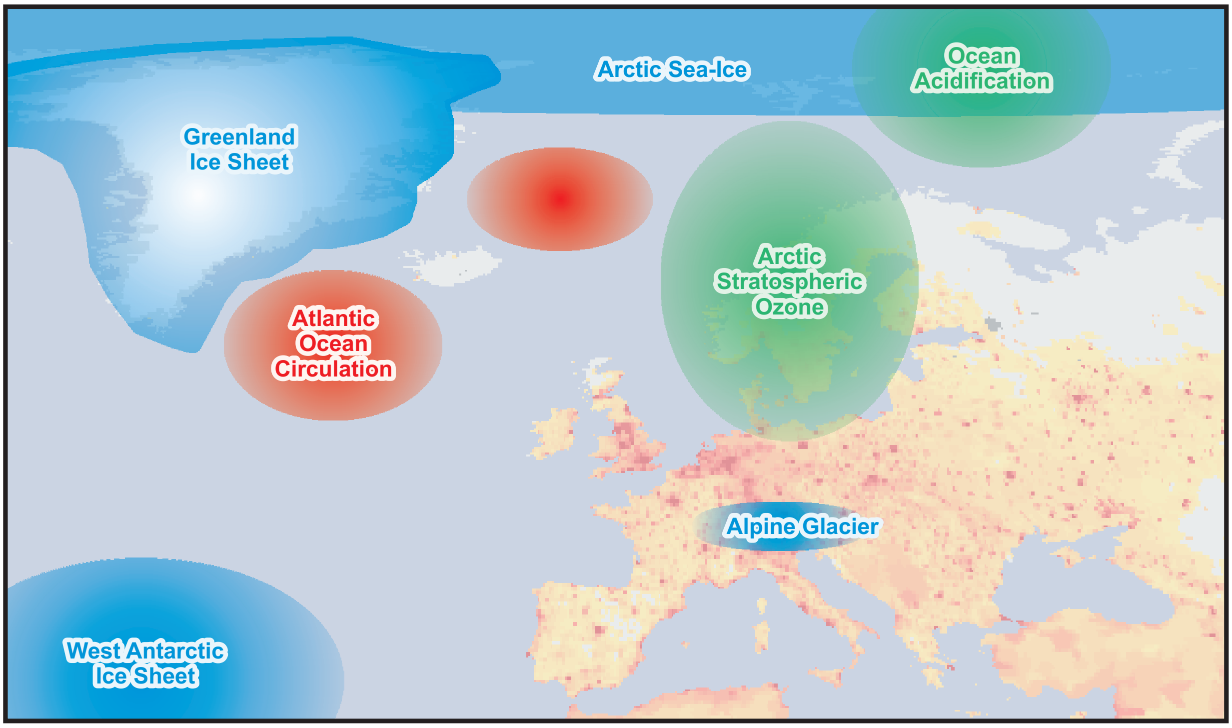
Climatic Tipping Elements with potential impact on Europe



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Potential Tipping Elements with direct impact on Europe as discussed in this paper. ©Potsdam Institute for Climate Impact Research, Potsdam, Germany

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Summary

This *Technical Paper* provides a brief overview of potential Tipping Elements of the climate system (Lenton *et al.*, 2008) with large-scale impact on Europe. Systems discussed are the ice sheets on Greenland and West Antarctica, the Atlantic thermohaline circulation, Alpine glaciers as well as summer sea ice and stratospheric ozone in the Arctic. The paper is aimed at a non-scientific audience. Information on **impacts, tipping mechanism and tipping potential** is based on published scientific literature. While the risk for a transition into a qualitatively different state is generally considered to increase with global mean temperature, it is regarded to be significant for all systems beyond a warming of two degrees above present-day levels. Alpine glaciers and the Arctic summer sea ice might exhibit a transition already at lower temperatures. The overall assessment is condensed into figure 15, where systems are ordered according to the severity of their impact onto Europe. The assessment is based on discussions initiated during an EEA workshop in Copenhagen, Denmark, October, 12^{th} -13^{th}, 2009.

Nature of the assessment   An assessment of the tipping potential of different Tipping Elements is as scientifically challenging as it is crucial for future societal, political and economic decisions. Such assessment needs to be based on a thorough understanding of the systems in question and might evolve while scientific insight deepens. Though based on scientific literature, some subjective assessment especially with respect to tipping potential by the authors was necessary. In light of associated risks even incomplete knowledge needs to be exploited to provide 'educated guesses' on the basis of available information. Such assessment will, by definition, always be preliminary and will permanently evolve. In light of natural climate variability, even the detection of a ongoing tipping of a climatic system presents a scientific challenge. Time series of relevant observables rarely exceed several decades in length which might not be sufficient to identify an acceleration in the system beyond any doubt. There are, however, a number of universal precursors when approaching a critical threshold which might be used for monitoring systems (Scheffer *et al.*, 2009). This potential has neither been explored nor applied to the largest possible extent.

Interlinkages between Tipping Elements   Matters are further complicated by the fact that some Tipping Elements are interlinked (Figure 14). For example, increased sea level by GIS melting will elevate ice shelves in Antarctica and might thereby induce a retreat of the grounding line. Most interlinkages, however, involve the Atlantic thermohaline circulation. A collapse or even only a reduction of its meridional circulation component will cool northern high latitudes which might stabilize melting of the GIS and Arctic sea-ice even though the cooling effect will be strongest in winter while the melting occurs in summer. On the other hand GIS melting will freshen the North Atlantic and might thereby trigger a THC break-down. Strong reduction in Arctic sea ice will change the salinity and heat budget of the Nordic Seas and thereby influence the Atlantic ocean circulation (Levermann *et al.*, 2007). Less sea ice cover will induce enhanced warming in

high northern latitudes and increase melting on Greenland and even in the Alps. In the Southern Ocean a THC reduction will lead to a warming around Antartica. Furthermore it might shift the subpolar wind belt (Vellinga & Wood, 2002), alter oceanic gyre circulation around Antartica and thereby induce changes in ice shelf melting (Hattermann & Levermann, 2010) and influence the stability properties of WAIS. Though these connections exist, so far neither model results nor paleo evidence has clearly shown the tipping of one system due to the tipping of another.

Tipping Elements and their tipping potential   The most recent *comprehensive* assessment of a number of Tipping Elements and their interlinkage was presented by Kriegler *et al.* (2009). They conducted an expert elicitation on subjective probabilities for the tipping under different future warming scenarios (figure 13). Results show that experts consider the risk of tipping of major climatic subsystems significant. This holds especially for high warming scenarios but numbers are still far from small for a moderate temperature increase within this century. Here we provide an attempt of a condensed assessment of the tipping potential in figure 15. Tipping elements are sorted according to the severeness of their impact on society. The color coding represents tipping potential for different global mean temperature increase. The width of the columns reflects the confidence that the authors have in their assessment. Naturally confidence is relatively high that no tipping has occurred for present-day conditions even though we can not be entirely certain about this. For most systems confidence in the assessment that tipping will occur increases with increasing levels of global warming. A special case is the collapse of the Atlantic thermohaline circulation. Here a qualitative change in the circulation is induced through changes in the North Atlantic salinity distribution which is only indirectly related to increasing temperature through GIS melting and changes in precipitation. Confidence about the likelihood of a collapse thus remains low even for high temperatures. The West Antarctic Ice Sheet bears the potential of abrupt solid ice discharge in response to oceanic warming, but currently no direct temperature estimates for such tipping is available. Paleo climatic evidence (Naish *et al.*, 2009) in combination with land ice dynamics simulations (Pollard & Deconto, 2009) suggest that abrupt discharge has occurred at temperatures 1-2°C above present. Available estimates of the threshold temperature for GIS of 3.1 ± 0.8°C (section 2) might not be robust since they are based on simplified parameterizations of the surface mass balance. Our current level of understanding suggests that Arctic sea ice and Alpine mountain glaciers are the most vulnerable to global warming of the presented short list of Tipping Elements with direct relevance for Europe. It is possible that even mitigated climate change, which does not exceed 2°C of global warming, is not sufficient to avoid qualitative change of these glacial regions. The risk of a Tipping Point in Arctic ozone depletion will become insignificant when chlorine levels drop below 1980 levels which will occur by 2060. Since it is very unlikely that global warming will exceed 4°C by 2030 no assessment with respect to Arctic ozone depletion is provided for higher temperatures.

Selection of Tipping Elements and structure of the paper Following a brief definition of Tipping Elements and associated self-amplification processes, six different Tipping Elements with direct relevance for Europe are discussed (figure 1). Even though we do not claim completeness, the Tipping Elements discussed were selected and sorted according to the severeness of their potential *direct* impact on Europe. It is important to note that a number of global Tipping Elements

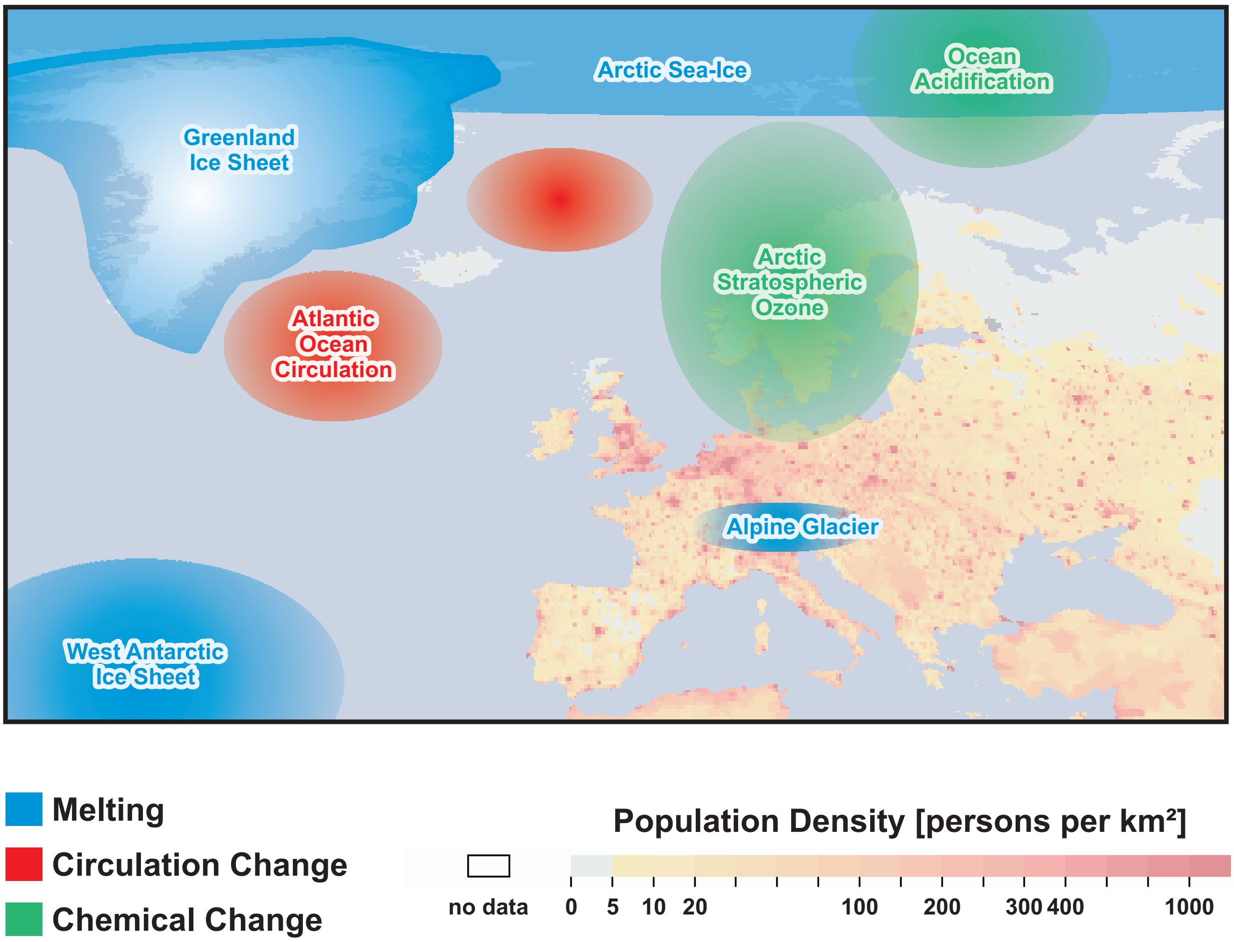

Figure 1 Potential Tipping Elements with direct impact on Europe as discussed in this paper.

