Exploring the boundaries of climate change

A review of thirteen climate eventualities

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Content

Summary

In the public debate, references are regularly made to possible climate events with potentially severe consequences. The scientific literature on 13 of these climate eventualities has been reviewed to give an overview of their characteristics such as the timing, likelihood and level of scientific understanding. It is argued that insufficient information is available on these events, particularly on the possible impacts, to assess and compare the *risks* they represent. These climate eventualities can be seen as extra sources of uncertainty that have the potential to accelerate, and in some cases delay, developments associated with global warming.

The information gathered confirms that of the 13 climate eventualities, rapid disintegration of the Greenland and West Antarctic Ice Sheets are the most dangerous prospects. However, if the enhanced greenhouse effect can be mitigated and global warming remains at or near 2°C, most of these eventualities can be avoided. But developments already taking place, such as ocean acidification, slow release of methane from permafrost and ocean regions and rapid melt of Arctic sea ice in summer, would continue to have impacts. It is not clear whether and how rapid the Greenland Ice Sheet would disintegrate in a climate that is 2°C warmer. The possible considerable risk related to *unknown* tipping points or eventualities *that we do not know about* cannot be estimated. This ignorance is perhaps the greatest climate threat.

1. Introduction

1.1 Climate eventualities

The report examines a number of possible climate events, most of which are highly uncertain. The literature is reviewed on these climate eventualities with the aim of presenting an overview. *No* new assessment, new research or new insights are presented.

In the public debate on climate change and in the current literature, a number of possible climate events or developments are discussed that are not well understood. Several of these may cause - or be seen as - extreme climate change.

In a paper entitled 'Tipping elements in the climate system,' Lenton et al. (2008) discuss a number of such events or developments with possible policy relevance. The short list prepared by Lenton et al. (2008, Table 1) is considered in this report.

In view of the current public debate, the list has been extended with:

- two examples of possible greenhouse gas feedbacks from melting permafrost and from oceanic methane clathrates;
- the possibility that changes in solar activity might impose a cooling trend on the climate.

The notion that our estimates of the sensitivity of the climate system to CO_2 changes may not be correct is also discussed, although not strictly an example of a climate event.

While exploring the boundaries of climate change, we look not only at possible events that would speed up global warming, but we also consider the possibility of climate warming slowing down.

Because of the heterogeneity in character or type of the events on list, the word 'eventuality' is used to indicate an entry. An overview of the selected eventualities is given in Table 1.1 below. In addition to a brief indication of the mechanism of a phenomenon and its main effects, this overview table indicates the shortest timescale at which the phenomenon may become manifest and the spatial scale of impacts to be expected. The terminology used in Table 1.1 is explained in Section 1.4.

Table 1.1: Overview of the 13 climate eventualities reviewed

Type of event	**Climate event**	**Mechanism**	**Onset possible in**	**Primary Effect**	**Spatial Scale**	**Character**
Enhanced greenhouse effect	Rapid permafrost CO_2 & methane release	Permafrost melts	Not known	Extra warming	Global	Accelerated change /positive feedback
	Rapid ocean bottom CH_4 release	Ocean heats up	Centuries - Millennia	Extra warming	Global	Accelerated change / positive feedback
	Estimated climate sensitivity too low	Model feedbacks wrong or lacking	Years	Extra warming	Global	Positive feedback
Rapid melt of land ice	GIS disintegrates	Rapid ice Dynamics?	Decades - centuries	Extra sea level rise	Global	Accelerated change/positive feedback
	WAIS disintegrates	Ocean warms base	Centuries - Millennia	Extra sea level rise	Global	Accelerated change / positive feedback /tipping point
Regional circulation changes	Atlantic MOC diminishes or collapses	North Atlantic less saline	Centuries	Shifts in regional climate	Several regions/ continental	Decelerated change / tipping point
	ENSO changes in character	Unknown	Decades	Shifts in regional climate	Several regions	Unknown
Rapid ecosystem change	Amazon forest collapses	Drying out and land use change	Decades	Shifts in regional climates	Several regions/ Continental	Positive feedback/ tipping point
	Boreal forest dieback	Sensitive ecosystem	Decades	Shifts in regional climates	Several regions/ Continental	Accelerated change
Possibility of special interest	Arctic sea ice disappears fast	Shift in ocean currents cause higher local water temperatures	Decades	Extra warming & Shifts in regional climate	Several regions/ Continental	Positive feedback/ accelerated change
	Solar induced cooling	Unknown	Years - Decades	Less warming	Continental / Global	Decelerated /accelerated change
	Estimated climate sensitivity too high	unspecified model deficiencies	Years -	Less warming	Global	Negative feedback
	Ocean acidification	Atmospheric CO_2 increase	Years	Marine ecosystems breakdown	Global	Gradual change

1.2 Motivation

Future climate scenarios reported by IPCC are based on future emission scenarios and on the physical properties of the climate system. Thoughts about the magnitude and timing of emission reductions and adaptation measures are currently based on projected climate change described by these scenarios. However, the precautionary principle also requires insight into more extreme climate scenarios, even though these may be less likely to occur. What is the worst that might happen with climate change is a question to which policymakers want an answer.

Current climate projections involve significant uncertainties and do not necessarily cover all possible future climate changes. Several climate phenomena cannot be reproduced with current models and some processes are not or insufficiently represented in models, for instance, the ice melting in Greenland and the stability of the West Antarctic ice sheet (WAIS). Another example is the representation of the amount and properties of clouds in models. These deficiencies are known as a source of uncertainty.

Policymakers and others working with climate scenarios have several reasons to look beyond the IPCC scenarios such as:

- Several climate *processes* and *phenomena* are *not* or *not well represented in climate models*.

- Paleo-science shows that in the *past, extreme* and *rapid climate changes* have occurred with natural causes. What are the chances that such changes occur in the foreseeable future, say the next few hundred years.

- In the climate change discussion, notions such as *run-away climate change*, where positive feedbacks would cause rapidly rising temperatures, and *tipping points* beyond which severe and possibly irreversible effects appear keep cropping up. The non-linear character of the climate system gives rise to these possibilities. Are such possibilities a real threat?

- Uncertainties do not always imply that the situation could be worse than anticipated. Instead of only looking for reasons why global climate warming could accelerate or create more havoc, the reasons or mechanism that *could slow down climate warming* (counter to expectations) delay it or make it *less than anticipated* need to be considered.

1.3 Objective and scope

This report is the second of a series of three. The first document reports on new insights in climate research gained in recent years that are relevant for policymakers. The third report documents policy options in the event of more extreme or more rapid climate change than projected by IPCC or the KNMI'06 scenarios for the Netherlands (KNMI, 2006).

This second report identifies, classifies and explores possibly extreme or abrupt changes and possible surprises in the climate system, even if the chance of occurrence is small. Most of the selected eventualities will have harmful impacts but eventualities that would slow down or lessen anthropogenic global warming have also been considered. The time horizon is several hundred years, which is beyond the IPCC outlook.

The eventualities examined in this report have in common a lack of knowledge on the physical mechanisms involved as well as a lack of observational data. For this reason, these events are not documented or only briefly in the IPCC assessment reports. There is no scientific consensus. In this report these phenomena and their likelihood of occurrence are discussed briefly. Uncertainties are discussed about the conditions, the likelihood, the timing and the possible impact of events and how these prevent an analysis of the risk.

No rigorous methodological framework is available in the literature to describe and assess the topics in this report in a consistent way and development of a framework is beyond the scope of this study. Therefore, those aspects on which literature is available are discussed. While recent literature covering a wide variety of climate phenomena was used, three documents were especially useful in the discussion:

Kriegler et al. (2009) *Imprecise probability assessment of tipping points in the climate system* in the Proceedings of the National Academy of Sciences USA, 105: 1786-1793. This paper uses judgement of 45 experts on the probability of the occurrence of a number of climate events, including a judgement on the uncertainty of these estimates. This compilation of subjective opinions should not be confused with scientific evidence, which is not obtained by this 'voting' procedure. Opinions may change rapidly as new theories of observations become available. We, therefore, explicitly indicate whether the likelihood is based on expert judgements such as given in Kriegler et al. (2009) or whether based more directly on observations and/or theory.

Lenton et al. (2008) *Tipping elements in the Earth's climate system in* Proceedings of the National Academy of Sciences USA, 105: 1786-1793 (2008).
In this paper, several policy-relevant climate eventualities are characterised and evaluated. In addition to an extensive review of scientific literature, expert judgement is used to assess the sensitivity of the eventualities to global temperature increase, to assess uncertainty about the underlying physical mechanisms, and to rank the threat of each of the phenomena.

CCSP (2008) *Abrupt Climate Change* is a report by the US Climate Change Science Program and the Subcommittee on Global Change Research [Clark, P.U., A.J. Weaver (coordinating lead authors), E. Brook, E.R. Cook, T.L. Delworth, and K. Steffen (chapter lead authors)] U.S. Geological Survey, Reston, VA, 459 pp.
This extensive report discusses rapid changes in ice sheets and glaciers, changes in the hydrological cycle, changes in the Atlantic Meridional Overturning Circulation (AMOC),

and the rapid release of methane from permafrost and the ocean floor. It focuses on possible changes within a few decades or less, based on an evaluation of paleo-climatic reconstructions and future climate projections.

1.4 Aspects considered

Because of the many uncertainties in the eventualities considered, exact or even approximate *quantitative* answers cannot be given to questions such as when might it happen; what is the spatial scale of effects; what is the expected impact; what is the likelihood of the event?

Therefore, subjective qualification is given similar to the IPCC qualifications for likelihood, ranging from *very likely*, *likely* and *as likely as no*t to *unlikel*y and *extremely unlikely*. The choice of subjective scales for likelihood, damages and losses, spatial scale and risk are presented in Appendix A.

No new knowledge or insight is generated when such subjective classifications are used. The subjective language makes it possible to discuss the phenomena in a systematic way and give overviews of barely known or estimated characteristics.

1.4.1 Character of the eventuality

Possible developments in the climate system may be characterised by their behaviour in time. Figure 1.1 in the Fourth IPCC Assessment Report (IPCC 2007, WGI, Chapter 10), illustrates different ways in which the climate system may respond to changing circumstances (indicated as *forcing* in the top panel).

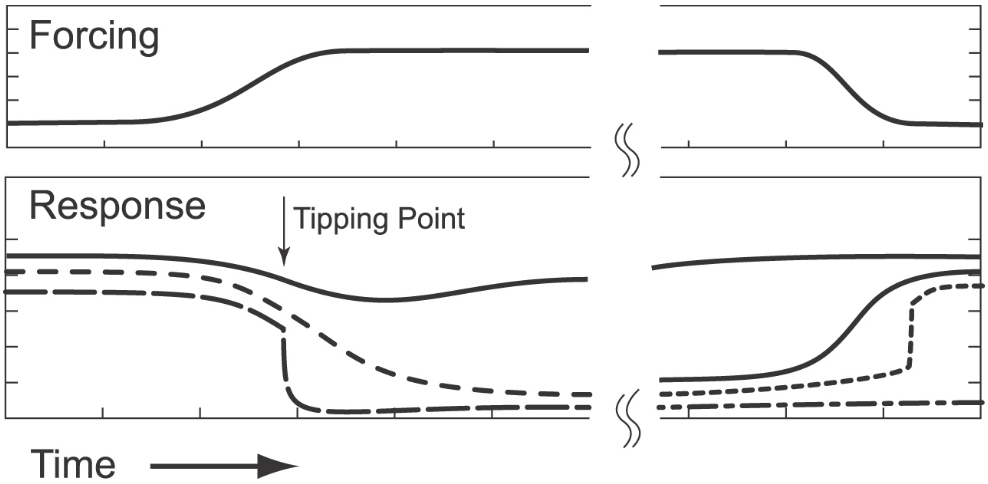

Figure 1.1: Sketch of possible climate system responses. The lower panel shows the various ways the climate system can respond to changing circumstances (indicated as *forcing* in the top panel):

- The drawn line on the left shows a *transient response*. The system changes due to the change in forcing but returns to its former state after forcing becomes constant again.
- The short dashed line on the left shows a *slow response* after the change in forcing.
- The long dashed line shows a response that reaches a *tipping point*, after which the system rapidly and autonomously changes to a new state.

The lower right panel shows various ways in which the climate system can respond when the forcing changes back. The system can remain in its new state (dash dotted line) or return to its former state. In the transition, there may also be tipping points.

In characterising the events, the following terms are used:

- Acceleration/deceleration of change
  When a change in the climate system that is already expected or ongoing becomes stronger or weaker, it is classified as an acceleration or deceleration.
  For example, a temporary cooling trend caused by lack of solar activity causes *deceleration* of global climate warming.

- *Feedback*
  When a change in the climate system creates conditions that make the change stronger or weaker, it is classified as positive or negative feedback, leading to acceleration or deceleration of global warming.
  For example, anthropogenic greenhouse warming could warm permafrost soils to the extent that previously frozen plants remaining in the soil thaw, begin to rot and emit greenhouse gases CO_2 and methane. These extra greenhouse gases would warm the planet further leading to more thawing of permafrost soils and more emission of greenhouse gases. This is an example of *positive feedback* that leads to amplification of the initial warming. Without limiting or damping effects, strong *positive feedbacks* may lead to *runaway climate change*[1] - unchecked amplification of an effect (long-dashed line, lower-left panel, Figure 1.1). *Negative feedbacks* may lead to *stabilisation* (straight line, lower-left panel, Figure 1.1).

- *Tipping point*
  A non-linear dynamic system, such as the climate system, may show relatively large and sometimes sudden transitions as a response to (small) gradual changes. This transition is caused by the internal dynamics of the system. The point in the gradual change where the transition occurs is called a tipping point.
  An example would be instability of the West Antarctic Ice Sheet. The bed of this ice sheet lies well below sea level and its edges flow into floating ice shelves. Since most of the ice sheet is grounded below sea level the intrusion of ocean water could destabilise it. *Control parameters* for this tipping point would be sea level height and local sea surface temperatures. The instability would begin when these parameters pass a certain critical value.

- *Special cases*
  A number of special cases were considered. Ocean acidification is an example that does not fit into one of the above categories. Acidification is characterised as a gradual change.

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[1] Not to be confused with “runaway greenhouse effect” which is often used to indicate oxidation of a major fraction of the Earth’s carbon and a strong water vapour feedback, establishing Venus-like conditions. With current levels of solar radiation, such an event is out of the question.

- The possibility that the estimated *climate sensitivity* (the estimated warming of the climate system after a doubling of the atmospheric CO_2 concentration) is considered as being either too high or too low. These cases are not characterised as changes in the climate system.

These characterisations are not mutually exclusive. For instance, *positive feedback* often results in *acceleration of change.* And a tipping point can result from *positive feedback* and show *accelerated change*. The gradual change in ocean acidification may, for instance, lead to accelerated change in some marine ecosystems if a tipping point is reached.

