The scientific motivation of the internationally agreed "well below 2°C" climate protection target: a historical perspective.

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Highlights

- The internationally agreed "well below 2°C" climate protection target has a long history;
- The target is scientifically well argued from many disciplinary perspectives;
- The target does not protect from all impacts (e.g. not for continued sea-level rise and damage to unique ecosystems) but is expected to protect from large scale disruption and non-linear climate responses;
- To achieve the target, emission reductions world-wide are urgently needed.

Abstract

The UNFCCC parties in their last 2015-meeting in Paris agreed to hold the increase in the global average temperature well below 2°C above pre-industrial levels. However, how this target came about is rarely substantiated in the scientific literature. We review and document the history of this target and the rapidly emerging scientific evidence to support it. The target was initially proposed after evaluating observed ranges of climate variation over the last 1.000 and 1.000.000 years by an US economist, Nordhaus. His conclusion was supported by paleo-ecologists, such as Davis who, on basis of the recolonizing vegetation after the retreat of the ice-sheets of the last glaciation, calculated that tree species could cope with a 2°C temperature increase per century. A more elaborated target including tolerable rates of temperature and sea-level change was presented by Vellinga and Swart at the Second World Climate Conference. The target was illustrated by means of a traffic light: 1°C global temperature rise meets an orange light, 2°C meets red. These notions led first to the 1989 Noordwijk Ministerial Declaration and later to the UNFCCC's 1992 objective to prevent dangerous anthropogenic interference with the climate system. Although the scientific evidence was limited, the European environment ministers in 1996 endorsed the 2°C target politically, after which it surfaced again in UNFCCC's 2009 Copenhagen summit.

The "well below 2°C" target was scientifically further analysed and motivates as part of the IPCC's third assessment report in its synthesis chapter, which assessed dangerous climate change. The resulting 'burning ember' diagram indicated that beyond 2°C warming adaptation possibilities rapidly deteriorated and vulnerabilities increased, especially for unique ecosystems and extreme events. The evidence that emerged since this assessment report, on observed climate-change impacts show that vulnerabilities likely are larger. Recently, accelerated and higher levels of sea-level rise and more frequent extreme events are reported. All these insights were likely considered in the wording (i.e. "well below 2°C") of the 2015 Paris Agreement.

Introduction

In December 2015 the Conference of Parties of the Framework Convention on Climate Change (UNFCCC) met in Paris and agreed on a global climate protection target of global average temperature well below 2°C and "pursue efforts to" limit the temperature increase to 1.5°C. This target responds to the political need to have an achievable goal. This "well below 2°C" target is arguably technically achievable and would simultaneously allow for effective adaptation measures to cope with impacts and to achieve the required mitigation efforts in an economically efficient way. This political target was initially proposed by the European environment ministers in 1996 and in the last night of UNFCCC's 2009 Copenhagen summit when the world leaders concluded the Copenhagen Accord. The final Copenhagen Accord (http://unfccc.int/meetings/copenhagen_dec_2009/items/5262.php; [4]) stated:

> "To achieve the ultimate objective of the Convention to stabilize greenhouse gas concentration in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system, we shall, recognizing the scientific view that the increase in global temperature should be below 2°C, on the basis of equity and in the context of sustainable development, enhance our long-term cooperative action to combat climate change."

In the last paragraph of this Accord, a possibility to further reduce the target to 1.5°C is mentioned. A particular weakness in the 2°C target is the question about future sea-level rise. Geological records of sea-level changes indicate that ice cap melt and sea-level rise likely continue as long as global temperatures are more than 1°C higher than pre-industrial temperatures. Although the Copenhagen Accord seems ambitious, it does not mention a reference period. Most delegates assumed that this target is relative to pre-industrial temperatures, but 1990 as the onset of the UNFCCC, or 2010 when the target was accepted, remained possible baselines. The recent Paris agreement clearly states that it is relative to pre-industrial temperatures. That the Paris agreement strives for maximally 1.5°C reflects the concern about the adequateness of a 2°C target.

