

Climate change and the Precautionary Principle

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Introduction

Scientific assessment of the risks of anthropogenic climate change has shown that there is a reasonable concern for the possibility of irreversible large-scale adverse effects on the long term. Examples of such effects are a severe reduction or shut down of the Gulf Stream and the North Atlantic current, accelerated species extinction and extreme sea level rise. But, deep scientific uncertainty on causality, timing, probability and magnitude of such adverse effects persists. This meets all the criteria of the definition of the Precautionary Principle (PP) adopted in this book:

"Where, following an assessment of available scientific information, there is reasonable concern for the possibility of adverse effects but scientific uncertainty persists, provisional risk management measures based on a broad cost/benefit analysis whereby priority will be given to human health and the environment, necessary to ensure the chosen high level of protection in the Community and proportionate to this level of protection, may be adopted, pending further scientific information for a more comprehensive risk assessment, without having to wait until the reality and seriousness of those adverse effects become fully apparent." (Von Schomberg, 2004)

In theory, the international community has acknowledged that the PP needs to be invoked here. In Art. 3.3 of the United Nations Framework Convention on Climate Change (UN-FCCC, 1992) it is stated that: *"The Parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost."* In practice however, actions have been delayed and postponed. The Kyoto protocol has watered down in the successive negotiations on the details of its mechanisms. Also, the level of protection for the climate case chosen by for instance the EU is increasingly challenged.

In this chapter we will review the management of climate risks from the viewpoint of the PP. Following the ingredients of the definition of the PP, we first explore the grounds for concern with a focus on potential irreversible large-scale adverse effects and associated uncertainties. Next we explore the issue of the chosen level of protection for climate change. Finally we discuss the implications of the PP for climate risk management and the science policy interface.

The risks of anthropogenic climate change

In the geological past, major global climate changes have occurred. These changes had natural causes, such as variation in the distance between the sun and the Earth, changes in solar luminosity, meteor impact, volcanic activity and continental drift.

Over the past 8000 years, climate on Earth has been relatively stable, which has been a key factor in the development of humanity. This development however brought far-

reaching changes in land use and vegetation patterns (disappearance of old growth forests, emergence of agriculture and cattle breeding etc.) along with exponential growth in the use of commodities to fulfill the energy and material demand of the fast growing world population. As a consequence, the emission of greenhouse gases (such as CO₂, CH₄, N₂O, SF₆, CFCs and HFCs) has increased to a point where it has changed the composition of the atmosphere significantly.

Analysis of the composition of air-bubbles trapped in ice in the Vostoc ice core suggests that in the past 420,000 years the CO₂ concentration has varied between 180 ppmv (parts per million by volume) during ice ages and 280 ppmv in the inter-glacial periods (Petit *et al.*, 1999). Since the first industrial revolution, the atmospheric CO₂ concentration has increased from the equilibrium concentration of 280 ppmv in 1750 to nearly 380 ppmv in 2005. For all greenhouse gases together, the CO₂-equivalent concentration is now more than 450 ppmv. Present-day atmospheric greenhouse gas concentrations thus exceed the natural variability of the past half million years.

After 10 years of Earth system research, the International Geosphere Biosphere Programme concluded that the human enterprise drives multiple, interacting effects that cascade through the Earth System in complex ways. The Earth's dynamics are characterized by critical thresholds and abrupt changes. Human activities could inadvertently trigger changes with catastrophic consequences for the Earth System. The Earth System has moved well outside the range of natural variability exhibited over the last half million years at least. The nature of changes now occurring simultaneously in the global environment, their magnitudes and rates, are evaluated as unprecedented in human history. According to Steffen and Tyson (2001), the Earth is now operating in a no-analogue state.

Assessment of the risks of climate change is based on a number of insights: understanding of the physical laws that govern the climate, historic trends, scenario analysis and model calculations. The increase in atmospheric greenhouse gas concentrations adds to the well known natural greenhouse effect of the atmosphere by absorbing and re-emitting infrared radiation emitted by the Earth surface, thereby increasing the net downward flux of infrared radiation emitted by atmosphere. The extra downward flux of infrared radiation to the Earth surface through this mechanism compared to the pre-industrial equilibrium energy balance of the earth is called the "radiative forcing" of the climate. The extent to which this radiative forcing leads to changes in climate (temperature, evaporation and precipitation, circulation patterns etc) depends on the complex interactions of a large number of poorly understood feedback loops in the Earth system.

