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Managing Climate Risk

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Abstract

At the heart of the traditional approach to strategy in the climate change dilemma lies the assumption that the global community, by applying a set of powerful analytical tools, can predict the future of climate change accurately enough to choose a clear strategic direction for it. We claim that this approach might involve underestimating uncertainty in order to lay out a vision of future events sufficiently precise to be captured in a discounted cost flow analysis in integrated assessment models. However, since the future of climate change is truly uncertain, this approach might at best be marginally helpful and at worst downright dangerous: underestimating uncertainty can lead to strategies that do not defend the world against unexpected and sometimes even catastrophic threats. Another danger lies on the other extreme: if the global community can not find a strategy that works under traditional analysis or if uncertainties are too large that clear messages are absent, they may abandon the analytical rigor of their planning process altogether and base their decisions on good instinct and consensus of some future process that is easy to agree upon.

In this paper, we try to outline a system to derive strategic decisions under uncertainty for the climate change dilemma. What follows is a framework for determining the level of uncertainty surrounding strategic decisions and for tailoring strategy to that uncertainty.

Our core argument is that a robust strategy towards climate change involves the building of a technological portfolio of mitigation and adaptation measures that includes sufficient opposite technological positions to the underlying baseline emission scenarios given the uncertainties of the entire physical and socioeconomic system in place. In the case of mitigation, opposite technological positions with the highest leverage are particular types of sinks. A robust climate risk management portfolio can only work when the opposite technological positions are readily available when needed and therefore they have to be prepared in advance. It is precisely the flexibility of these technological options which has to be quantified under the perspective of the uncertain nature of the underlying system and compared to the cost of creating these options, rather than comparing their cost with expected losses in a net present value type analysis. We conclude that climate policy — especially under the consideration of the precautionary principle — would look much different if uncertainties would be taken explicitly into account.

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1 Introduction

Global environmental risks are becoming increasingly important as the world is globalizing and as the accumulation of local human interventions in nature are becoming measurable on global scales and start to threaten stable development pathways for human societies and natural ecosystems. As globalization of commercial and political markets, overpopulation, new technological opportunities, and large scale environmental threats raise levels of uncertainty and rewrite definitions of sustainability and risks, the basic strategic choice of the global community has morphed into a more complex and high-stakes dilemma. Wrong strategic bets, whether intentional or unintentional, of the global community carry an increasingly higher risk than ever before.

Anthropogenic emissions of greenhouse gases (GHGs) account for a considerable amount of the net exchange between the geochemical pools and have already affected many physical and biological systems (IPCC, 2001c), while the global community is working hard on international processes to deal with the problem of global climate change. It has been recognized that humanity's transformation of the earth has increased the concentration of GHGs, thereby altering the earth's climate (IPCC, 2001a). The drivers and the potential consequences of climate change are interwoven with a huge variety of bio-geophysical and human-caused processes that complicate the analysis and possible implementation paths of policies designed to mitigate and adapt to climate change.

With respect to climate change, betting big today may, due to technological path-dependencies and long time-lags of global warming, fundamentally reshape our common future on a global scale to our advantage or quickly produce losses that can throw mankind into economic, social, and environmental bankruptcy. The global community may avoid foolhardy mistakes by waiting for climate change uncertainty to diminish, or it may squander the chance to lay claim to early mover advantage and lay the foundation of a wider global development risk scheme — making development not necessarily sustainable, but at least less volatile. The truth is that effectively, there is no dominant strategy as global governance is too weak and as the science of climate change and of its drivers is too complex to distill clear future signals that would press policy makers to take on more responsible commitments.

As our economic structure is based on a market system using costs, prices, and profits to resource allocation, strategy building both on the micro-level of firms all the way to problems of global governance has to be appraised within an analytical framework of a market system. In fact, it is through the market system's ability to deal with uncertainties of all kinds, that developed countries have managed so well, at the least cost, to allocate resources among myriads of possible and competing stakeholders. However, when it comes to environmental assets we have no semi-automatic controls or invisible hands analogous to those regulating production and consumption of markets of products and services. Indeed, here the system often works in reverse. Striving for the least cost for themselves, powerful stakeholder alliances use resources in ways that might impose the greatest cost on society in the long run. In this way, the market economy is a reasonably satisfactory organizing principle for allocating resources in production, but it does not help us and often hinders us in dealing with environmental assets and undesirable joint products if the economic incentives are not conducive. The number of success stories of preventive environmental policy regimes is very limited. Historically, we have observed that preventive policies have emerged after the perception of an 'environmental' catastrophe. In the case of climate change, such *ex post* learning bears a lot of risks. Symptomatic is that there is still little understanding and consensus on sustainable long-term management plans for the common good climate. In addition, there has been little capacity building in terms of human capital and technology that would allow for a pro-active global climate management scheme. It is the purpose of this paper to try to outline some of the main issues for a sound and robust climate risk management scheme that allows for a preventive organizing principle for allocating climate change related resources in a least cost way given an uncertain market and complex behavioral pattern of the environment.

2 Stabilization is the Dominant Thought Experiment So Far

The essential starting point of developing strategies coping with climate change is understanding the alternatives. Currently, one alternative has been extensively researched — stabilization of GHG in the atmosphere. There seems to be consensus among scientific and policy communities that stabilization of atmospheric GHG concentrations at a particular non-dangerous level is a viable strategy. In particular, the United Nations Convention on Climate Change (UNFCCC) considers as its ultimate objective, to stabilize GHG concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. This is a paradigm that needs to be challenged, because stabilization is a static concept that is in contradiction with the dynamic nature of the underlying climate system. This does not mean that we should not have a target — setting a target is important! The key point is that the validity of any target is uncertain and may have to be revised. For this reason, a regime to reduce total radiative forcing by negative emissions is necessary.

Stabilization at a target level is a non-robust strategy in an environment that is extremely uncertain and most likely nonlinear. Currently, it is impossible to judge how far-reaching the possible impacts of climate change are and how many avenues there are for compensation. The application of a trial-and-error principle that has, until now, dominated international institutions could lead to errors with global consequences that exceed the acceptable level. Given these insights, the more important a risk policy centered on precautionary measures becomes in order to prevent global disasters as far as possible (WBGU, 2000). The stabilization concept implicitly assumes no or little risk associated with a target level. However, it is impossible to safeguard against all global risks and their interdependence as well as their path dependency, particularly as opportunities will always entail risks. A supposedly no risk policy along the lines of the stabilization concept might turn out to be the highest risk of all if, for example, unforeseen interactions of GHG induced warming with the cyclical behavior of the climate pattern trigger a self-reinforcing climate regime, which could have been avoided if GHG concentrations were controllable downward. The static stabilization paradigm is based on a number of assumptions that are worth mentioning.

- ***Possibility of correct determination of safe atmospheric GHG concentrations ex ante***

  Imagine what would happen if stabilization would embark on a level that *ex post* is found to be excessively 'dangerous'. If the monsoon changes, the El Niño amplitude dramatically increases, the thermohaline circulation weakens, sea level rises at unanticipated rates or droughts in impoverished semi-arid zones lead to social unrest where entire societies might be in danger of being trapped on a non-sustainable development path. Even if such a scenario has a low probability of occurring, timely counter strategies to hedge for such low-probability events are essential for sustainable development. It is highly unlikely that science and policy makers would be capable of determining one correct target level *ex ante* and stabilize at this level due to uncertainties and knowledge gaps. For instance, critical parameters linking the GHG concentration in the atmosphere and the long-term behavior of the global climate system, as well as feedback mechanisms between other critical drivers, will continue to be insufficiently understood until the higher order dynamics (non-linearities) of the GHG concentration-climate relationship can be sufficiently assessed. An important feedback mechanism that is highly uncertain is the response of natural ecosystems like forests to increased climate variability and climate change. While El Niño events that are associated with high temperatures and droughts in many tropical regions, if they increase in frequency, may turn tropical regions into carbon sources, longer growing seasons in the boreal zone might lead to more standing stocks of carbon in forests (Royal Society, 2001). However, such sinks can be offset by the release of soil carbon caused by, e.g., thawing of permafrost (Goulden *et al*., 1998).

