IN THE HIGH COURT OF NEW ZEALAND
AUCKLAND REGISTRY

CIV-2021-404-1618

I TE KŌTI MATUA O AOTEAROA
TĀMAKI MAKAURAU ROHE

UNDER the Judicial Review Procedure Act 2016

IN THE MATTER OF an application for judicial review

BETWEEN **ALL ABOARD AOTEAROA INCORPORATED**
Applicant

AND **AUCKLAND TRANSPORT**
First Respondent

AND **THE REGIONAL TRANSPORT COMMITTEE FOR AUCKLAND**
Second Respondent

AND **AUCKLAND COUNCIL**
Third Respondent

AFFIDAVIT OF WILLIAM LEE STEFFEN

December 2021

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AFFIDAVIT OF WILLIAM LEE STEFFEN

I, William Lee Steffen, of Canberra, Australia, Emeritus Professor, Australian National University, swear –

1. I make this affidavit in support of All Aboard Aotearoa Incorporated's application for judicial review in relation to decisions made by Auckland Transport, the Regional Transport Committee for Auckland and Auckland Council concerning the Regional Land Transport Plan for Auckland.

2. I confirm that I have read and complied with the Code of Conduct for Expert Witnesses in preparing my evidence.

Qualifications and experience

3. I am an Earth System scientist. The Earth System is defined as the single, planetary-level system consisting of the interacting physical, chemical and biological processes and feedbacks that connect the atmosphere, cryosphere (ice), land, ocean, and lithosphere. My research interests span a broad range within climate and Earth System science, with an emphasis on incorporation of human processes in Earth System modelling and analysis; and on sustainability and climate change.

4. I am also:

   (a) a Councillor on the publicly-funded Climate Council of Australia, which delivers independent expert information about climate change;

   (b) an Emeritus Professor at the Australian National University, Canberra;

   (c) a Senior Fellow at the Stockholm Resilience Centre, Sweden;

   (d) a Fellow at the Beijer Institute of Ecological Economics, Stockholm;

   (e) a member of the International Advisory Board for the Centre for Collective Action Research, Gothenburg University, Sweden;

   (f) a member of the Anthropocene Working Group of the Sub-commission on Quaternary Stratigraphy, which is part of the International Union of Geological Sciences; and

   (g) Chair of the jury for the Volvo Environment Prize, one of the world's most prestigious environmental prizes.

5. From 1998 to mid-2004, I was Executive Director of the International Geosphere-Biosphere Programme, based in Stockholm.

6. I have a PhD in chemistry from the University of Florida, USA, and honorary PhDs from the University of Canberra and Stockholm University.

7. A copy of my complete curriculum vitae, including my relevant qualifications, is at schedule 2 of this affidavit.

Instructions

8. I am instructed to address the following issues:

   (a) The scientific consensus on climate change, including its causes and future effects;

   (b) The scientific consensus on the required mitigation of greenhouse gas emissions, including the need to stay within a total 'carbon budget' on the way to reaching emissions reduction targets;

   (c) The evidence that human emissions of greenhouse gases may result in Earth System changes that lead to a 'Hothouse Earth' scenario; and

   (d) The effect that the impacts of climate change will have on youth and future generations.

Summary of evidence

9. In summary:

   (a) The scientific consensus is that the global temperature has increased since the 1850-1900 period, and at an extraordinarily rapid rate since the mid-20th century. This rate of temperature increase is almost unprecedented in the entire 4-billion-year geological record.

   (b) It is accepted without doubt by the expert scientific community that human activity – specifically the emission of greenhouse gases, primarily carbon dioxide (CO2), into the atmosphere – is the cause of this rapid global temperature increase.

   (c) The effects of climate change are already being felt and will continue to intensify depending on future emissions scenarios. These include extreme heat events, sea level rises, and increases in the intensity of droughts, floods and tropical cyclones.

   (d) To keep the global temperature increase to less than 1.5°C (as per the Paris Agreement), only 320 billion tonnes of CO2 may be emitted in the future. At the current rate of emissions (approximately 40 billion CO2 per year), that will occur by the end of 2029. Significant reductions in greenhouse gas emissions by 2030 are required to have a reasonable chance of keeping the global temperature increase at less than 1.5°C.

   (e) Every tonne of CO2 emitted pushes the Earth closer to activating a series of 'tipping points'. These would risk creating a "Hothouse Earth" scenario that would threaten the habitability of the Earth for humans and many other forms of life. This is a real and credible risk. There are clear warning signs that many tipping point processes are already being activated.

(f) Persons born today may experience the “Hothouse Earth” scenario in their lifetimes if emissions are not significantly and rapidly reduced. That would be an exceptionally difficult world to survive in, much less live in with any decency, with collapse of human civilisation a possible outcome.

IPCC reports

10. I draw on the following Intergovernmental Panel on Climate Change (**IPCC**) reports in this affidavit:

(a) IPCC (2018) *Special Report on Global Warming of 1.5°C* (https://www.ipcc.ch/sr15/). [[303.0953]]

(b) IPCC (2019) *Special Report on the Ocean and Cryosphere in a Changing Climate* (https://www.ipcc.ch/srocc/). [[303.1094]]

(c) IPCC (2021) *AR6 Climate Change 2021: The Physical Science Basis*, the Working Group I contribution to the Sixth Assessment Report of the IPCC (https://www.ipcc.ch/report/ar6/wg1/). [[311.4760]]

11. Additional sources of information are included in the reference list in schedule 1 of this affidavit.

The scientific consensus on climate change

12. Climate change refers to changes in the climate system, whether driven by natural forcing factors (e.g., volcanoes, changes in solar radiation, etc.) or by human activities. Here I use the contemporary definition of climate change, which refers to human-driven changes to the climate system since the beginning of the industrial revolution (often taken as the 1850-1900 average). Over this period, human drivers of climate change have overwhelmed the natural factors that affect the climate and are, by far, the dominant drivers of the observed changes in the climate system (IPCC 2021).

13. Many changes in the climate system are associated with the term ‘climate change’ and have been observed over the last century. In addition to changes in temperature, climate change encompasses changes in the patterns and intensity of rainfall; changes in the frequency and intensity of extreme weather events such as heatwaves, droughts and bushfires; increases in sea levels and associated coastal flooding; and increasing intensity of tropical cyclones (IPCC 2021).

14. Many other features of the climate system, in addition to global average surface temperature, are changing as a result of anthropogenic greenhouse gas emissions (IPCC 2021). These include changes in the basic circulation patterns of the atmosphere and the ocean, increasing intensity and frequency of many extreme weather events, increasing acidity of the oceans, increasing rate of polar ice loss, rising sea levels and consequent increases in coastal flooding, and intensification of the hydrological cycle.

15. The global average surface temperature (hereafter ‘global temperature’) is a commonly used indicator for changes in the climate system as a whole. Figure 1 below shows the observed changes in the global temperature from 1850 to 2020 (right panel) and AD 0 to 2020 in the left panel (IPCC 2021).