State of the art climate research as reviewed by the Intergovernmental Panel on Climate Change (IPCC; Houghton *et al.*, 2001) shows that globally, the average Earth surface temperature has increased by $0.7 \pm 0.2^\circ\text{C}$ since the late 19th century. The largest increase has occurred over the past 20 to 30 years. At the North pole the observed temperature change is twice as big. In Europe, the observed warming is 0.95°C (European Environment Agency, 2004). Temperatures in winter have increased more than in summer. The observed rate of global warming is now $0.17 \pm 0.05^\circ\text{C}$ per decade. The seawater temperature has also increased. Differences in temperature increase between sea and land lead to changes in circulation patterns. Increased evaporation of

water has led to a 2% increase of precipitation over land. More important than the average rainfall is that at many places on Earth big changes in precipitation patterns have been observed, both positive and negative.

The IPCC concluded in their second (Houghton *et al.*, 1996) and third (Houghton *et al.*, 2001) scientific assessment report that the observed climate change is for a substantial part attributable to human activities.

Scenario studies by the IPCC (Nakicenovic and Swart, 2000; Houghton *et al.*, 2001) have shown that human activity is likely to lead to further climate change with possibly severe impacts. It should be noted that even if atmospheric composition were fixed today, temperature would continue to rise because thermal inertia of the oceans causes the realized warming to lag several decades behind changes in radiative forcing. Moreover, temporary aerosol cooling masks part of the greenhouse warming. A recent study by Wigley (2005) showed that committed warming for present day atmospheric greenhouse gas concentrations could exceed an additional 1°C on top of the 0.7°C that has already been realized.

However, without additional policies, greenhouse gas concentrations are projected to rise to 650 - 1215 ppmv, which could lead to a global mean temperature increase in 2100 of 1.5 to 6°C compared to 1990. These projection have been made using seven different climate models assuming a climate sensitivity - the equilibrium change in global mean temperature resulting from a doubling of atmospheric carbon dioxide concentrations - in the range 1.7 to 4.2°C. Recent uncertainty analysis of the sensitivity of the climate to changes in greenhouse forcing suggest that uncertainty in climate sensitivity spans up a wider range. Using the technique of ensemble modeling to explore the propagation of model parameter uncertainty in the Hadley Centre Global Climate Model, Murphy *et al.*, (2004) found a 5–95 % probability range for climate sensitivity of 2.4–5.4°C. Stainforth *et al.* (2005) found climate sensitivities on the high end of the range up to 11.5°C. Based on probability density functions representing uncertainty in climate sensitivity taken from eight different studies, Dessai and Hulme (2004) show that, while there appears to be confidence in the lower bound of climate sensitivity, the central value (50th percentile of the distribution) ranges from 2 to 6°C. The range for the upper bound (for instance the 95th percentile) is even wider: it ranges roughly from 5 to 9°C across the eight attempts to quantify the uncertainty. Projected ranges published by IPCC in 1996 and 2001 do not reflect these uncertainties. Further, IPCC projects and reports the transient temperature change for the year 2100, whereas committed climate change in that year is higher. Finally, one has to bear in mind that regional climate change can be significantly smaller (e.g. near the equator) or larger (especially near the poles).

The impacts of projected climate change are expected to be manifold. Because of limited understanding of a large number of feedback loops in the complex Earth system and inherent limitations to the predictability of climate on the local and regional spatial scales, uncertainty in climate projections are huge and partly irreducible. Effects can become manifest gradually and linear, but also non-linear as a singular event. Gradual changes include the increase of temperature, sea level rise, melting of glaciers, increase in length of the growth season, increase in precipitation and increase of extreme weather events such as heat waves and super storms. Examples of non-linear effects are the possible strong reduction or even shut down of the so called thermohaline circulation in

the oceans (which could lead to a cooling of North and North-West Europe), disintegration of gas hydrates in melting permafrost and in the oceans (which leads to massive emissions of the greenhouse gas methane), disintegration of the West Antarctic Ice Sheet or strongly increased melting of the Greenland Ice Sheet (which may lead to several meters of sea level rise on the long term).