- ***Organizational possibility of incentive compatibility***

  Secondly, in addition to organizational impossibilities due to institutional inertia, the current incentive structures provided by international and national policies are not conducive to control the global climate in an anticipatory responsive manner. The issues of free riding and free viewing in managing the common pool resource climate will continue to produce incentives that produce under-commitment in particular because damages are lagged and perceived as distant expectations. Defection of some Parties could then lead to unexpected deviations from the baseline emission path and consequently excessive GHG levels in the atmosphere.

- ***Heterogeneity in impacts and GHG concentration targets***

  Thirdly, there is no universal level of GHG concentrations that globally allows all ecosystems to adapt naturally to climate change, ensures that food production is not threatened, and enables economic development to proceed in a sustainable manner. At least there are several such levels for each system identified by the UNFCCC and within each system there is large geographic variability. Scientific knowledge on the critical loads of climate change and its resulting impacts is too limited to allow for static *ex ante* determination of GHG targets.

- ***Feasibility of inter-generational fairness***

  Fourth, in addition to the perceptions of danger and welfare associated with climate patterns their underlying drivers are also subject to change (e.g., catastrophic rare events). Therefore, our current decisions should not lead to irreversibility. The resilience of the climate systems — to the extent it is controllable by managing GHG concentrations in the atmosphere — should still be sufficient to allow future generations to improve climate patterns if they put a higher value on climatic conditions. If the state of the environment is to be compromised over generations, at least the option of improving the state should be reserved at a reasonable cost. Thus, intergenerational equity can be defined by two factors, one being the actual state of the future climate and overall wealth that is handed over to the subsequent generation, and the other being the option value to improve the climate or its effects.

- ***Presence of technological and economic constraints***

  Finally, there might be techno-economical impossibilities to mitigation in our economies. For example, decarbonization not only means to radically change energy systems, but also to fundamentally change the material metabolism of our economies as we are using and are surrounded by materials that directly or indirectly lead to emissions of GHGs currently accounting for at least one fifth of total GHG emissions.

In summary, we should acknowledge that mankind is still lacking the basic data and methodology to compute the long-term optimal path for concentration of GHGs in the atmosphere maximizing human welfare on a global scale, which avoids exceeding dangerous thresholds, and which incorporates short-medium term constraints on substantial reductions of GHG emissions. Until these analytical shortcomings are remedied, the global community is unlikely to address the real hazards arising from climate change in a targeted, effective, and efficient manner, even though it may want to benefit from the opportunities associated with risk taking. This is largely due to the fact that those who create the risks are neither willing to pay the risk premium nor to incur the costs of risk mitigation. Zartman (2001) calls such behavior in preventive negotiations on risk as *"managing risk by free viewing"*.

3 Defining Climate Risk Management

Looking at the scope of alternatives to the stabilization paradigm, there is a limited amount of scientific work available. In particular, theories and models that explicitly deal with the large uncertainties and implicit risks that are present in climate change are particularly rare. Ignorance of risk or simple aversion to risk is misguided when mitigation and adaptation measures can influence, if not determine, the outcome of key stochastic processes governing climate change.

Climate risk management, as discussed in this paper, is based on the knowledge that was built in the integrated assessment work and in the field of financial risk management.

Figure 1 illustrates the integrated assessment thinking and shows how changes in anthropogenic emissions will ultimately have environmental impacts on socioeconomic development pathways. There are large uncertainties related to each box and arrow in Figure 1. Clear signals or signposts are difficult to discern upon which either mitigation or adaptation measures should be taken. Figure 1 shows that mitigation of GHG emissions is different from adaptation with respect to its verifiability of effects. Mitigation reduces emissions at the start of the cycle and thus the effects have to work through the entire cycle. This is important because there are many unknowns and uncertainties in the effects and feedbacks; in consequence, mitigation reduces hazard much more than adaptation, which tends to be more associated with vulnerability to climate risks. Mitigation reduces anthropogenic emissions at the source and this explains the narrowing of the mitigation arrow and other arrows throughout the flow chart, including that for adaptation. Mitigation reduces concentrations, followed by climate change, then the impacts of climate change and finally (not shown) the required adaptation. The primary benefit of mitigation is avoided climate change, but it also has costs (e.g., higher energy costs) and ancillary benefits (e.g., in the form of reduced air pollution such as improvements in human health from reductions in air-borne fine particles (smog and dust), or more rural employment in biomass projects). Adaptation measures arise from the immediate short-term necessity and their benefits are measurable with much less uncertainty than those of mitigation. An investment calculation taking into account the uncertainty of the effectiveness of a measure in combination with a positive discount rate will thus always favor adaptation measures.

The use of mitigation and adaptation measures and their use in a climate risk-managing portfolio depends on mainly two factors:

1. The properties of the stochastic process governing climate change; and
2. The effectiveness and verifiability of the two risk reducing or containing measures.

The first factor relates to the question of how to construct a climate risk management portfolio that maximize welfare in a robust way conditional on a signal for action based on climate forecasts and its implicit losses. The economic risk associated with this factor is over- or undercommitment. We can also refer to this risk as a type one error, where a functioning technology was employed excessively or under-critically. The second factor relates to the issue whether risk-reducing measures actually work. We refer to this risk as a type two error, where a technology is committed to reduce climate risks, which however turns out to not serve the intended purpose.