1.4.2 Temporal aspects

For each of the climate eventualities, what is known (suspected or surmised) about temporal aspects has been compiled.

- *Event development*
  In most cases, there is no clear answer to the question *when* the event might occur, but only a rough indication of the timescales involved. In most of the eventualities discussed here, the possible onset of the event is influenced by global warming. Possible tipping points and the rate at which the phenomena might develop are, in most cases, related to changes in local temperature or precipitation. These local changes are often related to the anthropogenic global greenhouse warming that is going on. Therefore, answers are given in several cases to *when* the event could occur using terms such as *when global temperatures are between 1.5 and 2 degrees Celsius warmer* than the current climate.

- *Early warning*
  Are there *early warning signs* or could something be *monitored* somewhere to see the event coming? How much time would we have?

- *Timescale of transition*
  How long might the transition take once the event has begun? Will the transition be *abrupt* or *gradual*? How much *time for response* will there be, after it starts?

- *Duration*
  How long would the changed conditions last? Could the climate return to its former state or is the change irreversible?

1.4.3 Likelihood

We are interested in the *likelihood* of a climate eventuality occurring. Why is there a chance that this event may happen? Is there a theory or a model with which to *calculate probabilities*? Or, is sufficient known and understood to *estimate the likelihood?* And if no quantitative estimates can be made, are experts willing to make a *subjective guess* of the probability (as in Kriegler et al., 2009)?

What else is known about the likelihood? For instance, could the *likelihood increase with global temperature?* Or, would the *likelihood increase with time*, even if global temperatures stabilise?

The likelihoods presented in the report are taken from recent literature. The methodology to determine, estimate or propose the likelihoods in the literature differ for the different phenomena. Some likelihood qualifications are 'only educated guesses' (e.g., Kriegler et al., 2009), while other likelihood estimates are based on model runs and observations – perhaps inspiring more confidence.

1.4.4 Impact

To get an idea about the possible impact of an event, should it occur, several aspects of the impact are examined. Impact denotes the *cost* to society of an event. The changes in the climate system as a consequence of an event, such as *extra warming*, *extra sea level rise* or *shifts in regional climate(s)* are its primary effect. The spatial scale of primary effects can be *regional*, *several regions*, *continental* or *global*.

The primary effects lead to *secondary effects* such as ecosystem responses (e.g., loss of biodiversity), changes in agricultural productivity or increasing heat related mortality. Not all secondary effects related to the events discussed are detrimental. A possible cooling trend due to low solar activity, a much lower sensitivity of the climate system to CO_2 increases than currently assumed or a collapse of the North Atlantic MOC would all imply less rapid global warming than expected. An ice-free Arctic region would also bring opportunities for trade, exploration and exploitation. Wetter conditions (increasing precipitation) in parts of the Sahel would bring obvious advantages.

Secondary effects related to the climate eventualities considered are discussed extensively in the third report in this series. Secondary effects are mentioned in this report mainly where the ecosystem is involved in the mechanism that causes the event (i.e., collapse of the Amazon rainforest, or of boreal forests).

Another aspect of the severity of an impact is whether the event leads to *irreversible* changes or losses, such as loss of lives, erosion and species extinction.

The subjective estimates or qualifications of impacts presented are a systematic summary of the information in the literature and do not represent new insights in the phenomena. The classification used for the impact of an event is based on its spatial extent and on a subjective judgment of the damages it causes (Appendix A).

1.4.5 Level of Scientific Understanding

The common denominator for the eventualities discussed is the fact that little is known or understood about them. For each eventuality, the level of scientific understanding is assessed by considering the following questions:

- *How do we know* about this eventuality? Is it a *model result*? Is there evidence that *it happened in the past*? Is there *observational evidence* in recent measurement?

- How well *do we understand* the eventuality? Is there an *accepted theoretical framework*? Can it be *reliably modelled*? Is the phenomenon *controversial*? Or, is its possible existence only *anecdotal*?

1.5 Overview of the report

In Chapter 2, the 13 climate eventualities are presented in a common format, highlighting temporal aspects (such as, timing and duration), likelihood, possible impact and a brief indication of the level of scientific understanding. In Section 2.15, a tabular overview is presented of the properties, aspects and qualifications of the 13 climate eventualities.

In Chapter 3, the results presented in Chapter 2 are discussed. In Section 3.1, aspects of uncertainties are discussed. The role of natural and internal climate variability is highlighted, and the role of uncertain global warming in the possible triggering of these events. To give a view of the possible impacts of these events, the IPCC (2007) impact assessment framework is used.

In Section 3.2, a policy perspective on these climate eventualities is sketched, using of the IPCC framework of SRES scenarios, model projections and projected impacts. The climate eventualities are sources of extra uncertainty that may advance or delay expected developments and impacts. The risks associated with the climate eventualities are discussed in Section 3.3.

2. Thirteen climate eventualities with policy relevance

2.1 CO_2 and methane from permafrost soils release

One of the concerns about abrupt climate change caused by rapid changes of atmospheric methane stems from the large quantity of carbon stored in permafrost soils. When temperature rises, the thawed soil may become wetland emitting methane. As methane is a very effective greenhouse gas, rapid thawing of permafrost soils may lead to rapid increase in atmospheric methane concentrations.

Temperatures at the top of the permafrost layer have increased by up to 3°C since the 1980s in the Arctic. The maximum area of seasonally frozen ground has decreased by about 7% in the Northern Hemisphere since 1900 (IPCC, 2007; WGI, Chapter 4). Permafrost warming is observed with variable magnitude in the Canadian Arctic, Siberia, Tibetan Plateau, and Europe. Widespread increases in thaw depth occur over much of the permafrost regions. The permafrost base is thawing at a rate ranging from 0.02 m yr^{-1} on the Tibetan Plateau to 0.04 m yr^{-1} in Alaska.

Observations suggest *local* increases in CH_4 released from northern peat lands that are experiencing permafrost melt, although the magnitude and extent of this effect is not well quantified. (IPCC, 2007; WGI, Chapter 7). However, northern *background* stations observing methane do not confirm increased emissions.

Characterisation

The release of CO_2 and methane from permafrost soils as a result of global warming, and also possible increase in methane lifetime due to the negative impact of methane on the oxidation capacity of the atmosphere are both *positive feedbacks* in the climate system. In recent decades, the area of frozen soil has decreased and the seasonal thaw depth has increased (IPCC 2007; WGI, TS). It is therefore very likely that climate change will *accelerate* due to persistent methane and CO_2 emissions from northern wetlands.

Temporal aspects

Permafrost is already thawing, but the magnitude of the effect is not known. Widespread increases in thaw depth over much of the permafrost regions are projected in response to warming over the next century.

The current lifetime of atmospheric CH_4 is less than ten years so that a slow release will have only limited effects on atmospheric concentrations of CH_4, its oxidation product CO_2 and increased greenhouse gas warming. Atmospheric CO_2 produced by methane oxidation is currently about ~6% of the amount of CO_2 emission from fossil fuel combustion (CCSP, 2008).

Current models suggest that a doubling of CH_4 emissions in northern high latitudes could occur fairly easily (CCSP, 2008) on the *decadal timescale*. However, since these models do not realistically represent all processes thought to be relevant to future northern high-latitude CH_4 emissions, much larger or smaller increases cannot be discounted.

Likelihood
It is *more likely than not* that a small sustained release of methane and CO_2 from melting permafrost regions will enhance the anthropogenic greenhouse effect in the coming century. A rapid release leading to a substantial effect on global warming is *unlikely* (CCSP, 2008).

Impact
The primary effect of the release of greenhouse gases will be *extra warming on the global scale*. In the unlikely case that a large fraction of the stored carbon is released rapidly, the magnitude of the effect could be *major*. With a sustained but slow release, as is currently the case, the impact is *minor* (CCSP, 2008).

Level of scientific understanding
There is ample observational evidence that thawing permafrost regions emit methane but it is difficult to assess the contribution on the global scale. Modelling of the effect is still in its early days and current models do not realistically represent all the processes thought to be relevant to future CH_4 emissions in northern high latitudes. Atmospheric methane concentrations have levelled off since the late 1990s for reasons that are not yet completely understood. Measurements in 2007 and 2008 indicate that background concentrations are rising again due to extra emissions from both northern and tropical wetlands (Dlugokencky et al., 2009).

2.2 Ocean bottom methane release

The sudden release of large amounts of natural gas from methane clathrate deposits in the oceans has been hypothesized as a cause of past and possibly future climate changes (clathrate gun hypothesis). Since methane clathrates are only stable at high pressure and low temperature, methane may be released from ocean deposits due to global warming.

The size of the submarine methane clathrate reservoir is uncertain but has been estimated to be about 500 to 2500 Gt carbon (Milkov, 2004) and is much larger than the estimated global reservoir of natural gas. Since small changes in this large reservoir can have major effects on atmospheric concentrations, this uncertainty makes it difficult to assess the risks.

Characterisation
The release of methane as a result of global warming may lead to *positive feedback* in the climate system. Increased concentrations of methane will also decrease the oxidation capacity of the atmosphere leading to increased methane lifetime, which is again *positive feedback*. If methane is released from clathrates, then global *change* will be *accelerated*.

Isotope measurements suggest that during a rapid warming period 55 million years ago (known as the Paleocene Eocene Thermal Maximum, PETM), large-scale methane release from hydrates in the ocean floor may have occurred. However, model results indicate that the release of methane was too fast to be controlled by propagation of the temperature change into the sediments (Katz et al., 1999: Paull et al., 2003 cited in IPCC 2007; WGI, Chapter 7). This suggests that the hypothesized rapid release of 55 million years ago was not or not directly triggered by global warming.

Temporal aspects

The warming of 5 to 10°C approximately 55 million years ago *occurred over a period of 10,000 to 20,000 years*. The warmth *lasted* approximately 100,000 years (Wing et al., 2005). This timescale may indicate how long it takes for the carbon cycle and climate system to recover from a large perturbation.

Likelihood

In a modelling study, Harvey and Huang (1995) conclude that *destabilisation of hydrates* in permafrost as well as ocean sediments by global warming *is unlikely* over the next few centuries. On the timescale of the coming century, it is *likely* that most of the marine hydrate reservoir will be insulated from anthropogenic climate change, and thus remains *stable* (CCSP, 2008). The exception is shallow ocean sediments where methane gas is concentrated by subsurface migration. These deposits will *very likely* respond to anthropogenic climate change with an increased background rate of sustained methane release rather than an abrupt release. It is estimated that this type of release of methane in the ocean will lead to only a relatively small flux into the atmosphere (Lamarque, 2008).

Impact

The warming and associated environmental impact 55 million years ago, hypothesized to be caused by rapid methane release, had a *global* character. The impact was *major*. It was felt at all latitudes, and both at the surface and in the deep ocean. Evidence for shifts in global precipitation patterns is present in a variety of fossil records (Wing et al., 2005). The mass of carbon released 55 million years ago was sufficiently large to lower the pH of the ocean and drive widespread dissolution of sea floor carbonates (Zachos et al., 2005).

The more likely small sustained release of methane from clathrates in the oceans would have a *minor* impact.

Level of scientific understanding

There is only limited understanding of the events during the Paleocene Eocene Thermal Maximum (PETM). The high latitude warming during in that period was substantial (~20°C; Moran et al., 2006) and considerably higher than GCM simulations for the event (Sluijs et al., 2006) or in general for increased greenhouse gas experiments (IPCC, 2007; WGI, Chapter 10). The mechanism that could lead to the high rate of methane release needed to explain the PETM is unknown.

2.3 Estimated climate sensitivity too low

The climate sensitivity, which is the number of degrees Celsius, that indicates how much global climate would warm after a doubling of the CO_2 concentration and which is used in climate projections, is still rather uncertain. If the climate sensitivity is much larger than now thought, global warming will be faster and higher temperatures will be reached earlier than now anticipated.

Analysis of models together with constraints from observations suggest that the equilibrium climate sensitivity is likely to be in the range of 2 to 4.5°C, with a best estimate value of about 3°C. Since IPCC (2007), two review papers (Annan and Hargreaves, 2006; Knutti and Hegerl, 2008) have been published describing present views on climate sensitivity and particularly the constraints from various observations.

These studies find that the net feedback in the climate system is positive, since 1.1°C is the response to doubling CO_2 without feedbacks. Based on the observed response of the climate system most studies find a *lower 5% limit between 1.5 and 2 °C.* Studies that use available information in a relatively complete way generally find a *most likely value between 2 and 3.5 °C.* There is no credible line of evidence that yields very high or very low climate sensitivity as a best estimate. The *upper limit* for climate sensitivity is *uncertain and* in many studies *exceeds 6°C.*

Characterisation

Although realisation that the climate system is more sensitive to greenhouse gases than assumed earlier is not a climate event, it can be looked at as an *acceleration of change* compared to expectations. In a way, the climate sensitivity is the net result of all feedbacks in the system and since it is a positive number, it can be characterised as *positive feedback.*

Temporal aspects

The uncertainty about the value of the climate sensitivity on the *decadal* timescale is for a large part related to uncertainties in the representation of clouds in climate models. Cloud processes occur over a wide range of spatial scales, from sub mm size droplets to convective flows in the kilometre range. This huge range of scales together with the fact that fluid turbulence (which is a chaotic phenomenon that can only be described statistically) is at the core of the cloud processes suggest that these uncertainties will not be significantly reduced by better theories or computer power in the coming years or even decades.

But if the sensitivity is, due to errors in the modelling of clouds, much bigger than assumed this should become apparent in the coming decades because global warming will be ever more ‘ahead of the model projections’.

On the *longer* timescales slow feedbacks may be insufficiently incorporated in comprehensive climate models since these models can only be accurately validated against present climate over a relatively short period of time. Moreover, the impact of slow feedbacks on climate acts by definition on timescales of its slowness, centuries and beyond. Paleo data suggest that by including these feedbacks, the climate system may be twice as sensitive as our present "best estimate" of an eventual 3°C global temperature increase for a doubling of CO_2 (Dorland et al., 2009).

Likelihood

A rough estimate from Figure 2.1 shows that the likelihood that the climate sensitivity is larger than 6°C is 4% or less, qualified as *very unlikely*.