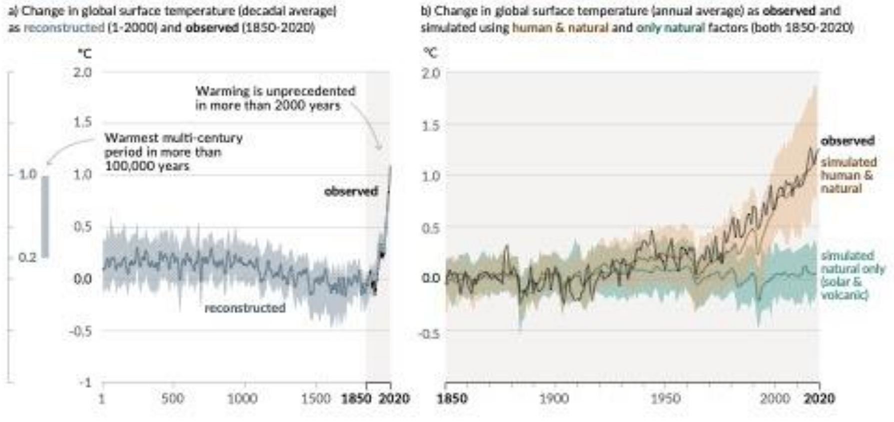


Fig. 1: Changes in global surface temperature relative to 1850-1900 and AD 0 to 2020 (IPCC 2021)

16. Figure 1 (right panel) shows the sharp rise in global temperature over the past half-century. Currently global average surface temperature is about 1.1°C higher than pre-industrial (1850-1900 average) levels, with each of the last four decades being successively warmer than any decade preceding it since 1850. The left panel places contemporary global temperature in a longer, 2000-year perspective. The observations clearly show that the contemporary rise in global temperature is extremely rapid in a geological timeframe, and that the current temperature level is unprecedented in more than 2,000 years and, in fact, is at its highest multi-century level in over 100,000 years (IPCC 2021).

17. The rate of climate change is extraordinary compared to the long-term geological records. The rise in atmospheric CO2 concentration is up to 10 times faster than the most rapid changes in the geological record (Lüthi et al. 2008). The rate of increase in global temperature is unprecedented over the past 2000 years at least, as shown in Figure 1 above. The large black spike in global temperature at the right-hand end of the graph on the left panel is the human-driven temperature increase of about 1.1°C during the industrial era (Kaufman et al. 2020; IPCC 2021). The long-term (ca. 2000 year) stability of surface temperature is shown by the coloured lines, varying by only 0.1 or 0.2°C around the long-term average.

18. On a shorter timeframe, global average surface temperature has been rising since 1970 at a rate of 1.7°C per century, compared to a 7,000-year background rate of change of about 0.01°C per century (NOAA 2016; Marcott et al. 2013). As noted above, temperature changes reconstructed from paleoclimate archives show that the current change in global surface temperature is very likely higher than the warmest multi-century period in the last 100,000 years (IPCC 2021). An analysis of much longer paleoclimate archives shows that the current speed of human-driven increase in atmospheric CO2 concentration and of the resultant increase in global average surface temperature are both nearly without precedent in the entire 4-billion-year geological record (Lear et al. 2020).

19. The impacts of climate change are already being felt around the world. As reported by the IPCC (2021), the most authoritative assessment body on the science of climate change, some of the most important impacts are:

    (a) Hot extremes (including heatwaves) have become more frequent and more intense across most land regions since the 1950s, while cold extremes (including cold waves) have become less frequent and less severe.

    (b) The frequency and intensity of heavy precipitation events have increased since the 1950s over most land areas with sufficient data.

    (c) Agricultural and ecological droughts have increased in some regions due to increased land evaporation.

    (d) It is likely that the global proportion of major (category 3-5) tropical cyclone occurrence has increased over the last four decades. That is, of all tropical cycles that occur globally, a greater fraction of them are now the more intense (category 3-5) cyclones.

    (e) It is likely that the chance of compound extreme events (e.g., concurrent heatwaves and droughts) has increased since the 1950s. Fire weather has increased in some regions of all inhabited continents and compound flooding has increased in some locations.

The scientific consensus on the causes of climate change

20. Climate change is caused by human-driven perturbations of the energy balance at the Earth’s surface. The most important of these human perturbations is the increasing emission of greenhouse gases, primarily carbon dioxide (CO2), into the atmosphere. The combustion of fossil fuels – coal, oil and gas – is the primary source of these emissions. It is the increasing concentration of these so-called greenhouse gases in the atmosphere that changes the Earth’s energy balance, as described in the following.

21. This basic physical understanding of the greenhouse effect is exceptionally well-proven by theory, experiments and observation, and is accepted without any doubt by the expert scientific community.

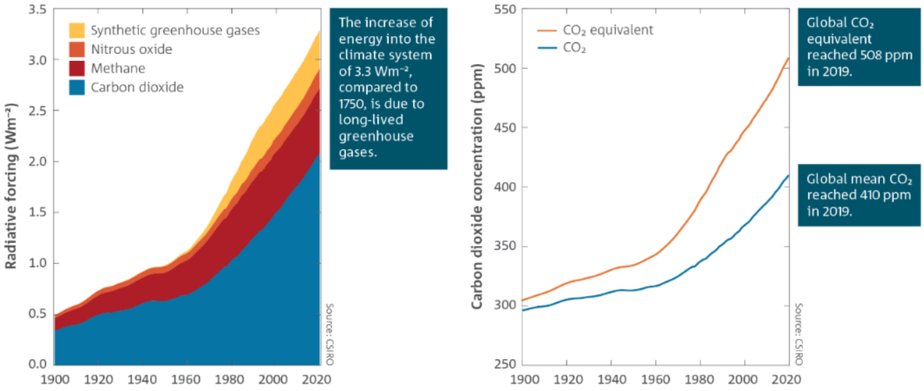
22. Greenhouse gases change the climate by trapping outgoing heat (long-wave radiation) from the Earth’s surface and retaining it in the lower atmosphere and at the surface, thus increasing the energy of the climate system and raising its average temperature (IPCC 2021).

23. The emission of CO2 from human activities at the Earth’s surface increases the atmospheric CO2 concentration. Slightly less than half (about 44%) of the CO2 emissions remain in the atmosphere (IPCC 2021), accumulating from year to year. The remainder is absorbed by land vegetation and by the surface ocean, in approximately equal amounts (slightly more absorbed by land vegetation). CO2 is a ‘greenhouse gas’ that absorbs outgoing infrared (long-wave) radiation (heat) from the Earth’s surface and re-emits it in all directions. Some of the re-emitted heat thus remains in the lower

atmosphere, warming the Earth's surface and lower atmosphere, and thus increasing the global average surface temperature.

24. Other greenhouse gases, such as methane (CH4), nitrous oxide (N2O) and synthetic compounds such chlorofluorocarbons (CFCs), also contribute to the warming of the atmosphere via the same process as for CO2 – they absorb outgoing infrared (long-wave) radiation (heat) from the Earth's surface and re-emit it in all directions.