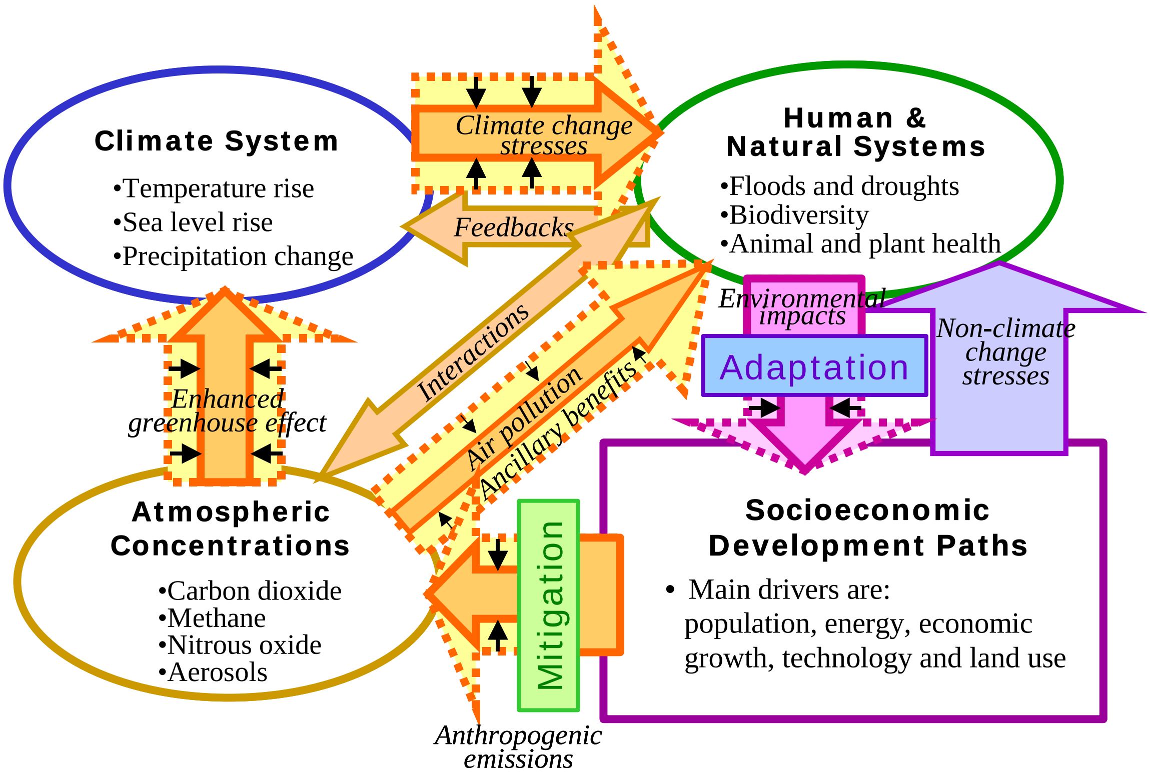

Figure 1: An integrated assessment framework for considering climate change. Adapted from Watson (2001).

A robust climate mitigation portfolio is then defined by the sufficiency of the capacity of opposite technological positions, of both mitigation and adaptation measures, to hedge against the hazard of excessive climate impacts. The impact signal can, in its simplest version, be described by a frequency and amplitude component. While the frequency component can, in this simple model, be more controlled by climate mitigation measures, the amplitude component (extent of damage) can be contained by adaptation measures. In other words, climate mitigation could be used to control the frequency of occurrence of impacts like inundations, while building dams and implementing wide insurance coverage could mitigate or contain the economic impact of storms, which would otherwise turn out to have catastrophic effects.

In the case of mitigation, an opposite technological position to GHG emissions is the option to use technologies that rapidly reduce emissions and remove GHGs from the atmosphere such as Biomass Energy Carbon Sequestration (BECS) and other technologies that reduce total radiative forcing (Obersteiner *et al.*, 2001a). The availability of such a technological option allows for a qualitative shift approaching the climate change dilemma. It is now also possible to develop an alternative approach to the stabilization paradigm — climate risk management. In the following paragraphs we will describe some key features of such a risk management scheme mainly focusing on mitigation options. We will avoid going into the details of describing analytical models and will mainly discuss qualitative features of climate risk thinking.

We will first outline some of the main components of a responsive climate risk management system that implicitly assumes a certain degree of foresight. We will discuss a categorization of risk management measures and their possible combinations in relation to the possible properties of climate change and their effects on human and natural systems. After describing the general system of risk management, we will provide some more detailed description of the main components — risk assessment, and climate mitigation and adaptation.

3.1 Responsive Climate Risk Management and Strategy Under Uncertainty

Independent of the dynamic characteristics of climate change, a backward- and forward-looking responsive approach seems more desirable in an environment of uncertainty. A responsive climate management regime that explicitly includes risk-taking, although in a precautionary manner, could ensure earth system trajectories along safe and desirable regions of sustainable development. Under such a regime, neither GHG concentrations nor climate patterns can or should be held constant, but should rather function as one decision variable among a larger set that maximize long-term welfare streams. Only in an analytical framework which explicitly accounts for uncertainty, will it be possible to account for unsettled value statements such as intergenerational equity (see, e.g., Newell and Pizer, 2001), large scale uncertainties along the drivers of climate related risks (see, e.g., Gritsevskii and Nakicenovic, 2000), and finally the uncertainty of the physical processes. The welfare maximizing strategies will have to be updated constantly as new information on signals and their uncertainty becomes available in a process of continuous cycles of information flow. Within a system of responsive climate risk management, in an uncertainty augmented risk analysis, expected losses (including non-monetary losses) from a changing climate should be constantly balanced with mitigation and adaptation costs in a continuous forward- and backward-looking sense-response mode. In addition to preventive measures, risk-hedging tools are needed that are able, in the case of abrupt climate change, to avoid or mitigate unintended outcomes that would endanger a stable and sustainable development path. Such measures are not only adaptation measures and disaster relief, but also backstop risk mitigation measures such as sink technologies.

The availability of 'strong' permanent sink technologies in combination with prompt emission reductions allows for a wider set of strategic postures to tackle the climate change issue. There are, in principle, three strategic postures vis-à-vis uncertainty and three types of actions can be used to implement that strategy (see, e.g., Courtney *et al.*, 1997). As mentioned earlier, a posture defines the intent of a strategy relative to the current and future state of the climate. Shaping strategies aim to drive the climate patterns proactively into a certain direction. With strong sinks at hand it is, in principle, possible to also provoke cooling and thereby to proactively control GHG levels in the atmosphere in both directions. Employing such a strategy will be necessary when forces of non-linear climate signals become very strong or when probability distributions of climate risks become too leptokurtic. By contrast, a more adaptive strategy will take the current structure and its average future evolution as given and reacts accordingly. The third strategic posture, reserving the right to play, involves making immediate incremental investments that allow to wait until the signposts for acting become less uncertain before formulating a full-fledged strategy.

A posture is not a complete strategy; it clarifies strategic intent but not the actions required to fulfill that intent. Three types of moves are especially relevant to implement a strategy under conditions of uncertainty. Note, however, that the choice of strategy is a function of the type of uncertainty one faces. The first is big bets — large (non-) commitments, such as no action for a better climate or no or negative emissions. Both might produce large payoffs in some scenarios and large losses in others. Shaping strategies usually involve big bets. Hedging strategies are needed to secure the big payoffs of the best-case scenarios while minimizing losses in the worst-case scenario. Both shaping and reserving the right to play strategies use options. Adaptation strategies fulfill their intent in cases of relatively low uncertainties and the assumption of being able to make reliable forecasts. Only a limited amount of hedging is needed in this case. Finally, no regret moves are just moves that will pay off no matter what happens. Such situations arise in the case of ancillary benefits to climate mitigation or adaptation measures. It can be expected that in the near future mostly no-regret moves might help in starting to jump-start real actions on large scales on the climate change agenda. However, even in highly uncertain environments such as the climate change dilemma that we face today, strategic decisions such as investing in the capacity of opposite hedging positions can be no regret moves as they are an essential part of a forward-looking hedging portfolio.

The concept of responsive climate management is general and does not distinguish between the different strategic postures outlined above. Currently, it is also very difficult to decide on the most appropriate posture, as the system is still too under-researched in order to make such a decision. *Nolens volens*, however, we are currently taking big bets without reserving the right to play by developing options.

A responsive climate management approach is outlined in Figure 2. Targeted research is needed to compile the necessary information to close biophysical and the anthropospheric loops aiming at synchronization. Uncertainty augmented assessment models might help to get the synchronization process started, as they might be helpful to provide information on the most important processes and their uncertainties.

As illustrated in Figure 2, human induced changes in the long-term exchange patterns between carbon (GHG) pools, is about to change the functionality of the earth systems' metabolism. In particular, the extraction of fossil carbon from the geological pool during industrialization has changed the concentration of CO_2 in the atmospheric pool at an unprecedented rate. As soon as adaptation measures and losses due to direct impacts of climate change and/or more indirect changes in the earth system metabolism on human welfare are becoming increasingly obvious, more favorable climate patterns will have a direct value to human societies. Despite the long time-lags between causes (emission of GHGs and autonomous climate cycles) and effects (climate change impacts), the global society will have to develop technologies to implement policies and institutions that are instrumental to change the human use pattern of the earth system in order to be better adapted to climatic conditions prior to the occurrence of excessive losses or to improve the long-term patterns of the climate by taking mitigation measures.