Poorly known probability, high impact events

A number of possible irreversible large-scale non-linear impacts of climate change has been identified, ranging from a regime shift in the thermohaline ocean circulation and sea level rise of several meters to extinction of species and loss of unique ecosystems, migration of human populations (environmental refugees), changes in frequency and intensity of extreme weather events, reduction of food security and changes in the geographical distribution of diseases. Although our state of knowledge suggests that on the long term such impacts are plausible, it is not possible to quantify the magnitude and probability of each of these potential effects especially at regional and local level. At the same time, the observed climate change in the past decades has led to several unanticipated impacts. An example of such a surprise is a recent collapse of a dike in the Netherlands (August, 2003) in a period of extreme drought, leading to the flooding of a village. The dike was made of local soil and it turned out that peat in the dike had dried out by which it had lost so much weight that the dike could no longer withstand the pressure of the water. It was then realized that the Netherlands has thousands of kilometers of dike made of local soil that contains peat. A large scale monitoring system has now been set up to assure early detection of peat drying in dikes. Never in history had this type of dike been exposed to such extreme drought and nobody had thought of this scenario. Because models anticipate climate change well beyond the natural variability of the climate in the past millennia, the climate may move outside of the part of the so called "parameter hyper space" on which our knowledge of the dynamics of the present climate system is based. This implies that more unanticipated impacts and surprises are likely to occur.

In the following we review in more detail grounds for concern of three poorly-known-probability, high-impact events that may occur in a warming world: a shut down of the thermohaline circulation in the oceans, extreme sea level rise through disintegration of ice masses and accelerated (massive) species extinction.

Thermohaline circulation

The Gulf Stream and the North Atlantic current are part of a larger ocean circulation system known as the thermohaline circulation (THC). The THC is driven by gradients in temperature and salinity and it transports large amounts of heat to the North Atlantic regions. It strongly determines present day climates in Western and Northern Europe. The main "pump" that drives the THC is the North Atlantic deep water formation: the combined effects of evaporation during the Northward transport and cooling and formation of sea ice in the North Atlantic increase the salinity and density of the water to a point where it sinks. Theoretical and paleoclimatic evidence point to the possibility of rapid changes in the THC. Global warming is likely to lead to an extra influx of fresh water in the North Atlantic through increased rainfall and increased amounts of melting water, while with higher temperatures less sea ice is formed and thus less fresh water extracted from the sea water. This could decrease salinity and density of the surface sea

water to a threshold point where it stops sinking which would imply a shut down of the THC. Model studies show that such a shut down once it occurs is quasi permanent due to a so called 'hysteresis' in the systems response to changes in fresh water input: the fresh water input has to go back to a point far below the shut-down threshold point before the THC is switched on again, which may take several centuries.

Paleologic evidence shows that such regime shifts in the THC have occurred several times in the geological past. This evidence also indicates potentially large regional climate impacts (Alley, 2003). Model studies suggest that a shut down of the THC could lead to a local cooling of several degrees in the North Atlantic region within a few decades (Rahmstorf, 1995; Stocker et al., 2001). A study with the UK Hadley Centre climate model showed that in the first decade after the extreme case of a total shutdown of the THC, the annual mean cooling in the UK might be 3-5°C and 2-3°C in the third decade. To put these numbers in context: typical decadal mean cooling during the Little Ice Age period was for the UK in the order of magnitude of 0.5°C and the coldest individual year in the UK during the Little Ice Age was 1740 with an anomaly in annual mean temperature of -2.5°C (Wood et al., 2003). Such a cooling of the Northern hemisphere would reduce local evaporation, precipitation and wind regimes and global circulation patterns, which in combination with the regional cooling may lead to wide range of severe impacts on ecosystems, agriculture, economies etc..