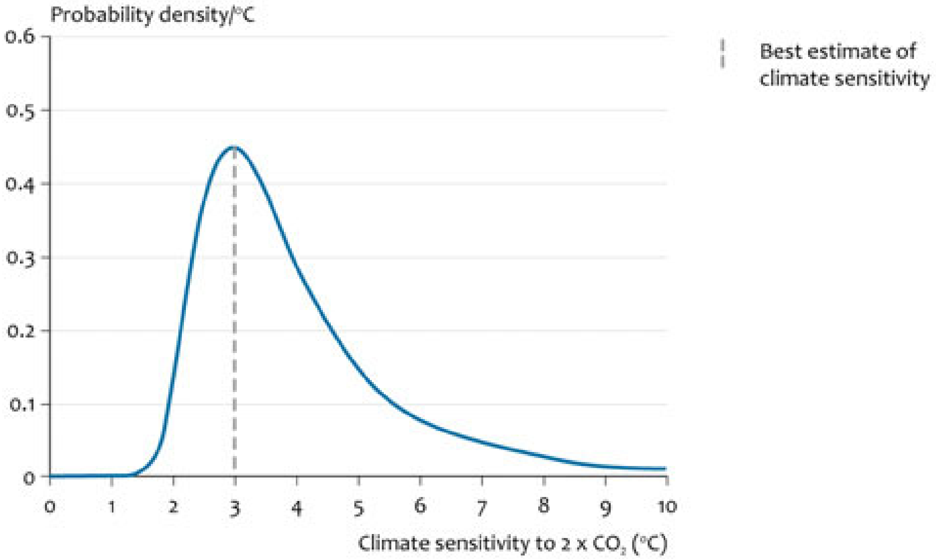


Figure 2.1: Skewed climate sensitivity distributions.

Impact

If the climate sensitivity is, in reality, a factor of two greater than now thought, all IPCC projections underestimate global temperature increases by up to a factor of two. The impact would be *notable* to *major*. Stabilisation scenarios that aim for instance to limit climate warming to two degrees Celsius would require much faster reduction of greenhouse gas emissions.

Level of scientific understanding

Cloud feedbacks particularly from low clouds are the largest source of uncertainty at decadal timescales. Cryospheric feedbacks such as changes in snow cover have been shown to contribute less to the spread in model estimates of climate sensitivity than cloud or water vapour feedbacks but can be important for regional climate responses at mid and high latitudes.

As Knutti and Hegerl (2008) commented: "The quest to determine climate sensitivity has now been going on for decades, with disturbingly little progress in narrowing the large uncertainty range."

2.4 Greenland Ice Sheet disintegrates

The Greenland Ice Sheet (GIS) is a vast body of ice covering roughly 80% of the surface area of Greenland. It is the second largest ice body in the world after the Antarctic Ice Sheet. The mass balance of the ice sheet is determined by accumulation due to precipitation and freezing, and by ice loss due to ablation and melt. GIS was more or less in equilibrium with climate over the last few centuries, but is currently losing mass at an increasing rate. Warming over the ice sheet accelerates ice loss from outlet glaciers and lowers ice altitude at the periphery, which further increases surface temperature and ablation. Disappearance of GIS would result in a global average sea level rise of up to seven metres.

Characterisation

Rapid melting of the Greenland Ice Sheet would be an example of *accelerated change*. The *positive feedbacks* are that, once the surface of the ice sheet is lower because it is thinning, temperatures are higher also in the accumulation region. This increases melting and causes more precipitation to fall as rain rather than as snow. The lower reflectivity of the exposed ice-free land causes local climatic warming and surface melt water might accelerate ice flow. Mean annual warming of *1.9 to 4.6°C in Greenland* would lead to a negative surface mass balance (Gregory and Huybrechts, 2006), which may be an upper limit for the threshold that leads to GIS disintegration (Lenton et al., 2008).

Temporal aspects

A possible threshold of ~3°C warming in Greenland could be reached when *global warming* is in the order of *1 to 2°C* (Lenton et al., 2008). If this threshold is passed, the IPCC (2007) gives a ~1,000-year timescale for GIS collapse. However, given the acknowledged lack of processes represented in current models that could accelerate collapse and the inability of models to simulate the rapid disappearance of continental ice at the end of the last ice age, a lower limit of 300 years is conceivable (Hansen, 2005). Total disintegration of GIS would be rapid initially, slowing down as the mass of the remnant becomes less and there will be less contact with open sea.

Likelihood

The Greenland Ice Sheet is currently losing mass at an accelerating rate. It is not known whether this is temporary, or the onset of total disintegration. Experts think it is *unlikely* that significant disintegration of the Greenland Ice Sheet would occur before 2050. On the centennial timescale (2009-2200), triggering collapse of GIS is thought to be *about as likely as not* if global warming is kept below two degrees Celsius, however with a large spread in the expert opinions. With *warmer scenarios,* onset of collapse on the centennial timescale is thought *likely* (Kriegler et al., 2009).

Impact

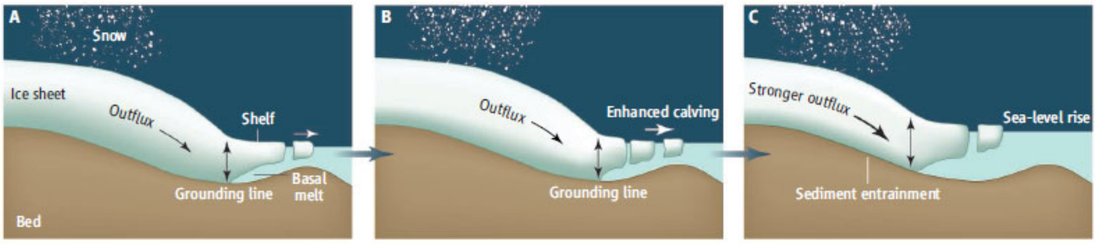
Disintegration of GIS would result in a global average rise in sea level of up to seven metres. Due to the reduced pull of the reduced ice sheet on the surrounding water (self gravity effect, see Section 3.1.4) Western Europe would experience much less rise in sea level from melting Greenland ice (60-80% less) than the global average. Nevertheless, the impact of a rapid disintegration of GIS is estimated as *major* to *devastating*.

Level of scientific understanding
Current models cannot capture accurately the observed dynamic deglaciation processes (i.e., the ice flow through narrow outlet glaciers). There is a lack of knowledge on natural GIS variability, and Greenland temperature changes have differed from the global trend, so interpretation of recent observations remains uncertain (Lenton et al., 2008).

2.5 West Antarctic Ice Sheet disintegrates

The West Antarctic Ice Sheet (WAIS) is a marine-based ice sheet. Its bed lies well below sea level and its edges flow into floating ice shelves (Figure 2.2). Recent gravity measurements suggest that the ice sheet is losing mass. Since most of the ice sheet is grounded below sea level, intrusion of ocean water could destabilise it. Weakening or collapse of the major West Antarctic ice shelves could be caused by intrusion of warm seawater and thinning due to basal melting.

Disintegration could result in a global average rise in sea level of up to five metres.



Runaway instability. Currently the grounding line sits to the right, upslope just outside the marine-based basin (A). Warm thermal ocean upwelling beneath the ice shelf (11) and lubrication by wet sediment at the base may exacerbate the potential instability and aid in accelerating the outward ice flow. As ice thickens at the transition zone (near the vertical arrow at the grounding line), ice flow increases. The runaway instability (evolving from **A** to **C**) does not stop until a new stable position is found and ice that was once grounded to the floor of the submarine basin has been lost to the global oceans. [Adapted from (5)]

Figure 2.2: Runaway instability from Ivins, 2005

Characterisation
More or less rapid disintegration of the WAIS would be an example of *accelerated change*. Most of the inland ice of West Antarctica is grounded below sea level and so could float if thinned sufficiently. Discharge promotes inland retreat of the grounding line, which represents a *positive feedback* by further reducing basal traction.

Possibly, there is a *tipping point.* No value for a tipping point is given IPCC (2007). Oppenheimer and Alley (2005) suggested that sustained global warming of *2°C* above present-day temperatures is a *threshold* beyond which there will be a commitment to a large sea-level contribution from the WAIS. Intrusion of *local* seawater causes the basal melting. Local changes in ocean circulation and temperature may be more important than global atmospheric warming.

Temporal aspects
The timescale is *highly uncertain*. A qualitative WAIS change could occur *within this millennium*, with *collapse within 300 years* being a worst-case scenario (IPCC 2007,

WGI, Chapter 10). Lenton et al. (2008) give a range of *5 to 8°C local warming or 3 to 5°C global warming* beyond which a collapse could be triggered.

Likelihood
IPCC (2007) states that no quantitative information about the likelihood of a disintegration of WAIS is available from the current generation of ice sheet models. There is a large spread in expert opinions (Kriegler et al., 2009) which indicates large uncertainties. The current status of WAIS is difficult to assess. At the *decadal* timescale (2009-2050), experts deem collapse of WAIS is *unlikely.* At the *centennial* timescale (2009-2200) under a warm scenario (4 to 8°C warming), the likelihood of collapse is thought to be *about as likely as not*. These estimates are expert opinion in the absence of objective quantitative information or understanding.

Impact
Disintegration of the WAIS could result in a global average rise in sea level of up to five metres, depending on the stability of remaining ice (Bamber et al., 2009). Due to the effects of self gravity (Section 3.1.5), the sea level rise on the coasts of Europe may possibly be 7 metres. Such an impact is classified as *major* to *devastating*.

Level of scientific understanding
Because the available models do not include all relevant processes, there is much uncertainty and no consensus about dynamic changes that could occur in the Antarctic ice sheet (Vaughan and Spouge, 2002; Alley et al., 2005; IPCC, 2007, WGI, Chapter 10).

Present understanding is insufficient to predict the possible speed or extent of a collapse. Observations, however, show that many floating ice shelves in the West Antarctic region are collapsing. The floating ice shelves exert back stress on the ice sheet. Disintegration of shelves causes the outlet glaciers of WAIS to accelerate.

2.6 MOC diminishes or collapses

The meridional overturning circulation (MOC) of sea currents in the Atlantic Ocean is driven by warm and salty surface water from tropical and subtropical oceans which flows to the North Atlantic and then cools and sinks at high latitudes. This process is known as deep-water formation. Because of the role of temperature and salinity in this process, the MOC is also referred to as Thermo Haline Circulation (THC).

If the inflow of freshwater to the North Atlantic increases, for instance from rivers, extra precipitation or melting glaciers, the density of the surface water decreases. This could drastically reduce or stop the deep-water formation. Under these conditions, the North Atlantic current would be disrupted, the North Atlantic sea surface temperatures would drop several degrees, sea level in the North Atlantic region would rise, and the tropical rain belt would shift. There is ample evidence that a shutdown of the meridional overturning in the Atlantic Ocean occurred in last glacial period with an ice sheet configuration much different from that of today.

Parts of the Atlantic MOC exhibit considerable decadal variability, but data do not support a coherent trend in the overturning circulation (IPCC 2007, WGI, TS).

Characterisation

Shutdown of North Atlantic Deep Water formation is a *tipping point* in the climate system. The *control parameter* is the density of surface water flowing into the area. Slowing down of the MOC, which is more likely than a shutdown during this century, could be characterised as *gradual change*.

Temporal aspects

A gradual slowing of the MOC is projected during the 21st century, but there are no observational indications that this is occurring. This is mainly due to lack of data. Natural variability on decadal timescales may hide such a signal for decades. Paleo evidence of previous events suggest that *shutdown* of MOC could take place *within decades* after its onset. Simulations show that the associated *cooling* of the North Atlantic sea surface and of European climate would last *several decades*, after which surface temperatures would start to rise again slowly. *Climate over Europe would recover after about 100 years*.

Since 2004, a consortium of research institutes has been *monitoring* MOC strength in the Atlantic Ocean at 26°.5 North with the RAPID array. (http://www.noc.soton.ac.uk/rapidmoc/).

Likelihood

It is *very likely* that the Atlantic MOC *will slow down* during the 21st century with an average model-estimated reduction by 2100 of 25% and ranging from zero to more than 50% (IPCC, 2007; WGI, TS Chapter 5). The projected reduction of the Atlantic MOC is due to the combined effects of an increase of high-latitude temperatures and precipitation, which reduce the density of the surface waters in the North Atlantic. While few atmosphere-ocean general circulation model studies have included the impact of additional fresh water from melting of the Greenland Ice Sheet, those that have do not suggest that this will lead to a complete MOC shutdown.

Taken together, it is likely that the MOC will weaken, perhaps associated with a significant reduction in Labrador Sea Water formation, but it is *very unlikely* that the MOC *will undergo a large abrupt transition* during 21st century (IPCC 2007, WGI, Chapter 10).

At this stage, it is too early to assess the likelihood of a large abrupt change in the MOC beyond the end of the 21st century. In experiments with the low (B1) and medium (A1B) scenarios, and the scenario in which the atmospheric greenhouse gas concentrations are stabilised beyond 2100, the MOC recovers from initial weakening within one to several centuries after 2100 in some of the models. In other models, the reduction persists (IPCC 2007; WGI, Chapter 10).

Impact

Temperatures are projected to increase globally, also over the North Atlantic and Europe, due to the influence of the increase of greenhouse gases, despite a projected slowdown of the MOC in most models (IPCC 2007; WGI, TS). The primary effect of MOC slowdown is a little less warming over the North Atlantic and Europe. Such an impact could be beneficial for these areas in a warming world.

During a complete shutdown, the North Atlantic sea surface temperatures would drop dramatically (several degrees Celsius). Sea level in the North Atlantic region would rise and the tropical rain belt would shift. A much cooler North Atlantic would also influence temperature in Western Europe with many negative secondary effects on for instance water availability, energy consumption, and food production (Arnell et al., 2005). Based on this, the impact of MOC collapse is considered to be *notable* to *major*.

Level of scientific understanding

There is low confidence in observations of trends in MOC due to decadal variability and inadequate long-term observations (IPCC 2007, WGI, Chapter 6). There is a large spread in model simulations of MOC and of possible changes. Some models give a MOC strength inconsistent with the range of present-day estimates (Smethie and Fine, 2001; Ganachaud, 2003; Lumpkin and Speer, 2003; Talley, 2003).

Generally, Atlantic MOC simulated for the late 20th century shows a spread ranging from a weak MOC of about 12 Sv to over 20 Sv (Sv stands for Sverdrup: $1 \text{ Sv} = 10^6 \text{ m}^3\text{s}^{-1}$). When forced with the SRES A1B scenario, the models show a reduction in MOC of up to 50%, but in one model, the changes are not distinguishable from the simulated natural variability.

There is some evidence that the sensitivity of the MOC to freshwater anomalies and the likelihood for rapid change is determined by the Atlantic saltwater balance. Tentative analyses indicate that most climate models are too stable and have a bias in the North Atlantic salt and freshwater budgets (Weber and Drijfhout, 2007).

2.7 ENSO changes character

El Niño is an irregular climate phenomenon of the atmosphere and ocean in the Tropical Pacific which returns on the average every three to four years. Characteristics of an El Niño are warmer than normal sea surface temperatures around the equator in the eastern half of the Pacific basin and a lower than normal pressure difference between the western and eastern Pacific. The reverse situation, with colder than normal sea surface temperatures and a higher than normal pressure difference over the Pacific, is called a La Niña. The changes in pressure and wind over the Pacific are known as the Southern Oscillation giving the phenomenon its name - El Niño and Southern Oscillation (ENSO).