might have *indirect* effect on Europe, for example through migration of climate-change-induced refugees. For example, Himalayan glaciers store water which is released into the rivers of India, China and neighbouring countries. Current water supply during the dry season in these countries with more than two billion inhabitants depends on this storage mechanism. Comparable to other mountain glaciers the Himalayas are vulnerable to global warming through, for example, the albedo-feedback described in section 5. Similarly important, monsoon systems in India, Asia and Africa support the livelihood of hundreds of million of people by providing precipitation for regional agriculture. Since monsoon circulations are sustained by a self-amplification process, they might show abrupt cessation (Levermann *et al.*, 2009). Although monsoon rainfall in Asia seems to have undergone abrupt transitions in the past (Wang *et al.*, 2008), their tipping potential has not been evaluated and no robust assessment can be given at this point.

Other processes might further amplify global warming and thereby affect also Europe. An example of a Tipping Element with such characteristic is thawing of northern hemispheric permafrost (Lashof, 1989). The associated biological activity induces the release of methane and carbon dioxide from the ground. These are greenhouse gases and currently represent the two strongest anthropogenic contribution to global warming. The release per degree of global warming depends on a number of regional biological factors and is difficult to assess but poses a potential source of additional warming. Current assessments suggest that the self-amplification is, however, small (Stendel & Christensen, 2002, Lawrence & Slater, 2005).

In this background paper we focused on Tipping Elements with *direct* impact on Europe. Each section briefly describes the Tipping Element and its potential impact, followed by an explanation of the associated self-amplification process and a brief assessment of its tipping potential. We conclude with a comparison of tipping potentials and their interlinkages.

1. General concept of Tipping Elements

Definition of Tipping Elements for the paper In this background paper we follow the formal definition of Tipping Elements given by Lenton *et al.* (2008), which was formulated less rigorously for the Synthesis Report of the IARU Congress on climate change (Richardson *et al.*, 2009). For all practical purposes the following concise formulation, which we will adopt for this paper, is sufficient.

"Tipping Elements are regional-scale features of the climate that could exhibit a threshold behaviour in response to climate change - that is, a small shift in background climate can trigger a large-scale and abrupt shift towards a qualitatively different state of the system."

Such a transition is illustrated in figure 2. It should be noted that this definition includes the possibility of irreversible shifts and multiple stable states of a system for the same background climate (so-called hysteresis behaviour). It is, however, not restricted to these.

Role of self-amplification for Tipping Elements The word *Tipping Element* suggests the existence of a self-amplification process at the heart of the tipping dynamics. Once triggered it dominates the dynamics for a certain period of time and thereby induces a qualitative change within the system, e.g. from an ice-covered to an ice-free Arctic. If existent, understanding the self-amplification process is crucial to prevent tipping. A prominent example of such self-amplification is the ice-albedo feedback (figure 2) that is discussed to be operational in the Arctic sea-ice region and on mountain glaciers such as the Alps and the Himalayas: An initial warming of snow- or ice-covered area induces regional melting. This uncovers darker ground, either brownish land or blue ocean, beneath the white snow- or ice-cover. Darker surfaces reflect less sunlight inducing increased regional warming[1]- the effect self-amplifies.

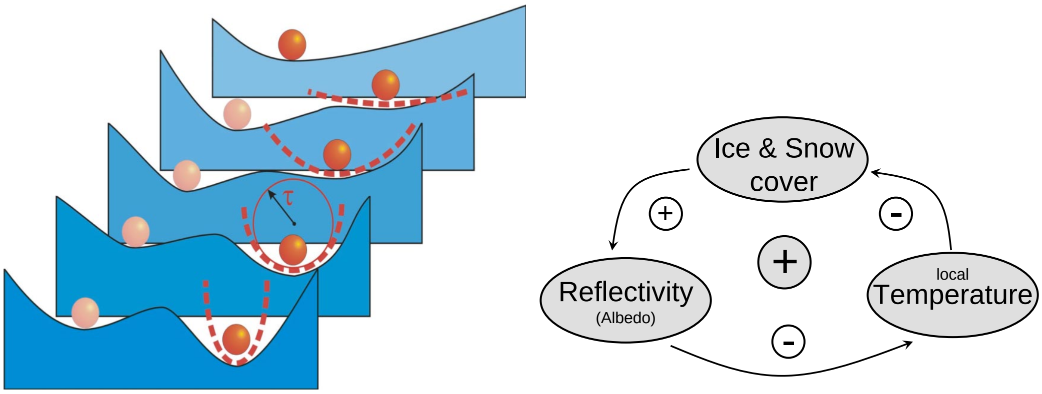

Figure 2 **Left**: Schematic illustrating the tipping of a system (Lenton *et al.*, 2008). Initially (front), the system (dark orange ball) is stable within its background climate (blue valley). Initial changes in background climate do not alter the ball's position (or system's state). At a certain threshold small changes cause the ball to roll-over. The system is tipping into a qualitatively different state. **Right**: The ice-albedo feedback as an example of self-amplification which is at the heart of most *Tipping Elements*. A plus between two processes denotes an enhancing influence; a minus denotes reduction. For example, increased temperature reduces ice cover. An even number of minuses yields a self-amplification loop (denoted by '+' in the center of the loop).

Here, following Lenton *et al.* (2008), the tipping of a system is not defined through such self-amplification, but rather through the ratio of small external perturbation to strong system's response. Such a definition does not comprise any dynamic element. This is justified especially from some stakeholders' perspective (Lenton *et al.*, 2009) which are mainly interested in whether a region will undergo exceptionally strong climate-related changes. For the example of the Arctic summer sea ice, we describe below that it is currently not clear whether the Arctic sea ice decline shows signs of internal acceleration. From the stakeholders' perspective, however, internal self-amplification is of secondary importance as long as the process is abrupt. For local communities as well as Arctic ecosystems it is more important that the sea ice is declining rapidly and that summer sea ice will most likely vanish for a further warming of 1-2°C.

As mentioned above, in this paper, we adopt the stakeholders' perspective and define *Tipping Elements* through a strong response to small external perturbations. The authors emphasize however that a dynamical perspective might better reflect the public perception of the word *Tipping Element* and thus the dynamical perspective will be emphasized whenever it is applicable.

1 The phrase ice-albedo feedback is commonly used and refers to the changing reflectivity or *albedo* of the surface.

2. Ice sheets on Greenland (GIS) & West Antarctica (WAIS)

Potential impact on Europe Most European coast line protection was initially built for the last century's sea level conditions and has mainly been readjusted moderately since. Though the situation may strongly differ from region to region, the maximum height to which dykes may be elevated rarely exceeds 1 m. Beyond this region-specific threshold significant rebuilding is necessary to protect land against storm surges and flooding. Most coastlines can not be protected against sea level rise of several meters. Therefore it is important to assess the potential for rapid **sea level rise (SLR)** within this century and beyond due to accelerated melt of the large ice sheets on Greenland and Antarctica.

Global warming of about 0.8°C during the last century has increased global sea level by about 0.15-0.2 m (Church & White, 2006). Mountain glaciers and ice caps (MGIC) were responsible for about 0.05 m of SLR during 20^{th} century. A similar contribution was due to oceanic thermal expansion. A possible source for the missing 0.05-0.10 m are the large ice sheets on Greenland and Antarctica. Direct observational data are, however, extremely limited prior to the 1970s. In the last 10-15 years this has changed. It has now been shown that both the Greenland Ice Sheet (GIS) and the West Antarctic Ice Sheet (WAIS) have been losing mass and this loss has been accelerating (Velicogna, 2009). During this period, the much larger East Antarctic Ice Sheet (EAIS) has been approximately in balance (Rignot *et al.*, 2008). These changes in ice sheet behaviour are recent and rapid and were not predicted by any of the current generation of ice sheet models. As a consequence, the Intergovernmental Panel on Climate Change (IPPC) suggested only modest contributions from the large ice sheets in its fourth assessment report in 2007 (Meehl *et al.*, 2007). It was acknowledged in the report that ice sheet processes were not adequately incorporated into projected sea level rise due to the inadequacy of the current generation of models. As a result, the projected global SLR of 0.20 - 0.60 m by 2100 underestimate the potential contribution of the ice sheets.

In recent years (since the mid 1990s) Antarctica exhibits net ice loss and is currently contributing about as much to global SLR as Greenland (Velicogna, 2009). An assessment of the potential contribution of the great ice sheets within this century is the subject of intense research efforts. The water stored in GIS is sufficient to raise global sea level by about 7 m. Although WAIS contains enough ice to increase global sea level by approximately 5 m, only about 3 m SLR equivalent are subject to potential self-amplifying ice discharge because they are grounded below current sea surface (Bamber *et al.*, 2009). The East Antarctic Ice Sheet could raise sea level by another $\sim$50 m. Even though also in East Antarctica large areas of bedrock are below sea level there evidence for the possibility of abrupt discharge there is extremely weak.

During the last glacial period (about 20 thousand years ago) large water masses were stored in ice sheets on the Northern Hemisphere. Furthermore colder ocean water was contracted and sea level was about 120-130 m below present levels. About 3 million years ago, global temperatures were higher than presently observed and reconstructions of past sea level show an elevation of 20-30 m above that seen today. Even higher temperatures 40 million years ago were associated with even higher levels of about 60-70 m above present levels. Despite large uncertainty it is clear that, in the past sea level has responded to temperature changes of a few degrees by sea surface elevations of the order of tenth of meters. These changes might have occurred in steps and not gradually and over long periods of time. The most recent period that was warmer than the present was the last interglacial, known as the Eemian, from 130-115 thousand years before present. During this period, sea level was 4-6 m higher than today and summer temperatures were 3-6°C warmer (CAPE-Last Interglaicial Project Members, 2006, Sime *et al.*, 2009). Thus, it is evident that there is a profound difference between the equilibrium response of sea level to temperature and the transient, centennial to millennial, response that is important here.