The "well below 2°C" target has surfaced early in the international climate protection debate but its origin is not fully clear. Generally the target assumingly stems from a reversed cause-effect approach. Dangerous climate change is defined by its impacts on natural and human/societal systems. These impacts constrain the allowable climate change and radiative forcing, and consequently greenhouse-gas concentrations and emissions. This approach was pioneered by acid-rain research in the seventies and eighties [e.g. 5] and resulted in defining critical loads of sulphur and nitrogen on ecosystems. A similar approach was adopted by Vellinga and Swart [6**] for climate protection. They designed a traffic light (Figure 1) with steps from green, through yellow to red on basis of tolerable sea-level rise and temperature increase levels. Their maximally acceptable sea-level rise was 50cm and temperature 2°C, including a maximum decadal rate of 0.2°C and 0.05m sea-level rise. These targets were motivated on basis of impacts on ecosystems and society including food production and water management. The selected levels combined scientific analyses and expert judgements. At that time they provided comprehensive emissions reduction pathways for industrialized and developing countries.

<<< INSERT **FIGURE 1** NEAR HERE >>>

This review takes the UNFCCC's objective as specified in Article 2 (Box 1) as a starting point. However, the philosophy and much of the wording of this objective can already be found in the Noordwijk Ministerial Declaration on Climatic Change [7]. This declaration lists the three criteria for tolerable climate-change targets: ecosystems should be able to adapt naturally, food production should not be threatened and the economy should be allowed to develop in a sustainable manner. Later this wording evolved into the UNFCCC phrasing "to avoid dangerous anthropogenic interference" that clearly refers to different climate (and weather) events and their impacts. The final UNFCCC text is carefully drafted to solely focus on the anthropogenic causes of climate change. It also shows a very good understanding of what causes climate change because its focusses on atmospheric greenhouse gas concentrations and not on just emissions. So far, so clear. But how did this lead to the "well below 2°C" target remains obscure. The purpose of this paper is therefore to carefully review the old climate-change impact literature and trace the various discussions that contributed to establishing this target. This review tries to be complete but as much of the early debates and evidence is not documented or available on-line, we also rely on our experiences in the climate debate (Vellinga as one of the main Dutch climate and sea-level rise impacts researchers, climate negotiator in the early phases of UNFCCC and researcher on the societal implications of climate change; Leemans as an ecologist and impact and integrated assessment modeller, and scenario developer; and both of us were involved in the AGGG and

IPCC). Although many state that the "well below 2ºC" target is just a political preference [e.g. 8], we will show that it actually is supported by scientific evidence from various disciplines.

<<< INSERT **BOX 1** NEAR HERE >>>

The early arguments for a two degree target

Nordhaus [9] did one of the first analyses to control climate change. He clearly stated that standards for greenhouse gas concentrations (and thus climate protection targets) are not yet specified, partly because all the carbon-cycle uncertainties involved and partly because 'standards' have to be set by society. (Nordhaus acted as an honest broker long before the term was coined by Pielke [10]). He then discussed and elaborated upon a possible approach by assuming that climate change should be kept well within the normal range of long-term climatic variation. This limits impacts and allows for adaptation. By evaluating centennial and millennium and longer climate variabilities, he inferred that "global temperatures more than 2°C or 3°C above current average temperatures would take the climate outside of the range of temperature observations which have been made over the last several hundred thousand years" [9, p23]. He then elaborated this target in a series of different emission-control scenarios to optimistically conclude that controlling CO_2 emissions is technically and economically feasible. This study laid the groundwork for his influential DICE model and his many seminal studies on managing climate change [e.g. 11,12,13].

Another line of reasoning emerged In 1981. The paleo-ecologist Davis published a study on the colonization of trees across landscapes after the last glaciations [14]. She showed that trees respond and adapt to climate change by migrating towards their most suitable climates. These dynamics can be determined on basis of historic pollen profiles, which allow to reconstruct past landscapes and ecosystems. Together with some of her other studies [15,16**], she determined that the pace of common tree species (oak and beach) is about 20-40km per century. If trees should 'adapt naturally' (c.f. Article 2 UNFCCC), this parallels a maximum increase of global mean temperatures of c. 2ºC per century as limited by the corresponding polewards shifts in tree distributions. Her seminal research indicated not only the importance of an absolute change but also the rate of temperature change. Beyond a certain rate of change, individual species would not be able to effectively adapt. As such she established the dynamic ecological reasoning, using past evidence into the earlier impact assessment by the Intergovernmental Panel on Climate Change (IPCC) [17,18]. Her research led to the early analyses of the potential shifts in global vegetation patterns under climate change [e.g. 19,20] that confirmed the vulnerabilities of ecosystems.