Climate models have indicated that the character of ENSO might change in a warming world, for example, with more frequent or stronger El Niño events. Since ENSO influences weather patterns in many parts of the world, a change in ENSO character would have widespread impacts.

Characterisation

It is not clear whether or how ENSO might change. There are multi-decadal fluctuations in ENSO amplitude in observations and long simulations. While these make detection of externally driven changes difficult, they also suggest that any such change could show up as a *gradual change* in the frequency or amplitude of the oscillation. However, there are also indications of more abrupt changes.

Temporal aspects

Due to the presence of natural multi-decadal fluctuations, it may take *many decades* to detect possible changes in ENSO statistics caused by global warming.

Likelihood

Subjective estimates by experts (Kriegler et al., 2009) indicate that it is *unlikely* that the mean state of the climate system will change toward a configuration with more El Niño when global temperature rises less than four degrees Celsius.

Impact

A clear relationship has been found between the weather in many parts of the world and the occurrence of an El Niño or La Niña. The effects depend greatly on the location and season. The strongest effects on precipitation are in South-East Asia and the western Pacific Ocean, especially in the dry season (August to November), with significant drying in Indonesia and increase of precipitation in the tropical Pacific Ocean. Also, the north-east of Brazil is drier than usual during El Niño. There are temperature effects throughout most of the tropics. The number of tropical cyclones also depends on El Niño in most basins. For example during an El Niño, there are fewer hurricanes over the Atlantic Ocean. La Niña often brings more.

A major change in the frequency of occurrence or the magnitude of El Niño or La Niña in a future climate may therefore influence weather in *several regions* creating a *notable* to *major* impact.

Level of scientific understanding

Using the most realistic 6 of 19 models, Oldenborgh et al. (2005) found no significant changes in the ENSO variability in the future (IPCC 2007; WGI, Chapter 10). Significant multi-decadal fluctuations in El Niño amplitude in observations and in long coupled model control runs complicate attempts to discern whether any future changes in El Niño amplitude are due to external forcing (i.e., global warming) or a manifestation of internal multi decadal variability (Meehl et al., 2005). At present, there are no clear indications of future changes in El Niño amplitude in a warmer climate (IPCC 2007, WGI, Chapter 10).

2.8 Amazon rainforest collapses

Changes in precipitation over Amazonia, particularly in the dry season, are probably the most critical determinant of the future fate of the Amazonian rainforest (Malhi, 2009). A reduction in precipitation may transform rainforest into savannah vegetation with higher surface temperatures. Lengthening of the dry season, and increases in summer temperatures will make it difficult for the forest to re-establish. This effect is stronger when, as expected, during the dry season the frequency of forest fires also increases. Large-scale deforestation (converting rainforest to pasture and cropland) combined with global warming will probably reduce rainfall in the Amazon region by up to 30% (Lenton et al., 2008). Without global warming, large-scale land-use change alone could also bring precipitation to a critical threshold for the survival of the remaining tropical rainforest.

Other factors influencing precipitation are the frequency of future ENSO events (during an El Niño phase there is less precipitation in North and East Amazonia), and the north-south SST gradient in tropical Atlantic (increased gradients lead to decreased precipitation in the dry season of South and East Amazonia).

Only a part of the effect of precipitation reduction is offset by a more water-efficient production of biomass due to the increased CO_2 concentration in the atmosphere.

Characterisation

The critical threshold or *tipping point* is the water availability below which tropical forests cannot persist and are replaced by savannah systems is estimated at 1,200 to 1,500 mm rainfall per annum (Lewis et al. in Schellnhuber, 2006). The frequency and extend of forest fires can also be seen as a *tipping point* which is, however, hard to quantify. A third *tipping point* is the fraction of deforestation in Amazonia beyond which the remaining rainforest may not survive, with an estimated value of 40% (Sampaio et al., 2007; Nobre and De Simone Borma, 2009).

Temporal aspects

Models project dieback of the Amazon rainforest to occur under two to four degrees Celsius global warming (Sampaio et al., 2007). Dieback would occur within decades after passing the tipping point.

Likelihood

Mahli (2009) concludes in an analysis of IPCC model data (using A2 emission scenario) and observations that there is a 30 to 50% probability for a transition in the 21st century to a rainfall regime in Eastern Amazonia that is more suited for seasonal forests. A lower probability (0-25%) is found for a transition to a regime typically for savannah. Western Amazonia is likely to remain in a rainforest-favouring climate.

Impact

As the Amazonian rainforest hosts about 20% of the terrestrial species (IPCC, 2007, WGII) transition from rainforest to savannah would mean a significant and *irreversible* decline in biodiversity of the Earth - a *major impact*. Furthermore, it will affect fresh water resources, *global* circulation, economic livelihood and cultural heritage of the local population. There will be an increase in atmospheric CO_2 due to the release of vegetation and soil carbon, enhancing the *global* greenhouse warming.

Level of scientific understanding
There has been no overall trend in region-wide annual mean precipitation in recent decades, but evidence of increasing frequency of dry events in southern Amazonia over the period 1970 to 1999 has been found. This, however, may also be part of natural variability. IPCC (2007) models underestimate precipitation in the current Amazonian climate (Mahli, 2009). This mismatch between observed and modelled climate as well as the large variation in modelled future trends (Cook and Vizy, 2008) renders the interpretation of GCM scenarios in Amazonia difficult.

2.9 Boreal forest dieback

Boreal forests are the coniferous forests that cover large parts of Alaska, Canada, Scandinavia and Siberia. These forests consist of trees that are able to survive the cold high-latitude winters. Rising summer temperatures, increased water stress and increased frequency of forest fires and diseases could lead to large-scale dieback of these forests. Since winter temperatures may still be too cold for trees from warmer mid-latitude climates, boreal forest may transform into open woodland or grassland. Less precipitation and more rapid water drainage from newly thawed regions might increase water stress although higher atmospheric CO_2 concentrations may lead to more water-efficient production of biomass and a decrease of water stress.

Characterisation
Dieback of boreal forest controlled by local precipitation and temperatures is possibly the result of crossing a *tipping point* in the climate system. But the extent of boreal forest may also change *gradually* as climate warms.

Temporal aspects
Boreal forest mortality is apparently increasing in many parts of the world (Allen et al., 2009). However, natural climate variation has triggered widespread forest mortality in the past, but available evidence is not conclusive. Studies suggest a *threshold* or *critical value* for boreal forest dieback of 3 to 5°C global warming (see Lenton et al., 2008), but this value is also highly uncertain.

Likelihood
Experts consulted by Kriegler et al. (2009) consider that a dieback of 50% of the boreal forest is *unlikely before 2050*, *as likely as not before 2200 in a moderate global temperature increase (2 to 4°C)* and *likely to occur when temperature changes by 4 to 8°C in 2200*.

Impact
The impact of a significant dieback of boreal forest would be *notable*: large in the forestry sector on *continental scales* and moderate on *regional cultures and economies*. There would also be positive feedback on *global* greenhouse warming because the amount of carbon stored in the forest biomass would decrease.

Level of scientific understanding
There is no conclusive observational indication for the occurrence of boreal forest dieback (Allen, 2009).

2.10 Arctic sea ice disappearing fast

Arctic sea ice is disappearing faster than anticipated by current models. As sea ice melts, it exposes a much darker ocean surface, which absorbs more radiation than white sea ice, so amplifying warming. A critical threshold for *summer* Arctic sea ice loss may exist, after which summer sea ice would further reduce and eventually collapse without further warming. A further threshold for *year-round* ice loss is more uncertain and considered less likely in this century.

Given that the current models significantly underestimate the observed rate of Arctic sea ice decline (Stroeve et al., 2007), a summer ice-loss threshold, if not already passed, may be very close and a transition could well occur within this century (Lenton et al., 2008). Over the last 16 years, ice cover during summer has declined markedly. Developments in 2007 (Figure 2.3) and 2008 suggest that fluctuations in the Arctic weather may affect the rapid decline more strongly than most models suggest.

The retreat of Arctic sea ice in recent decades has improved marine access, changed coastal ecology/biological production, had adverse effects on many ice-dependent marine mammals, and increased coastal wave action.

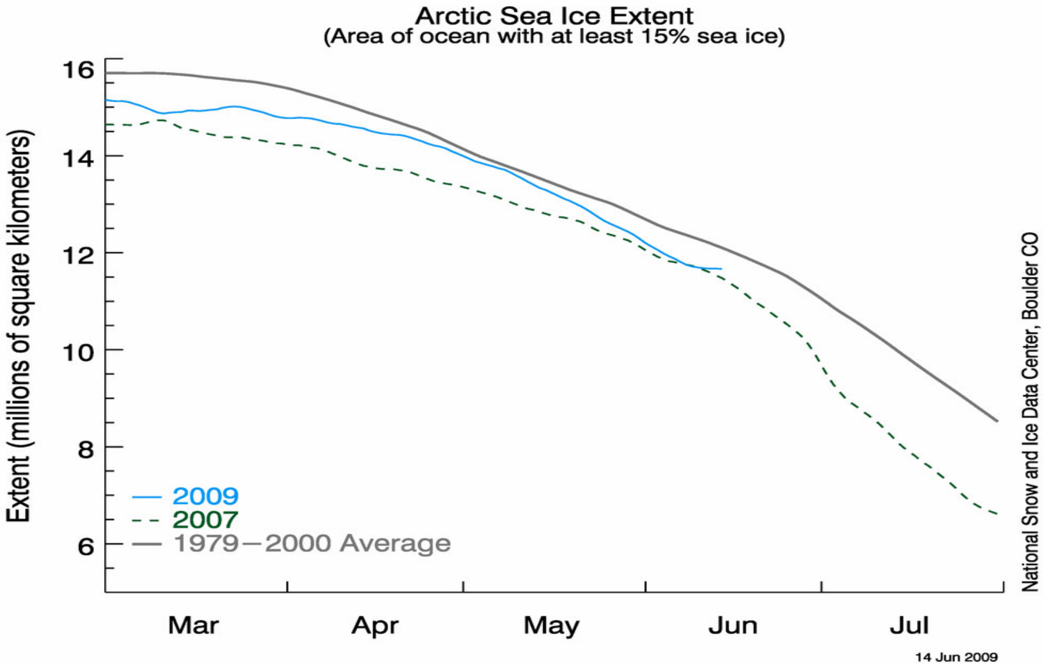


Figure 2.3: Arctic sea ice extent

Characterisation

The retreat of Arctic sea ice is a very likely consequence of climate change and part of a key feedback process that can accelerate global warming. Disappearing Arctic sea ice is an example of *positive feedback* (albedo feedback) leading to *accelerated change* especially in the Arctic region. Changes in ocean circulation and wind climatology could also contribute to ice loss.

Temporal aspects

Some models project that the summer sea-ice cover disappears entirely in the high emission A2 scenario in the latter part of the 21st century (IPCC, 2007, WGI, Chapter 10). The observed rate of Arctic sea ice decline seems to be greater than projected by most models, and an ice-free Arctic summer could be reached within *decades*. However, the recent extra loss of summer ice was mostly caused by anomalous wind and pressure fields over the Arctic. It is not known whether this is related to climate change or whether to natural variability. A year-round ice-free Arctic is not projected by any of the models.

Likelihood

If the observed climate warming continues, it seems *likely* that ice-free conditions in the Arctic in summer will develop *this century*. And it is *as likely as not* that this happens *within decades*. A year-round ice-free Arctic seems *very unlikely this century* (Lenton, 2008).

Impact

The primary effect of disappearing sea ice in the Arctic will be extra global warming and shifts in regional climate on the scale of several regions to a continent. An example of projected changes in the Arctic regions under the A1B scenario is given in Figure 2.4.

As already mentioned, an ice-free Arctic region would bring opportunities for trade, exploration and exploitation. But disappearing ice, shifting rainfall patterns and changing temperatures affect ecosystems (e.g., polar bear population) and require adaptation. Assuming light to moderate damage in those areas, the impact of disappearing sea-ice would be *notable*.

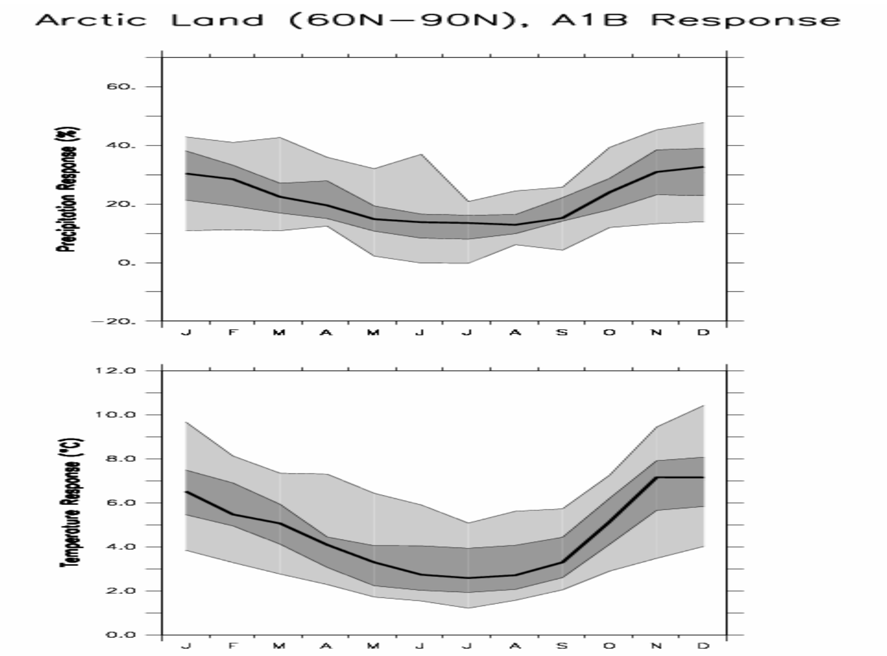


Figure 2.4: Annual cycle of Arctic area mean temperature and percentage precipitation changes (averaged over the area north of 60°N) for 2080–2099 minus 1980–1999, under the A1B scenario. Thick lines represent the ensemble median of 21 models. The dark grey area represents the 25% and 75% quartile values among the 21 models, while the light grey area shows the total range of the models. (IPCC 2007, WGI, Chapter 11)

Level of scientific understanding
The physical processes of sea-ice formation and decay are poorly modelled. The limited modelling skill is best illustrated by the severe underestimation of the modelled sea-ice retreat when compared to sea ice observations over the last few years (IPCC, 2007, WGI). Also, the observed warming over Arctic land when sea ice declines is greater than models suggest.

There is a projected reduction in sea ice in the 21st century both in the Arctic and Antarctic with a rather large range of model responses. Most climate models share common characteristics, such as peak surface warming in autumn and early winter, sea ice rapidly becoming seasonal, Arctic ice decaying faster than Antarctic ice, and northward ocean heat transport increasing into the northern high latitudes. However, models have little agreement on the amount of thinning sea ice (Flato, 2004; Arzel et al., 2006) and the overall climate change in the polar regions (Holland and Bitz, 2003; IPCC 2007, WGI, Chapter 10).