Consequently current projections of SLR for the 21st century are one to two orders of magnitude smaller than the expected equilibrium response of SLR for the same temperature derived from paleodata. This is due to strong inertia in the system which causes sea level response to temperature changes to be relatively slow but also long lasting. The question is: How quickly can sea level rise in response to rapid temperature increase? Due to their potentially self-amplifying ice loss mechanisms, GIS and WAIS are particularly important in a risk assessment of future SLR. Mass loss of an ice sheet is not just associated with more water in the ocean. Loss of big ice masses affects Earth's gravitational field and thereby regional sea level. For example, the loss of the GIS reduces the gravitational pull into the North Atlantic, hence lowering sea levels and offsetting SLR in that region but enhancing SLR in other regions. As a consequence the water distribution within the oceans is changed which alters the sea level pattern. Figure 3 shows the combined effects of additional water and associated gravitational effects for GIS and WAIS. Northern European coastlines will thus be less affected by mass loss in Greenland, while a reduction in WAIS leads to even stronger sea level rise on the European and North American coast compared to the global mean.

Mechanism: Self-amplifying ice loss from Greenland GIS covers most of Greenland and reaches a thickness of up to 3500 m. Since atmospheric temperatures decline with altitude[1], GIS's highly elevated surface is significantly colder than it would be at sea level. This gives rise to a potential self-amplification process: If GIS loses ice, as it is currently the case (figure 4), its surface elevation is lowered and its surface temperature increased. This enhances ice loss through melting and possibly the acceleration of iceberg discharge (**surface-elevation-feedback**).

Assessment of tipping potential for Greenland Ice Sheet (GIS) It is important to note that due to the surface-elevation-feedback, simulations suggest that GIS would not regrow under present climate conditions once it is eliminated and that its present existence is a relict of the last glacial period (Toniazzo *et al.*, 2004, Ridley *et al.*, 2010). From a stakeholder's perspective the relevant question, however, is whether there is a critical threshold temperature at which a complete disintegration of GIS is certain. In 2007, the IPCC-AR4 estimates this threshold to be 4.5 ± 0.9°C

1 On average temperatures decline by about 7°C for each kilometre altitude. Locally and temporarily this 'lapse rate' depends on weather conditions, but its order of magnitude is a robust feature which is fundamentally linked to Earth's gravity.

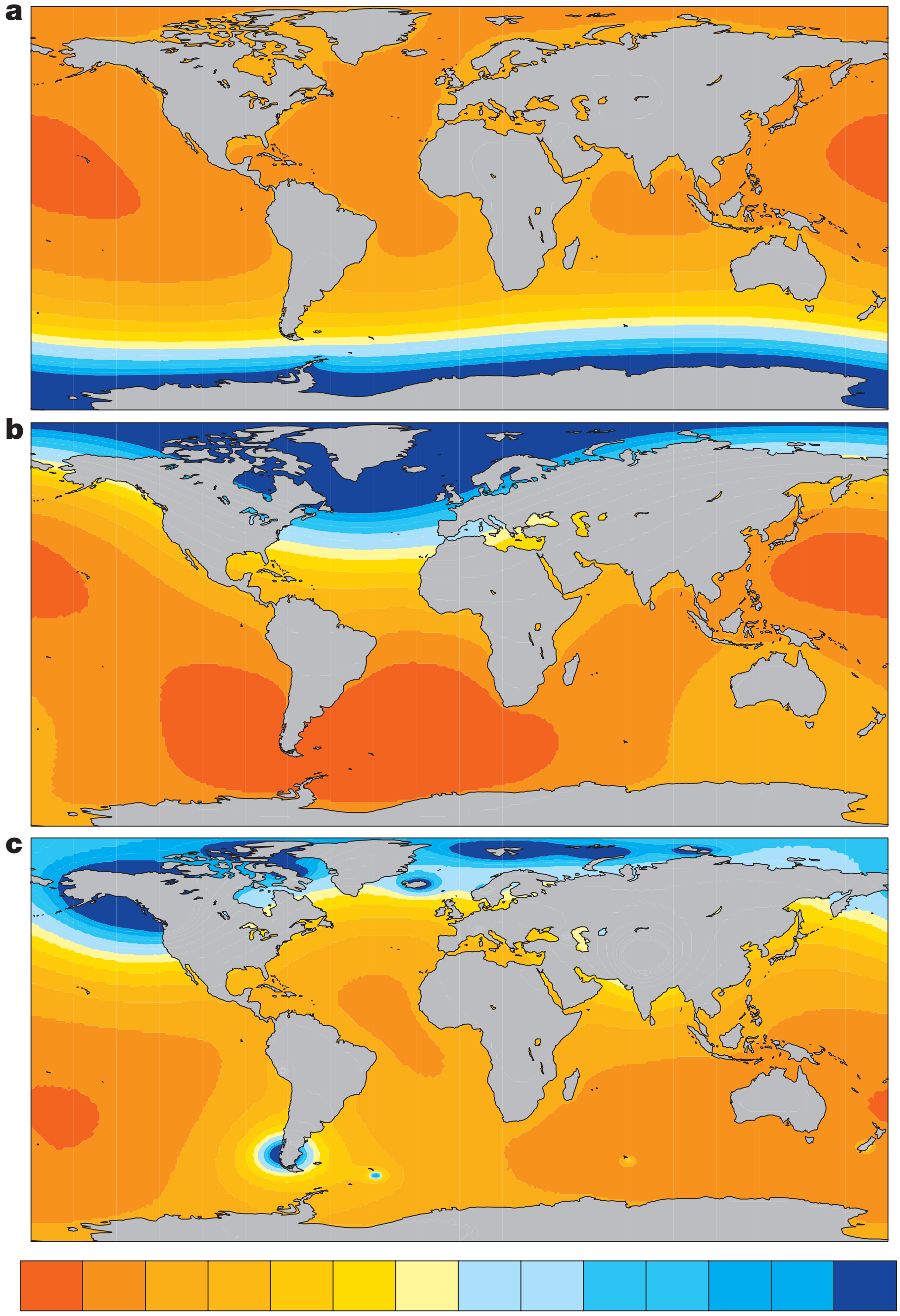

Figure 3 Regional distribution to sea level rise from (a) West Antarctic Ice Sheet, (b) Greenland Ice Sheet (GIS) and (c) mountain glaciers. Regional heterogeneity arises from gravitational effects and slight changes in Earth rotation. Actual sea level rise in meters is obtained by multiplication of values in panel a with ∼3.5 m (Bamber *et al.*, 2009) and values in panel b with ∼7 m. Figure from (Mitrovica *et al.*, 2001)

of warming over Greenland. Due to enhanced warming in high northern latitudes (figure 8) the

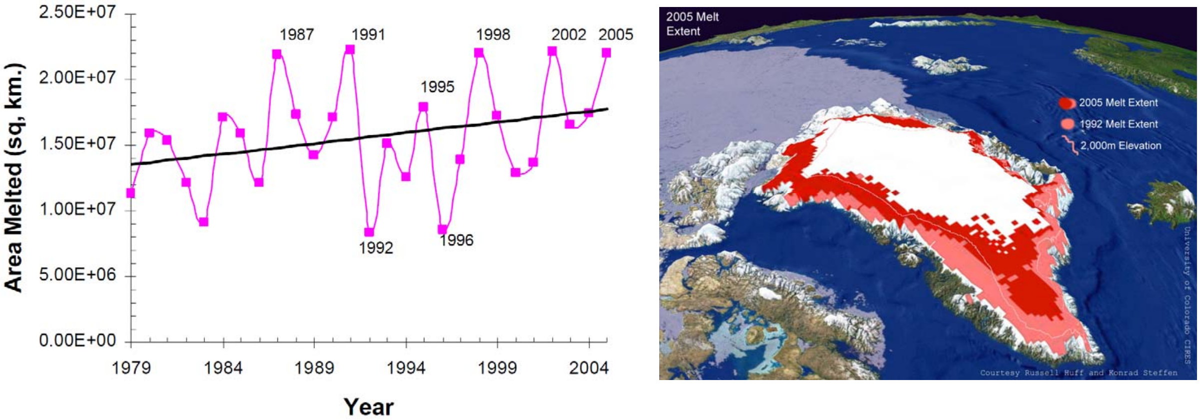

Figure 4 GIS melting area shows strong variations from year to year with some underlying trend towards larger areas of melting (left). Since 1979 with the first available satellite images of the region, the largest melting area was observed during the warmest year on record, 2005, while the smallest melting area was recorded in 1992 after the Mount Pinatubo volcanic eruption (right). Figures from K. Steffen, University of Colorado, USA.

associated range in global mean temperature is slightly lower (estimated to 3.1 ± 0.8°C by Gregory & Huybrechts (2006)) and depends on the rapidity of Arctic sea-ice retreat (section 4) as well as atmospheric dynamics that contribute to polar amplification of the anthropogenic warming signal. The IPCC states that this threshold could be crossed within this century.

This estimate is, however, based on the so-called Positive-Degree-Day (PDD) approach, which employs an empirical relationship between surface melting and surface temperature. This parameterization needs to be calibrated using presently observed climatic conditions and it is questionable whether this calibration is valid for strongly altered boundary conditions so as in a markedly warmer climate. More physically based energy-balance models tend to have a reduced sensitivity of the surface mass balance to increasing temperatures which might shift future threshold estimates towards higher values. Nonetheless, it is certain that increased temperatures in the Arctic will result in increased mass loss from the GIS. What is less certain is the temperature at which the fate of the ice sheet is sealed. There is currently no evidence from model simulations or observational data that suggest that a near-complete disintegration might occur quicker than on a millennial time scale even for quite extreme warming scenarios (Ridley *et al.*, 2005).

Land ice models are currently not able to capture observed acceleration of ice streams on GIS as for example the doubling in ice speed in the fastest flowing ice stream in Jacobshaven Isbrae (Joughin *et al.*, 2004). Due to difficulties of current state-of-the-art models to simulate fast ice flow processes, models are likely to underestimate GIS sea level contribution of this century. Consequently scientists have employed a different approach to estimating the GIS sea level contribution within **this** century. Avoiding model simulations, Pfeffer *et al.* (2008) estimated the maximum contribution of GIS to global SLR as constrained by the maximum local ice flow possible and the width of potential ice discharge outlets, to 0.54 m within this century.

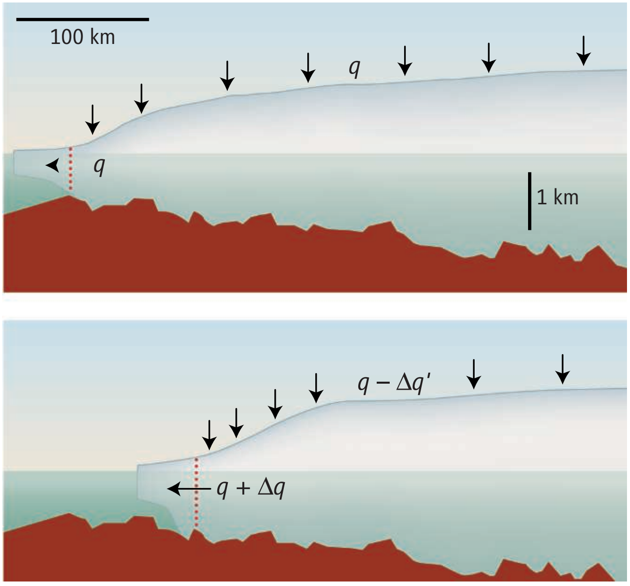

Figure 5 Tipping of the West Antarctic Ice Sheet (WAIS). Possible self-amplification process of WAIS discharge (schematic from Vaughan & Arthern (2007)). For regions in which the ice sheet is grounded below sea level ice flow across the grounding line (dashed vertical line) grows with ice thickness. If the bed is sloping down, ice discharge may self-accelerate.