It is unknown what the threshold point is to trigger a shut down of the THC and where the present THC is on the hysteresis curve that describes North Atlantic deep water formation as a function of fresh water input. Hence it is also not yet possible to assess whether this threshold point can be reached for any of the projected climate change scenarios presently considered. Some experts believe that there is a 50% chance that a shut down occurs for a global warming of 4-5°C. The present day Global Climate Models fed with IPCC's emission scenarios show a gradual weakening, but not a shut down of the THC. Simplified Earth System models however have shown the possibility of a shut down under plausible greenhouse gas forcings. (Wood et al, 2003) Deutch et al. (2002) argue that the present ocean observation system is so incomplete and infrequent that it would detect a change in THC intensity only after the point at which climate policy would be able to respond with effective mitigation.

Extreme sea level rise

In the assessments of the risk of sea level rise through anthropogenic climate change, four factors play a role: thermal expansion of sea water, ice-sheet dynamics, natural trends and other man-made causes of sea level rise (mainly ground water extraction). The ice sheet dynamics constitutes the most problematic factor in the assessments of future sea level as it harbors the largest uncertainties and can be non-linear. In table 1 the present ice volumes and sea-level equivalents of the Earth are given. If all ice on Earth would melt, the worldwide average sea level would rise about 80 meters.

	Ice volume (10 ⁶ km ³)	Sea level rise equivalent (m)
East Antarctica	25.92	64.8
West Antarctica	3.40	8.5
Greenland	3.0	7.6
Small ice caps and mountain glaciers	0.12	0.3
Permafrost	0.03-0.7	0.08-0.17

Table 1 Ice components of land ice and their sea level rise equivalents (Titus, 1986).

The mass balance of ice sheets is quite complicated. Increase of temperature at the poles leads to increased evaporation of seawater and increased snowfall, positively contributing to the mass balance. At the same time the melting rate increases, which is a negative contribution. Morphological aspects (profiles of the bottom, shape and thickness of the ice shelves etc.) are a third factor, as they influence calving and streaming of the ice.

The research into the behavior of ice sheets was originally part of a scientific discussion on the causes of sea level changes in the recent geological past. The debate on the stability of the West Antarctic Ice Sheet (WAIS) was initiated by John H. Mercer, a glaciologist. He was interested in the dramatic sea level changes during the last glaciation. He developed a hypothesis that sought to explain interglacial high sea levels by the deglaciation of West Antarctica. This hypothesis pointed out that fringing ice shelves, which are essential for the continued existence of an ice sheet grounded far below sea level, must consist of 'cold' ice below the pressure melting point, and will rapidly disintegrate by calving, if the average temperature of the warmest month rises above freezing point at sea level. (Mercer, 1970)

This theory opposed the accepted theory of Emiliani, which suggested that the high interglacial sea levels were the result of significant melting of the Greenland Ice Sheet. In 1978, Mercer linked up for the first time the stability of the WAIS with anthropogenic climate change. He suggested in an article in "Nature" that: *"If the global consumption of fossil fuels continues to grow at its present rate, atmospheric CO₂ content will double in about 50 years. Climate models suggest that the resultant greenhouse warming effect will be greatly magnified in high latitudes. The computed temperature rise at latitude 80 degrees South could start rapid deglaciation of West Antarctica, leading to a 5 meter rise in sea level."*

and:

"... deglaciation of West Antarctica would probably be the first disastrous result of continued fossil fuel consumption. ... If so, major dislocations in coastal cities, and submergence of low lying areas such as much of Florida and the Netherlands, lies ahead."