25. The warming potential of the various greenhouse gases is different, depending on the capacity of the individual molecules of the gas to absorb infrared radiation and the lifetime of the gases in the atmosphere. CO2-e (CO2 equivalent) concentrations are based on the global-warming potential (GWP) of a particular gas by converting a given amount of that gas to the equivalent amount of CO2 with the same global warming potential. A 100-year timeframe is normally used for this comparison. For example, the GWP for CH4 is 25 and for N2O is 298 (European Commission 2021). If shorter timeframes are used, the GWPs of GHGs with shorter lifetimes, such as CH4 (half-life of about 9 years) rise sharply.



The increase of energy into the climate system of 3.3 Wm^{-2}, compared to 1750, is due to long-lived greenhouse gases.

Source: CSIRO

Global CO_2 equivalent reached 508 ppm in 2019.

Global mean CO_2 reached 410 ppm in 2019.

Source: CSIRO

Fig. 2. Radiative forcing relative to 1750 due to the long-lived greenhouse gases carbon dioxide, methane, nitrous oxide and the synthetic greenhouse gases, expressed as watts per metre squared. Right: Global mean CO2 concentration and global mean greenhouse gas concentrations expressed as CO2 equivalent (ppm), or CO2-e (CSIRO 2021).

26. Figure 2 shows the human-driven increase in radiative forcing since 1990, using 1750 values as the baseline (left panel), and the increase in atmospheric concentration of both CO2 itself and of all long-lived greenhouse gases, CO2-e (orange curve in the right panel) from 1900 to 2019.

27. Here I take 'human industrial activity' to include emissions of CO2 and other GHGs from fossil fuel combustion for electricity production, transport, manufacturing etc. and from industrialised agricultural activities such as deforestation to increase agricultural land (i.e., land-use change). These activities have increased the atmospheric CO2 concentration from about 278 ppm in the pre-industrial era to the current level of 412.5 ppm (the mean annual concentration for 2020; NOAA 2021a) and have increased the atmospheric CO2-e concentration to about 508 ppm in 2019 (Figure 2). The global average surface temperature has increased by 1.2°C compared

to the pre-industrial level (WMO 2021), or by 1.1°C if the 2011-2020 average is taken as the current temperature (IPCC 2021).

The scientific consensus on the future effects of climate change

28. At the global level, the projected future impacts of climate change include (IPCC 2021):

    (a) The frequency and intensity of extreme heat events will increase, with the magnitude of increase scaling with the magnitude of the increase in global average surface temperature.

    (b) The frequency of marine heatwaves will continue to increase.

    (c) The global water cycle will continue to intensify, with precipitation and surface water flows projected to become more variable over most land regions.

    (d) A warmer climate will intensify very wet and very dry weather and climate events and seasons, with implications for flooding or drought.

    (e) The proportion of intense tropical cyclones (categories 4-5) is projected to increase at the global scale.

    (f) Mountain and polar glaciers are committed to continue melting for decades or centuries.

    (g) It is virtually certain that global mean sea level will continue to rise over the 21st century and beyond. Depending on the emissions scenario, the likely global mean sea level rise by 2100 could range from 0.28 m to 1.01 m, compared to the 1995-2014 level.

    (h) Many regions are projected to experience an increase in the probability of compound extreme events, such as concurrent heatwaves and droughts.

The scientific consensus on the required mitigation of greenhouse gas emissions

29. The scientific approach to estimating the required mitigation of greenhouse gas emissions to achieve a given temperature goal is normally based on a number of emissions scenarios (projected future trajectories of human emission of greenhouse gas emissions) that are used to drive Earth System models (ESMs). ESMs are mathematical representations of the dynamics of the Earth System. They simulate the trajectory of the Earth System in response to the assumed human greenhouse gas emissions.

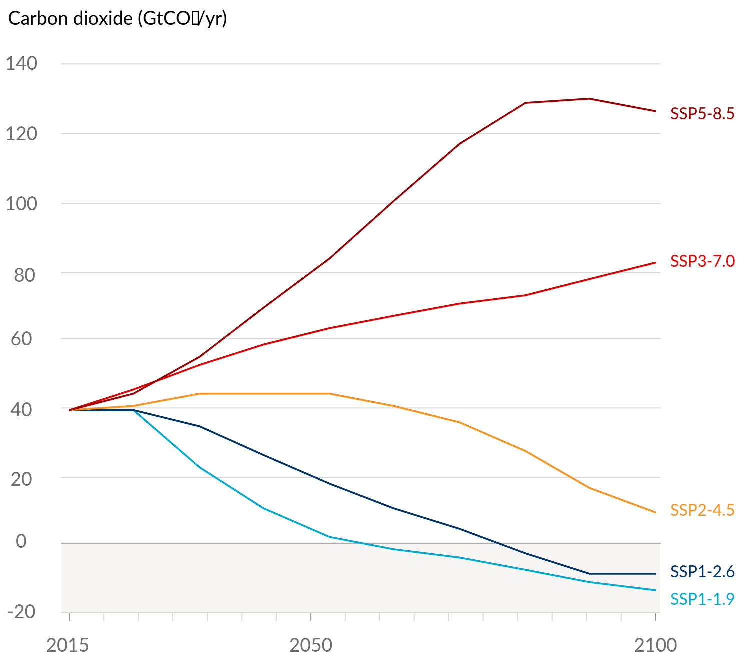


Fig. 3: Future annual emissions of CO2 for five illustrative scenarios (IPCC 2021).

30. Figure 3 above shows five scenarios of human emissions of CO2, ranging from very low emissions (SSP1-1.9)[1], through intermediate scenarios such as SSP2-4.5, to high emissions scenarios such as SSP3-7.0 and SSP5-8.5 (IPCC 2021). The two low emissions scenarios drop below zero in the second half of the century. This is the result of so-called ‘negative emissions’, in which human drawdown of CO2 from the atmosphere coupled with secure storage away from the atmosphere is larger than the residual human emissions to the atmosphere. The technologies required for the large magnitudes of negative emissions do not yet exist, but are assumed in this scenario to be developed by the second half of the century.

31. These scenarios of CO2 emissions can be used in ESMs to estimate the increase in global temperature that would result from a given CO2 emission scenario. Table 1 below shows the results of these ESM simulations for the five emissions scenarios of Figure 3. A desired temperature goal can then be connected to the emissions scenario that is required to meet the goal. Importantly, only the most stringent of the five emissions scenarios (SSP1-1.19), can meet the lower Paris Agreement goal of 1.5°C., and even then, 1.5°C is temporarily breached around mid-century before significant drawdown of CO2 from the atmosphere in the second half of the century returns the global temperature to below 1.5°C. Only one of the emissions reduction scenarios, SSP1-1.9 keeps the temperature rise at 2100 at 1.7°C or below. Thus, the SSP1-1.9 scenario is the required emissions reduction trajectory to meet the Paris Agreement goal.