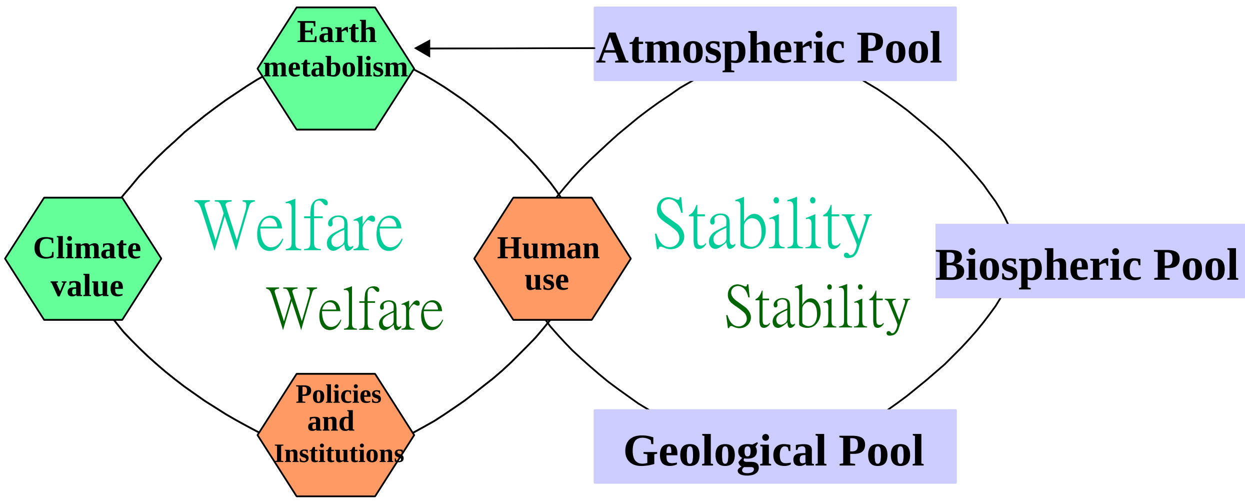

Figure 2: Stylized scheme of responsive climate management.

Instrumental for a robust climate risk management system are:

- Technologies that constrain the hazard and the vulnerability of climate risk (hardware);
- Sound science that identifies, assesses, and models risk and risk-hedging strategies (software); and
- Strong institutions that steer human earth use systems in a continuous sense-response mode (orgware).

Before we ask ourselves institutional questions on responsive climate management, we need to explore the technologies (hardware) that can help us not only to reduce the likelihood of climate worsening but also to actively increase the likelihood of climate improvement by removing GHGs from the atmosphere. Such 'hardware' becomes relevant either if welfare gains are to be expected or if new information tells us that GHG concentrations have exceeded the probabilistic limit for the safety threshold with current climate strategies that are poised to become non-robust.

An entire package of combined risk modulating technologies and measures needs to be deployed to construct an optimal portfolio to protect human welfare development and natural assets from excessive damage related to climate change. Due to the reasons discussed, climate policies should be regarded as a risk management process that is characterized by a variety of options and an inter-relationship of these options. Risk, in this context, refers to the potential adverse impacts that will potentially be experienced in the future due to climate change. Risk management denotes the sum of measures instituted by persons or organizations to reduce, control, and regulate risks (WBGU, 2000). The following risk management measures that allow to limit and hedge the risk associated with climate change are presented in Table 1.

Table 1: Risk management measures.

Risk Identification and Assessment	Mitigation	Adaptation
• GHG emissions and concentrations • Radiative forcing • Climate pattern • Impacts • Hazard and Vulnerability assessment	• Anticipatory emission reduction. • Reactive emission reduction and GHG removal	• *Ex ante* risk reduction: vulnerability reduction • *Ex post* risk sharing: sharing of residual risk.

Risk identification and assessment is the first step of a risk management system providing an understanding of the kinds and magnitudes of risks that must be dealt with. Information on GHG emissions and concentrations, the resulting radiative forcing and potential impacts due to radiative forcing, as well as the uncertainties related to these levels of information, have to be gathered. An account of possible feedback mechanisms is needed with climate modeling focused on methodologies for assessing their thresholds, rather than on further refinements of mainstream projections under various scenarios. This provides information on "dangerous" climate change and may define the option space for climate change mitigation and adaptation measures (WBGU, 2000). Mitigation measures aim at reducing hazard by reducing GHG concentrations in the atmosphere. It is argued that this is the area where the main thrust of activities should be aimed at, however, competition between adaptation and mitigation measures will heavily depend on the effective discount rate and its uncertainty (see, e.g., Newell and Pizer, 2001). Adaptation measures target potential impacts due to increased radiative forcing; this risk can either be reduced or shared among a number of parties. In combination, these measures define a precautionary risk management approach, where (un-)intentional risk taking always has to be counterbalanced by sufficient opposite technological positions. In an uncertainty augmented risk analysis robustness of a technological portfolio is then defined by an uncertainty multiplier or option value of the risky portfolio (see, e.g., Farrow, 2001). In such models greater caution will be exercised with increasing uncertainty.

The UNFCCC provides some long-term guidance for a type of climate management that is consistent with a system of "precautionary" climate risk management. On the one hand the UNFCCC calls for stabilization at a safe level, on the other it also advocates the use of other risk management measures:

> "*The parties should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost-effective so as to ensure global benefits at the lowest possible cost…*" (UNFCCC, 1992: Article 3.3).

In this sense, the UNFCCC can be understood as a climate management scheme that allows for precautionary and anticipative risk-taking within certain climate risk limits. A variant of such a precautionary risk management scheme is, e.g., the "tolerable windows" approach (WBGU, 2000) or the Robust Strategy approach (Lempert *et al.*, 1996; Lempert and Schlesinger, 2000).

Climate risk management is by nature closely related to risk management of natural disasters. The expected damages from adverse effects of climate change become measurable as climate related natural disasters that are above the baseline natural level of dangerous climate events. The current level of climate related natural disasters can be interpreted as the underlying asset in financial market risk models, with the resulting losses being the associated payoff. The additional exposure to climate related natural risk in the form of *inter alia* droughts, flooding, temperature extremes, storms, and dying coral reefs need to be benchmarked against the costs of hazard reduction and decreasing vulnerability. An important element in an uncertainty augmented risk management process must be the analysis of costs and benefits of all measures that are available to construct a technological portfolio under certain boundary conditions on the total risk exposure of the portfolio. Only such an approach, if augmented by explicit treatment of uncertainty, would guarantee compliance with the precautionary rationale and the least cost principle of the UNFCCC.

The optimal combination of these instruments highly depends on the underlying nature of climate risks. The type of climate related risks that need to be counteracted by the above mentioned instruments can be classified in a number of ways. The IPCC (2001b) distinguished five reasons of concern: (1) risks to unique and threatened systems, (2) risks from extreme climate events, (3) distribution of impacts, (4) aggregate impacts, and (5) risks from future large scale discontinuities, and tried to establish a relation with the expected temperature change associated with the SRES scenarios. In this paper, we will distinguish only three categories, as these require different treatment with respect to risk management:

(a) risks from incremental climate change (2), (3), and (4);

(b) risks from self-reinforced radical climate change (5); and

(c) risks from the interconnection with other risk factors than climate change (1), (3), and (4).