2.11 Solar-induced cooling

The weight of evidence suggests that changes in solar activity have contributed to small climate oscillations on timescales of a few centuries. These are similar in type to the fluctuations classically described for the last millennium: the Medieval Warm Period (900-1400 A.D.) followed on by the ‘Little Ice Age’ (1500-1800 A.D.). Fluctuations in solar activity such as the Maunder minimum (a period when almost no sunspots were observed, roughly between 1645 and 1715) and Dalton minimum (a period with low solar activity roughly between 1790 and 1830) certainly contributed to lower global temperatures, but by how much is still disputed. This introduces additional uncertainty for global temperature change in the near future.

Renewed interest in this topic is due to the claim of astrophysicists (e.g., De Jager and Duhau, 2009a and 2009b) that solar activity possibly declines in the coming decades.

Characterisation

A Maunder minimum type of event on the sun causing a relative cooling trend would be an externally driven *deceleration* (and later *acceleration) of change*, also indicated as *natural variability*.

Temporal aspects

Expectations of solar physicists differ about future behaviour of solar activity. Callebaut (2008) expects a grand minimum similar to the Maunder minimum for the coming decades. De Jager and Duhau (2009a) foresee a period with ‘regular cycles’ of activity (with relatively low activity), starting with the next solar cycle. Many predictions for the maximum number of sunspots in the next solar activity cycle (no. 24) have been made (Figure 2.5).

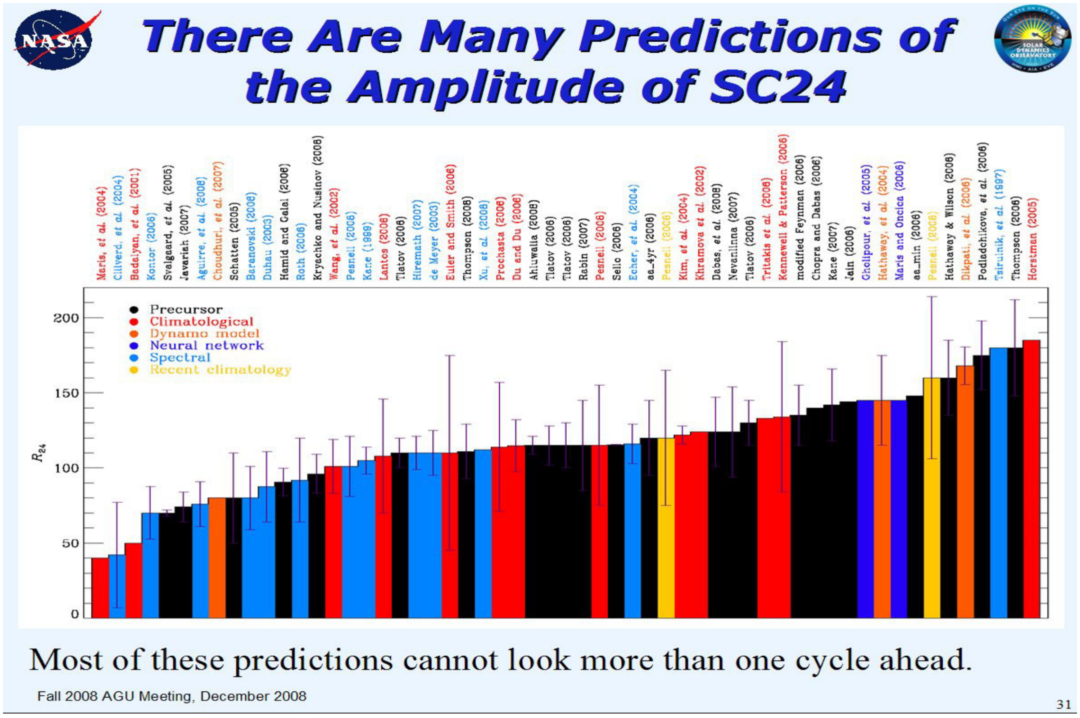
Basically, such predictions are ‘expert judgment’ based on observations of regularities in solar activity. Solar maxima during the Dalton Minimum had maximum sunspot numbers between 50 and 100.

The *duration* of the Maunder and Dalton minima was several decades to a century.

Likelihood

About half of the estimates in Figure 2.5 predict that the next solar cycle will be rather weak (maximum number of sunspot below 100). Interpreting this as a likelihood, it could be assumed to be *about as likely as not* that the coming decades will show low solar activity.

From the behaviour of sunspot cycles over the past four centuries, it seems *likely* that there will be a Maunder or Dalton type minimum of solar activity sometime *in* the coming *two centuries*.



There Are Many Predictions of the Amplitude of SC24

Most of these predictions cannot look more than one cycle ahead.

Fall 2008 AGU Meeting, December 2008

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Figure 2.5: The so called ‘Piano Plot’ presented by Dean Pesnell at the Fall 2008 AGU meeting shows estimates or predictions of the strength of the next solar cycle.

Impact

In the North Atlantic region, the solar Maunder and Dalton minima were associated with southward advances of sea ice whereas in Western Europe climate turned cool and wet. During the ‘Little Ice Age’, global climate is reported to have changed by 0.3 to 0.4°C but locally over the Northern Hemisphere continents, changes were much larger, especially in winter (1 to 2°C).

The primary effect of decreased solar activity could be a *global-scale cooling trend* of 0.3 to 0.4°C over a period of decades, accompanied by regional-scale climate changes in the Northern Hemisphere. Such a global cooling trend would work counter to the anthropogenic global warming at the time. The current rate of global warming is 0.1 to 0.2°C a decade and in most scenarios, the rate of global warming accelerates. This suggests that reduced solar activity later this century would not necessarily lead to global cooling; it could induce a period of slower global warming.

The impact of slowed-down global warming could be expected to be positive delaying the negative impact associated with the further warming that would have occurred otherwise. However, there would also be *regional to continental scale changes in climate* that would require adaptation. *After* the recovery of solar activity, global temperature increase would be accelerated as anthropogenic and solar forcing both point in the direction of global warming. Such a recovery period of solar activity might last several decades and any positive effects of the previous cooling trend will disappear. The impact of a Maunder minimum type solar event will be *notable* at least.

Level of scientific understanding
The link between solar activity and global climate is empirical. There is *no unequivocal link*: climatic events occur without corresponding solar forcing and vice versa. Some minima in solar activity do not seem to have a corresponding climatic anomaly. Also, a convincing mechanism for such a link has not been identified.

The variable solar activity is believed to be an aspect of the 'solar dynamo' which generates and destroys large-scale electric currents and magnetic fields in the solar atmosphere by the interaction between convection and differential rotation. For this solar dynamo, no generally accepted theory has as yet been developed. *Predicting* solar activity is currently *not possible* but there are some weak phenomenological indications that solar activity may decrease in coming decades.

2.12 Estimated climate sensitivity too high

In Section 2.3, the climate sensitivity and the possibility that the number may be underestimated was discussed. There is also a possibility that climate sensitivity is overestimated. If that is the case, climate projections of the IPCC err on the high side. If the climate sensitivity is only half as great as we now think (i.e., 1.6 to 1.8°C instead of 3.5 to 4°C), climate projections of global temperature increase would be only about half of the values given by IPCC (2007).

Characterisation
While this is not a climate event, global temperature rise would be at only half the warming rate expected earlier. This could be referred to as *decelerated change.*

Temporal aspects
As indicated in Section 2.3, a better theoretical basis on the climate sensitivity is not likely to be developed in the near future. Observations will give a better indication of the value in *decades* to come.

Likelihood
The likelihood that the climate sensitivity is in the range of 1.6 to 1.8°C is estimated at less than 5% or *extremely unlikely*.

Impact
A low climate sensitivity would result in less global warming than expected and thus more time to act to prevent dangerous levels of warming.

Level of scientific understanding
Cloud feedbacks (particularly from low clouds) remain the largest source of uncertainty. Cryospheric feedbacks such as changes in snow cover have been shown to contribute less to the spread in model estimates of climate sensitivity than cloud or water vapour

feedbacks, but they can be important for regional climate responses at mid- and high-latitudes.

2.13 Ocean acidification

About one-third of the CO_2 emitted into the atmosphere from burning fossil fuel is absorbed by the oceans. This results in acidification of ocean water (lowering the pH) and a reduction in the concentration of carbonate ions (CO_3^{2-}) used for the shell of many marine organisms (made of calcium carbonate $CaCO_3$). Near the surface, the ocean water is saturated with calcium carbonate used by marine organisms to built their shells and skeletons. Below this surface zone, the water is under-saturated and solid $CaCO_3$ dissolves.

Coral reefs are found in shallow tropical waters along the shores of islands and continents. The reef substrate is mainly composed of calcium carbonate from living and dead polyps. Coral reefs have extremely high productivity and biodiversity, and as such are referred to as 'the Tropical Rainforests of the Oceans'. With increasing acidity of the ocean, the depth of the saturated zone decreases with detrimental effects on the formation of shells and coral.

Characterisation
Ocean acidification is a *gradual change*. It could, however, trigger accelerated change in marine ecosystems that are already affected by global warming, pollution and (over)fishing.

Temporal aspects
To prevent undesirable or high-risk changes to the marine food web, the pH of near surface waters should not drop more than 0.2 units below the pre-industrial average value of 8.18 (WGBU, 2006).

Field studies suggest that impacts of acidification on coral reefs may already be detectable. Compared to pre-industrial times, the pH of the ocean surface water has dropped on an average of about 0.1 (IPCC 2007, WGI, Chapter 5), the acidity of the ocean has thus increased at the surface.

The various IPCC emission scenarios indicate that if the atmospheric CO_2 concentration reaches 650 ppm by 2100, a decrease in average pH value of 0.30 units can be expected compared to pre-industrial values. With an atmospheric concentration of 970 ppm, the pH value would drop by 0.46 units. But if the CO_2 in the atmosphere can be limited to 450 ppm, then the pH reduction will only amount to 0.17 units (Caldeira and Wickett, 2005).

Likelihood
The pH changes mentioned above are predicted with a high degree of certainty. It would seem *likely* that ocean pH will decrease substantially during this century.

Impact
The primary effect of pH changes in the ocean is of a *global* nature. Secondary effects

will be irreversible loss of biodiversity and effect on fisheries, affecting food security and economies on *regional scales*. The full impact of ocean acidification and how these impacts may propagate through the marine ecosystems and the food chain, and the effects on fisheries remain largely unknown. Millions of livelihoods are closely linked to coral reefs and the fisheries they support. The possible impact is qualified between *notable* and *major*.

Level of scientific understanding
While acidification of surface ocean waters is well understood, study of the effects on marine ecosystems has only just begun.

2.14 Summary tables

An overview of the 13 climate eventualities with policy relevance are presented in Table 2.1 and of the qualifications related to probability and impact in Table 2.2**.**

Table 2.1: Overview of the 13 climate eventualities with policy relevance

Type of event	**Climate event**	**Character**	**Control by**	**Threshold**	**Global warming**	**Transition timescale**
Enhanced greenhouse effect	Rapid permafrost CO_2 & methane release	Accelerated Change /Positive Feedback	T_{local}	Not Known	Not Known	Not Known
	Rapid ocean bottom methane release	Accelerated change / positive feedback /tipping point?	$T_{sediment}$	Not Known	Not Known	10,000 – 20,000 Yr
	Estimated climate sensitivity too low	Positive Feedback /Accelerated Change				Centuries
Rapid melt of land ice	GIS disintegrates	Accelerated change /positive feedback	T_{local}	~3°C Warming	1 to 2°C	Centuries
	WAIS disintegrates	Accelerated Change / Positive Feedback /Tipping Point	Local T_{air} & T_{ocean}	~5-8°C Warming	3 to 5°C	Centuries
Regional circulation changes	MOC diminishes or collapses	Gradual Change /tipping point	NA fresh water input	0.1-0.5 Sv	3 to 5°C	Decades / Centuries
	ENSO changes in character	Unknown	unknown			
Rapid ecosystem change	Amazon forest collapses	Tipping point	Precipitation deforestation.	1.1m/yr 40% Deforest.	3 to 4°C	Decades
	Boreal forest dieback	Accelerated change /tipping point	T_{local}	~7°C Warming	3 to 4°C	Decades
Eventuality of special interest	Arctic ice free in summer	Positive feedback/ accelerated change	T_{local}	None	Current	Decades
	Solar induced cooling	Decelerated /accelerated change	Solar activity	None	None	Decades /Century
	Estimated climate sensitivity too high	-				Centuries
	Ocean acidification	Gradual change	atm. CO_2 concentrat-ion	None	Current	Decades /Century

Table 2.2: Overview of qualifications related to probability and impact.

Type of event	**Climate event**	**Onset possible in**	**Likelihood[1] (warm sc)**	**Primary effect**	**Scale**	**Impact**
Enhanced greenhouse effect	Rapid[*] Permafrost CO_2 & methane release	Not known	Unlikely	Extra warming,	Global	Major
	Rapid[*] Ocean bottom methane release	Centuries - Millennia	Unlikely	Extra warming,	Global	Major
	Estimated climate sensitivity too low	Years	Very unlikely (> than 6°C)	Extra warming	Global	Notable – major
Rapid melt of land ice	GIS disintegrates	Decades - Centuries	About as likely as not	Extra sea level rise	Global	Major – devastating
	WAIS disintegrates	Centuries - Millennia	About as likely as not	Extra sea level rise	Global	Major – devastating
Regional circulation changes	MOC collapses	Centuries	Very unlikely	Shifts in regional climate	Several regions/ Continental	Notable - major
	ENSO changes in character	Decades	Unlikely	Shifts in regional climate	Several regions	Notable - major
Rapid ecosystem change	Amazon forest collapses	Decades	Unlikely	Shifts in regional climates	Several regions/ Continental	Major
	Boreal forest dieback	Decades	About as likely as not	Shifts in regional climates	Several regions/ Continental	Notable
Eventuality of special interest	Arctic ice free in summer	Decades	Likely	Extra warming & Shifts in regional climate	Several regions/ Continental	Minor – notable
	Solar induced cooling	Years - Decades	Likely	Less warming	Continental / Global	Minor – notable
	Estimated climate sensitivity too high	Years -	Very unlikely	Less warming	Global	Minor
	Ocean acidification	Years	Likely		Global	Notable - major

[1] *Likelihoods* are estimated for a *centennial* timescale with a warm scenario (4 to 8°C warming in 2200).
[*] *Gradual* release of methane from permafrost and ocean bottom clathrates is *likely* to occur and will have *minor* impact.

3. Discussion

3.1 Uncertainties

Knowledge on these climate eventualities is incomplete and uncertain. How uncertainties complicate our view on the future is discussed.