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[1] SSPx-y refers to a greenhouse gas emissions scenario, where ‘SSPx’ refers to the Shared Socio-economic Pathway or ‘SSP’ describing the socio-economic trends underlying the scenario, and ‘y’ refers to the approximate level of radiative forcing (in W m^{-2}) resulting from the scenario in the year 2100.

	Near term, 2021–2040		Mid-term, 2041–2060		Long term, 2081–2100	
Scenario	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)	Best estimate (°C)	*Very likely* range (°C)
SSP1-1.9	1.5	1.2 to 1.7	1.6	1.2 to 2.0	1.4	1.0 to 1.8
SSP1-2.6	1.5	1.2 to 1.8	1.7	1.3 to 2.2	1.8	1.3 to 2.4
SSP2-4.5	1.5	1.2 to 1.8	2.0	1.6 to 2.5	2.7	2.1 to 3.5
SSP3-7.0	1.5	1.2 to 1.8	2.1	1.7 to 2.6	3.6	2.8 to 4.6
SSP5-8.5	1.6	1.3 to 1.9	2.4	1.9 to 3.0	4.4	3.3 to 5.7

Table 1: Changes in global surface temperature, relative to the temperature of the 1850-1900 period, assessed based on multiple lines of evidence for selected 20-year time periods and five illustrative emissions scenarios (IPCC 2021).

The need to stay within a total 'carbon budget' on the way to reaching emissions reduction targets

32. The 'carbon budget' is a common approach to estimate the level of mitigation of greenhouse gas emissions that is required to meet a specific temperature target. The carbon budget is the cumulative amount of carbon that can be emitted by human activities consistent with achieving a particular temperature goal (i.e., limiting the increase in global average surface temperature to a desired level). It is based on the near-linear relationship between cumulative CO2 emissions and the increase in global temperature. The baseline for both the cumulative carbon emissions and the temperature goal is the 1850-1900 period (cf. Fig. SPM.10 in IPCC (2021)). The carbon budget is thus a conceptually simple, yet scientifically robust, approach to estimating the level of greenhouse gas emission reductions required to meet a desired temperature target, for example, the Paris Agreement '1.5°C or well below 2°C' targets (Collins et al. 2013; IPCC 2018; IPCC 2021).

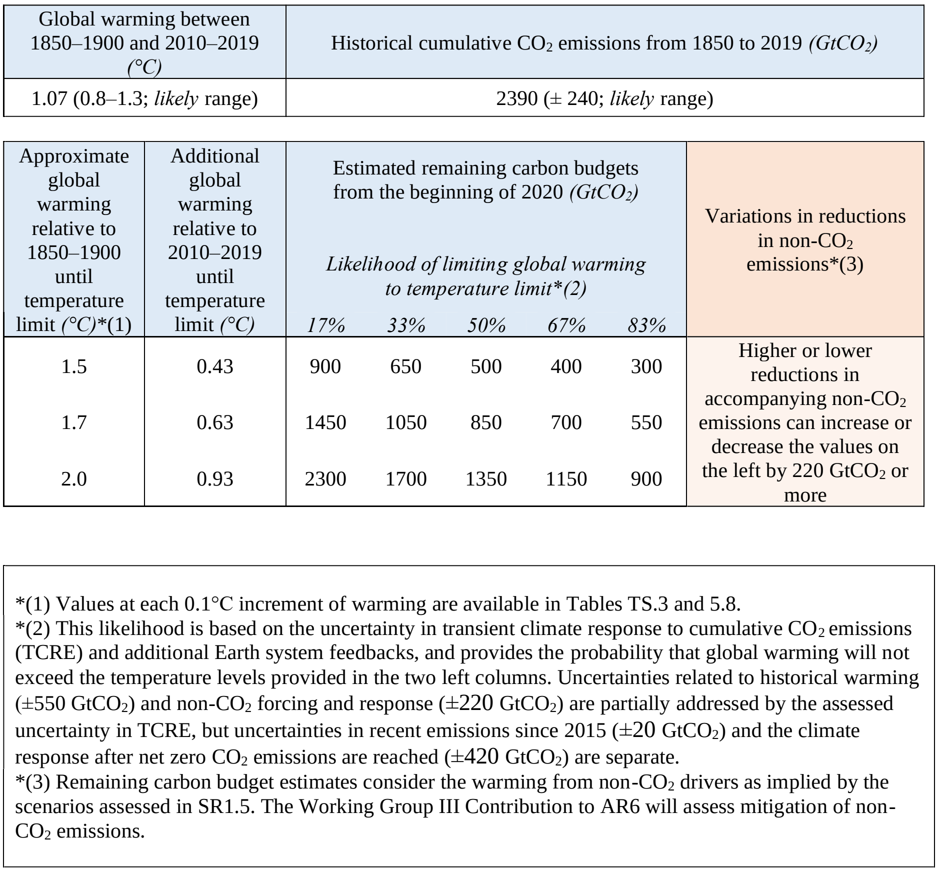
33. Once the carbon budget has been 'spent' (emitted), then emissions need to be net zero to avoid exceeding the temperature target.

34. There are several key areas of uncertainty that influence the carbon budget required to meet a temperature target:

    (a) **Probability of meeting the target**. Higher probabilities of meeting a given temperature target (e.g., 2°C) require a more stringent carbon budget. Thus, there is a critical trade-off: relaxing the carbon budget to make it more feasible to meet means that there is a lower probability of achieving the desired temperature target.

    (b) **Accounting for other greenhouse gases**. Non-CO2 gases (e.g., CH4 and N2O), which are important contributors to warming, are assumed to be reduced to zero at the same rate as CO2 is reduced to zero. If non-CO2 gases are not reduced, or reduced more slowly than CO2, then the CO2 budget is reduced accordingly. Many of the CH4 and N2O emissions arise from the agricultural sector, where emission reductions are generally considered to be more difficult and expensive to achieve than for the energy generation and transport sectors. Thus, carbon budgets are often configured on the basis that reduction of CO2 emissions from the electricity and transport sectors is more technologically feasible and less expensive than for the non-CO2 gases, and therefore CO2 emissions should be reduced even further to compensate for the slower reduction in emissions (or continued emission) of non-CO2 gases. The warming effect of a given amount of these gases is normally converted to the equivalent amount of CO2 that produce the same warming effect over the given time period. This equivalent amount of CO2 is usually designated as CO2-e, or CO2-equivalent.

(c) **Accounting for feedbacks in the climate system**. Earth System feedbacks, such as permafrost melting or an abrupt shift of the Amazon rainforest to a savanna, are generally not accounted for in the carbon budget approach. Including estimates for these would reduce the budget further (Ciais et al. 2013; Steffen et al. 2018). However, in the IPCC AR6 version of the carbon budget approach, which I adopt here as it is the most up-to-date version, the uncertainty in the magnitude of Earth System feedbacks has been included in the estimate of the probability of achieving a given temperature goal. Thus, higher probabilities assume that a higher level of Earth System feedbacks has been implicitly accounted for in the budget analysis, leading to a lower remaining budget (see Table 2 below). Thus, in my analysis below, I do not include any off-line reductions in the budget to account for Earth System feedbacks.