These types of risks are not separable in the sense that they will always go together. However, depending on the climate conditions and the vulnerability of the human- or ecosystem, one risk type will be dominant. Thus, risk exposure is path-dependent. Maybe today we are still in a phase, where risk from incremental climate change dominates, risks of self-reinforced radical climate change are not yet visible, and the interaction of the climate related damages with, e.g., food security, ecosystem stability, and resilience of infrastructure supply still seem within an acceptable range. Such a scenario is along the lines of the IPCC (2001a) assertion that after GHG concentrations have stabilized, global average surface temperatures would rise at a rate of only a few tenths of a degree per century rather than several degrees per century as projected for the 21st century without stabilization. The lower the level at which concentrations are stabilized, the smaller the total temperature change. However, it could well be that due to non-linear response processes of natural ecosystems (e.g., coral bleaching) transmitted through complex cause-effect chains would lead to a sudden upward shift in the level of climate related damages and disasters that finally result in civil unrest in some regions of the world as those societies lost their capacity to deal with the additional climate risk(s). In such a scenario, the latter two types of risk dominate and the accumulation of climate related damages threatens the viability of entire societies and peoples.

Given the current state of knowledge and the absence of credible political commitment, it is impossible to judge which combinations of risk types we can expect in the medium- to long-term future. Climate risks are too complex and scientific forecasts are subject to large uncertainties. The full risk of climate change is not yet fully identified and we are far from a thorough assessment of full climate risk, which would allow for efficient and targeted policies that allow for rational risk taking. Therefore, *nolens volens*, we are taking the risk in an environment that is subject to large uncertainties and knowledge gaps. We are also far from a robust international climate risk management regime that would safeguard current and future generations from climate related risk exposure such that scientifically sound and ethically acceptable decisions could be made. This question of intergenerational equity is of special importance as there is a lag between the triggering event (emission of GHGs) and the occurrence of the damage. Risk management under changing climate conditions is especially difficult as both factors of the risk equation — extent of damage and the frequency of damage — are unknown for at least the second and third risk categories, (b) and (c) above. In addition, there is a large geographic and structural heterogeneity of risk exposure as there are regional disparities in impacts of not only climate change but also in the efforts and the resulting burden of adapting to and mitigating climate change.

3.2 Risk Assessment

Although science has significantly advanced over the last decade, there is still a 'cascade of uncertainties' compound through a series of modeling stages of the climate system (Schneider, 2001). There is uncertainty on how the level of GHG concentrations relates to climate change and how stable climate patterns are given a particular GHG level. There is large uncertainty on the effects of increased concentrations of GHGs in the atmosphere with respect to the higher moments of the dynamics of the climate system and the geographic distribution of climate change. More important are the uncertainties of the dynamic aspects of the relationship between GHG concentrations and climate change. With respect to stability, it has been argued that the climate system could turn out to be chaotic in the sense that it would suddenly change its pattern (e.g., reversal of the golf stream) under conditions that would not have happened at lower concentrations of GHGs in the atmosphere. A mechanism that might lead to abrupt climate change would need to have the following characteristics (NAP, 2002):

- A trigger or, alternatively, a chaotic perturbation, with either one causing a threshold crossing (sometimes this initiates the event);
- An amplifier and globalizer to intensify and spread the influence of small or local changes; and

- A source of persistence, allowing the altered climate state to last for up to centuries or millennia.

The next important uncertainty component along the uncertainty cascade is on how a changing climate leads to dangerous impacts. The UNFCCC, in its objectives, tries to define dangerous as a level that should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner.

A number of recent studies are starting to explore quantitatively possible impacts of climate change. Just to mention a few: Scheffer *et al*. (2001) model accumulating change of climate that courts ecosystem catastrophes; Fischer *et al*. (2002) studied the disparity and heterogeneity of climate change impacts on global food production; and Freeman *et al*. (2001) provide a quantitative assessment of the macro-economic impacts of natural catastrophes. Read (1994, Chapter 3) suggests an approach that gives the risk of climate catastrophe (Antarctic ice meltdown, or reversion to ice age glaciations) infinite 'social objection', effectively prohibiting policy directions that open or enhance such possibilities. Despite the fact that climate impacts are beginning to be studied more thoroughly, climate risk as such still remains to be classified as an unknown risk. Much work lies ahead of us to sufficiently assess climate risk and assign risks and feedbacks to various risk classes, for example, by using the decision tree for classifying risk developed by the WBGU (2000). In particular, the potential for large scale and possibly irreversible impacts poses risks that have yet to be reliably quantified (IPCC, 2001b).

The uncertainty discussion is, in some respects, still in its infancy because very basic definitions are still not agreed upon. The ecological, social, and economic dynamics of the changing earth all encompass uncertainties that can be categorized as statistical uncertainty, model uncertainty, or fundamental uncertainty (Hilborn, 1987). Peterson *et al*. (1997) describe these three categories of uncertainty as follows: statistical uncertainty is the uncertainty that surrounds a variable when its state at any one point is unknown, but the probability distribution that characterizes that variable is known. Model uncertainty occurs when the connections between variables are uncertain. Such uncertainty allows the prediction of outcomes, but makes it difficult to assess their likelihood. For example, the Atlantic conveyor has periodically been turned off, but the processes causing this are not understood well enough to predict the likelihood that the event will occur under possible future climatic conditions (Broecker, 1996). Finally, fundamental uncertainty describes novel situations for which existing models do not apply. The discovery of the ozone hole falls into this category of uncertainty. Peterson *et al*. (1997) then conclude that careful science can reduce but not eliminate these uncertainties. However, such science is often expensive, especially for large, weakly replicable systems such as the global climate system. Clearly, such statements make clear that a robust hedge on climate risks will always involve opposite technological positions.

As the current climate change models still lack the capacity to fully describe the delicate interplay of already highly uncertain triggers and modulators of the dynamic system, the uncertainties and complexity of the forces driving the social, biological, and physical dimensions of global change ensure that it will most likely have surprising outcomes

(Clark, 1986; Schneider and Root, 1996). Another additional complication for quantifying uncertainties and thus risk is that uncertainty is path-dependent. Although historical studies can help scientists to understand ecological and political-economic processes, they do not provide analogues for a future earth system that is transformed by global change and other changes triggered by human influence. As we continue to change processes at a global scale, past experience will serve less often as an accurate model of future conditions, shifting the balance of the uncertainties we face from the more easily managed categories of statistical and model uncertainty to that of fundamental uncertainty. One way out of this dilemma is a forward- and backward-looking approach integrating multiple sources of information on risk relevant uncertainties. Moltchanova (2001) developed a methodology that can be used to integrate this kind of information. In a responsive (adaptive) way new information from the past and projections of the future are constantly updating current assessments of uncertainties that enter the risk management models, with continual 'back-casting' employed to check plausibility. The updating of risk assessment should be consistent with a wider system of responsive climate risk management along the lines of the work of Holling (1978), Walters (1986; 1997), Lee (1993), and the IGBP (2001). The wider concept of responsive climate management, following a sense-response mode, has yet to be developed in further detail so that risk assessment and risk management can fully be integrated with these concepts.

3.3 Mitigation

Mitigation measures from a risk perspective reduce the hazard of climate change impacts. In Table 1 we distinguish between two types of climate mitigation measures:

1. Anticipatory emission reduction, and
2. Reactive emission reduction and GHG removal.

Anticipatory mitigation measures imply a safe global climate regime that keeps climate related natural hazards within manageable boundaries. If it can be assumed that there is a clear relationship between the concentrations of GHGs in the atmosphere on the one hand and climate pattern and impacts on the other, channels of atmospheric GHG concentrations, limited by ceilings and floors, could be defined. In other words, anticipatory mitigation aims at the ranges of robust emission strategies that are worked out in a responsive manner and that are based on a precautionary rationale as defined by Article 3.3 of the UNFCCC.