Mercer's theory gave rise to public concern and to a scientific debate on the stability of the WAIS. Further research in the 1980s pointed in the direction that the WAIS might be more stable than hitherto assumed and anticipated warming in the coming century would not be large enough to initiate the complete melting of the West Antarctic ice shelves. (Van der Veen and Oerlemans, 1987). It should be noted that this assessment was biased by the time horizon chosen of one century, which is short in comparison to

the typical time scales of ice sheet dynamics and does not account for committed warming. Later assessments exhibit the same bias. The first IPCC report concludes in 1990: "*Within the next century, it is not likely that there will be a major outflow of ice from West Antarctica due directly to global warming.*" (Houghton *et al.*, 1990). In the third assessment report (Houghton *et al.*, 2001) IPCC concludes that, ice-dynamic instability of the WAIS and accelerated sea level rise are very unlikely during the 21st century for the range of projected warming. However, for warming of more than 10°C, simple runoff models predict that a zone of net mass loss would develop on the ice sheet surface. Irreversible disintegration of the WAIS would result because the WAIS cannot retreat to higher ground once its margins are subjected to surface melting and begin to recede. According to IPCC, once started, such disintegration would take at least a few millennia.

The thresholds for total disintegration of the East Antarctic Ice Sheet by surface melting is estimated to be about 20°C warming (Houghton *et al.*, 2001).

The Greenland ice sheet is the most vulnerable to climate warming but is not as potentially unstable as the WAIS, meaning that the melting would be a more gradual process. Models project that a local annual-average warming of larger than 3°C sustained for millennia would lead to virtually a complete melting of the Greenland ice sheet. For a local warming over Greenland of 5.5°C the Greenland ice sheet contributes about 3 m in 1,000 years. For a warming of 8°C, the contribution is about 6 m, the ice sheet being largely eliminated. (Houghton *et al.*, 2001)

Species extinction

Shifting climate zones may lead to habitat loss and thereby to species extinction. Using projections of species' distributions for future climate scenarios, Thomas *et al.* (2004) assessed extinction risks for sample regions that cover some 20% of the Earth's terrestrial surface. On the basis of mid-range climate-warming scenarios for 2050, they found that 18–35% of species will be 'committed to extinction'. Note that committed to future extinction as a consequence of climate change over the next 50 years is not the same as the number of species that will become extinct during this period. Information is not currently available on time lags between climate change and species-level extinctions, but decades might elapse between area reduction (from habitat loss) and extinction. Land use should also be incorporated into analyses: extinction risks might be higher than projected by Thomas *et al.* if future locations of suitable climate do not coincide with other essential resources (such as soil type or food resources).

According to the UN Millennium Ecosystem Assessment (2005) observed changes in climate, especially warmer regional temperatures, have already had significant impacts on biodiversity and ecosystems in many parts of the world. There have been changes in species distributions, population sizes and the timing of reproduction or migration events, as well as an increase in the frequency of pest and disease outbreaks, especially in forested systems.

Although it is not possible to determine whether the extreme temperatures were a result of human-induced climate change, many coral reefs have undergone major, although often partially reversible, bleaching episodes when sea surface temperatures have increased during one month by 0.5–1°C above the average of the hottest months.

Extensive coral mortality has occurred with observed local increases in temperature of 3°C .

The Millennium Ecosystem Assessment further concludes that by the end of the century, climate change and its impacts may be the dominant direct driver of biodiversity loss and changes in ecosystem services globally. It will increase the risk of extinction for many species, especially those already at risk due to factors such as low population numbers, restricted or patchy habitats and limited climatic ranges.

The chosen level of protection

In risk management a widely used approach is agreeing on a normative choice for an acceptable risk level for the risky activity and putting enough measures in place to keep the risk below that level. This is problematic for three reasons. First, the degree to which people consider a risk acceptable or not depends not only on the magnitude of the damage and the probability that damage will occur, but on other risk dimensions as well. A given risk tends to be seen as less acceptable if the (perceived) controllability of consequences is lower; if the nature of the consequences is unfamiliar and dreadful; if one is exposed to the risk involuntarily; if the benefits of the activity are less clear and smaller; if the effects are more acute and more nearby in space and time; if risk and benefits are unfairly distributed; and if the likely harm is intentional (Vlek, 2004).

Second, attitudes towards risks vary from person to person and across cultures. Some people have a risk-seeking attitude whereas others have a risk-averse attitude.