In the summer of 1988, the NASA scientist Hanssen testified to the US Senate to start immediate climate protection measures [21]. His testimony coincided with a very strong heat spell in the Eastern USA, which made Hansen conclude that "global warming has begun". This warmer weather fitted into the observed warming trend of the eighties. He was confident that this trend was attributable to the greenhouse effect and that NASA's climate models show that the trend would soon accelerate. He urged for strong measures to stabilize concentrations and limit climate change. His attribution statements were highly criticized but his testimony surely affected the media and the public debate. Since, Hansen has always been very outspoken on devastating impacts [22*] and an advocate for immediate action.

At the same time, the German climate scientist Bach was one of the most outspoken European scholars on the threats of climate change [23]. Like Nordhaus, he developed an early integrated model linking energy use, CO_2 emissions and climate change [24]. This model clearly showed the time lags between emissions, concentrations and temperature increase. In an interview in Spiegel Magazine (November 1988), he clearly stated that strict emission-reduction measures must be taken to keep the global temperature increase between 1ºC and 2ºC in 2100. He argued this on basis of the long-term physics of the climate system (more heat trapped means more available energy) and the consequently expected increase in the frequency and intensity of droughts, floods and heatwaves. Such events would affect millions of people. In his calculation he also presented the necessary emission reductions to achieve this target (based on his scientific understanding of the carbon cycle): before 2000, the global emissions should be reduced by at least one third relative to 1980. This can be achieved by increases in energy efficiency and conservation, and shifting away from fossil fuels.

All these arguments have also been presented at the early international climate-change conferences (Box 2), several of which led to strong declarations to deal with this rapidly emerging problem.

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Integrated Assessments of the "well below 2°C" target

All these early scholars and their research argued for a 2°C target (or below) but did not consider all the potential impacts on systems and sectors, and in different regions or periods. Most arguments were anecdotal. The first comprehensive science-policy assessment was done by the Advisory Group For Greenhouse Gases (AGGG), which was established immediately after the international climate-change conferences at Villach and Bellagio (Box 2). The final AGGG assessment included a report on targets and indicators [25]. The objectives for developing such targets and indicators included to:

- limit the impacts on human society and natural ecosystems;
- limit the rate and magnitude of sea-level rise;
- limit the rate and magnitude of temperature change;
- stabilize the ambient concentrations of specific greenhouse gases;
- stabilize and/or reduce emissions of greenhouse gases and enhance sinks to stabilize the atmospheric concentrations of greenhouse gases; and
- take measures to reduce greenhouse gas emissions in an equitable manner among the different actors.

These comprehensive objectives resulted in indicators such as global mean temperature change, sea-level rise and CO_2 concentrations. The targets set for these indicators included both the rate of change and maximum levels. The selected values emerged from an extensive literature review and broad expert consultations. For example, the maximum rate of acceptable sea-level rise is between 20 and 50mm per decade (depending on the region), while the maximum allowable sea-level rise is less than 0.5m above the 1990 global mean sea level (c.f. Figure 1).

To set the target values for the other indicators, the uncertainties related to climate sensitivity[1]were explicitly considered [26]. Again both the rate of change and a maximum allowable change was proposed for either a low or high climate sensitivity.

The maximum rate of temperature change was set to 0.1°C per decade. This rate refers to the already realized warming and the possibility of individual (tree) species to adapt [c.f. 16**]. The maximum global mean temperature increase of 1.0°C above pre-industrial temperature results from assuming a high climate sensitivity (i.e. 4.5°C) and a maximum increase of 2.0°C for a low sensitivity (i.e. 1.5°C). It recognizes that temperature changes greater than the lower limit may be unavoidable due to greenhouse gases already emitted. Temperature increases beyond 2.0°C may prompt rapid, unpredictable, and non-linear impacts that could lead to extensive economic and ecosystem damages. A weakness of this global target approach is that the actual impacts are caused by local changes in weather and climate, and not by changes in the global mean. Large regional variations in climate change and impacts are likely and half of these impacts are probably worse than the mean impact.