Mechanism: Self-amplifying ice loss from West Antarctica Low temperatures in Antarctica inhibit ice-sheet melting and ice loss predominantly occurs (99%) through discharge across the so-called grounding line into ice shelves[1]. Ice shelves are floating ice masses of several hundred meters thickness which are subject to oceanic melting and refreezing, as well as calving into icebergs. Most bedrock beneath the WAIS is below current sea level. For such situations (figure 5), theoretical considerations suggest that ice flow through the grounding line increases with ice thickness (Weertman, 1974, Schoof, 2007b). Since bedrock is sloping down landward from the coastline in most of West Antarctica, this may lead to self-amplification: A retreat of the grounding line shifts its position towards regions of greater ice thickness. This enhances ice flow through the grounding line and yields a thinning of the still grounded ice which causes further retreat of the grounding line.

Assessment of tipping potential for West Antarctic Ice Sheet (WAIS) WAIS has collapsed at least once during the Quaternary, over the last 750 Kyrs. The most likely period for a collapse

1 The grounding line is the position at which land ice starts to float, i.e. at the grounding line the grounded ice sheet becomes floating ice shelf. Since the melting of floating ice does *not* raise sea level, it is the ice flow across the grounding line that matters for global sea level rise.

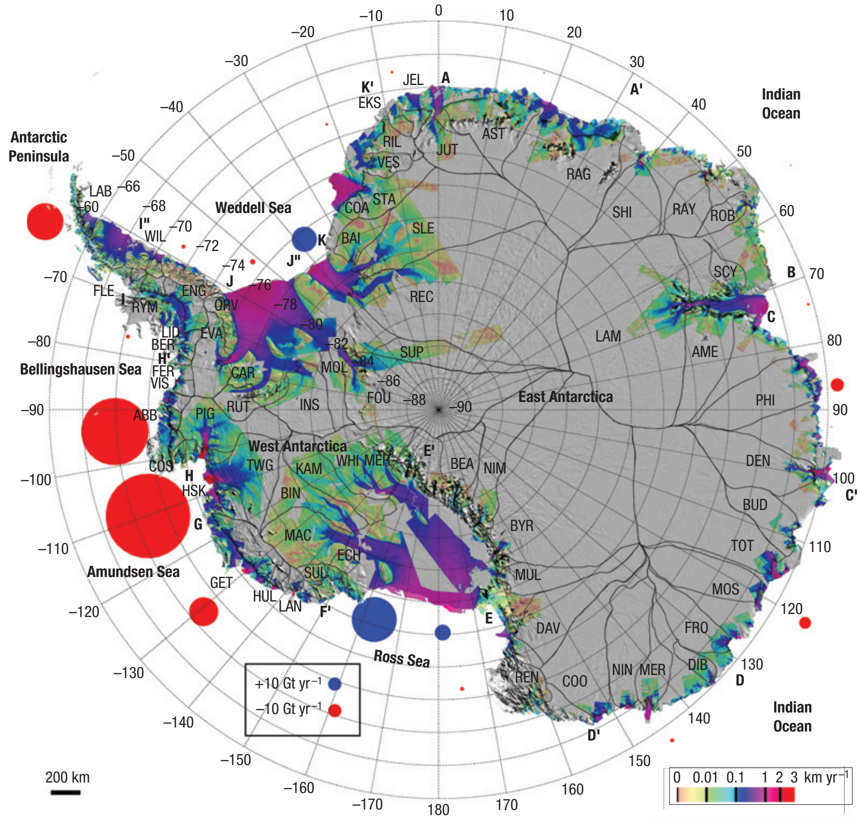

Figure 6 Ice discharge along the West Antarctic coast has increased by more than 50% in 10 years (Rignot *et al.*, 2008). Red dots indicate mass loss, blue dots mass gain.

is at 400 KyrBP during a particularly warm interglacial (Scherer *et al.*, 1998). Simulations in combination with paleo records suggest that a collapse took place several times during the last period of prolonged warming about 3 million years ago (Pollard & Deconto, 2009, Naish *et al.*, 2009). During these periods Antarctica, as a whole, contributed to global SLR by about 7m within a time interval of 1000-7000 years. For a complete collapse of the WAIS it would be necessary to largely remove the biggest ice shelves in Antarctic: the Filchner Ronne and Ross. These buttress much of the vulnerable inland ice and regional warming of $5°$C or more may be required to achieve this (Pollard & Deconto, 2009). A partial collapse or retreat of the WAIS is, however, also possible and recent observations from satellites support theoretical analysis of how this might occur (Rignot, 1998).

Recent observations in West Antarctica between 1992 and 1998 show a fast grounding-line retreat of the Pine Island Glacier of 1.2 ± 0.3 km (Rignot, 1998), and an equally rapid grounding-line retreat (1.4 ± 0.2 km) and mass loss of the Thwaites Glacier (Rignot, 2001, Rignot *et al.*, 2002) between 1992 and 1998 (figure 6). Dynamic thinning along ice margins has been observed for most of the West Antarctic coast line (Pritchard *et al.*, 2009) that is consistent with what would be expected in the case of grounding line instability. An integrated assessment of the risk of a WAIS collapse is currently not available. An estimate of a maximum contribution to global SLR from WAIS using the same approach as for GIS (Pfeffer *et al.*, 2008) is questionable since outlet glaciers are less constrained by topography in Antarctica compared to Greenland and thus discharge is potentially quicker than on Greenland.

3. Atlantic thermohaline circulation (THC)

Potential impact on Europe   The Atlantic thermohaline circulation (THC) is a large-scale ocean conveyor-belt circulation which transports about 1 PW $=10^{15}$W of heat towards the Nordic Seas (Ganachaud & Wunsch, 2000) and thereby contributes to milder winters in northern Europe compared to regions of similar latitudes in North America and Asia. Without this heat transport (figure 7) the Nordic Seas would be about $8°$C cooler, and northern Europe, depending on atmospheric conditions and latitude, would be several degrees cooler than at present (Vellinga & Wood, 2002). Europe would suffer from significant drying and reduced precipitation. Westerly winds would shift southward with reduced winds in the northern part and increased winds in the southern half of Europe (Laurian *et al.*, 2010). Furthermore, simulations suggest that a THC collapse would increase sea level around European coast lines by up to 1m (Levermann *et al.*, 2005). This regional contribution would add on to global SLR and could be ten times quicker than presently observed rates, depending on the rapidity of the oceanic circulation changes.

In addition to these regional changes, the global climate system would be significantly perturbed by a THC collapse. Oceanic uptake of heat and carbon dioxide would strongly decrease and thereby accelerate global warming. Atlantic ecosystems are likely to be disrupted (Schmittner, 2005, Kuhlbrodt *et al.*, 2009) and the tropical rain belt would shift by several hundred kilometres in the Atlantic sector affecting populated areas in West Africa and the Amazon rain forest (Stouffer *et al.*, 2006). Reconstructions of past climate suggest far reaching influences on the Asian monsoon system (Goswami *et al.*, 2006).

Mechanism: Self-amplified slow-down of THC   The Achilles heel of the THC is deep water formation in the North Atlantic which is an essential component of the circulation. The density of North Atlantic water determines the strength of deep water formation and thereby of the THC. In the North Atlantic densification occurs through heat loss and salinity inflow which is partly provided by the circulation itself through import from the south. An initial reduction of the circulation thus reduces salinity transport to the north and further weakens the circulation (Rahmstorf, 1996).

Assessment of THC tipping potential   There are three lines of scientific reasoning on which the risk of a THC collapse is based. First, if the THC does indeed transport salt to the North Atlantic, the associated self-amplification process is based on robust large-scale features of the circulation and it is likely to have a significant influence. Observational data suggest that the present-day THC does transport salt into the Atlantic basin (Rahmstorf, 1996, Weijer *et al.*, 1999).

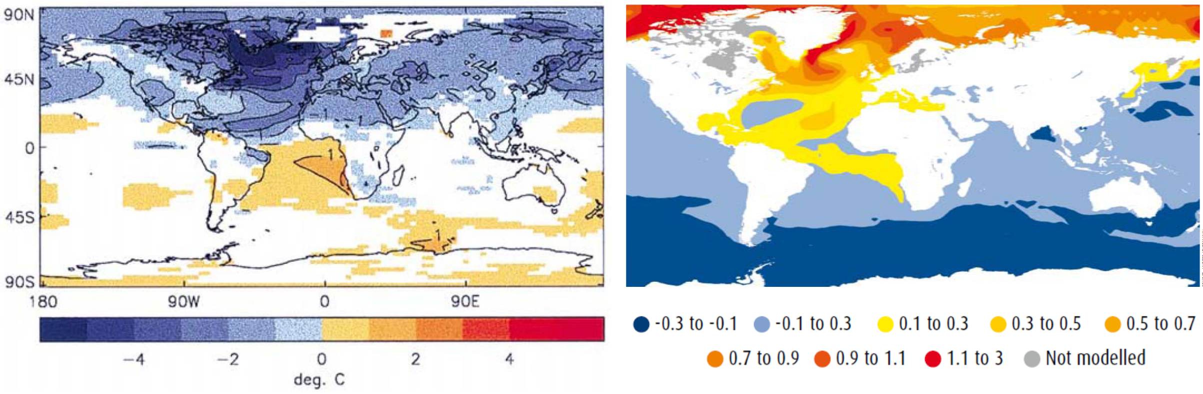

Figure 7 A collapse of the Atlantic Thermohaline Circulation (THC) would have severe global consequences. **Left:** Temperatures in the Nordic Seas would drop by up to 8°C. Depending on atmospheric transport this yields several degrees of cooling in Europe (figure from Vellinga & Wood (2002)). **Right:** In addition to global SLR due to warming, sea level would rise by up to 1m along the European and North American coast (figure from Levermann *et al.* (2005)).

Secondly, rapid reorganizations of the North Atlantic ocean circulation have occurred during the last glacial period (McManus *et al.*, 2004). These were associated with strong global climatic disruptions (Rahmstorf, 2002, Clark *et al.*, 2002) and occurred on decadal to centennial time scales. Freshwater fluxes that caused past circulation changes have been estimated (Ganopolski & Rahmstorf, 2001) to be of the order of expected melt water contributions from Greenland (Huybrechts *et al.*, 2004) and potential future changes in North Atlantic precipitation (Miller & Russell, 2000, Winguth *et al.*, 2005). It is, however, possible that stability properties of the Atlantic overturning are different under glacial and interglacial boundary conditions (Weber & Drijfhout, 2007). Thirdly, a variety of coupled climate models at different levels of complexity have shown abrupt THC collapse in response to systematically increased artificial Atlantic freshwater forcing (Rahmstorf *et al.*, 2005). More complex and thus computationally less efficient models which were used for the IPCC-AR4 future projections are not able to perform this kind of systematic analysis. In these models a less systematic approach has been taken in order to assess the stability properties of the THC (Stouffer *et al.*, 2006). Freshwater was externally applied for a period of one hundred years which forces a THC collapse. The cessation of the freshwater flux led to a resumption of the circulation in all of these models. Furthermore none of the IPCC-AR4 models show a THC cessation even for the strongest global warming scenarios (Gregory *et al.*, 2005). This results seems to hold even when taking GIS melt water inflow into account (Jungclaus *et al.*, 2006).