Global warming between 1850–1900 and 2010–2019 *(°C)*	Historical cumulative CO_2 emissions from 1850 to 2019 *($GtCO_2$)*
1.07 (0.8–1.3; *likely* range)	2390 (± 240; *likely* range)

Approximate global warming relative to 1850–1900 until temperature limit *(°C)**(1)	Additional global warming relative to 2010–2019 until temperature limit *(°C)*	Estimated remaining carbon budgets from the beginning of 2020 *($GtCO_2$)* *Likelihood of limiting global warming to temperature limit*(2)*					Variations in reductions in non-CO_2 emissions*(3)
		17%	*33%*	*50%*	*67%*	*83%*	
1.5	0.43	900	650	500	400	300	Higher or lower reductions in accompanying non-CO_2 emissions can increase or decrease the values on the left by 220 $GtCO_2$ or more
1.7	0.63	1450	1050	850	700	550	
2.0	0.93	2300	1700	1350	1150	900	

*(1) Values at each 0.1°C increment of warming are available in Tables TS.3 and 5.8.
*(2) This likelihood is based on the uncertainty in transient climate response to cumulative CO_2 emissions (TCRE) and additional Earth system feedbacks, and provides the probability that global warming will not exceed the temperature levels provided in the two left columns. Uncertainties related to historical warming (±550 $GtCO_2$) and non-CO_2 forcing and response (±220 $GtCO_2$) are partially addressed by the assessed uncertainty in TCRE, but uncertainties in recent emissions since 2015 (±20 $GtCO_2$) and the climate response after net zero CO_2 emissions are reached (±420 $GtCO_2$) are separate.
*(3) Remaining carbon budget estimates consider the warming from non-CO_2 drivers as implied by the scenarios assessed in SR1.5. The Working Group III Contribution to AR6 will assess mitigation of non-CO_2 emissions.

Table 2: Estimates of historical CO2 emissions and remaining carbon budgets (IPCC 2021, which includes more detail on the construction and interpretation of the budgets).

35. In the IPCC Sixth Assessment Report, Summary for Policymakers, the carbon budget framework has been applied to estimate the remaining emissions that are allowable for achieving various desired temperature goals (see Table 2 above) (IPCC 2021). The carbon budget framework was also used extensively in the IPCC Special Report on Global Warming of 1.5°C to explore the policy options for meeting that temperature goal (IPCC 2018).

36. Here I use the carbon budget approach, and the specific estimates of remaining in budgets in Table 2 above, to estimate the required rate of emissions reductions from present to the time at which net zero is achieved that is required to meet a specific temperature goal.

37. For the lower Paris Agreement goal of 1.5°C, the allowable budget from the beginning of 2020 for a 67% probability of meeting the goal is 400 Gt CO2, where Gt is a billion tonnes (Table 2). However, the observed emissions for 2020 and 2021 must be subtracted to give the remaining budget from 1 January 2022. The observed emissions for these two years are approximately 80 Gt CO2, reducing the remaining budget to 320 Gt CO2. At the current rate of emissions of about 40 Gt CO2 per year, the remaining budget for the 1.5°C would be consumed in only 8 years, that is, at the end of 2029.

38. Consistent with Table 2 above (IPCC 2021), I assume that the upper Paris Agreement goal of ‘well below 2°C’ can be quantified as approximately 1.7°C. Based on this assumption, the allowable budget from the beginning of 2020 for a 67% probability of meeting the goal is 700 Gt CO2 (Table 2). Again, I subtract the observed emissions for 2020 and 2021 of 80 Gt CO2 to give the remaining budget from 1 January 2022. The remaining budget is thus 620 Gt CO2. At the current rate of emissions of about 40 Gt CO2 per year, the remaining budget for the 1.7°C would be consumed in only 15.5 years, that is, at the end by the middle of 2036.

39. Both of these emission reduction targets are challenging, and both require significant reductions in greenhouse gas emissions by 2030 to have a reasonable chance of achieving the desired temperature goals.

The evidence that human emissions of greenhouse gases may result in Earth System changes that lead to a ‘Hothouse Earth’ scenario

40. A ‘Hothouse Earth’ scenario is a colloquial term that refers to a pathway leading to a future state of the Earth System that would be (i) very much hotter than pre-industrial conditions (at least 4°C hotter), (ii) stable for a long period of time (thousands of years), and (iii) an extremely difficult state of the Earth System for humans.

41. In general, there are two pathways that could lead to Hothouse Earth conditions. The first is the high emissions SSP5-8.5 scenario of the IPCC scenario set (IPCC 2021). In that scenario, human emissions of greenhouse gases are the dominant driver of the temperature rise, and on their own, are projected to lead to a temperature rise of 4.4°C by 2100 (IPCC 2021). The second pathway consists of a combination of direct human forcing via greenhouse gas emissions, coupled with feedback processes within the Earth System, which, once triggered by the temperature rise resulting from human emissions, drive the Earth System to even hotter conditions and ultimately to Hothouse Earth. The first pathway is the highest of the scenarios already described in IPCC reports (e.g., IPCC 2021). Here I focus on the second pathway, involving significant contributions from feedback processes.

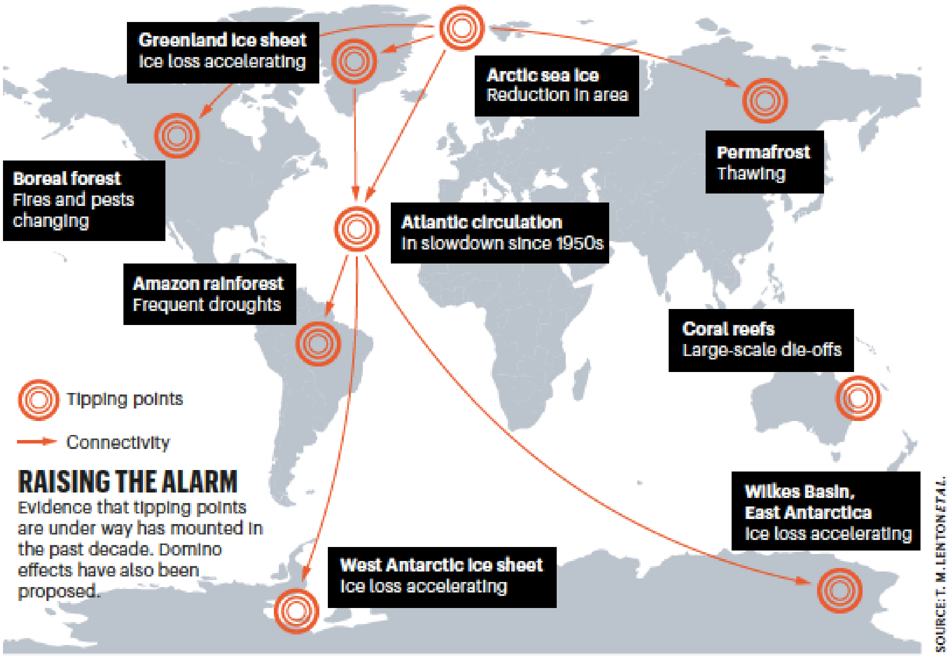
42. I first describe what a ‘tipping cascade’ is, and then discuss the variables that could trigger such a cascade. I then outline the consequences of a tipping cascade, before assessing the likelihood of such a cascade occurring.