The outcome of this AGGG assessment was summarised in the Greenhouse Marathon paper [6**] and influenced the formulation of the UNFCCC and the decision of the European environment ministers to limit global mean temperatures to 2°C in 1996. However, such indicators and targets were not included specifically in the UNFCCC from 1992. It only stated a quantitative target that developed country parties should aim to return their greenhouse-gas emissions to 1990 levels by

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[1] The climate sensitivity is a measure for the amount of global mean warming at a doubling of greenhouse gas concentrations in the atmosphere.

2000. The AGGG assessment was also discussed in the IPCC's second assessment [27]. The IPCC assessment, however, concluded then that setting impact or temperature targets was less useful and IPCC thus strongly focused on emission reduction targets. Both IPCC's first [28] and second assessments [27,29] showed already that to stabilize atmospheric concentrations, global emissions drop must drop substantially below 1990 levels.

IPCC held a workshop in Fortaleza, Brazil (October 1994), to help provide the scientific underpinnings for the ultimate objective of the United Nations Framework Convention on Climate Change (UNFCCC): "… stabilization of greenhouse gas emissions at a level that would prevent dangerous anthropogenic interference with the climate system …". The outcome was reflected in the 1995 IPCC report [18], which did not quantify "dangerous anthropogenic interference ..." but only provided the scientific, technical and economic information to evaluate whether the projected range of plausible impacts signify this. Interpreting what is "dangerous" involves political judgment and this role is reserved to governments and the Conference of Parties to the UNFCCC [18].

In the UNFCCC discussions towards the Conference of Parties in Kyoto, the Dutch IMAGE modelling group evaluated different scenarios and discussed them with European and developing-countries climate negotiators [30,31]. The purpose was to address the negotiators questions and inform them on the latest scientific insights. In these discussions the indicators and targets surfaced again to link short term emission-reduction measures to long-term climate protection measures. The resulting Safe-Landing approach [32] allowed for an interactive selection of temperature, sea-level rise and reduction-costs targets for 2100 to obtain the range of allowable emissions in 2010. This approach was highly influential during the Kyoto negotiations and copied by many other integrated assessment groups. Such approaches are now commonly known as guardrail approaches [33].

IPCC's 'Reasons for concern' or 'Burning Ember' diagram

In IPCC's third assessment report the 2°C target emerged but only indirectly. We both were involved in assessing impacts, adaptation and vulnerabilities [34] and were charged by IPCC to synthesize ways to quantify "dangerous anthropogenic interference with the climate system" (UNFCCC's Article 2). This synthesis should rely on information from all the other regional, sectoral and ecosystem chapters. However, we needed a conceptual approach to include and visualise all available information. The chapter's author team decided to select the global mean temperature target because its trends are well observed [35]; it is easily derived from various climate models; it is internationally accepted as a measure; and it is generally also the main indicator of the climate-change scenarios. Other indicators, such as sea-level rise and the rate of temperature change, and regional climate change and its impacts can be related to global mean temperatures. All available impacts studies were thus ranked along a scale of an increasing temperature change relative to the climatic normal of 1961 to 1990. Two patterns emerged from this ranking.

First, different classes of impacts could be distinguished. Many involved individual species or ecosystems (e.g. coral reefs or alpine meadows) and sectors (e.g. forestry and agriculture), but others focused on extreme events (e.g. droughts, floods, storms and heat waves). Other aspects that frequently were addressed, were the regionally and globally aggregated impacts (e.g. sea-level rise, food and water security or distribution of costs and damages) or the singularities (e.g. surprises or low probability but high risk events). Finally, five classes or 'reasons for concern' were elaborated and all impacts studies were grouped in these classes and ranked along global mean temperature.

Second, very few studies were available in the former century on impacts below 2°C. Most impacts assessments focussed on future impacts for the mere severe climate-change scenarios (i.e. more than 3°C). Very few of these assessments investigated transient impacts. To deal with this gap, the other chapter teams were asked to also assess the actually observed impacts because over the 20th century climate had already warmed globally by 0.7°C. Initially, many resisted to do so, because traditionally impact assessments were done on the basis of future climate-change scenarios and impact models. Only few teams provided essential information to assess the consequences of low levels of temperature increase. This pioneered interest in observed impacts [36,37] and eventually led to their attribution to (anthropogenic) climate change [38**,39]. In the last IPCC reports, dedicated chapters on observed impacts are included.