One needs to keep in mind that this does *not* prove that the models do not have two stable states. Neither is it certain that the models properly represent stability properties of the real ocean. In fact Weber *et al.* (2007) showed that while in the real ocean the THC transports salt into the Atlantic basin, this is not the case in all of these models. Thus state-of-the-art models seem to have a bias towards mono-stability. Under global warming scenarios, all IPCC AR4 models, for which salt and freshwater fluxes are available, show an increased salt import into the Atlantic, i.e. the modeled circulations are moving towards a potential critical threshold (Drijfhout *et al.*, 2010). An elicitation of experts on THC stability provided no clear picture on the risk of a future THC collapse. Subjective probabilities of different experts for triggering a breakdown within this century ranged from 0% - 90% (Zickfeld *et al.*, 2007). The IPCC AR4 assesses the probability of a THC collapse within this century to 10% (Jansen *et al.*, 2007).

4. Arctic sea ice

Potential impact on Europe   While global mean temperature has risen by about $0.7° \pm 0.1°$C during the last century, Arctic warming has locally been two to four times higher. This polar amplification has a number of causes one of which is melting Arctic sea ice and associated surface-albedo changes (van Oldenborgh *et al.*, 2009, Winton, 2006a). As a consequence, Europe has also warmed more than the global average - an effect that is going to persist under future increase of atmospheric greenhouse gas concentration (figure 8) and would accelerate during accelerated deglaciation of Arctic sea-ice cover. Although models do not provide a uniform picture, sea-ice retreat can influence the North Atlantic atmospheric pressure system and thereby the Atlantic storm track into Europe (Kattsov & Källén, 2004). Honda *et al.* (2009) have shown that strong reduction in Arctic summer sea-ice cover is associated with anomalously cold Eurasian winters. Furthermore, reduced sea-ice cover has profound impact on Arctic ecosystems. This includes marine mammals such as polar bears, seals, walrus and narwhales (Loeng, 2004). Strongly reduced sea-ice cover yields improved accessibility to the Arctic including access to potential resources of fossil fuels in the region. The US Geological Survey estimates that about 25% of global oil resources may be found in the Arctic. The estimates are highly uncertain and the error bars range from 0% to 60% (http://www.usgs.gov/). However, potential recovery of these reservoirs will have significant environmental and geo-political implications.

Mechanism: Self-amplification of northern sea-ice melt   Possible self-amplification of Arctic sea-ice melt could arise from the aforementioned ice-albedo feedback (figure 2), one of four fundamental climatic feedbacks discussed to be responsible for enhanced global warming in response to increasing greenhouse gas concentrations (Soden & Held, 2006). The mechanism for the ice–albedo feedback is simple to understand: An initial temperature increase in high northern latitudes leads to melting of sea ice. As a consequence, less of the dark ocean is covered by highly reflective ice and snow, which leads to more absorption of sunlight at Earth's surface. This in turn causes more local warming and hence more melting of ice and snow. This self-amplification is mainly relevant for the Arctic summer sea-ice cover, since high-latitudinal solar insolation is strongly reduced in winter and much of the extra ice lost in the summer can be regained in the winter.

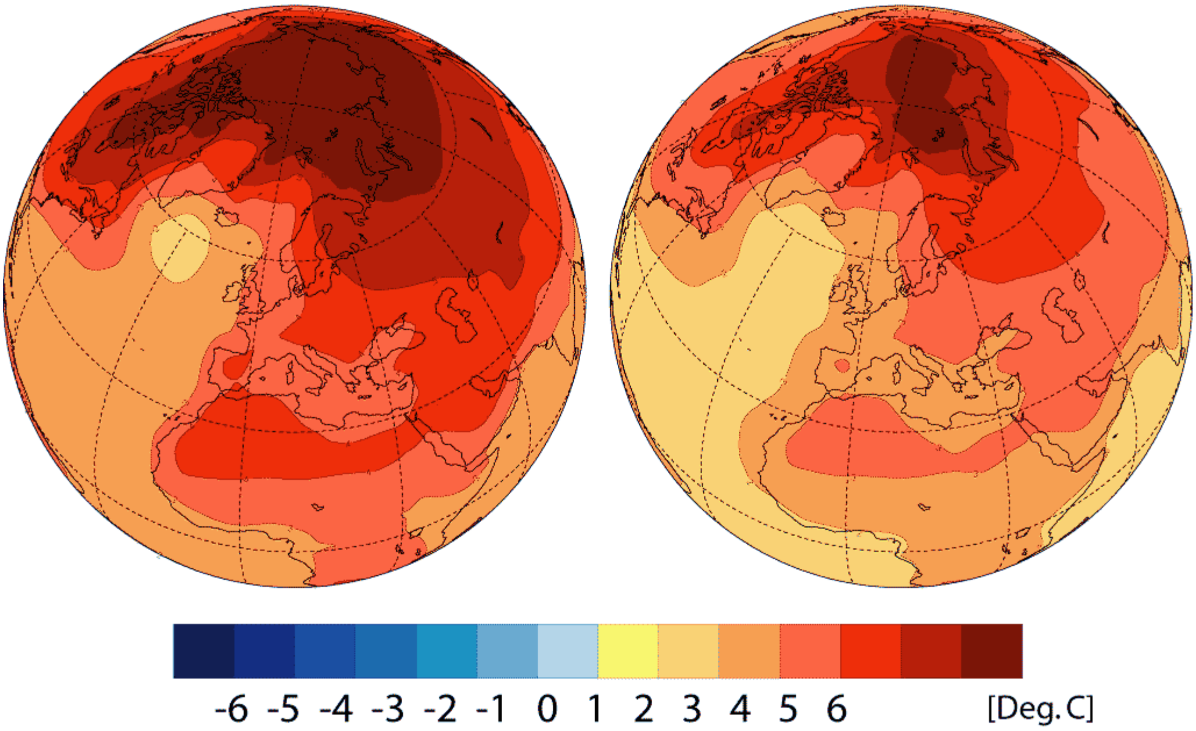

Figure 8 Polar warming amplification partially caused by sea-ice melting for two scenarios (A2 (left) and B1 (right)). Temperature anomaly patterns compared to present-day for the year 2070 were averaged over all models participating in the IPCC AR4 (Solomon *et al.*, 2007). (Visualisation: M. Boettinger, DKRZ, Hamburg, Germany)

Assessment of tipping potential for Arctic sea-ice cover   While all IPCC models agree that Arctic sea ice will decline in a warmer climate, these models do not show an irreversible or self-amplifying meltdown of Arctic summer sea ice (Winton, 2006b). Hence, any slow down or even reversal of global warming will have a corresponding effect on Arctic summer sea ice (Notz, 2009).

There are at least three factors which compensate the self-amplifying ice–albedo feedback and stabilise the Arctic sea ice cover such that its retreat is not self-amplified or irreversible: First, for a reduced summer sea-ice cover more open water is exposed to the atmosphere at the onset of winter. Because during winter ocean water is warmer than the surrounding sea ice, the ocean releases large amounts of heat to the atmosphere. In this way, the heat that has accumulated in the water in summer because of the ice–albedo feedback is released to the atmosphere during winter. Hence, the heat that accumulated in one summer is not carried over to the next summer (Tietsche *et al.*, 2010). Second, thin ice grows much faster than thicker ice also because of the rapid loss of heat. Hence, after an extreme summer minimum the rapid growth of thin ice in winter is a stabilizing feedback that counter-acts the destabilizing ice-albedo feedback. Again, this resets the sea-ice extent each year and thereby eliminates the tipping potential for Arctic summer sea ice (Eisenmann & Wettlaufer (2009); figure 9b). Third, in areas that become ice free during summer, the snow that falls at the onset of winter (when snowfall rates are highest) does not accumulate on the ice but simply falls into the water. Hence, snow thickness on the ice that forms late in the season will be greatly reduced. Since snow is a very efficient insulator, such reduced snow cover also allows the ice to recover somewhat during winter.

However, these stabilising feedbacks are only functioning as long as there is still significant ice formation during winter. In an even warmer climate with a much reduced sea-ice cover also during winter, a tipping point for the loss of winter sea ice might well exist. In such climate, Arctic winter sea ice vanishes abruptly and thereby constitutes a qualitatively different Tipping Element (figure 9b).

Notwithstanding the low probability for a formal "tipping" during the ongoing decline of Arctic summer sea ice, the Arctic sea ice is currently undergoing a significant transition both with respect to its areal extent and to its thickness. Satellite observations show a reduction in ice extent of almost 50% over the last 50 years (figure 9). Also ice thickness has reduced significantly in past decades (Haas *et al.*, 2008). Since variability in ice extent is very strong between years and is highly influenced by atmospheric pressure conditions and associated winds (Deser & Teng, 2008), it is difficult to assess whether the retreat of Arctic sea ice is currently accelerating. The situation is further complicated by the fact that the variability of Arctic sea ice extent is probably going to increase in a warming climate: As the mean ice thickness in the Arctic Ocean thins the summer extent is more subject to interannual variability in atmospheric conditions and we expect to see much larger negative and positive excursions from the mean downward trend in extent, such as that observed during the record sea-ice minimum in 2007 (Goosse *et al.*, 2009, Notz, 2009, Lindsay *et al.*, 2009).