3.1.1 The role of internal variability

Some uncertainty is inherent in the climate system due to internal variability. The climate system is extremely complex and there is chaos in many places. Even when the climate system is not ‘forced’, by changing solar irradiation, for example, or by presence of volcanic dust or increasing CO_2 levels, there will be variability.

In 1976, Klaus Hasselmann introduced a stochastic climate model that describes how low frequency fluctuations in the climate system arise spontaneously as a result of interaction between the oceans and the atmosphere. The short-term fluctuations in the atmosphere (e.g., weather events) will be integrated by the oceans with their much larger heat capacity and sluggishness. The Hasselmann (1976) model predicts that the climate system exhibits spontaneous fluctuations at timescales of decades and centuries (timescales associated with ocean circulation), and that the slower fluctuations have the most energy (such fluctuations are also indicated as ‘red noise’). The prediction has been verified successfully in many cases and datasets.

The large irregular swings in temperature, wind and precipitation in the Tropical Pacific, known as El Niño – Southern Oscillation (ENSO) - are a well-known example of such *internal* variability in the climate system at the timescale of years to decades. We know of several other modes in the climate system that generate variability at timescales of decades. Low frequency noise that dominates the internal variability in the climate system is inherently unpredictable and thus complicates efforts to predict or project possible climate developments.

Examples of this were given in the discussion of possible slowing down of the North Atlantic Meridional Overturning Circulation (MOC). Models suggest that MOC could already be slowing down but the presence of decadal variability prevents detection. Another example is the possibility of changes in the character or strength of ENSO. Because ENSO varies in strength, character and duration on decadal timescales. It may well take decades to gather enough statistics to detect a change. Also the possibility that estimated climate sensitivity is in fact too high or too low can remain hidden for decades due to low frequency internal variability of the climate system.

In addition to *hiding the onset* of an event *or the detection* of a condition, natural internal variability could also *influence the triggering* of a change. Local weather events, unusual high pressure and relatively clear skies enhanced summer melting of Arctic sea ice in 2007 to a record low, perhaps making an ice-free Arctic (in the summer) more likely at an earlier stage than anticipated. A strong ENSO event or a period of long-lasting El Niño conditions might trigger collapse of the Amazonian rainforest long before it would have happened otherwise. A temporary deceleration of global warming due to solar influences could postpone the possible triggering of an event.

The presence of largely unpredictable natural variability with decadal and centennial timescales complicates efforts to detect or project the onset of possible changes. Even conditions or developments that we expect and understand to some extent may surprise us because their possible presence or triggering might be obscured in the 'noise' of natural variability.

3.1.2 Uncertain global warming as a trigger

As discussed in Section 1.4.3, several of the climate events will become more likely or could reach a tipping point at a certain level of global warming. The tipping point for disintegration of the West Antarctic Ice Sheet, for example, could be reached when the local air and ocean temperature have increased by 5 to 8°C. It is estimated that global warming in the range 3 to 5°C would create such conditions. The 13 events discussed in this reported are placed in this perspective in Figure 3.1.

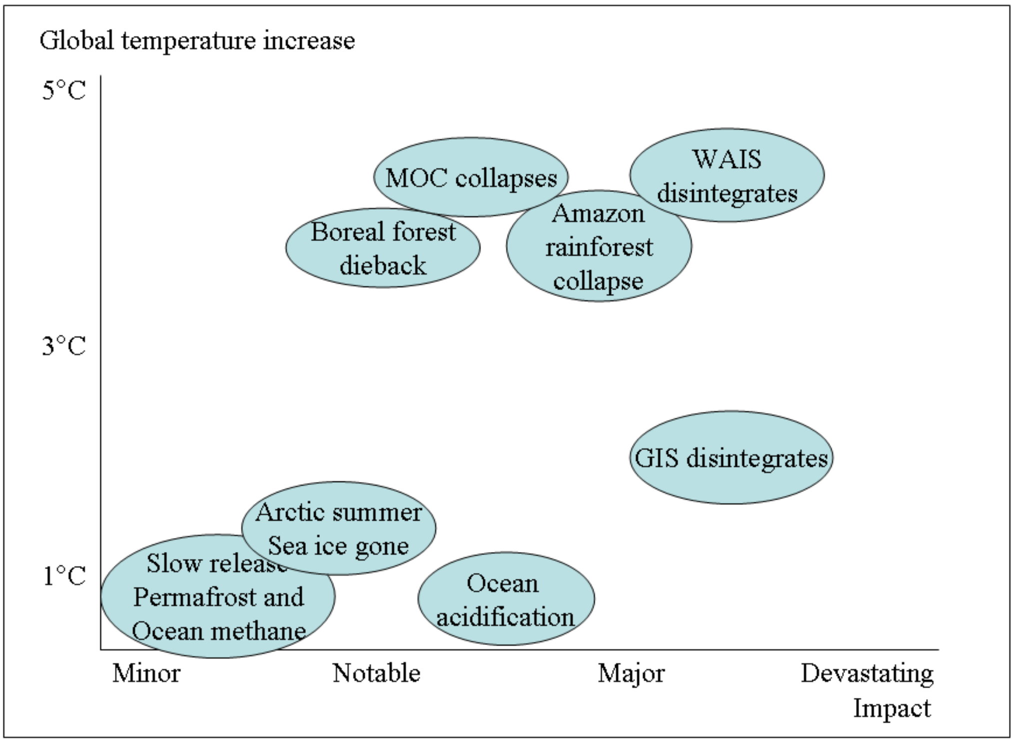

Figure 3.1: Background global warming at which the onset of the 13 events could occur and the estimated impact. The shape and size of the ovals do NOT represent uncertainties in impact and background global warming, which may be significant.

Figure 3.1 is a simplified and somewhat subjective summary of the available information but without information on the timing of the event. "The Amazon rainforest might collapse if the global warming exceeds 3 to 4°C and this could have a major impact" is a simple, straightforward statement. But it does not indicate if or when the global warming reaches such levels. The statement also obscures the notion that a very large ENSO event or rapid deforestation could also trigger collapse of the rainforest even in the absence of global warming.

The events are grouped along a diagonal in Figure 3.1, suggesting that events with a major impact are 'harder to trigger' than smaller scale events. This is possibly a coincidence or a selection effect. The upper left corner of the graph is empty because at a global warming of 3 to 5°C, there will be notable to major impact and smaller events would not be seen as relevant, or seen as part of the larger impact. The empty lower right corner of the figure is just a lucky coincidence. Climate events that might be triggered at relatively low global warming and that would lead to major or devastating impacts are unknown. Greenland Ice Sheet disintegration comes closest to this description.

Figure 3.1 also illustrates the notion that the worst consequences of climate warming would be avoided if greenhouse gas emissions can be decreased to keep global warming below 2°C. Except possibly for the onset of GIS disintegration, a number of high impact events could be avoided if global warming is no more than 2°C.

Although Figure 3.1 and the estimates on which it is based suggest these outcomes, the level of scientific understanding of most of these events is low and the estimated numbers and qualifications have large uncertainties. Also, global warming to a certain level is not the only way to trigger some of the events that are to be avoided.

3.1.3 Interactions

Section 3.1.2 shows that uncertainties in global warming introduce uncertainties in the timing of the events discussed. *Additional* uncertainties are introduced by the possibility that these events could interact or occur more or less simultaneously. If an event causes extra and accelerated climate warming or extra rise in sea level, the likelihood of other events may increase.

The possibility has been discussed that a series of strong ENSO events or a change in ENSO characteristics that would enhance drought in the Amazon region could trigger collapse of the rainforest. The reverse effect could also occur. ENSO changes could lessen drought and shorten the drought season in the Amazon region, which would postpone problems for the rainforest.

Because the hydrology of the permafrost regions is affected by wide spread melting, melting of permafrost could be linked with water stress in the boreal forests often adjacent to these areas. Rapid melting of permafrost regions may hasten the possible collapse of boreal forests.

The melt water from the Greenland Ice Sheet freshens the North Atlantic Ocean. Rapid disintegration of GIS would, therefore, slow down or destabilise the Atlantic MOC. Rapid disintegration of GIS would also affect WAIS stability, for example due to sea level effects. Simulations show that collapse of the Atlantic MOC would cause the Southern Ocean to warm, which in its turn could affect the stability of WAIS.

3.1.4 Ignorance: unknown eventualities

The Earth's climate system is extremely complex and unexpected events have occurred in the past. A good example is the rapid seasonal depletion of the stratospheric ozone above the Polar Regions (ozone hole), which was discovered in 1985. It is quite possible that there are tipping points or other eventualities in the climate system that are not known. Dessai and van der Sluijs (2007) consider it is *likely* that, as the global warming proceeds, one or more unexpected developments will occur in the climate system.

With vigorous and extensive research, some of these unknown surprises may be identified before they become manifest. But it is wise to acknowledge that we do not understand Earth's climate system well enough to predict and possibly avoid all possible outcomes.

3.1.5 Impacts

Much research has been devoted to possible impacts of a warming climate. The IPCC assessments present summaries of the results, such as Figure 3.2 below that present examples of progression of global impacts projected for various sectors.

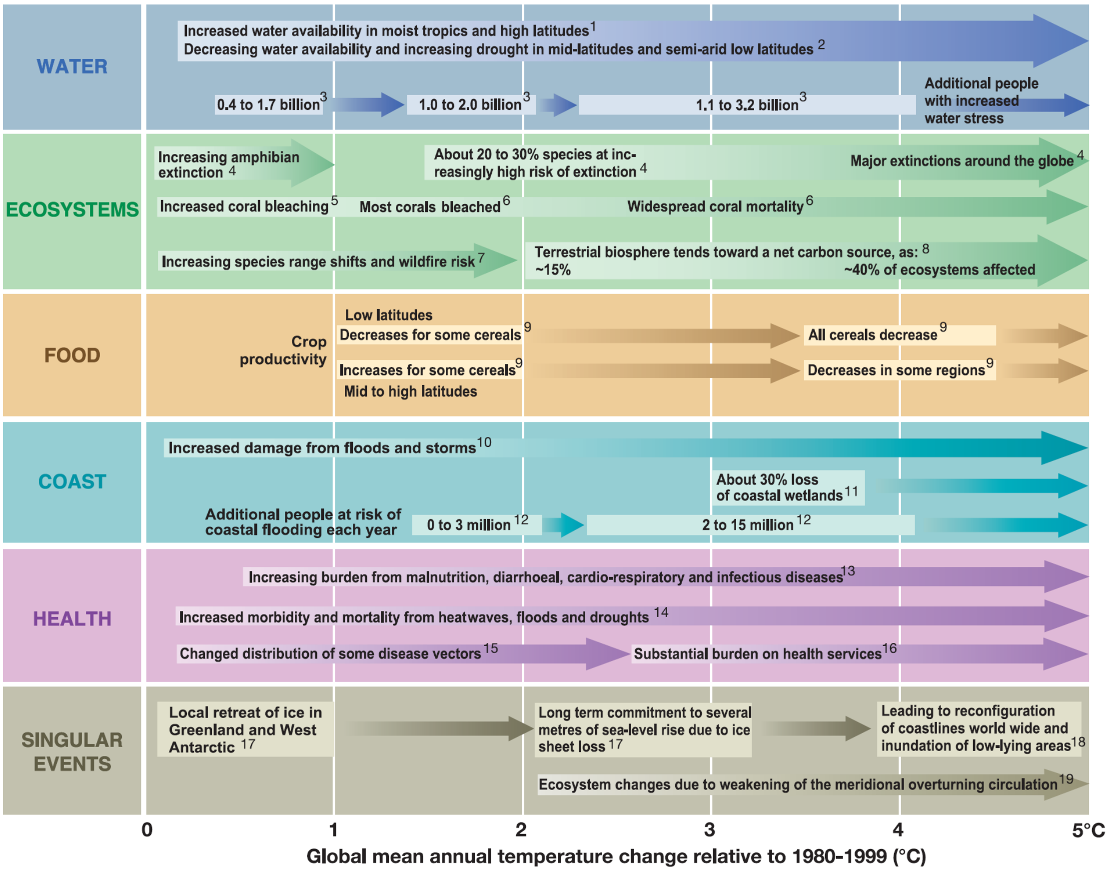

Figure 3.2: Examples of global impacts projected for warming climate. The superscript numbers are references to IPCC (2007) text.

A similar figure of the results of research into *regional* impacts is also presented in IPCC (2007). In most cases, projected damages and costs of the impacts cannot be quantified. At present, there is no convincing or agreed method to construct a *quantitative* scale for the magnitude of the impacts such as presented in Figure 3.2.

For this report, an impact scale with the subjective qualifications has been adopted: *minor*, *notable*, *major* and *devastating*. In Appendix A,it is explained how these impact qualifications have been chosen in a combination of the *geographical scale* (from *regional*, *continental* to *global*) and the character of the *damage* (*light*, *moderate*, *heavy* or *extreme*). To indicate what a '*devastating* impact' would mean, we point to the rightmost side of Figure 3.2. A *devastating* impact is an impact as projected for global warming levels of 5 degrees Celsius or higher. *Extreme* damage, such as major extinctions and substantial burden on health services at a global scale. A *minor* impact would be the impact projected for global warming levels of 0 to 1 degrees Celsius, with *light* damage on a regional scale.

The other impact categories are associated with intermediate levels of warming. The impacts presented in Figure 3.2 are examples of global impacts projected for certain levels of global warming. Impacts related to the climate events described in this report would be additional to these.

Though we have classified extra rise in sea level rise as a *global* impact, there is considerable regional differentiation in sea level rise. One example is due to the self-gravity effect (Mitrovica et al., 2001). The mass of large ice sheets, such as WAIS and GIS, exerts gravity which attracts the surrounding ocean waters. For thousands of kilometres around such ice sheets, the sea level is higher than it would have been without the gravity effect of the ice sheet. If the ice sheet melts, the gravity effect disappears and the sea level around the area where the ice sheet was decreases. In this area, the sea level rise resulting from ice sheet melt is a combination of sea level rise due to the extra melt water and sea level decline because the gravity effect declines. As a result the west coast of Western Europe, for example, would experience only about 20 to 40% of the global average rise in sea level from melting of land ice on Greenland.

Other regional sea level effects that complicate the picture are, related to possible local or regional ocean circulation changes, and to changes in salinity and temperature of the surrounding seawater due to cold and fresh melt water from the ice sheet.

The *possibility of positive impacts* was also examined. If our estimate of climate sensitivity is too high, or if an inactive sun imposes a cooling trend on global climate, climate warming might slow down for decades. While this would allow more time to work on mitigation and adaptation, it would surprise a world preparing for major changes. This may influence support for implementing climate policies.

3.2 Policy perspectives

3.2.1 Eventualities as sources of uncertainty

If warming of the global climate continues, it is possible that after a certain period significant and unexpected climate events may occur (see Figure 3.3).The question is how can the scarce and fragmented information available be reconciled with ongoing efforts in climate change mitigation and adaptation.