However, more realistically we have to acknowledge that the relationship between GHGs and impacts is still poorly understood and subject to exogenous stochastic shocks, such that attractors of a climate of unpredictable and undesirable outcomes (including rare catastrophic events) can only be avoided with sufficient probability (if, indeed, these can be avoided) by additional 'reactive'[1] emission reduction and GHG removal. The quantitative difference between the two types of mitigation can be

[1] Note that reactive still requires substantial capabilities of foresight. Reactive shall be understood as a response to an unexpected change in the expectation of impacts.

described by the stronger dynamical moments of the latter mitigation strategy, which we will also call opposite technological position to (baseline) emissions.

It follows that benefit-cost analysis of mitigation technologies should be carried out in an uncertainty augmented analytical framework defined by a quantifiable precautionary threshold of action — where the degree of risk taking must be reflected by commitments in opposite technological positions.

3.4 Anticipatory Emission Reduction

A number of studies (IPCC, 2001c; Riahi and Roehrl, 2000; Steinberg, 1997; Edmonds *et al*., 2000) identify in many scenario analyses three principle mitigation measures for the energy system: (1) fuel switching to less GHG intensive fuels, (2) enhanced energy conservation, and (3) CO_2 capture and sequestration from fossil fuels. All three principle mitigation measures are about emission reduction and can not be regarded as an opposite technological position for hedging climate risks. Such mitigation options fall into the more exotic mitigation categories of carbon sinks and geo-engineering measures. The effects of fertilization of marine ecosystems and other geo-engineering proposals remain unresolved and therefore such technologies are, according to the IPCC (2001c), not ready for the near-term application. Forests, agricultural lands, and other terrestrial ecosystems are on the other hand considered to offer significant carbon mitigation potential. Although not necessarily permanent, conservation and sequestration of carbon in terrestrial ecosystems may allow time for other mitigation options to further develop and thereby add considerablY more flexibility to manage GHG concentrations in the atmosphere on a least cost basis. However, there is still considerable uncertainty in the scientific understanding of the causes, magnitude, and permanence of the land carbon sink. The IPCC (2001a) reports that changing land use could influence atmospheric CO_2 concentration. Hypothetically, if all of the carbon released by historical land-use changes could be restored to the terrestrial biosphere over the course of the century (e.g., by reforestation), CO_2 concentration would be reduced only by 40 to 70 ppm. A number of studies indicate that the potential to enhance the land carbon sink through changes in land management practices is finite in size and duration is small in comparison to the ever-increasing global emissions of GHGs (Royal Society, 2001). These boundaries of the absorption capacity of natural terrestrial sinks are also referred to as saturation (see, e.g., Schulze *et al*., 2000; Schlamadinger and Marland, 2000). Saturation is of special importance since, according to IPCC (2001a), it is expected that as the CO_2 concentration of the atmosphere increases, ocean and land will take up a decreasing fraction of anthropogenic CO_2 emissions. The threshold for the reversal of the terrestrial sink enhancement process due to CO_2 fertilization being outweighed by enhanced rates of decomposition of humus and increased plant respiration under thermal stress may be only a few decades away under business-as-usual warming (Cox *et al*., 2000). The net effect of land and ocean climate feedbacks as indicated by models is to further increase projected atmospheric CO_2 concentrations, by reducing both the ocean and land uptake of CO_2.

Without going into further detail on mitigation measures (see, IPCC, 2001c), we can conclude that the knowledge on the feasibility to pro-actively manage global GHG concentrations in the long run and thereby influence the exposure to climate related hazards is still rather limited. In particular, reliance on natural sinks that counteract continued fossil fuel emissions might turn out to be a weak strategy. Combined with other factors mentioned earlier, there is considerable uncertainty on the effectiveness of the three main mitigation measures to control climate related impacts in the long-run and to sufficiently react to unanticipated events that hamper compliance to atmospheric GHG concentrations in accordance to the UNFCCC.

3.4.1 Reactive emission reduction and GHG removal

While the above mentioned 'baseline' mitigation measures are, in principle, designed to smoothly aim at "bullet-proof" safe concentrations of GHGs in the atmosphere, opposite mitigation positions are a must for a robust climate risk management portfolio if there is, among others, uncertainty on the safe level of GHG concentrations, uncertainty on the effectiveness of mitigation measures, uncertainty in the climate pattern and its implicit impacts, uncertainty on the functioning of global policies and institutions, uncertainties on the response of natural ecosystems to climate change, and finally socioeconomic uncertainties.

Despite concerns that "the potential for an unspecified, low probability, but catastrophic turn of events haunts the problem" (IPCC, 2001b, d), climate change has been seen as a long run issue with substantial focus on problems of intergenerational equity. The pre-publication version of the National Academy of Science Committee's Report 'Abrupt Climate Change: Inevitable Surprise' (NAP, 2002) demonstrates that comfortable decision framework to be illusory. The problem becomes one of preparing for surprise and taking actions designed to enable the worst surprises to be avoided: *"…taking steps that will make it possible, if need be, to get control of global warming at acceptable cost in the opening decades of the next century"*. What has changed with NAP (2002), is a new and stark reality that 'need' does indeed 'be', and the disturbing possibility that control may be infeasible if anthropogenic emissions were overly excessive.

If unforeseen climate change related catastrophic damages are expected to significantly decrease human welfare and ecosystem functioning, mitigation options that will avert or prevent catastrophes of escalating will be highly valued and will be exercised. However, such technologies usually need some lead-time to be developed and, therefore, such technologies are to be fully designed well before they are really needed and sufficient resources need to be readily available to exercise such technological options. This is in line with the strategic posture of reserving the right to play discussed earlier. In situations of increased hazard, also the value of climate risk mitigation will increase accordingly, which in turn will justify high costs of BECS and other removal technologies combined with enhanced emission reduction of the 'standard' mitigation technologies. Under a credible, however, unforeseen and sudden emergence of a large climate related hazard, the total benefits from employing BECS can be expected to greatly exceed costs. Note, that hazard shall not be perceived *ex post*, but is always anticipatory even under the reactive mitigation regime. If critical thresholds are exceeded even the strongest BECS might turn out to be ineffective.

It is interesting to observe that 'classical' sinks might turn out to be a competitive mitigation technology under the Kyoto mechanisms and, thereby, the absorptive capacity (sinks and BECS assets) that will be built along the baseline produces a risk-hedging value as a joint product. Thus, by using BECS as a mitigation option to compensate and/or to substitute fossil fuels one builds, at the same time, the capacity for risk-hedging as a free good. Early development of sufficient sink capacity (stock effect of terrestrial carbon), based on early pro-active land use change, is crucial. This is important in light of the stickiness of land markets. The faster resources are needed in order to exercise the BECS technology, the larger the overall costs and environmental damage will be. Without sufficient absorptive capacity, it will not be possible to exercise the real option BECS. Sathaye *et al*. (2001) identified the large carbon mitigation potential of forestry options at negative costs. Given the large rates of deforestation and these no regret negative cost opportunities, it should be possible to prepare or conserve a minimum stock of regenerative carbon stocks to build a robust technological portfolio to hedge climate risks. At the same time, there are a number of other forest related or forest specific international processes that aim at similar goals, preserving the integrity of forest ecosystems and sufficient forest coverage (see, Obersteiner *et al*., 2001b).

Probably, more important than the provision of sufficient absorptive capacity, is the development of BECS as a technological cluster. There are, of course, a number of technological questions to be solved as identified above. Significant inputs into respective research and development (R&D) are required to develop the cluster as such in order to use BECS as a sustainable technology in a wider sense.