During that record summer, minimum sea-ice extent dropped by about 23% compared to the previous record in 2005. Though this decline was caused by anomalous atmospheric and ocean conditions which can not directly be attributed to global warming (Kay *et al.*, 2008, Perovich *et al.*, 2008, Zhang *et al.*, 2008, Ogi *et al.*, 2008, Lindsay *et al.*, 2009), the ice in the basin was also preconditioned to be quite thin due to both anomalous wind patterns in previous years and warming winters (Lindsay *et al.*, 2009). The anomalous wind patterns, particularly in the early 1990's, caused much of the older ice in the basin to be exported through Fram Strait so that the area covered by multiyear ice is now much smaller than in previous years and the average age of the ice is younger and the mean thickness is thinner (?). While ice that is less than one year old rarely exceeds 2m thickness, older ice grows to an average of about 3m thickness. Since a number of processes such as ice dynamics and ice transport through winds and ocean currents complicate the picture, current climate models have difficulties in capturing summer sea-ice evolution. Currently observed decline in Arctic sea-ice cover (figure 9) is stronger than simulated by any climate model that took part in the latest IPCC intercomparison (Stroeve *et al.*, 2007). This shortcoming of the models is probably caused by a combination of very large internal variability of Arctic sea-ice extent that can lead to extreme minima and a lack of understanding of some underlying processes that are responsible for the recent sea-ice retreat. Since then models have improved and some capture sea-ice decline more satisfactorily. Projections are highly

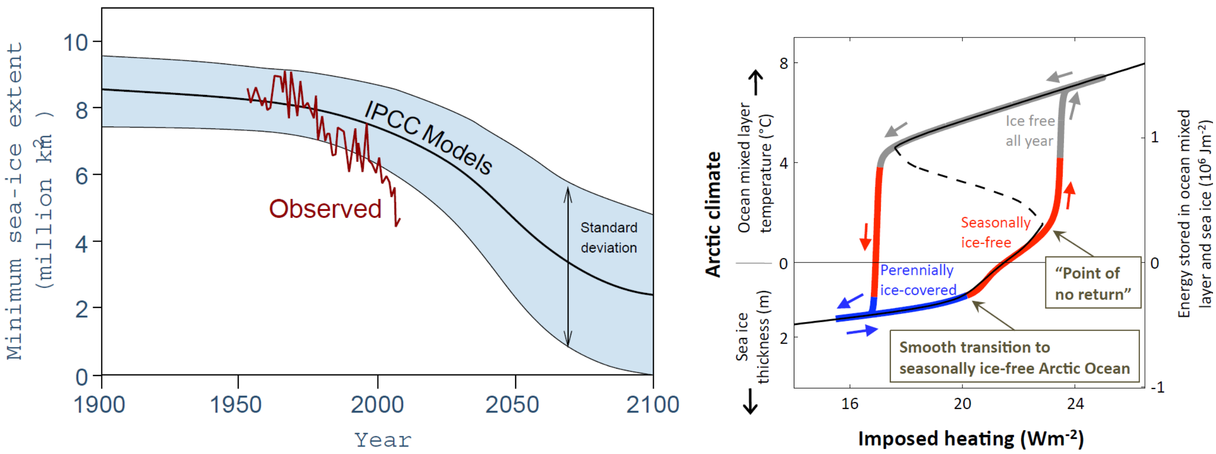

Figure 9 **Left**: Observed decline in minimum Arctic sea-ice cover typically reached in mid-September of each year (red line, in million square kilometres). The year 2007 showed an anomalously strong reduction of ∼23% compared to the previous record in 2005. 2008 exhibited a mild recovery, but 2009 summer sea-ice extent was back on the previous trend before 2007. IPCC model simulations of 2007 (shading) strongly underestimated (currently observed) sea-ice decline (after (Stroeve *et al.*, 2007)). **Right**: Evolution of Arctic sea ice in response to warming simulated with an idealized physical model (Eisenmann & Wettlaufer, 2009). The vertical axis represents the annual mean state of the upper ocean in terms of how much energy it would take to get to this point from an ice-free ocean that is at the freezing point. Initially (bottom left) there is a perennial sea-ice cover (blue curve) with an annual mean thickness of about 1.5 meters. A transition to seasonally-ice free conditions (red curve) occurs in response to warming. At this point, cooling the climate would cause the ice cover to grow back to its original thickness. Further warming, however, causes the system to cross a point of no return and undergo a rapid transition to conditions which are ice-free throughout the year (gray curve). This transition represents an "irreversible process": considerable cooling would be required to get the ice to grow again (arrows to left along upper branch of the hysteresis loop). The stable and unstable steady-state solutions are indicated by the solid and dashed black curves, respectively.

dependent on the greenhouse gas emission scenario. Under unmitigated climate change[1] Holland *et al.* (2006) project an abrupt decline of Arctic summer sea ice starting around 2040 with a complete melting in 2050. This result is supported by Smedsrud *et al.* (2008) using a different model. While model studies suggest that Arctic summer sea ice will vanish at an additional global warming of $1-2$°C, winter sea-ice cover is not likely to be eliminated for a warming of less than 5°C.

1 That is, greenhouse gas emissions follow the so-called business-as-usual scenario, A2, of the IPCC Special Report on Emissions Scenarios (SRES).

5. Alpine glaciers

Potential impact on Europe   In concert with mountain glaciers world-wide (figure 10), glaciers in Europe have retreated considerably over the last 150 years (Braithwaite & Raper, 2002, Oerlemans, 2005, Kaser *et al.*, 2006, Zemp *et al.*, 2008, Cogley, 2009). According to most recent estimates the ice volume of glaciers in the European Alps has been reduced from about 200-300 km^3 in the year 1850 to 90 $\pm$ 30 km^3 at present (Haeberli *et al.*, 2007, Farinotti *et al.*, 2009). Shrinkage of Alpine glaciers and snow cover is reducing surface reflectivity and thus leads to amplified temperature increase in the region. In combination with a generally enhanced continental warming this contributed to the anomalously strong Alpine warming which was about twice as high as the global average with significant acceleration in recent years (Auer *et al.*, 2006).

Glaciers are the symbol for a healthy mountain environment. Their retreat thus receives a high public interest, and will have strong impacts on tourism in Europe (Beniston, 2003). Since mountain glaciers and Alpine snow cover serve as freshwater reservoirs over seasonal to decadal time scales, glacier wastage will affect water availability in the region, in particular during summer. Through reduced run-off into large rivers such as Rhine and Rhone downstream regions will be affected. A change in hydrological regime is a robust feature of future projections for the European Alps (Eckhardt & Ulbrich, 2005, Zwierl & Bugmann, 2005) and is therefore expected by the IPCC 2007 assessment report (Kundzewicz *et al.*, 2007).

Generally it is observed that seasonality of run-off into rivers has increased. That is, stronger flow has been observed in the peak flow season and reduced flow or even drought in the low-flow season (Arnell, 2004). Initially, snow melt and associated glacier retreat is projected to enhance summer flow from the Alps into European rivers. When snow cover and glaciers shrink, however, summer flow is projected to be strongly reduced (Hock *et al.*, 2005, Huss *et al.*, 2008b). Consequently, strong impacts on hydropower production in Europe are expected (Schaefli *et al.*, 2007). In addition, thawing of Alpine permafrost will destabilize the ground and result in land slides and debris flows that have been increasingly observed in recent years (Gruber & Haeberli, 2007). Although thawing of permafrost is generally a slow process, strong 20th century warming in the Alps has already induced a pronounced thermal anomaly down to about 50-70m below the surface (Harris *et al.*, 2009, Noetzli & Gruber, 2009). During the last century melting of mountain glaciers worldwide contributed to about 25% of the observed global sea level rise (Oerlemans *et al.*, 2007). Over the next decades it is expected to contribute significantly although only about 0.5 m of global SLR equivalent remain in mountain glaciers (Meier *et al.*, 2007). The Alpine contribution is however small compared to other sources like glaciers in Alaska, Patagonia and central Asia.

Self-amplification of Alpine glacier melt   Several positive feedback mechanisms amplify the rate of Alpine glacier retreat: The reduction in snow- and ice covered area induces increased regional warming and ice melt through the ice-albedo feedback illustrated in figure 2 (Paul *et al.*, 2005). Furthermore, enhanced dust accumulation on the bare ice has significantly decreased surface albedo leading to accelerated ice melt (Oerlemans *et al.*, 2009). Over the last decades a

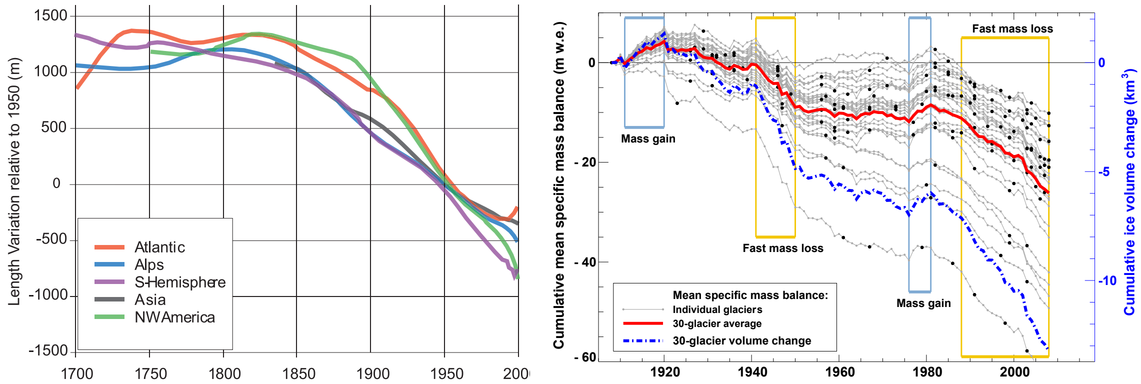

Figure 10 **Left panel**: Mountain glaciers are retreating globally. Large-scale regional mean length variations of glacier tongues (Oerlemans, 2005). (Figure from IPCC fourth assessment report (Solomon *et al.*, 2007) chapter 4, p. 357., data from various sources (reconstructions, long-term observations) extrapolated to large regions). **Right panel**: Cumulative mean specific mass balance of 30 Swiss glaciers and their total cumulative volume change in the 20th century. Series for the individual glaciers are shown in grey. The solid red line represents the arithmetic average, and the dash-dotted blue line the cumulative total volume change of the 30 glaciers. Two short periods with mass gain and two periods with fast mass loss are marked. Figure from (Huss *et al.*, 2010). The volume loss, indicated in blue, is calculated from a multiplication of thickness and area losses.

prolongation of the melting season by one month has been inferred for glaciers in the European Alps, and the fraction of precipitation in the form of snow has decreased by more than 10% (Huss *et al.*, 2009). Both processes have significant negative effects on glacier mass balance. The rapid changes in the climate system furthermore induce processes of down wasting of glacier tongues and collapse rather than "active" glacier retreat. This involves the disintegration of glacier systems into small individual parts, subglacial melting out of large cavities and lake formation. The protective effect of increasingly debris covered glacier tongues cannot compensate for the above mentioned positive feedback mechanisms.

Assessment of tipping potential for Alpine glacier melt Over the last century glaciers in the European Alps experienced an average annual ice thickness loss of 0.2 to 0.6 m, the best estimate for the century average mass balance being -0.25 to -0.35 m water equivalent per year (Haeberli & Hoelzle, 1995, Vincent, 2002, Hoelzle *et al.*, 2003). Strong variability in time and space can be documented (Huss *et al.*, 2008a, Paul & Haeberli, 2008): Fast glacier mass loss comparable to present-day rates has already taken place in the 1940s and time periods of slightly positive mass balances with intermittent glacier readvance are documented for the 1890s, the 1920s and the 1970/80s (Figure 10b). The year 2003 showed exceptional mass loss with a decrease in mean ice thickness of almost 3 meters over the nine measured Alpine glaciers. This rate was four times higher than the mean between 1980 and 2001 and exceeded the previous record of the year 1996 by almost 60% (Zemp *et al.*, 2009).

Glaciers in the Alps probably lost about half their total volume (roughly -0.5% per year) between 1850 and 1975. Roughly another 10% (20 - 25% of the remaining amount) may have vanished between 1975 and 2000 (updated after Haeberli *et al.* (2007)) and again within the first decade (2000 - 2009) of our century (corresponding now to about -2% per year of the remaining volume). The melting out of the Oetztal iceman in 1991 clearly demonstrated to a worldwide public that conditions in the Alps have reached if not exceeded the "warm" or "energy-rich" limits of glacier and climate variability during many thousands of years before (Solomina *et al.*, 2008).