The final 'Reasons for Concern' diagram consists of five bars (Figure 2; [40]). The bars are coloured along a gradient of white, yellow and red, meaning respectively little risk, increasing risks and dangerous risks. This colour scheme resembles the traffic light of the greenhouse marathon but green (no risk) seemed inappropriate, and inspired the diagram's nickname 'The Burning Embers' [41]. The red of the first two, most sensitive bars starts at the 1.7°C limit and reach a deep red colour at 2.0°C. This indicates 'dangerous climate change'. The other bars start respectively at 2.3, 2.5 and 4.5°C (Figure 2). This 'burning ember' approach was frequently used by others to assess impact risks [e.g. 42,43,44]. The analysis was not repeated in the fourth assessment report but some of the earlier author team published an update in 2009 [45] on basis of the reports information. Generally the red colour moved lower indicating larger vulnerabilities. Both diagrams supported the "well below 2°C" target and influenced the final policy discussions leading up to the Copenhagen Accords.

<<< INSERT **FIGURE 2** NEAR HERE >>>

These burning ember approaches also rapidly triggered comments by Nordhaus [46] and Hansen (www.nasa.gov/vision/earth/environment/danger_point.html). Nordhaus strongly emphasized the economic mitigations costs (which are partly covered by the aggregated impacts) and concluded an optimal economic target of maximally 2.8°C, while Hansen also included his knowledge on climate sensitivity, sea-level rise and models, and concluded on a 1.0°C target. Different perspectives thus lead to different targets.

The fifth IPCC assessment report [47] revived the burning ember diagram to synthesise vulnerabilities and risks [48]. Their analysis was strongly based on many observed impacts all around the world [39,49**]. This analysis provided ample evidence that many observed impacts are already dangerous. This finding expanded the colour scheme of the diagram by adding the colour purple indicating 'very high risks'. And again, the transition from yellow to red was lowered based on the currently available scientific evidence. This assessment clearly showed that achieving the "well below 2°C" target does not mean that limiting climate change to this level will be without dangerous impacts.

For example Hansen et al. [50*] argued on the basis of geological analogues of increased temperatures and atmospheric CO_2 concentrations that sea level likely continues to rise as long as global temperatures are more than 1°C above pre-industrial levels or atmospheric concentrations are beyond 350 ppm. Rohling et al. [51] provide more detailed information on geological episodes of sea-level rise. They come to a similar conclusion, implying that when global temperatures rise is kept "well below 2 degrees" but atmospheric greenhouse gas concentrations remain above 350 or 400 ppm, sea level will likely continue to rise for many centuries to come at a rate in the order of 0,5 to 1,0 m per century. The urgency to mitigate the impacts of climate change is obvious, and this knowledge probably helped to agree upon a more strict target (i.e. 1.5 to 2.0°C) in Paris by the Conference of Parties of the UNFCCC. This requires that global emissions peak (i.e. do not rise anymore) soon and then are rapidly reduced and reach almost zero levels halfway this century [52*].

Conclusions: The emission consequences for achieving the "well below 2°C" target

Our historical review of the origins of the "well below 2°C" target shows that, although initially the first arguments were based on anecdotal and indirect evidence, since the AGGG assessment [25] a broader expert-based approach emerged based on highly aggregated arguments and evidence. Over the last two decades of impact assessments, as evaluated by the IPCC, the obvious risks are comprehensively visualised and compellingly linked to emission-reduction and climate change scenarios. We showed that the "well below 2°C" target is based on clear scientific reasoning but that staying below this target does not 'guarantee' no (local) impacts but only fewer global scale risks and better possibilities for local adaptation. The biggest challenge, however, still is to compliment these global assessments with comprehensive regional and local assessments that can be used to develop and plan local adaptation measures.

Our analysis also shows that such aggregated data as displayed by 'burning ember' diagrams can be interpreted differently by different people. Defining dangerous climate change is foremost a political choice. But, science can surely provide essential information to make such a choice.

Acknowledgements

The Carbon Brief website (www.carbonbrief.org/two-degrees-the-history-of-climate-changes-speed-limit) provided useful insights into the history of the 2°C target. We appreciate their efforts and used them as a starting point for this study. We also thank Alexandra Drozdowska, Thibault Costaz and Linda van Garderen for helping finding relevant literature and commenting on earlier drafts.