43. Tipping cascades are built on ‘tipping elements’, where a ‘tipping element’ is defined as a feature of the Earth System that can undergo significant change when it is pushed beyond a critical point by an external forcing factor (e.g., rising temperature driven by human GHG emissions). The point at which the tipping element is pushed out of its stable state and on to a trajectory of change is often called the ‘tipping point’.

44. Tipping cascades refer to a process whereby one or two tipping elements can activate other feedbacks or tipping elements in the Earth System (of which the climate system is a major feature), leading to a cascading effect. This cascading effect could create a global tipping point beyond which the system is driven into a new state, that is, into fundamentally different

conditions (Lenton et al. 2019; Figure 4 below). A good analogy is a row of dominoes, where tipping one or two dominoes causes the whole row of dominoes to fall.

45. Here a 'feedback' in the Earth System refers to a response of the system to an anthropogenic forcing factor or to an internal forcing factor. For example, human-driven warming of the atmosphere (from GHG emissions) increases the temperature of the Earth's surface, which then leads to a release of CO2 from warming soil organic matter, which in turn amplifies the warming. This is called a 'positive (reinforcing) feedback' because it acts to intensify the original forcing factor.



SOURCE: T. M. LENTON ET AL.

Fig. 4: Observational evidence shows that several tipping elements in the Earth System are already being activated, increasing the risk of a tipping cascade (Lenton et al. 2019).

46. As noted above, a 'tipping point' refers to the phenomenon in which a small increase in a forcing factor leads to an unexpectedly large, and often rapid, response in the system (tipping element) being perturbed. There are many such tipping points in the climate system, many of them irreversible on timescales of relevance to humans.

47. An example of a tipping point is the bleaching of coral reefs: a very small increase in water temperature can lead to very large and widespread coral bleaching events (see Figure 4 above). This occurs because a critical threshold in the physiology of the coral organisms is crossed, leading to the bleaching. Australia's Great Barrier Reef (GBR) suffered three mass bleaching events in the 2016-2020 period (Climate Council 2021a), which has led to the loss of over 50% of the GBR's hard corals (Dietzel et al. 2020).

48. In terms of other tipping elements, some of these produce reinforcing feedbacks that accelerate warming of the Earth System. Examples include (i) melting of Arctic sea ice, which uncovers darker seawater, which absorbs more sunlight (in the northern hemisphere summer) and accelerates warming; (ii) increasing drought in the Amazon basin, which

increases fire frequency, leading to an increase in the emissions of CO2; and (iii) melting of permafrost, which releases both CO2 and CH4 to the atmosphere, accelerating warming.

49. As the global average surface temperature rises towards 2°C and beyond, the risk of activating such feedbacks increases. Given that many of these feedback processes are linked (see Lenton et al. 2019 for details on tipping cascades), a global tipping cascade could form that takes the trajectory of the Earth System out of human control or influence and leads to a much hotter Earth. This scenario is often called the 'Hothouse Earth' scenario (Steffen et al. 2018; Figure 5 below).

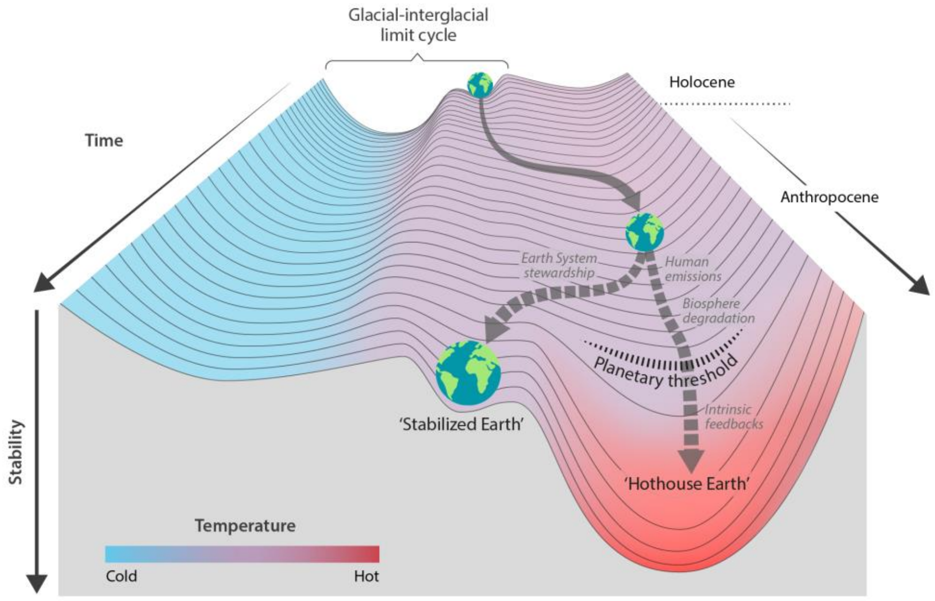


Fig. 5: Stability landscape showing the pathway of the Earth System out of the Holocene to its present position in the hotter Anthropocene. The "fork in the road" is shown here as the two divergent pathways of the Earth System in the future (broken arrows). Currently the Earth System is on a 'Hothouse Earth' pathway, driven by human emissions of greenhouse gases and biosphere degradation towards a potential planetary threshold at ~2°C, beyond which the system follows an essentially irreversible pathway driven by intrinsic biogeophysical feedbacks. The other pathway leads to 'Stabilised Earth', a pathway of Earth System stewardship guided by human-created feedbacks to a quasi-stable, human-maintained basin of attraction (Steffen et al. 2018).

50. The feedback processes that could drive the Earth System onto a Hothouse Earth trajectory include climate change-driven degradation of large biomes (e.g., Amazon rainforest; boreal forests in Canada and Siberia) and subsequent release of CO2; melting of polar ice such as the Arctic sea ice over the north pole, and changes in ocean and atmospheric circulation, such as a weakening of the Atlantic Ocean thermohaline circulation (Lenton et al. 2019). There is a risk that even a 2°C temperature rise could trigger a Hothouse Earth trajectory, but the probability of such a scenario is much lower for a 2°C temperature rise than for a 3°C temperature rise.

51. This Hothouse Earth scenario would lead to the following changes in the Earth System:

(a) The global average surface temperature would continue to rise throughout the 21st century with no stabilisation until sometime in the 22nd century or later centuries, depending on the rate of the feedback processes, and at a temperature of at least 4°C above pre-industrial and probably higher.

(b) Stabilisation would be dictated by Earth System processes and not by human actions. There are currently no climate system models that can simulate a Hothouse Earth trajectory (that is, the Earth System feedback processes that would drive a Hothouse Earth trajectory are not included in the model architecture) so it is not possible to suggest what may be ‘required’ to stabilise at that level.