Simulations of Alpine glacier extent over the 21st century using different model approaches indicate unequivocally that an increase in global mean air temperature of 2°C (corresponding to +3-4°C locally) leads to an almost complete loss of glacier ice volume in the Alps (Zemp *et al.*, 2006, Le Meur *et al.*, 2007, Jouvet *et al.*, 2009). Whereas small glaciers are expected to disappear in the next few decades, considerable amounts of "left-over" ice from large glaciers will persist throughout the 21st century due to thick ice bodies originating from colder conditions.

Mountain glaciers are highly sensitive to small changes in air temperature and precipitation and are thus excellent indicators for climate change. Their reaction to a temperature increase is almost linear and no clear tipping point can be detected. However, many Alpine glaciers currently experience accelerated wastage due to the various positive feedbacks in the system. Potential re-growth of Alpine glaciers would require decades of cooler and wetter conditions. Near-complete deglaciation of the Alps during this century could only be avoided by strong mitigation efforts. A global limit of two degree temperature increase might not be sufficient to accomplish this goal.

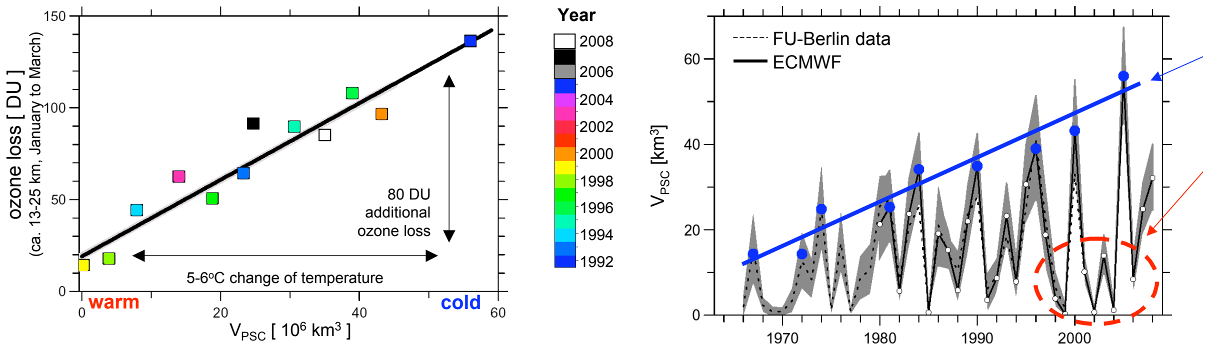

Figure 11 Polar stratospheric clouds (PSC) **Left**: PSC enhance stratospheric ozone loss (Harris *et al.*, 2008) **Right**: Volume of PSC increases under global stratospheric cooling (Rex *et al.*, 2004).

6. Arctic ozone depletion

Potential impact on Europe Stratospheric ozone is blocking **ultra-violet (UV)** solar radiation, especially UV-B radiation which is particularly harmful for human skin. The stratospheric ozone layer therefore provides protection against dermatological diseases, corneal and DNA damage. Ozone depletion especially above populated areas may enhance the risk of skin cancer and may cause immune suppression. Due to the generally very low UV-radiation in high latitudes a UV-increase has profound influence on society and ecosystems in the Arctic. The marine food chain is affected through UV-sensitivity of surface layer algae. Due to a very stable atmospheric polar vortex over Antarctica, ozone depletion in response to anthropogenic emissions has been observed in the southern hemisphere for several decades. In contrast the Arctic vortex is less stable than over Antarctica, owing to hemispheric circulation patterns. However, for most years since 1992, ozone depletion has been observed also in the Arctic - locally up to 70% below normal [Boreal winter 1999/2000 (Rex *et al.*, 2002)]. Substantial reduction in ozone levels can be observed up to mid-latitudes ($35°$N) of southern Europe.

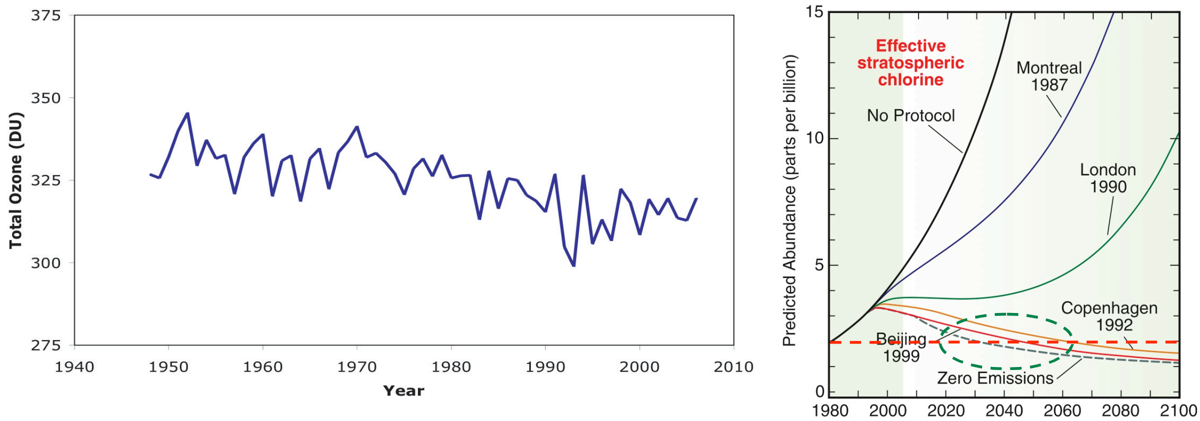

Figure 12 **Left**: Artic ozone depletion reaches far into Europe: Time series of annual mean values of total ozone abundance in Arosa, Switzerland ($\sim 45°$N, figure from WMO (2007)). **Right**: Projected effective abundance of stratospheric chlorine in response to international treaties. The observed abundance closely follows the projected one, i.e. the line of zero-emissions will be crossed around 2030 after which Arctic ozone ceases to be a *Tipping Element*.

Mechanism: Self-amplifying northern ozone depletion   Low stratospheric temperatures support the formation of **Polar stratospheric clouds (PSC)** which generally enhance ozone depletion due to chemical reactions at their surface (figure 11). A strengthening of the polar vortex and associated cooler stratospheric temperatures lead to ozone depletion which further cools the stratosphere (e.g. Weatherhead *et al.* (2004)).

Assessment of tipping potential for Arctic ozone depletion   The main driver for upper stratospheric ozone loss and for spring losses in the polar stratosphere is the chemistry associated with chlorine and bromine (Solomon, 1999). Associated chemical reactions are strongly influenced by human emissions of CFCs which have been banned with the Montreal protocol in 1987. As a consequence northern hemisphere stratospheric ozone has shown a decline from late 1970s to mid 1990s (figure 12). Since then no clear trend is detectable.

Interannual variability is particularly strong in the Arctic. This is mainly due to a less stable polar vortex compared to the southern hemisphere and shows the influence of stratospheric dynamics on the ozone layer in the northern hemisphere. Stratospheric dynamics, including stability, strength and temperature of the polar vortex, determines the onset of ozone depletion and also influences the rate and severity of the depletion processes. Global warming of Earth's surface is associated with cooling in the stratosphere which enhances polar ozone depletion. The accumulation of greenhouse gases in the troposphere (<~10 km altitude) warms Earth's surface but cools the stratosphere.

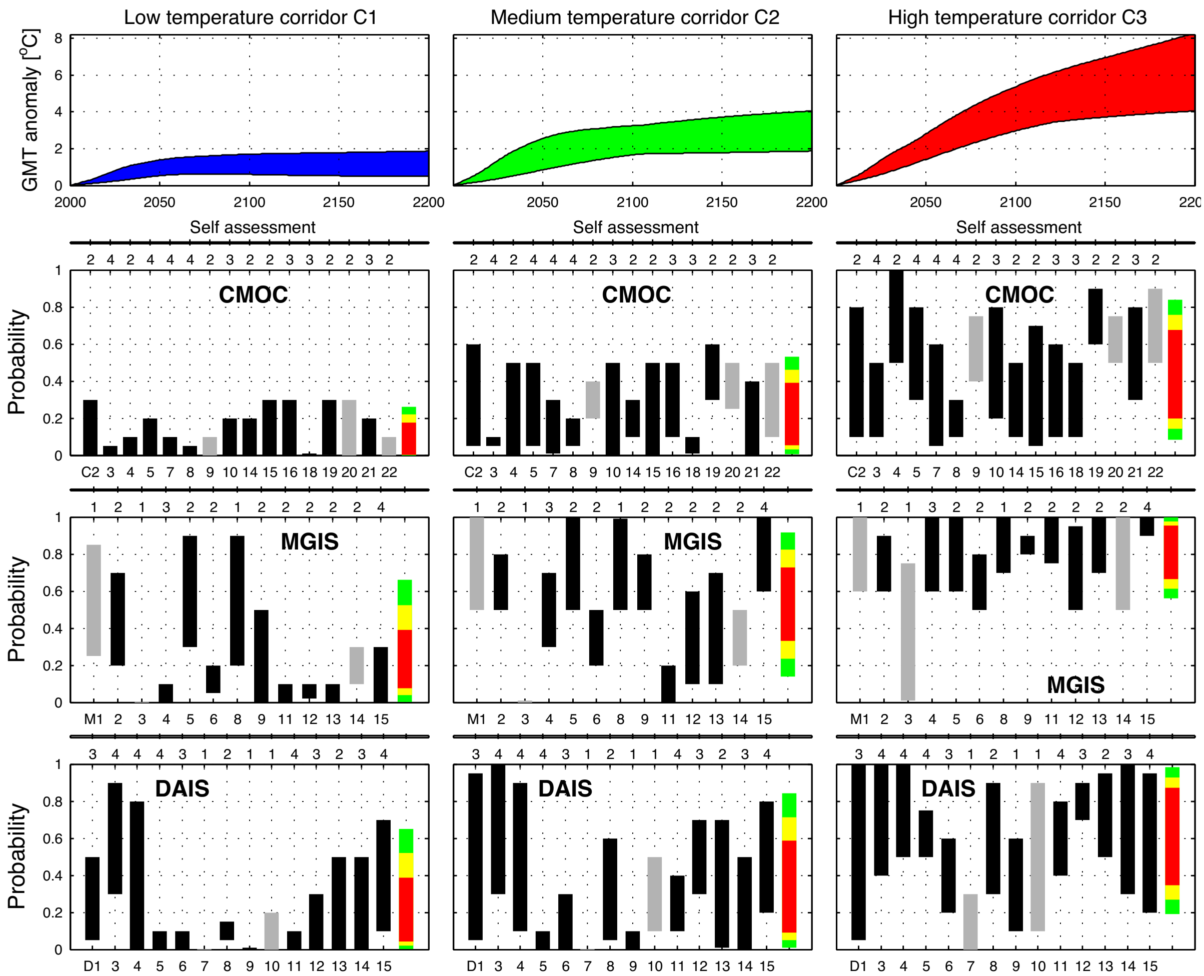

Figure 13 Subjective probabilities provided by experts for the tipping of THC (denoted CMOC), GIS (denoted MGIS) and WAIS (denoted DAIS). The x-axis provides the number of the expert. Coloured bars represent a *core group* of experts for each Tipping Element which are actively publishing on the subject. The upper panel row provides the corresponding climate scenarios as represented by the evolution of the global mean temperature (GMT) during the 21^{st} and 22^{nd} century. High emission scenarios (right panels) yield probabilities predominately above 50% for each system and even for low warming scenarios (left panels) the elicited tipping potentials are not negligible. For details confer (Kriegler *et al.*, 2009).