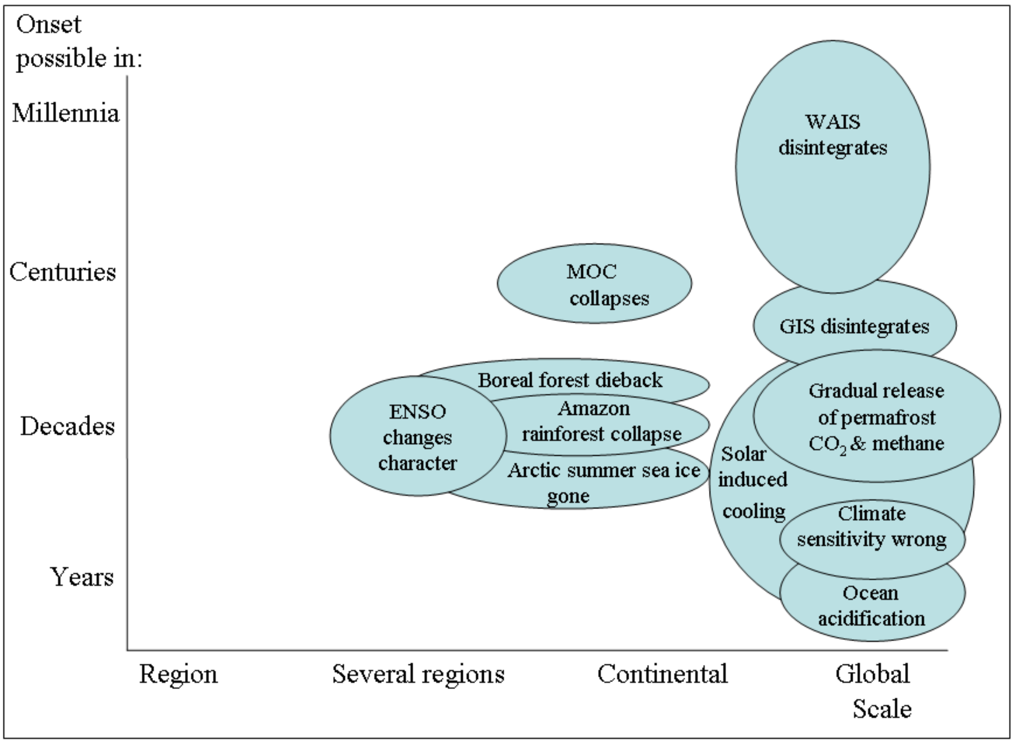

Figure 3.3: Possible timing of the onset of several events (assuming climate warming continues) and the spatial scale of their effects.

Climate change mitigation and adaptation activities have different motives, face different climate challenges and have different scientific tools available for different time horizons (Table 3.1).

Table 3.1: The need for policy information and the science tools to obtain that information, as a function of time horizon. The climate events discussed are indicated in yellow as extra sources of uncertainty at the decadal and centennial timescales.

Time frame→		**Years**	**Decades**	**Centuries**
Policy	*Governments*	Norms & normative dimensions	Spatial planning, infrastructure	Security (flooding, sea defence)
	Private	Production planning	Building	Developing, investing
Climate	*Climate change signal*	Dominated by global trend and (weather) variability	Regional patterns and trends visible. Climate variability	Major changes projected. Secondary effects
	Sources of uncertainty	ENSO, volcanoes, natural variability	Emissions, **eventualities**	Society, **eventualities**
Science	*Method of projection*	Statistical extrapolation of climatology & trends	Physical extrapolation, RCM, downscaling	Earth system models, impact assessment models
	Resolution	10 km	50 km	100 km
	Extremes	Yes	Uncertain	No
	Probabilities	Available	Doubtful	Not available

At the *short timescale of years,* basically the concern is current climate and weather. What are the average conditions and what type of extreme conditions may occur? Authorities responsible for road safety or for water availability, for example, need to know about frost incurrence or extreme rainfall. At these short timescales, the climate change 'signal' is not visible. Internal and externally driven natural climate variability and weather dominate. Knowledge tools for these short timescales are derived from classic climatology. Long-term monitoring of regional and local climates has provided reasonable knowledge about the average and extreme weather in many locations. With statistical techniques, climatology and observed trends can be extrapolated to give good projections of possible extremes, often even in a probabilistic context.

On *intermediate timescale of decades,* information is needed for long-term projects, such as buildings, road systems and other infrastructure. At these timescales, global warming can play an important role. IPCC (2007) stated that in the coming decades, the rate of global warming will be in the order of 0.1 to 0.2°C per decade. Over several decades, such a signal would be larger than most natural variability, similar to the past several decades where the still slower warming was most conspicuous and could even be attributed to anthropogenic forcing. At this timescale, regional patterns and trends of global warming become visible. An example from the past few decades is the warming rate in Western Europe. As shown by Oldenborgh et al. (2009), Western Europe has been warming at roughly twice the rate of global average warming. This finding was *not* expected.

Projecting climate at regional scales for the timescale of several decades is very difficult. Extrapolation of climates and trends from the past misses the changed dynamic interplay of oceans, atmosphere, land cover and snow and ice that determine future global and regional climates. The global climate models coupled with general circulation models of oceans, atmosphere and cryosphere are much more comprehensive in this respect, but are still too coarse and imperfect for regional scale projections. Down-scaling projections, for example using Regional Climate Models with finer resolution, that are embedded in the large-scale model does not lead to a robust and consistent view on regional climate change. In particular, the possible statistics of extreme weather events in a changed climate several decades in the future is difficult to assess.

Climate information for *timescales of centuries* is needed for long-term planning (city development, sewer systems) and security considerations, such as the need to build dikes as defence against sea level rise. Global climate models are used to project global warming typically for one or two centuries ahead. Though these models do generate weather and weather events (such as a storm), their resolution is too coarse for realistic extreme weather events. And though the global models paint a consistent picture of future warming on the global scale, regional scale responses differ in the models.

At the different timescales, different *sources of uncertainty* dominate. In the short range, weather and short-term natural variability dominate the uncertainties. At decadal and centennial timescales, the emission scenarios are a large uncertainty. The differences in climate response due to different emission scenarios become important in the second half of this century. At these timescales and at regional or ocean basin spatial scales, regional atmospheric and oceanic circulation changes play a role. Such flow changes give rise to nonlinearities that may introduce chaotic and unpredictable behaviour. Reliable information about probabilities or extreme weather cannot be deduced. Several of the eventualities described in this report such as changing ENSO character and possibly collapsing ecosystems in the boreal or tropical forests can be seen as consequences of such nonlinearities. Large-scale events, such as disintegration of WAIS or GIS, and the greenhouse gas feedbacks from melting permafrost are basically parts of the global climate system that should be incorporated in global climate models.

*From the policymakers' perspective, the eventualities discussed in this report can be seen as sources of extra uncertainty (*as indicated in colour in Table 3.1).

3.2.2 Eventualities can advance or postpone expected developments in time

The primary effects of many of the climate events discussed are extra warming, extra rise in sea level and shifts in regional climates (Table 1.1). The view on climate change sketched by IPCC with SRES scenarios, climate responses and corresponding impacts can also be used to get an indication of the possible role and impact of these eventualities.

Impact of the climate eventualities discussed in this report are characterised in terms of, extra warming or extra rise in sea level. This may be interpreted as more rapid "moving to the right" in impact in Figure 3.2.

An example is given and illustrated in Figure 3.4 below. Suppose in 2050 greenhouse gas concentrations have increased approximately according to the A1B scenario. Global temperature will have risen by about 1.7°C relative to 1980-1999 (from IPCC, 2007, Figure 3.3). Suppose CO_2 and methane emissions from melting permafrost regions are discovered to be rising faster than expected. According to the *average* climate model projections (the coloured lines in Figure 3.4) global warming of up to 2.5°C in 2080 could be expected under the A1B scenario. However, the extra greenhouse gases from the permafrost regions imply that concentrations of these gases no longer follow the A1B scenario but have higher values, perhaps towards values in the A2 scenario. Models forced with the A2 scenario project on the average 2.9°C of global warming in 2080, 0.4°C warmer than under the A1B scenario. Under the A1B scenario, 2.9°C warming would have been reached in 2105, 25 years later than in the A2 scenario. Looking at Figure 3.2 this would also mean extra damage and more severe impact in 2080. Primary effects of extra warming and extra rise in sea level imply a shift to a higher scenario and to progressively earlier and more severe impacts.

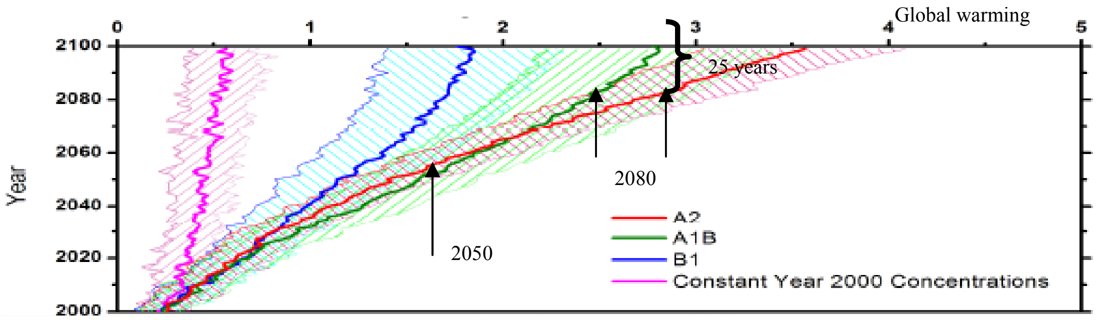

Figure 3.4: Extra greenhouse gases emissions from an unexpected climate event, starting in 2050 lead to a shift from the A1B scenario to the A2 scenario. Impacts related to ~3 degrees Celsius warming expected only after 2100 arrive 25 years earlier (Source: IPCC, 2007)

In reality, neither the emission pathway to 2050, nor the 'new' emission pathway with extra greenhouse gases emissions is likely to be one of the SRES scenarios. The differences in greenhouse gas emissions between the A1B and the A2 scenario are much larger than the emissions expected from permafrost and wetland regions. The example, however, illustrates how the IPCC framework of emission scenarios, projected climate response and projected impacts (both global and regional) can be used to understand possible effects of accelerated or decelerated global change.

Examples of the impact of rising sea level are also given in Figure 3.2. Even in the case that climate warming would be stabilised at, for example, two degrees Celsius warming, sea level will continue to rise as the warming is transported into the deep ocean (thermal expansion) and as land ice masses adjust to the warmer climate. The IPCC (2007) chapters referred to in Figure 3.2 give more examples of the impact of rising sea level with, for example, specific problems in small island states and low-lying deltas. Similar to the reasoning above, a climate event that results in *extra rise in sea level* would occur in a world that is already impacted by global warming and sea level rise and would cause specific impacts to appear earlier than expected.

3.2.3 Risk estimation

Facing dangerous developments or possibilities, a risk assessment can sometimes guide decision makers. As reflected by the classic formula Risk = Probability * Impact, risk is the expectation value of impact. If the estimates for Probability (in our case a subjective estimate of likelihood) and for Impact are plotted, the picture emerges as presented in Figure 3.5.

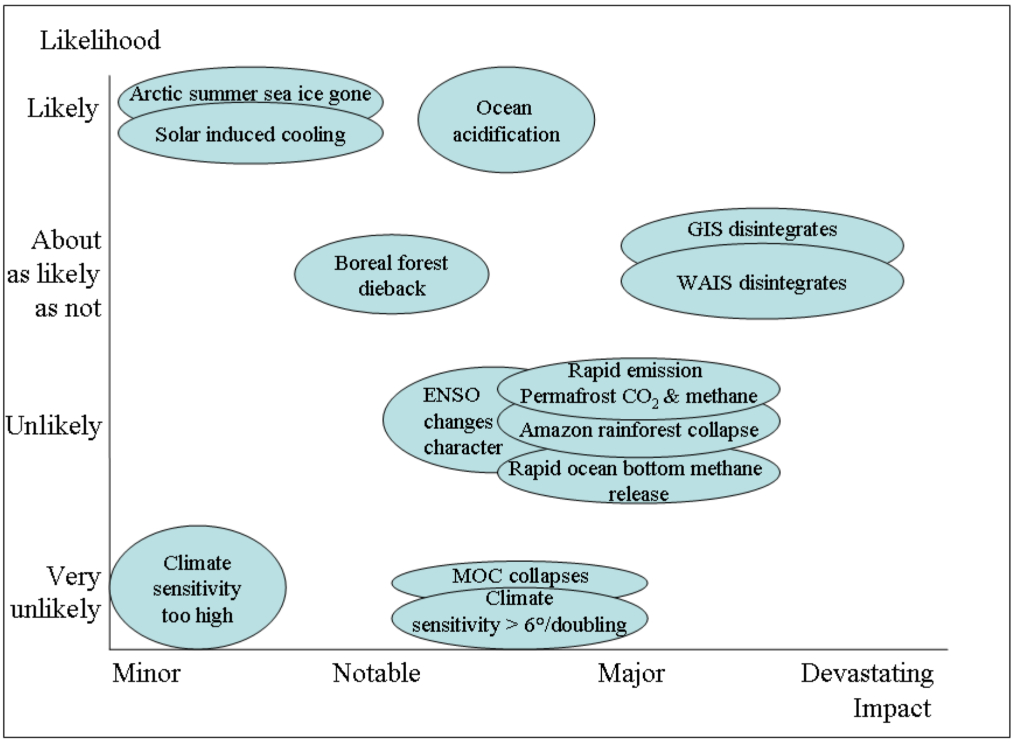

Figure 3.5: Probability and impact estimates for the ‘high temperature’ centennial timescale (i.e., 4 to 8°C warming in 2200). The size and shape of the ovals are arbitrary and they do NOT indicate uncertainties in impact and likelihood. For this information we refer to the text.

The risk of an event occurring is given by its position in Figure 3.5. Events with a high risk are those with high probability and high impact (in the upper right corner). Those of low probability and low impact, implying a low risk are in the lower left corner. We can rank the risks associated with events are placed along the diagonal from lower left to upper right. The possible rapid disintegration of the Greenland Ice Sheet represents a greater climate risk than the possible collapse of the meridional overturning circulation (MOC) in the North Atlantic. This is a straightforward conclusion because *both* the probability and the impact of GIS disintegration are estimated to be greater than those estimated for the MOC collapse.

But the question is whether the risks associated with ‘off diagonal’ events in this graph can be compared. No comparison can be made while little is known about numerical values associated with the qualitative labels along the horizontal and vertical axes (Figure 3.5). As an example, boreal forest dieback is estimated to be more likely than rapid emission of CO_2 and methane from melting permafrost soils. The impact of boreal forest dieback, however, is estimated to be less than the impact of massive emissions from permafrost soils.