(c) The time of stabilisation is difficult to predict but would occur sometime in the 22nd century at the earliest or, more likely, well beyond. Many of the feedback processes that drive the Hothouse Earth trajectory are slow from a human perspective but very fast in a geological timeframe.

(d) Human CO2 emissions are less relevant for this scenario (stabilisation at Hothouse Earth conditions), as once a tipping cascade is initiated, the internal dynamics of the Earth System comprise the controlling factor, with CO2 emissions from feedbacks such as permafrost melt and forest dieback becoming an important source of CO2.

(e) Once a tipping cascade is initiated, there is a high probability that the Earth System will be stabilised at much hotter conditions (4°C or higher) compared to pre-industrial. Based on a complex systems framework (see Figure 5 above), a Hothouse Earth state could be stable for hundreds of thousands or perhaps a few million years. An appropriate analogue is the mid-Miocene period, about 15 to 17 million years ago, when atmospheric CO2 concentrations were in the 300-500 ppm range (current atmospheric CO2 concentration is 410 ppm; IPCC (2021)) and global average surface temperature was 4 to 5°C higher than pre-industrial (Greenop et al. 2014; Kominz et al. 2008).

(f) Feedbacks are the key feature of this scenario. The risk is that a set of interacting Earth System feedbacks could drive a cascade that would drive the Earth System to a much hotter state. To summarise again, the feedbacks are of three basic types: (i) melting ice, such as the melting of Arctic sea ice, the loss of ice from the Greenland and Antarctic ice sheets, and the melting of permafrost; (ii) forest dieback through drought, heat and fire – the Amazon and boreal forests are appropriate examples; and (iii) changes in Earth System circulation patterns, such as the Atlantic Ocean circulation or the northern hemisphere jet stream circulation. The risk of triggering a tipping cascade increases with the rise in global average surface temperature. As noted above, there is a risk, albeit small, that a cascade of these tipping elements could be initiated at a rise in global average surface temperature as low as 2°C. In fact, recent observations show that at the current rise in global average surface temperature (~1.1°C), several of these tipping elements are already being activated (Figure 4 above; Lenton et al. 2019).

52. The implications of the Hothouse Earth scenario for humanity are profound. The Earth System would be irreversibly (on any timescale of relevance for humans) driven into very hot and inhospitable conditions, with global average surface temperature about 4-5°C above the pre-industrial level. These conditions were described in Steffen et al. (2018) as:

> Hothouse Earth is likely to be uncontrollable and dangerous to many, particularly if we transition into it in only a century or two, and it poses severe risks for health, economies, political stability, and, ultimately, the habitability of the planet for humans.

53. A critical question is at what level of global temperature rise could a global tipping cascade, with a consequent trajectory into Hothouse Earth, be activated? There is much uncertainty around this question given the uncertainties around the degree of warming that would activate many of the tipping elements. A risk-averse approach is therefore the most appropriate approach to addressing this question.

54. The IPCC employs a 'reasons for concern' approach to evaluate the risk that climate change will drive various impacts, including the risk of activating tipping elements (Figure 6 below).

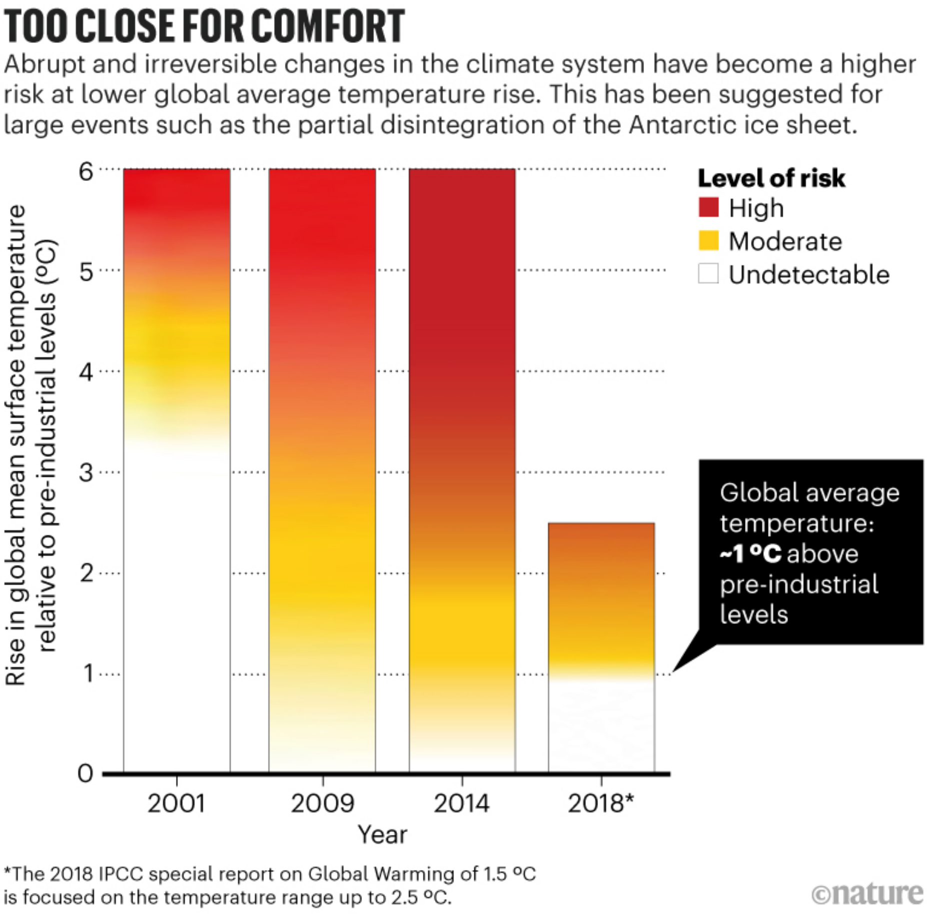


Fig. 6: The risk of activating a tipping cascade increases with the rise in global surface temperature (Lenton et al. 2019).

55. Even at a temperature rise of about 1°C above pre-industrial (the current level is 1.1°C above pre-industrial (IPCC 2021)) there is a moderate risk of activating tipping elements. The risk rises as global surface temperature rises, reaching a moderate-high level at a 3°C rise in global temperature.

56. In a massive collective action problem like climate change in which millions or hundreds of millions of individual projects and activities cause the problem through their emission of GHGs, it is easy to lose sight of the importance of each one of the individual contributions because their emissions of GHGs appear so small in comparison to the global total. The flaw in this logic is apparent through a short series of simple, clear statements:

(a) Every tonne of CO2 emissions adds to global warming.

(b) Every increase in global warming increases the risk that tipping point(s) will be crossed.

(c) The risk of a very damaging global tipping cascade rises with every tipping point that is crossed.