Environmental risk attitudes tend to correlate with the way that people view nature. Those that see nature as robust tend to be risk-seeking, those that see nature as fragile tend to be risk-averse. In between are those that have a risk-regulating attitude, corresponding to a view of nature as 'robust within limits', and those that are indifferent to risk, corresponding to a view of nature as capricious or risk as fate. (Douglas and Wildavski, 1982)

One should further be aware that being risk-averse to ecological risks is not the same as being risk-averse to economic risks. This cultural plurality in risk attitudes implies that the question of how society ought to deal with risks can only be answered in public debate – a debate in which people will necessarily discuss their perception of risks and risk management from different points of view and different conceptual and ethical frameworks (Davidson, 2002).

Third, in the case of the PP the acceptable risk approach is problematic because the uncertain nature of the risks makes it very difficult to set a safe level. Some argue that the PP reframes this choice into the question of how much harm can be avoided. Tickner (1999) for instance, illustrates that estimating a safe level of temperature increase is difficult and controversial. Reframing the question would change the focus from assessing a safe level to reducing greenhouse gas emissions as much as possible. Anyway, the international community has taken the more traditional risk approach seeking to agree on a level of protection. This is laid down in Article 2 of the UN FCCC: "*The ultimate objective of this Convention (. . .) is to achieve (. . .) 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.*"

The parties have not yet agreed on a quantified stabilization level for atmospheric greenhouse gas concentrations that is considered to meet this vaguely described level of protection. Because ecosystems have a maximum speed in keeping up with shifting

climate zones, it is widely held that the rate of global warming has to be limited. Also, a maximum allowable global temperature increase has to be set. Further, in order to protect coastal ecosystems and coral reefs, limits have to be set on total sea level rise and rate of sea level rise. Finally, it is often argued that the third criterion mentioned in Art. 2, to enable economic development to proceed in a sustainable manner, can be made operational by setting a limit to the maximum rate of emission reduction per year, so protecting economies from disruption by unrealistically strict policies.

During their 1987 Villach-Bellagio workshops, the Advisory Group on Greenhouse Gasses (AGGG, the precursor of the IPCC) for the first time proposed long term climate targets for temperature change and sea level rise to protect ecosystems (Jäger, 1990). They proposed for sea level rise: a maximum rate of increase of between 2 and 5 cm per decade and a maximum rise of between 0.2 and 0.5 m above the 1990 mean global sea-level. For temperature, a maximum rate of increase of temperature of 0.1°C per decade was proposed, along with a maximum temperature increase of 1.0°C or 2.0°C above pre-industrial global mean temperature.

These "Villach-Bellagio targets" have played an important role in the climate policy debates since. They have inspired for instance the EU in their 6th Environment Action Programme (EC, 2001), to set a long term climate target of a maximum global temperature increase of 2°C over pre-industrial levels (which means 1.3°C above current global mean temperature) and a CO₂ concentration below 550 ppmv. In December 2004 the EU revised its interpretation, stating that the 550 ppmv target is for the CO₂-equivalent concentration (all greenhouse gasses together rather than CO₂ only). For CO₂ this implies a stabilization level of 450 ppmv. This is likely to require a global reduction in emissions of greenhouse gases by at least 70 % as compared to 1990.

In the discourses about the quantification of such levels of protection, key arguments have been parallels with past climates and paleological insights regarding how ecosystems have responded to major natural climate changes in the past. In the following we will review the underpinnings of such quantified levels of protection for climate change.

Maximum rate of warming

Much research has been done to the climate tolerance of ecosystems and species. The speed by which ecosystems can keep up with shifting climate zones depends on many factors. A major limiting factor is the seed-cycle of trees. Analysis of pollen in sediment since the previous ice age show that maximum migration speed of trees varies between 4 and 200 km per century, depending on the species (Davis, 1989; Hinckley, 1997; Watson et al., 1997). For boreal forests, the speed by which climate zones shift towards the poles is critical. For Alpine ecosystems it is the speed by which climate zones shift upward. For coastal ecosystems the rate of sea level rise is critical. Roughly, a warming rate of 1°C per century produces a rate of sea level rise of 20 cm / century, a poleward shift of climate zones by 100 km per century and an upward shift of Alpine climate zones of 150 m. The most vulnerable ecosystems are the Alpine ecosystems. Many Alpine species are already committed to extinction for the current warming rate. Oak forests are also quite sensitive; the maximum rate of global warming with which they can keep up is estimated to be 0.12°C per century.

