to global mean temperature; "moderate" (yellow) indicates that associate impacts are both detectible and attributable with at least medium confidence for specific criteria of "key risk" (see SOM for the list of eight criteria; "high" (red) indicates severe and widespread impacts, now for wider coverage across the criteria of key risk; finally, "very high" (purple) is new in this latest iteration of the RFCs and reserved for very high risk across many if not all eight criteria of key risk. Initialed notations for some years indicate when certain sectors or drivers became a focus of concern for the O'Neill et al. (2017) evaluation; the demarcations are biodiversity (BI), Arctic systems (AS), heat waves (HW), agriculture (AG), human health (HH), Greenland ice sheet (GI), mountain systems (MS), extreme precipitation (EP), water stress (WS), economic damages (ED), coral reefs (CR), and Antarctic ice sheet (AI)



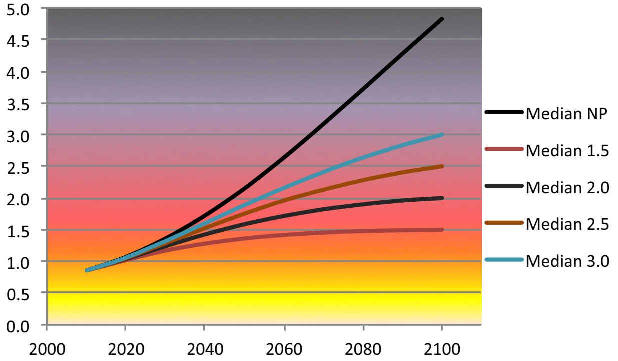
Year	5th %ile 1.5	Median 1.5	95th %ile 1.5
2010	*MS AS CR* 0.85	*MS AS CR* 0.85	*MS AS CR* 0.85
2020	0.99	1.02	*1.04*
2030	1.09	1.17	1.21
2040	1.15	1.28	1.36
2050	1.18	1.36	1.50
2060	1.18	1.42	1.63
2070	1.16	1.45	1.75
2080	1.13	1.48	1.86
2090	1.09	1.49	*BI AS CR* 1.98
2100	1.05	1.50	2.10

Year	5th %ile 2.0	Median 2.0	95th %ile 2.0
2010	*MS AS CR* 0.85	*MS AS CR* 0.85	*MS AS CR* 0.85
2020	1.01	1.04	1.06
2030	1.16	1.24	1.29
2040	1.28	1.43	1.52
2050	1.37	1.59	1.75
2060	1.43	1.72	*BI AS CR* 1.97
2070	1.46	1.82	2.18
2080	1.46	1.90	2.39
2090	1.44	*BI AS CR* 1.96	2.60
2100	1.40	2.00	2.80

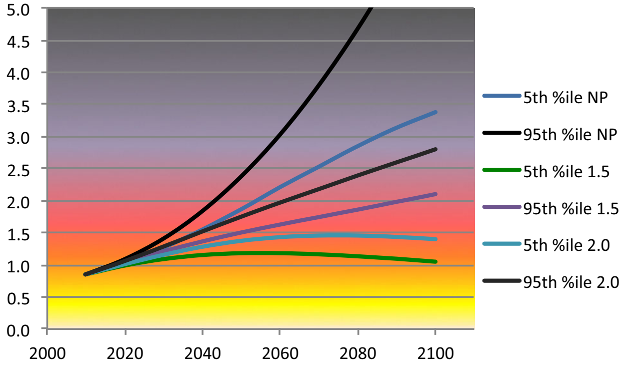
Year	5th %ile 2.5	Median 2.5	95th %ile 2.5
2010	*MS AS CR* 0.85	*MS AS CR* 0.85	*MS AS CR* 0.85
2020	1.02	1.05	1.07
2030	1.20	1.29	1.33
2040	1.37	1.52	1.63
2050	1.52	1.75	*BI AS CR* 1.93
2060	1.63	*BI AS CR* 1.96	2.25
2070	1.71	2.13	2.56
2080	1.75	2.28	2.87
2090	1.76	2.40	3.19
2100	1.75	2.50	3.50