57. In summary, every additional emission of GHGs to the atmosphere matters as it contributes to the warming of the atmosphere. With every increment of additional warming, the risk of a global tipping cascade increases, thereby ultimately threatening the habitability of the Earth for humans, and for many other forms of life. In my opinion, the risk of a tipping cascade is not only credible, but of increasing concern. As shown in Figures 4 and 6 and the accompanying discussion, warning signs that many tipping elements are already being activated at the current global warming level are clear and unequivocal. The precise level of warming at which a tipping cascade will be activated can only be known for certain by crossing the critical threshold. Given that the consequences of a global tipping cascade are so serious, a strongly risk-averse approach is the only sensible one to take to ensure a habitable planet for future generations.

The effect that the impacts of climate change will have on youth and future generations

58. I refer to Table 1 above. The escalating risks of climate change are highly skewed towards today’s youth and towards future generations. All humans will experience the same level of worsening climate conditions and more severe impacts over the next two decades, as shown in Table 1 by the projected temperature in the 2021-2040 interval. All five of the scenarios show that the best estimate of temperature will be 1.5-1.6°C above pre-industrial in that time interval. However, those humans who are currently in the 30-40 age group are likely to experience much worse conditions later in their life, with temperatures at least 1.6°C above pre-industrial but perhaps up to 2.4°C warmer, depending on the emission scenario that we choose in the future. A 2.4°C world would a very difficult one in which to live, given the escalating climate impacts, particularly much more severe extreme weather, that are unavoidable at that temperature level (IPCC 2018).

59. The disproportionate effect is even more pronounced for those humans who will come into the world in the next decade. If they live the current average lifespan of around 80 years, they could experience a wide range of possible futures, from the 1.4°C world that would result from the most ambitious emission reduction scenario (still a more difficult world to live in than our world today) to a worst-case Hothouse Earth scenario with global temperatures reaching 4°C and beyond. That would be an exceptionally difficult world to survive in, much less live in with any decency, with collapse of human civilisation a possible outcome (Steffen et al. 2018).

60. In summary, the risks to current youth and future generations from climate change are already significantly greater than those facing today's middle-aged and older people. However, these risks could escalate enormously into the future if the current generation of leaders do not take decisions that lead to deep and ongoing emission reductions from now.

WS

SWORN at Canberra, Australia
this 9th day of ~~December~~ ~~2021~~ February 2022
before me:

William L Steffen

ACT
SUSAN McLAY
Justice of the Peace # 2691

William Lee Steffen

A person authorised to administer oaths by the law of the Australian Capital Territory, Australia

AUSTRALIAN FEDERAL POLICE
CITY POLICE STATION
16-18 London Circuit
CANBERRA CITY ACT 2601

SCHEDULE 1 – REFERENCES

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SCHEDULE 2 – QUALIFICATIONS AND EXPERIENCE

Education and degrees

PhD (Honoris causa)	University of Canberra, Australia (April 2015)
PhD (Honoris causa):	Stockholm University, Sweden (September 2010)
PhD (Chemistry):	University of Florida, USA (August 1975)
MS (Chemistry):	University of Florida, USA (August 1972)
BS (Chemical Engineering):	University of Missouri, USA (May 1970)

Academic affiliations

Emeritus Professor, The Australian National University, Canberra

Senior Fellow, Stockholm Resilience Centre, Stockholm University, Sweden

Adjunct Professor, The University of Canberra, Australia

Fellow, Beijer Institute of Ecological Economics, Stockholm

Senior Associate, University of Cambridge Institute for Sustainability Leadership, UK

Positions held

Aug 2021-present	Member, High-level OECD (Organisation for Economic Cooperation and Development) External Advisory Panel on *Building Climate and Economic Resilience in the Transition to a Low-Carbon Economy.*
Sept 2013-present	Climate Councillor (with the independent, publicly funded Climate Council of Australia)
Nov 2011-Jun 2019	Member, ACT Climate Change Council
Feb 2011-Sep 2013	Climate Commissioner (with Australian Government Climate Commission)
Jul 2008-Jun 2012	Executive Director, ANU Climate Change Institute, The Australian National University (ANU), Canberra
Aug 2004-Jan 2011	Science Adviser (part-time), Department of Climate Change and Energy Efficiency (earlier Australian Greenhouse Office), Australian Government, Canberra
Mar 2007-Jul 2008	Director, Fenner School of Environment and Society, and Director, ANU Institute of Environment, The Australian National University (ANU), Canberra

Oct 2006-Feb 2007	Pro Vice-Chancellor (Research), The Australian National University, Canberra
Oct 2005-Oct 2006	Director, Centre for Resource and Environmental Studies, and Director, ANU Institute of Environment, The Australian National University (ANU), Canberra
Jul 2004–Jun 2006	Chief Scientist, International Geosphere-Biosphere Programme (IGBP), Stockholm
Aug 2004-Sept 2005	Visiting Fellow, Bureau of Rural Sciences, Department of Agriculture, Fisheries and Forestry, Australian Government, Canberra
Mar 1998-Jun 2004	Executive Director, International Geosphere-Biosphere Programme (IGBP), Stockholm, Sweden
Dec 1990-Feb 1998:	Executive Officer, Global Change and Terrestrial Ecosystems (GCTE) Core Project, International Geosphere-Biosphere Programme (IGBP), based at CSIRO, Canberra
Apr 1981-Nov 1990:	Editor and Information Officer, CSIRO Centre for Environmental Mechanics, Canberra
Aug 1977-Jul 1980:	Research Fellow, Research School of Chemistry, The Australian National University, Canberra
Sep 1975-Jun 1977:	Postdoctoral Fellow, Department of Chemistry, Cornell University, New York, USA

Advisory/honorary positions and review panels

Apr 2016-present	Member, International Advisory Board, Centre for Collective Action Research, Gothenburg University, Sweden
Jan 2011-present	Member, Volvo Environment Prize jury, Sweden (Chair of Jury from May 2013)
Jul 2004-Dec 2015	Member, National Committee for Earth System Science (NCESS), Australian Academy of Science
Oct 2010-Jul 2011	Member, Multi-Party Climate Change Committee, Australian Government
Oct 2009-Dec 2014	Chair, Antarctic Science Advisory Committee, Australian Government
Aug 2009-May 2011	Member, Science Advisory Committee, APEC Climate Center, Busan, Korea
Jan 2005-May 2010	Chair, International Advisory Board, QUEST (Quantifying and Understanding the Earth System) programme, UK

Oct 2005-Nov 2008	Chair, Advisory Panel, Earth and Sun System Laboratory, National Center for Atmospheric Research, Boulder, CO, USA
Jan 2006-Dec 2008	Member, Advisory Board, Australian Bureau of Meteorology
May 2007	Review of the Australian Climate Change Science Program. Australian Government. Carried out with Dr Susan Solomon, NOAA, USA and Convening Lead Author, Working Group 1, IPCC Fourth Assessment Report
Apr 2007	Member of review panel, Potsdam Institute for Climate Impact Research, Germany
Aug 2006-Dec 2006	Member, PMSEIC (Prime Minister's Science, Engineering and Innovation Council) working group on Australia's S&T Priorities for Global Engagement
Feb 2005	Member of review panel for du Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Paris, France
Apr 2004	Member of review panel for the Tyndall Centre, UK (Climate Adaptation Research)