The main policy conclusion is that investments in both, expanding the absorptive capacity for carbon (expanding carbon stocks) and R&D investments, for developing BECS as a viable technology cluster should not only be (socially) priced against all other mitigation technologies by simple Net Present Value calculation (working only with the average expected loss), but according to a real option valuation given the full uncertainty spectrum of expected (economic) losses due to human induced climate change (working with the higher moments of the loss distribution).

3.5 Adaptation

Reduction of GHG emissions has to be seen, due to the indirect nature of cause and effect and the long time lags, as medium- to long-term measures. In contrast, adaptation to the impacts of climate change can be effectively applied on a much shorter term. This distinction is important since the social discount rate plays an important role dividing the total capital resources towards the short-term adaptation measures and the longer-term mitigation measures. The uncertainty on the effectiveness of adaptation measures is much smaller than that for mitigation measures. Therefore, the market for climate risk management will by construction be ‘biased’ toward adaptation due to discounting and its higher efficiency. Furthermore, there is the moral hazard problem that relies on the credible expectation that based on implicit arrangements (e.g., existence of World Bank bail out funds, or Red Cross emergency help) in future there will be someone that comes to immediate help in cases of climate disasters — in the form of, e.g., disaster relief programs or supported migration.

As mentioned earlier, mitigation measures can be used to control the hazard factor in the risk formula, adaptation measures are associated with the vulnerability factor. Adaptation can be defined as the adjustment in ecological, social or economic systems responding to current or expected climatic stimuli or their effects reducing potential adverse effects or making use of beneficial opportunities (IPCC, 2001b).

There are basically two adaptation options:

(1) reduction of impacts (extreme and average): vulnerability reduction, and

(2) financial adaptation: residual risk remains that must be shared — international and national risk-sharing.

Vulnerability reduction reduces the susceptibility of human or natural systems to potential adverse effects due to climate change. As a result, potential impacts or risk can be reduced.

Financial adaptation, on the other hand, deals with a certain level of risk — residual risk — that is consequently shared by implicit (e.g., disaster relief by the international donor community) or explicit arrangements (e.g., re-insurance) reducing individual risk to be borne by an entity.

Although risk mitigation and adaptation should be applied in combination, they affect risk independently. On a temporal scale, there are two types of adaptation: reactive and anticipatory (IPCC, 2001b).

Reactive, autonomous adaptation in ecosystems is closely related to the concepts of resilience and ecological reorganization (Peterson *et al*., 1997). Ecological resilience, the ability of an ecosystem to persist despite disruption and change (Holling, 1973), depends upon the continuity of ecological processes at smaller and larger scales (Peterson *et al*., 1998). The pervasive and synergistic impacts of global change threaten to reduce ecological resilience at local to global scales, producing ecosystems that are increasingly brittle and sensitive to disruption. Thus, adaptation of the ecosystem brings about ecological costs depending on the process of ecological reorganization. Different species and populations migrate, establish, and become extinct at different rates. Climate change, therefore, will cause the dissolution of existing ecosystems and the formation of new ecosystems. Ecological collapses will probably eliminate some species entirely, and these species losses may cause the elimination of entire ecosystems. Similar processes of autonomous adaptation can be expected for social, political, and economic systems. A main distinction between the processes of ecological systems and human systems is that humans are capable of forming expectations on future states of the world and can thus remove some of the 'inefficiency' of the trial-and-error system of nature by applying a responsive climate risk management regime with respect to adaptation.

While adaptation in natural systems is reactive, in human systems it can be both reactive and anticipatory (IPCC, 2001b). Anticipatory adaptation comprises diverse measures such as early-warning systems, incentives for relocation or purchase of insurance. Whereas the ecological, social, and economic costs of relying on autonomous adaptation can be substantial, anticipatory adaptation provides the opportunity to avoid or decrease those costs by planning ahead of time.

Anticipatory adaptation often provides ancillary benefits, as adaptation to future climate change is generally consistent with adaptation to current climate variability such as floods and droughts. Thus, measures in this area often constitute no-regret options. Currently, international efforts organized by the Global Environment Facility (GEF) in this area are underway to develop adaptation strategies for vulnerable developing countries subject to climate change for coping with climate change impacts based on current exposure to extreme events. An integrated approach is aimed at, which treats coping with present climate variability as an effective way to reduce longer-term vulnerability to climate change. Integration in this context assumes the uncertainty augmented assessment of both mitigation and adaptation measures.

4 Concluding Summary

This article dealt with the question of whether robust and precautionary climate risk management is at all possible. There are a few key features of the climate problem that, at least from a theoretical point of view, allow for the conclusion that mankind will most likely maneuver itself into a situation where climate change related risks will increase in the future. These factors are:

- There is a substantial time lag between the cause (emission of GHGs) and effects (climate change related impacts) and the link is not yet fully understood.
- Science is unable to predict full-scale long-term impacts accurately enough so that it could socially be interpreted as a strong signpost for action.
- There is large heterogeneity in current and historical emissions among countries and sectors; and there is no single “culprit” identifiable.
- Variance and heterogeneity of climate related hazards and benefits are large.
- There is large heterogeneity in vulnerability among countries, sectors and ecosystems.

From this we can conclude that the problem of climate change is internationally and sectorally diffused and signposts are blurred. However, despite the high social and scientific complexity and uncertainty, the risks of climate change are real and uncertainty is by no-means equivalent to no knowledge and to an even lesser extent a reason to abstain from strategic decision-making. According to the Precautionary Principle of Article 3.3 of the UNFCCC, a lack of full scientific certainty should not be used as a reason to postpone climate risk mitigating measures. In this paper we argue that uncertainty augmented integrated risk assessment models could help in formulating strategies that are compatible with the precautionary principle. Climate strategies in this respect are expressions of institutional arrangements of the global community dealing with the climate change issue through negotiations based on the principles and objectives of the UNFCCC. Independent of the character of the institutional arrangement — whether the Parties follow a proactive shaping strategy or a more reactive adaptation strategy — the precautionary principle can be implemented. This is possible by constructing technological hedge portfolios. Intended risk taking by, e.g., choosing a high level of carbon in the atmosphere, must then be hedged with the option to readily implement opposite technological positions such as an appropriate mix of fast emission reduction and sequestration technologies. Thus, in accordance with the Precautionary Principle, also under climate risk management, it holds that the higher the uncertainties about future climate related impacts are and the higher the degree of risk taking is, the stronger must be the opposite technological position.

Of course, such a proposition of a robust portfolio approach to climate can only work if mankind is capable of predictions and quantification of the models. In addition, the technological 'put' option, protecting against downside risk, must be well prepared in order to be exercised when needed. Taking risk without insurance could otherwise lead to an undesirable climate bubble and would run counter to the Precautionary Principle. Finally, international institutions should ideally be built around an "Uncertainty augmented Precautionary Principle" which does not exclude risk-taking behavior. Such institutions also allow for more heterogeneity in strategic postures, which could help in facilitating negotiations.

References

Broecker, W.S. (1996). Thermohaline Circulation, the Achilles Heel of our Climate System: Will Manmade CO_2 Upset the Current Balance? *Science*, 278, 1582–1588.

Clark, W.C. (1986). Sustainable Development of the Biosphere: Themes for a Research Program. In: W.C. Clark and R.E. Munn (eds.) *Sustainable Development of the Biosphere*. Cambridge University Press, Cambridge, UK, pp. 4–48.

Courtney, H.G., J. Kirkland and S.P. Viguerie (1997). Strategy Under Uncertainty. *Harvard Business Review*, Vol. 75, Issue 6, November–December, pp. 66–79.