A subjective risk approach allows comparison of *some* of the risks that the various eventualities might pose, but we *cannot rank* all the subjective risks from the information gathered here. Approximate costing of the possible impacts, at least in magnitude, would be required.

The possibly considerable risk related to unknown tipping points or eventualities (see Section 3.1.4) cannot be estimated at all. Ignorance is a threat.

3.2.4 Early warning and monitoring

Early warning may help to prepare for an event and its impacts. Some impacts may be avoided by a warning in advance for instance rapid extra rise in sea level. Coastal countries often have sea defences that may be strengthened or raised. Early warning may even help to prevent or postpone a climate event.

In most cases, early warning does not seem very promising. It has already been argued that natural variability in the global climate system makes it difficult to detect and project the onset of events. In addition, there is also natural variability in the subsystems at the focus of the events. The MOC, for example, shows considerable variability at decadal timescales. From many changes observed in the ice dynamics in the Greenland and Antarctic Ice Sheets, it is not clear whether they are part of natural variability at decadal timescales or caused by external changes.

Theoretical work by Scheffer et al. (2009) suggests that in noisy complex dynamic systems (for example, components of the climate system), the approach to a critical transition, such as a tipping point, may be marked by changes in the statistical characteristics that may be detected in advance. This means that in some cases, the variability may not prevent early warning.

But even where prospects for successful early warning are deemed low because of variability, *monitoring* subsystems such as the Arctic sea ice, ice sheets and forests helps to enhance understanding of these systems. Scientific understanding of these events leaves room for improvement and some of the uncertainty about these events could be reduced with better observations and understanding. Issues on decadal timescale variability should be addressed using observation series with at least decadal timescales. Regarding many issues such long observation series are not yet available.

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Appendix A: Subjective scales

A.1 Assessing uncertainties

When conducting risk assessments of climate change for national and local adaptation decisions, a cascade or explosion of uncertainty arises. Particularly for the climate events / developments discussed, quantifying probability and impact is currently very difficult or impossible. The nature of the uncertainty is multi-dimensional. It includes statistical uncertainty, scenario uncertainty and recognised ignorance in observed data, in climate models, in climate impacts and in policy context. According to Dessai and van der Sluijs (2007), these uncertainties are both epistemic (imperfect knowledge) and stochastic (intrinsic variability in the climate system).

Different regimes of uncertainty concerning future events require different vocabularies and tools:

- With very little uncertainty, future events can be predicted ‘exactly’ using a deterministic model. For example, astronomical tides in the North Sea are such deterministic events.
- Events that are more uncertain may be reasoned in *probabilistic* terms. The outcome cannot be predicted exactly, but more or less exact numbers can be calculated for the likelihood of a range of outcomes. An example of a successful probabilistic approach towards the uncertainties is the use of ensembles in modern-day weather forecasting.
- When events may happen but outcomes, probabilities and impacts cannot be quantified, the discussion turns to *possibilities*. Tools such as expert judgment and scenarios can help in decision making in such circumstances.
- *Ignorance* about events or their impacts forms the limiting case for uncertainty about future events. From experience, we are sometimes confronted with unforeseen developments. A resilience based approach guides decision making in such circumstances.

Little is known about the climate events discussed in this report about either the likelihood of such events or the possible outcome. Quantitative assessments will be impossible, and assessments can only be sketchy using subjective probabilities and other expert judgment. Such assessments require a special vocabulary. Even when scientific uncertainty is hard to quantify, a well-argued judgment may still be expressed of the likelihood of the occurrence of a particular risk. In the present assessment, the qualitative scales presented below are used.

A.2 Method of characterisation of likelihood

Where probabilities cannot be calculated rigorously, approximate values can be estimated and expressed in a subjective scale. A classification of probability intervals has been adopted which is a subset of the scale introduced for IPCC assessments (IPCC 2007, WGI, TS).The IPCC scale has been adjusted for the following reasons:

a) For the climate events discussed the *virtually certain*, *extremely likely* and *very likely* categories, which represent probabilities greater than 90% are not relevant in most cases. *Likely* (>65% probability) cover all of these likelihoods. Occasionally, the literature does allow more refined categorisation. In such cases, *very likely* is used which will, nevertheless, be categorised as *likely* in our impact and risk framework.
b) For many or most of the climate events discussed, a distinction between a < 10% probability (*very unlikely*), a < 5% probability (*extremely unlikely*) and a < 1% probability (*exceptionally unlikely*) is not possible so the latter two categories are not listed.

The qualitative scale for classification of probabilities or likelihood used is presented in Table A.1.

Table A.1: Qualitative scale for classification of probabilities or likelihood

Qualification	**Probability**	**Criteria**
Likely	> 65 %	Likely to occur
About as likely as not	33% - 65%	Is as likely as not to occur
Unlikely	< 33%	Unlikely to occur
Very unlikely	< 10%	Very unlikely to occur

The terms *likely* and *likelihood* are reserved for *subjective* probabilities, while *probability* has a numerical value.

A.2.1 Time and scenario dependence

The probabilities for the climate events discussed depend on the timeframe considered. The probability of a *once in five hundred years* storm occurring in a given ten-year period is 2%, while the probability for such an event occurring in a 100-year time interval is 20%.

In a changing climate, the probabilities of the occurrence of certain events may also change over time. If the climate becomes more variable, the *once in five hundred years storm* of today could be a *once in three hundred years storm* at the end of this century. Similarly, the probabilities for the extreme climate events discussed depend on the amount of global warming. For example, the probability of rapid rise in sea level from disintegrating land-based ice sheets is much less in a world where the global climate has warmed by only two degrees Celsius than in a scenario in which global temperature is 4 to 8 degrees Celsius higher than today.

Thus the term *probability* in risk assessment pertains to a certain timeframe and in this case also to a certain warming scenario during the chosen timeframe.

In this report, we will consider the timeframes 2009 – 2050 (decadal) and 2009 – 2200 (century; see Table A.2). For 2050, most of the IPCC warming scenarios project global warming between 1 and 3°C. In view of the uncertainties about the occurrence of the climate events discussed, this is a relatively small temperature range and differentiating between high and low scenarios is not feasible. For 2200, the range of projected warming in different scenarios is much broader and differentiation is made between low global warming (< 2°C) in 2200 and high global warming (4 – 8°C) in 2200.

Table A.2: Timeframes and scenarios for which risks are estimated

Decadal	2009 - 2050
Century (low)	2009 - 2200 (< 2°C warming in 2200)
Century (high)	2009 - 2200 (4 to 8 °C warming in 2200)

The low and high century timeframes were adopted from Kriegler et al. (2009). In that paper, subjective probability assessment were made for a number of tipping points in the climate system. By adopting the same scenario ranges, the subjective probabilities published by Kriegler et al. (2009) are used in our risk assessment procedure (see Figure A.1).

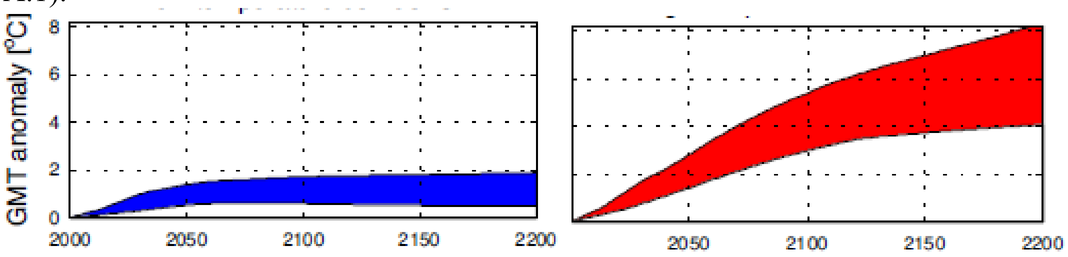

Figure A.1: Two scenario ranges from Kriegler et al. (2009)

A.3 Judging primary and secondary effects

A.3.1 Impact from global climate warming will be the background for extra impacts
Climate eventualities are discussed that may take place while the global climate is warming. Two timeframes (2009 – 2050 and 2009 – 2200) and two scenario ranges in the latter timeframe are considered. This implies that any such event would take place in a world already affected by greenhouse gas warming. The impacts of these separate climate events cannot be easily isolated from the impact of the general warming at the time. The magnitude of the extra impact from such an event may also depend on the impact of the general warming. Even a relatively small extra warming or extra rise in sea level may have devastating and irreversible consequences in a world where temperatures and sea level have been rising substantially for decades.

Also, the climate events discussed are or may be interdependent. For example, a change in El Niño frequency and intensity could affect drought in the Amazon rainforest area, increasing the likelihood of collapse. And an event that would cause extra global warming would also influence the likelihood of rapid ice melt.

A.3.2 Primary effects

The following primary effects are identified as associated with the climate eventualities discussed (see Chapter 2):

- Extra global warming
- Extra rise in sea level
- Ocean acidification
- Shifts in regional climates such as altered rainfall patterns, increasing drought and changes in extreme events including increasing numbers of intense storms.

While the first three of these primary effects are global, shifts in regional climate affect only part of the globe such as change in the frequency or strength of the El Niño phenomenon. The impacts of El Niño and of La Niña are distributed over the globe by *teleconnections* to a limited number of regions.

These primary effects are not independent from one another. For example, *extra global warming* may automatically bring about *extra rise in sea level*, *extra acidification of the oceans* and most probably also *shifts in regional climate.*

A.3.3 Secondary effects

As is well known and discussed in the scientific literature, the primary effects of changing climate bring a host of secondary effects. Agriculture is affected by changing temperatures, by changing precipitation patterns and by changing water availability. Fisheries are affected by changes in marine ecosystems because of warming and acidification. Changes in weather extremes affect vulnerable groups or whole societies. The costs associated with climate change are mostly in these secondary effects.

The contribution of IPCC Working Group II to the Fourth Assessment Report summarises and assesses research in this area. Projected impacts of global warming are discussed and listed, grouped by geographical region, by ‘sector’ (e.g., water availability, food, ecosystem, health or coast) and by the degree of global warming. However, comprehensive estimates of the overall costs associated with these projected impacts are not available. In our subjective assessment of the impacts, reference is made to the qualitative assessments of IPCC WGII.

A.4 Classification of impacts

Many physical and biological systems are affected by changing climate. The contributions of IPCC working groups II and III to the IPCC reports, which assess knowledge about impacts, adaptation and mitigation, show that estimating impacts of future climate changes is challenging and far from mature. The magnitude and timing of impacts varies with the amount and timing of climate change and, in many cases, the capacity to adapt. Some impacts, especially when loss of human lives or the extinction of species is implied, are irreversible. Other impacts may be lessened or avoided by adaptation. Some impacts, such as rapid rise in sea level, are global while others, such as changes in ENSO behaviour, are only of direct importance in one region or restricted to several regions around the globe.

Impact assessment is fraught with uncertainties and other complications, such as the incomparability of various types of damages and losses. Primary effects, such as changes in weather parameters, patterns and extreme events, give rise to secondary effects such as damage and loss, ecosystem changes, changes in water availability, changes in agricultural productivity, and migration. The contributions of IPCC Working Group II to the IPCC Assessment Reports show steady progress in understanding possible future impacts and capability to estimate their magnitude.

In our subjective risk assessment procedure, only a small number of ranked subjective categories are needed for the magnitude of impacts. The following categories are proposed:

- minor
- notable
- major
- devastating.

In order to establish criteria to rank expected or projected estimated impacts of the extreme climate events in this report, a further subdivision is made of the impacts:

- *Spatial scale* of the impact is discerned as *global* scale and *continental* scale impacts, impacts in *several regions* around the globe (such as ENSO teleconnections or shifting storm patterns) and *regional* scale impacts.
- *Damage* and loss in the impacted area are ranked in subjective categories - *light*, *moderate*, *heavy* and *extreme.* As indicated, introduction of this scale 'side steps' or 'hides' extremely complex and uncertain considerations in impact assessment.

Table A.3 maps these aspects to the chosen categories for the magnitude of impact.

Table A.3: Relationship between the magnitude estimate of impact of a climate event and estimates of damages and spatial scale

Damages \ Scale	**Global**	**Continental**	**Several regions**	**Regional**
Extreme	Devastating	Major	Major	Notable
Heavy	Major	Major	Notable	Notable
Moderate	Major	Notable	Notable	Minor
Light	Notable	Notable	Minor	Minor

This subdivision can also be presented as a list of *criteria* for the various categories of impact magnitude as shown in Table A.4.

As an example, projected or expected impact with heavy to moderate damage on a global scale is classified as a *major impact*; while an impact with extreme damage and loss at a regional scale is classified as *notable impact*.

Table A.4: Criteria for classification of impacts

Qualification	Damage	Spatial scale
Devastating	Extreme	Global
Major	Heavy-moderate	Global
	Extreme-heavy	Continental
	Extreme	Several Regions
Notable	Light	Global-Continental
	Moderate	Continental-Several Regions
	Heavy	Several Regions-Regional
	Extreme	Regional
Minor	Light	Several Regions-Regional
	Moderate	Regional

A.5 Risk classification

The risk associated with a climate event is the expectancy of damage and loss due to that event (during a chosen period of time and with a chosen warming scenario). To characterise such a risk, a simple scale ranging from *low*, *moderate, high* and *extreme* risk was chosen. In the IPCC assessments, the notion of climate change risks is discussed in terms of 'reasons for concern'. In Table A.5, IPCC terminology is linked to the risk categories chosen in this study.

Table A.5: Categories of risk

Category	Qualification
Low	Worrisome
Moderate	Reason for concern
High	Significant reason for concern
Extreme	Dangerous prospect

A.5.1 From likelihood and impact magnitude to risk

The final step in the method of qualitative risk assessment is 'multiplying' the probability by the impact. This cannot be done if the subjective labels do not have a numerical value. An example of such multiplication is arbitrarily Minor =1, Notable=51, Major = 101 and Devastating = 151 as given in Table A.6, or alternatively in Table A.7 of criteria.

Table A.6: Risk formula 1 in qualitative form

Likelihood of impact	**Minor**	**Notable**	**Major**	**Devastating**
Very unlikely	*Low*	*Low*	*Moderate*	*Moderate*
Unlikely	*Low*	*Moderate*	*High*	*High*
About as likely as not	*Moderate*	*High*	*High*	*Extreme*
Likely	*Moderate*	*High*	*Extreme*	*Extreme*

Table A.7: Criteria for risk categorisation

Risk	**Likelihood of event**	**Impact magnitude**
Low	Very unlikely	Minor - Notable
	Unlikely	Minor
Moderate	Very unlikely	Major - Devastating
	Unlikely	Notable
	Likely – About as likely as not	Minor
High	Unlikely	Major - Devastating
	About as likely as not	Notable - Major
	Likely	Notable
Extreme	About as likely as not	Devastating
	Likely	Major - Devastating

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