Year	5th %ile 3.0	Median 3.0	95th %ile 3.0
2010	*MS AS CR* 0.85	*MS AS CR* 0.85	*MS AS CR* 0.85
2020	1.03	1.06	1.08
2030	1.23	1.32	1.37
2040	1.44	1.60	1.71
2050	1.64	1.89	*BI AS CR* 2.08
2060	1.80	*BI AS CR* 2.16	2.48
2070	*BI AS CR* 1.93	2.41	2.90
2080	2.02	2.64	3.32
2090	2.08	2.83	3.76
2100	2.10	3.00	4.20

Year	No Policy 5th %ile	No Policy Median	No Policy 95th %ile
2010	*MS AS CR* 0.85	*MS AS CR* 0.85	*MS AS CR* 0.85
2020	1.03	1.07	1.09
2030	1.27	1.36	1.41
2040	1.55	1.72	1.84
2050	1.87	*BI AS CR* 2.15	*BI AS CR* 2.38
2060	*BI AS CR* 2.02	2.64	3.03
2070	2.53	3.17	3.80
2080	2.85	3.72	4.68
2090	3.14	4.28	5.67
2100	3.38	4.83	6.76



Median trajectories for alternative policy goals



Median, 5th and 95th trajectories for selected policy alternatives

Fig. 4 Visual calibration of five "reasons for concern (RFCs)" along policy-driven transient temperature pathways (calibrated against increases in global mean temperature in °C). The various panels reflect ranges of increases in global mean temperature in decadal increments along pathways that are aimed at achieving temperature limits of 1.5, 2.0, 2.5, and 3.0 °C through 2100 (along the median temperature trajectory—so values above or below the target are possible and portrayed for 5th and 95th percentile runs). A "no-policy" case is also portrayed for emissions that were calibrated to the median no-policy case in Fawcett et al. (2015). The background colors correspond roughly to the visual portrayal of intensity in concern across the five RFCs as depicted in Fig. 1 in O'Neill et al. (2017): "undetectable" (white) indicates no associated impacts that are detectible and attributable to global mean temperature; "moderate" (yellow) indicates that associate impacts are both detectible and attributable with at least medium confidence for specific criteria of "key risk" (see SOM for the list of eight criteria; "high" (red) indicates severe and widespread impacts, now for wider coverage across the criteria of key risk; finally, "very high" (purple) is new in this latest iteration of the RFCs and reserved for very high risk across many if not all eight criteria of key risk. In all cases, the top graph superimposes the median transient temperature trajectories for the five policy cases upon a background that reflects the "burning ember" for the specified reason for concern; the bottom graph does the same for the 5th and 95th percentile trajectories for the no policy case as well as cases where emission reductions target the median trajectory to achieve limits of 1.5 and 2.0 °C. **a** Risk to unique and threatened systems RFC1—calibrated from key risk criteria KRi, KRvii, and KRviii (see SM for definitions of these criteria from O'Neill et al. (2017))

4 Concluding remarks

It is hoped that transient temperature trajectories like those derived here for alternative temperature targets along plausible emission scenarios will help researchers to locate their impacts in work in time, help assessors to locate their text in socioeconomic context as well as time, and help cutting adaptation research locate their work not only in space but also in time so that they can investigate the limits of adaptation. They, and their readers, should thereby be able to understand more about not only observed climate risk but also about the ex post character of projected risk over time that can be associated with alternative policy objectives.

Trajectories of policy-driven transient temperatures are reported here because it is they, and their associated manifestations in other impact and risk dimensions, that natural and human and natural systems see in real time as their common future unfolds, and so, it is they that inform both the reactive adaptation and (for human systems) anticipatory responses that embedded decision-makers would contemplate in the future. The two illustrations should provide provocative context within which to begin to see their potential value across a wide range of applications.

While this synthesis should advance understanding of net vulnerability to climate risk over time in these applications, it should also be noted that the planet is committed, over the long-term, to equilibrium temperature increases that are twice whatever observed transient values emerge as the future unfolds up to and beyond 2100. The need to respond with continued mitigation and accelerated adaptation will therefore continue long after transient temperatures have peaked—well into the future especially along transient temperature pathways that do not peak before 2100.

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