In the Arctic, this cooling is likely to lead to increased ozone destruction, as lower temperatures result in the formation and persistence of PSCs which aid in the activation of ozone-depleting compounds and can therefore accelerate ozone depletion. The Arctic Climate Impact Assessment of 2004 thus drew the conclusion that such cooling may induce self-amplification through the stabilization of the polar vortex (Weatherhead *et al.*, 2004). Stratospheric cooling resulting from climate change is therefore likely to lead to an increased probability of larger and longer-lasting ozone holes in the Antarctic and extensive, more severe ozone losses over the Arctic (Dameris *et al.*, 1998). In an analysis of approximately 2000 ozone-sonde measurements, Rex *et al.* (2004) found that each 1°C cooling of the Arctic stratosphere resulted in an additional 15 DU[1] of chemical ozone loss due to increased PSC volume. Their findings indicate that over the past four decades, the potential for the formation of PSCs increased by a factor of three, resulting in stratospheric conditions that have become significantly more favourable for large Arctic ozone losses.

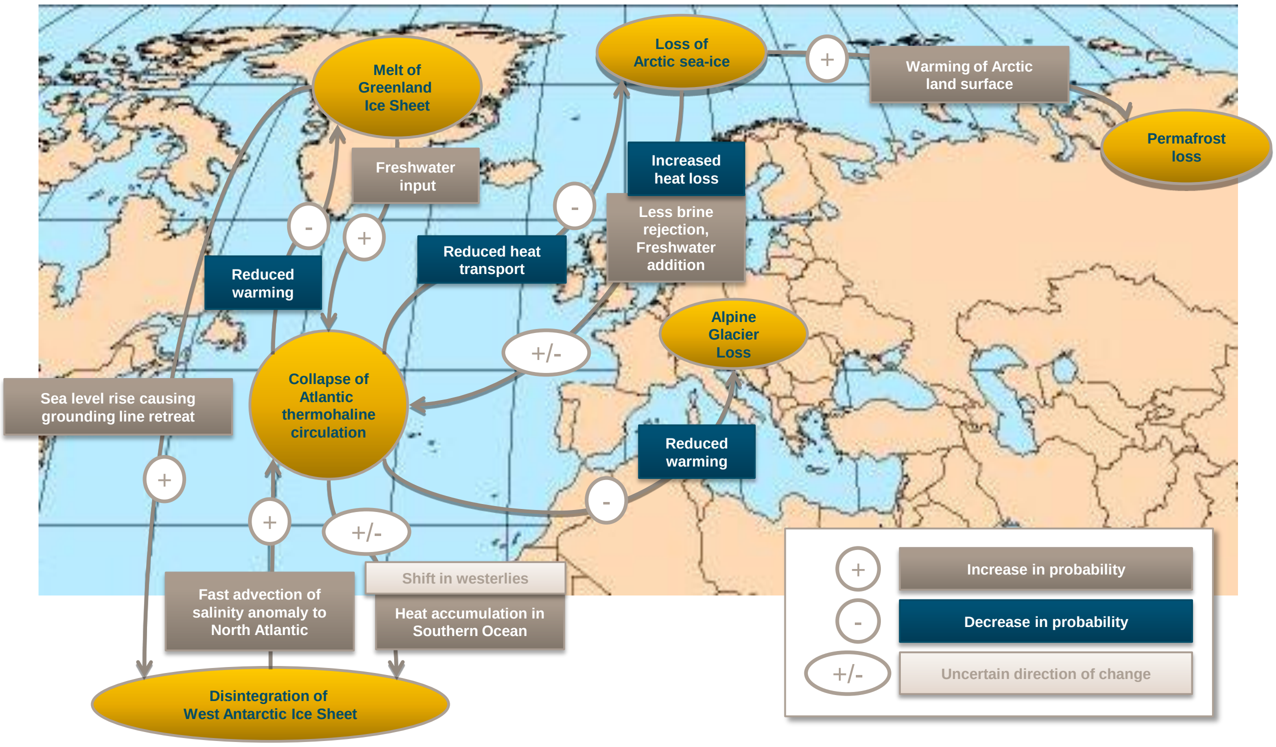

Figure 14 Potential interlinkages between Tipping Elements.

The situation is complicated through other radiative effects that influence the ozone budget of the stratosphere. One is a potential increase in stratospheric water vapour due to changes in tropopause temperatures (Evans *et al.*, 1998). Increased water vapour is likely to contribute to increased ozone destruction by affecting the radiation balance of the stratosphere (Forster

1 DU=Dobson unit measures atmospheric ozone content. 1 DU corresponds to 0.01mm ozone layer thickness under standard conditions of 0°C and 1 atm. pressure.

& Shine, 2002, Shindell, 2001). Greater water vapour concentrations in the stratosphere can raise the threshold temperatures for activating heterogeneous chemical reactions on PSCs, and can cause a decrease in the temperature of the polar vortex (Kirk-Davidoff *et al.*, 1999). Few long-term datasets of water vapour concentrations are available, but previous studies of existing observations have suggested that stratospheric water vapour has been increasing up to 1999 (Oltmans & Hofmann, 1995). Analyses of 45 years of data (1954-2000) by Rosenlof *et al.* (2001) found a 1% per year increase in stratospheric water vapour concentrations. Since 1999 there is no evidence for an increasing trend (Jones *et al.*, 2009, Randel *et al.*, 2004) while an overall decrease is observed which feeds back onto the tropospheric temperatures temporarily decelerating the global warming trend (Solomon *et al.*, 2010).

On the other hand, climate change could possibly trigger an increase in planetary waves, enhancing the transport of warm, ozone-rich air to the Arctic (Schnadt *et al.*, 2002). This increased transport would counter the effects of heterogeneous chemistry and possibly accelerate recovery of the ozone layer. Recently Tegtmeier *et al.* (2008) showed that dynamical transport of ozone into the Arctic polar vortex in the past has contributed equally strong to interannual variability as variations in chemical ozone loss. It is currently not possible to make definite statements about the tipping point in the chemical destruction of Arctic ozone. If the emission of ozone-reducing chemicals is reduced in the future following the signed treaties, then the specific risk of a tipping of the Arctic ozone will become insignificant between 2030 and 2060 (figure 12). After that, unabated global warming, however, may lead to qualitative changes in atmospheric circulation patterns associated with the polar vortex. Since the lower stratospheric wintertime circulation can strongly influence the probability of extreme surface weather such as minimum daily temperatures in Europe (Scaife *et al.*, 2008), these circulation pattern changes have the potential to exhibit Tipping-Element-like behaviour in a statistical sense.

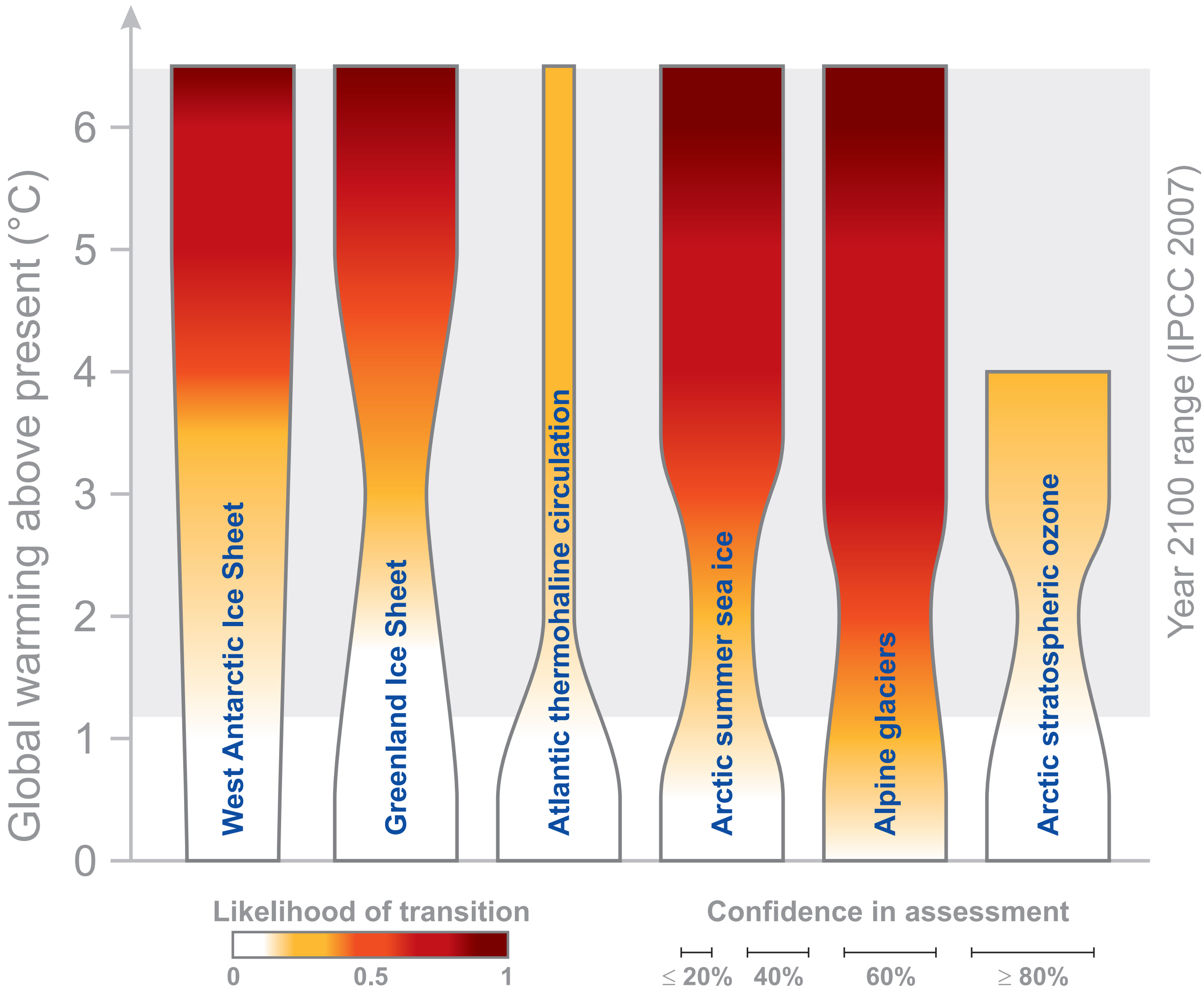

Figure 15 General assessment of tipping potential systems discussed in this paper. Color coding represents the authors assessment of the likelihood of tipping for different global temperature increase. The width of the column represents the authors' confidence in their assessment. For all systems the risk of tipping increases with temperature along with the confidence in such an assessment. A potential collapse of the Atlantic thermohaline circulation depends on the freshwater inflow into the North Atlantic which is only indirectly related to the global mean temperature increase through Greenland melting and precipitation changes. Especially because of uncertainty with respect to future precipitation changes, confidence in the tipping potential for the THC does not increase with temperature. The risk of a Tipping Point in Arctic ozone depletion will become insignificant when chlorine levels drop below 1980 levels which will occur by 2060.

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