Box 1: The objective of the UNFCCC (1992)

The ultimate objective of this Convention and any related legal instruments that the Conference of the Parties may adopt is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner.

Other elements of the UNFCCC included to distribute the burdens [1]; to adhere to "equity" and "common but differentiated responsibilities" principles [2]; to deal with uncertainty through the precautionary principle [3]. When the UNFCCC was ratified in 1994, they agree that industrialized countries should take the lead in emission reductions.

Box 2: The various climate conferences in the eighties leading to the UNFCCC (source UNFCCC)

Climate change was recognized as a serious problem by the 1979 First World Climate Conference. This scientific meeting explored how climate change might affect human activities. It issued a declaration calling on the world's governments "to foresee and prevent potential man-made changes in climate that might be adverse to the well-being of humanity". It also endorsed plans to establish a World Climate Research Programme (WCRP) jointly sponsored by the World Meteorological Organization (WMO), the United Nations Environment Programme (UNEP), and the International Council of Science (ICSU).

Several conferences discussed the increasing scientific evidence and raised concern about climate change. Participants included government policymakers, scientists, and environmentalists. The meetings addressed both scientific and policy issues and called for global action. The key events were the Villach (October 1987) and Bellagio (November 1987) conferences, the Toronto Conference (June 1988), the Ottawa Conference (February 1989), the Tata Conference (February 1989), the Hague Conference and Declaration (March 1989),the Cairo Compact (December 1989), and the Bergen Conference (May 1990).

All scientific concerns were discussed in the Noordwijk Ministerial Conference (November 1989). Its declaration phrased the climate protection objective as follows: "For the long term safeguarding of our planet and maintaining its ecological balance, joint effort and action should aim at limiting or reducing emissions and increasing sinks for greenhouse gases to a level consistent with the natural capacity of the planet. Such a level should be reached within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and permit economic activity to develop in a sustainable and environmentally sound manner." This wording found its way later in the UNFCC objective.

The 1990 Second World Climate Conference called for a framework treaty on climate change. Sponsored by WMO, UNEP and other international organizations, this key conference featured negotiations and ministerial-level discussions among 137 states (including the EU). Its final declaration, adopted after hard bargaining, did not specify any targets. However, it supported several principles later included in the UNFCCC. These were climate change as a "common concern of humankind", the importance of equity, the "common but differentiated responsibilities" of countries at different levels of development, sustainable development, and the precautionary principle.

In December 1990, the UN General Assembly approved the start of treaty negotiations. The Intergovernmental Negotiating Committee for a Framework Convention on Climate Change (INC/FCCC) met for five sessions between February 1991 and May 1992. Facing a strict deadline - the June 1992 Rio "Earth Summit"- negotiators from 150 countries finalized the Convention in just 15 months. It was adopted in New York on 9 May 1992.