Maximum allowable warming

The fore mentioned Villach Bellagio target specified two levels for maximum temperature increase, respectively 1.0°C and 2.0°C above pre-industrial global mean temperature. The lower temperature target was set on the basis of their understanding of the vulnerability of ecosystems to historical temperature changes. Temperature increases beyond 1°C could trigger rapid, unpredictable and non-linear responses that could lead to extensive ecosystem damage. The absolute temperature limit of 2°C was motivated as the limit beyond which the risks of grave damage to ecosystems and of non-linear responses are expected to increase rapidly.

Krause et al. (1989) have sketched a context to grasp what different levels of global warming imply, by comparing them to the climate history of the Earth:

- An increase of 1 -1.5°C in global average surface temperature would imply a climate warmer than it ever was since 6,000 years ago in the Holocene period, which was roughly the beginning of agricultural societies.
- A 2-2.5°C warming would imply a climate not experienced since the so-called Eem-Sangamon interglacial period some 125,000 years ago. At that time, human society consisted of hunter gather societies and the West Antarctic ice sheet had partially disintegrated, raising sea levels by up to 5-7 meters.
- A 3-4°C warming would represent a climate not experienced since humans appeared on Earth (about 2 million years ago). The last time the Earth was this warm was in the Pliocene period (5 to 3 million years ago)
- A global average warming of 5°C and above corresponds to a climate not experienced for tens of millions of years. In that period there were no glaciers in the Antarctic and Greenland.

Risks for different levels of warming have been visualised qualitatively by IPCC on the basis of five risk indicators (Fig. 1).

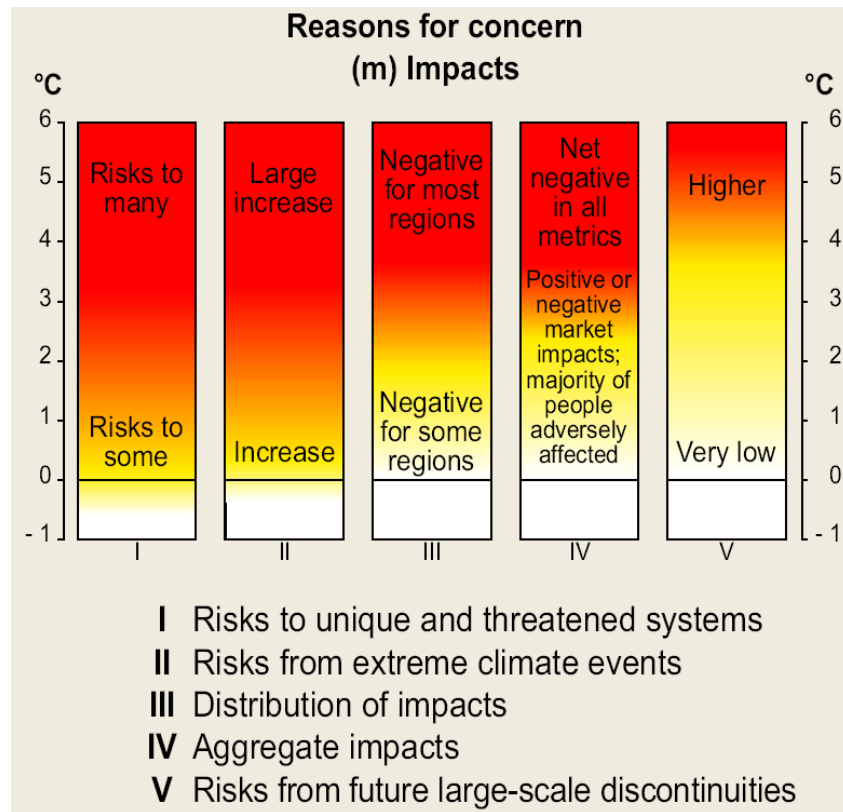


Figure 1 Risk evaluation diagram for different levels of global temperature change (IPCC, 2001)