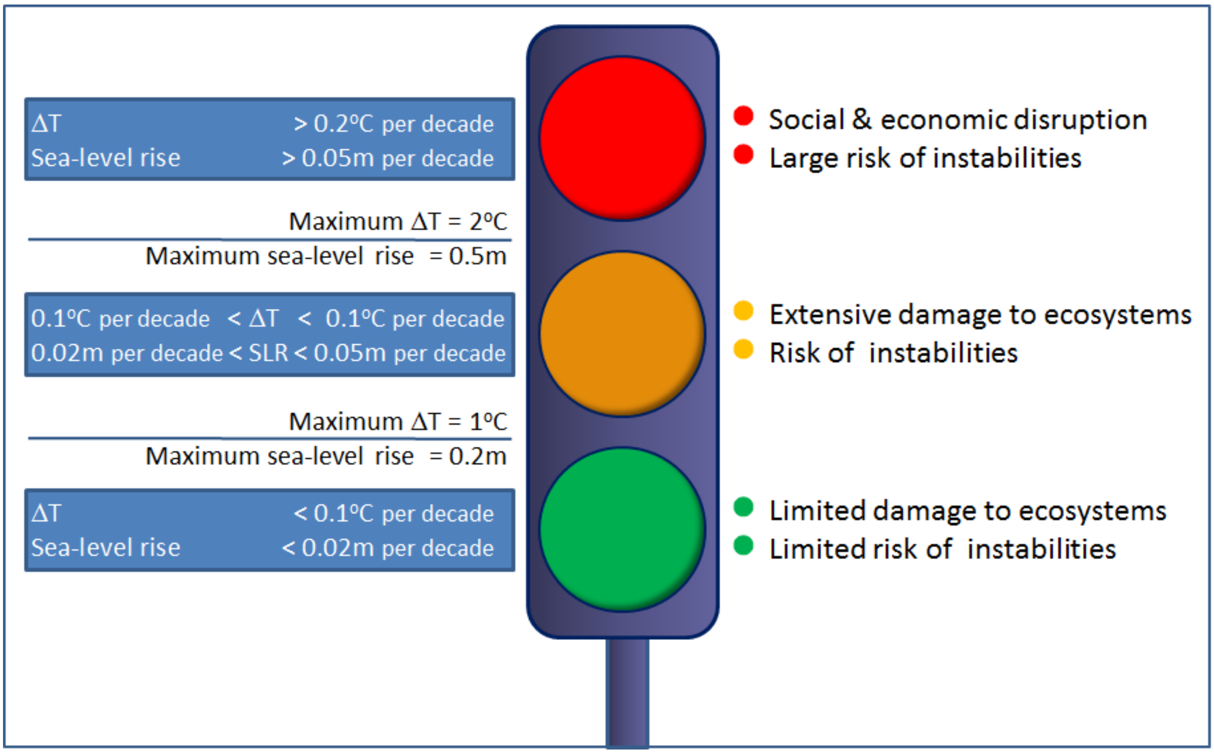

Figure 1. Targets for climate change limitation, presented at the 1990 Second World Climate Conference in Geneva (adapted from [6**]).

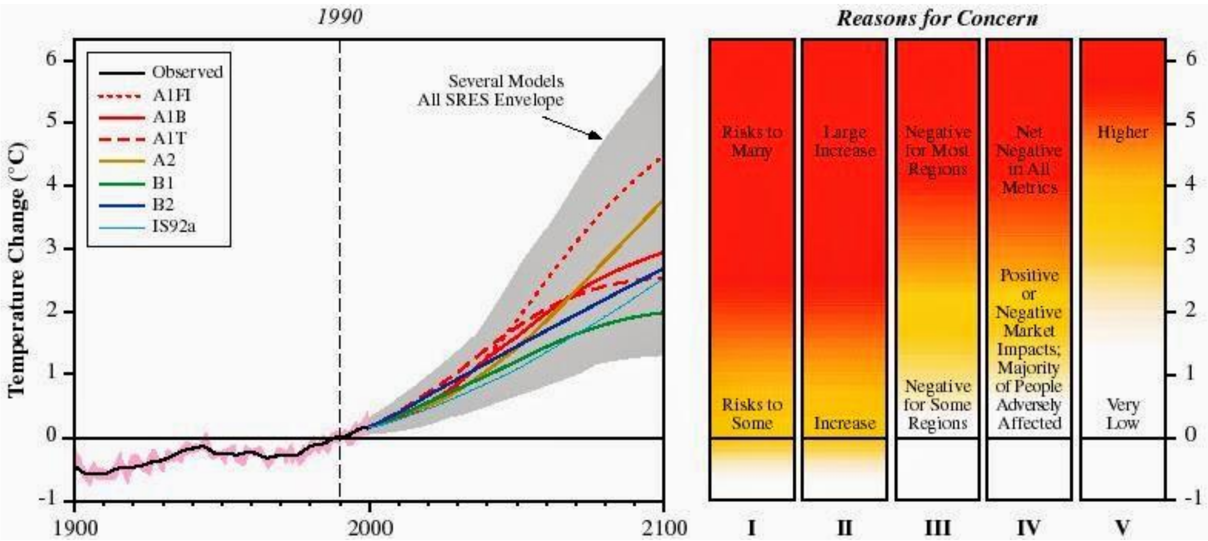

Figure 2. The IPCC-SRES scenarios and the original Reasons for Concern diagram (I: unique and threatened systems; II extreme events; III distribution of impacts; IV aggregated impacts; and V large-scale discontinuities) (adapted from [34]).

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