The indicators used in this risk evaluation diagram are (IPCC, 2001):

- I. *Unique and threatened systems*: Some changes in species and systems have already been associated with observed changes in climate, and some highly vulnerable species and systems may be at risk for very small changes in climate. Greater warming would intensify the risks to these species and systems, and place additional ones at risk.
- II. *Extreme climate events*: Increased frequencies and intensities of some extreme events have already been observed and are likely to increase with further warming, as would the risks to human life, property, crops, livestock, and ecosystems. These risks increase where development is occurring in inherently dynamic and unstable zones (e.g., river floodplains and low-lying coastal regions).
- III. *Uneven distribution of impacts*: In general, developing countries are at greater risk of adverse impacts from climate change than are developed countries, of which some of the latter may experience market sector benefits for warming less than a few °C. For greater warming, most regions are at risk of predominantly negative effects from climate change. But developing countries generally would continue to be more severely impacted than developed countries. Within countries, vulnerability varies and the poorest populations often have higher exposure to impacts that threaten their lives and livelihoods.
- IV. *Global aggregate impacts*: Globally aggregated market sector impacts may be positive or negative up to a few °C, though the majority of people may be negatively affected. With greater warming, the risk of negative global market

sector impacts increases, and impacts would be predominantly negative for most people.

V. *Large-scale, high-impact events*: The probability of large-scale, high-impact events within a 100-year time horizon such as shutdown of the THC or collapse of the West Antarctic ice sheet is very low for warming less than a few °C. For greater warming, and over a time horizon longer than 100 years, the probabilities and the risks increase, but by an amount that cannot now be estimated.

Many ecosystems are sensitive to temperature. For instance, coral reefs around the Equator are sensitive to seawater temperature. When even during a short period the local seawater temperature exceeds 32-34°C, coral bleaching occurs.

In a recent study, Leemans and Van Vliet (2005) found that over the last decade, many more ecological responses to climate change have been observed than expected from the average 0.7°C warming trend alone. Current impact assessments of climate change therefore likely underestimate ecological impacts and vulnerability. Ecosystems respond faster to changes in extreme weather than to 'normal' climate characteristics. Based on these new insights in the vulnerability of species and ecosystems, Leemans and Van Vliet suggest that the EU target is not strict enough and claim that ecosystem protection, in particular protection of coral reefs, requires to limit the increase in global mean surface temperature to 1.5°C above pre-industrial levels and limit the rate of change to less than 0.05°C per decade.

Based on the paleoclimate evidence, James Hansen, director of the NASA Goddard Space Center recently suggested that the highest prudent level of additional global warming (above the increase of 0.7°C already) is not more than about 1°C if we want to avoid the risks of large scale ice sheet break up and associated extreme sea level rise. To achieve that, the atmospheric CO₂ concentration should remain below 450 ppmv. (Hansen, 2004)

Maximum sea level rise

The Villach-Bellagio workshops (Jäger, 1990) proposed a maximum rate of sea level rise of between 2 and 5 cm per decade and a maximum rise of between 0.2 and 0.5 m above the 1990 mean global sea-level. Later on these targets have been criticized because they do not protect species and ecosystems that are highly sensitive to sea level rise such as coral reefs, mangrove eco systems and coastal wetlands. Mangrove ecosystems protect 25% of the tropical coastline. It is estimated that protection of Mangrove ecosystems requires that the rate of sea level rise stays below 10 cm/century. (Hinckley, 1997)

Maximum rate of emission reduction

The rate by which greenhouse gas emissions can be reduced without disrupting the economy is limited. This is because the existing energy infrastructure can (without capital destruction) only be changed in a time frame of several decades. Krause *et al.*, (1990) suggest a maximum rate of emission reduction of 2-3% per year. Other studies that focus on energy efficiency improvement, renewables, technology development and structural changes of economies are more optimistic and suggest percentages up to 4% per year (see for an overview, Van der Sluijs and Turkenburg, 1998).