Cox, P.M., R.A. Betts, C.D. Jones, S.A. Spall and I.J. Totterdell (2000). Acceleration of Global Warming Due to Carbon-cycle Feedbacks in a Coupled Climate Model. *Nature*, 408, 184–187.

Edmonds, J.A., P. Freund, and J.J. Dooley (2000). The Role of Carbon Management Technologies in Addressing Atmospheric Stabilization of GHGs. Proceedings 5th International Conference on GHG Control Technologies, 13–16 August 2000, Cairns, Australia.

Farrow, S. (2001). Using Risk Assessment, Benefit-cost Analysis, and Real Options to Implement a Precautionary Principle. Paper prepared for the Association of Environmental and Resource Economists (AERE) Workshop on Assessing and Managing Environmental and Public Health Risks, 13–15 June, 2001, Bar Harbor, Maine, USA.

Fischer, G., M. Shah, H. van Velthuizen and F.O. Nachtergaele (2002). Global Agro-ecological Assessment for Agriculture in the 21st Century. Research Report RR-02-002. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Freeman, P.K., L. Martin and G. Pflug (2001). Developing Countries' Problem of Investments Endangered by Natural Catastrophes: Optimal Investment and Insurance Policies. International Institute for Applied Systems Analysis, Laxenburg, Austria. Unpublished manuscript.

Goulden, M.L., S.C. Wofsy, J.W. Harden, S.E. Trumbore, P.M. Crill, S.T. Gower, T. Fries, B.C. Daube, S.M. Fan, D.J. Sutton, A. Bazzaz and J.W. Munger (1998). Sensitivity of Boreal Forest Carbon Balance to Soil Thaw. *Science*, 279, 214–217.

Gritsevskii, A. and N. Nakicenovic (2000). Modeling Uncertainty of Induced Technological Change. *Energy Policy*, 28, 907–921.

Hilborn, R. (1987). Living with Uncertainty in Resource Management. *North American Journal of Fisheries Management*, 7, 1–5.

Holling, C.S. (1973). Resilience and Stability of Ecological Systems. *Annual Review of Ecology and Systematics*, 4, 1–23.

Holling, C.S. (1978). *Adaptive Environmental Assessment and Management*. John Wiley, London, UK.

IGBP (2001). The Carbon Challenge. An IGBP-IHDP-WCRP (International Geosphere and Biosphere Program/International Human Dimensions Program/World Climate Research Program) Joint Project. International Geosphere and Biosphere Program (IGPB), Stockholm, Sweden.

IPCC (2001a). *Climate Change 2001. The Scientific Basis Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC). R. Houghton *et al*. (eds.). Cambridge University Press, Cambridge, UK.

IPCC (2001b). *Climate Change 2001. Impacts Adaptation and Vulnerability Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC). J.J. McCarthy, O.F Canziani, N.A. Leary, D. Dokken and K.S.White (eds.). Cambridge University Press, Cambridge, UK.

IPCC (2001c). *Climate Change 2001. Mitigation. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC). B. Metz, O. Davidson, R. Swart and J. Pan (eds.). Cambridge University Press, Cambridge, UK.

IPCC (2001d). *Climate Change 2001: Synthesis Report*. Cambridge University Press, Cambridge, UK. Available on the Internet: http://www.ipcc.ch/pub/tar/syr/001.htm.

Lee, K.N. (1993). *Compass and Gyroscope. Integrating Science and Politics for the Environment*. Island Press, Washington, DC, USA.

Lempert, R.J. and M.E. Schlesinger (2000). Robust Strategies for Abating Climate Change. *Climatic Change*, 45, 387–401.

Lempert, R.J., M.E. Schlesinger and Steven C. Bankes (1996). When We Don't Know the Costs or the Benefits: Adaptive Strategies for Abating Climate Change. *Climatic Change*, 33, 235–274.

Moltchanova, Elena (2001). Image Restoration from Multiple Sources. Interim Report IR-01-045. International Institute for Applied Systems Analysis, Laxenburg, Austria.

NAP (2002). *Abrupt Climate Change: Inevitable Surprises*. Committee on Abrupt Climate Change, National Academic Press (NAP), Washington DC, USA, 244 pages. Available on the Internet: http://www.nap.edu/catalog/10136.html?onpi_newsdoc121101.

Newell, R. and W. Pizer (2001). Discounting the Benefits of Climate Change Mitigation: How Much Do Uncertainty Rates Increase Valuations? Report prepared for the Pew Center on Global Climate Change. Resources For the Future, Washington DC, USA, December.

Obersteiner, M., C. Azar, P. Kauppi, K. Möllersten, J. Moreira, S. Nilsson, P. Read, K. Riahi, B. Schlamadinger, Y. Yamagata, J. Yan and J.-P. van Ypersele (2001a). Managing Climate Risk. *Science*, 294, No. 5543, Issue of 26 October 2001, pp. 786–787.

Obersteiner, M., E. Rametsteiner and S. Nilsson (2001b). Cap Management for LULUCF Options: An Economic Mechanism Design to Preserve the Environmental and Social Integrity of Forest Related LULUCF Activities Under the Kyoto Protocol. Interim Report IR-01-011. International Institute for Applied Systems Analysis, Laxenburg, Austria.

Peterson, G., G.A. De Leo, J.J. Hellmann, M.A. Janssen, A. Kinzig, J.R. Malcolm, K.L. O'Brien, S.E. Pope, D.S. Rothman, E. Shevliakova and R.R.T. Tinch (1997). Uncertainty, Climate Change, and Adaptive Management. *Conservation Ecology* 1(2), 4. Downloaded from and available on the Internet: http://www/consecol.org/vol1/iss2/art4.

Peterson, G.D., C.R. Allen and C.S. Holling (1998). Diversity, Ecological Function, and Scale: Resilience Within and Across Scales. *Ecosystems*, 1, 6–18.

Read, P. (1994). *Responding to Global Warming: The Technology, Economics, and Politics of Sustainable Energy*. ZED Books, London and New Jersey.

Riahi, K. and A.R. Roehrl (2000). Energy Technology Strategies for Carbon Dioxide Mitigation and Sustainable Development. *Environmental Economics and Policy Studies*, 3(2), 89–123.

Royal Society (2001). The Role of Land Carbon Sinks in Mitigating Global Climate Change. Policy document 10/01, July, London. Available on the Internet: http://www.royalsoc.ac.uk.

Sathaye J.A., W.R. Makundi, K Andrasko, R. Boer, N.H. Ravindranath, P.Sudha, S. Rao, R. Lasco, F. Pulhin, O.Masera, A. Ceron, J. Ordonez, X. Deying, X. Zhang and S.A. Zuomin (2001). Carbon Mitigation Potential and Costs of Forestry Options in Brazil, China, India, Indonesia, Mexico, The Philippines, and Tanzania. *Mitigation and Adaptation Strategies for Global Change*, 6, 185–211.

Scheffer, M., S. Carpenter, J.A. Foley, C. Folke and B. Walker (2001). All Ecosystems are Exposed to Gradual Changes in Climate, Nutrient Loading, Habitat Fragmentation or Biotic Exploitation. Nature is Usually Assumed to Respond to Gradual Change in a Smooth Way. *Nature*, 413, 591–596.

Schlamadinger, B. and G. Marland (2000). Land Use and Global Climate Change: Forests, Land Management and the Kyoto Protocol. Pew Center on Global Climate Change, Arlington, VA, USA. Downloaded from and available on the Internet: http://www.pewclimate.org/projects/land_use.cfm.

Schneider, S.H. (2001). What is 'Dangerous' Climate Change? *Nature*, 411, 17–19.

Schneider, S.H. and T.L. Root (1996). Ecological Implications of Climate Change will Include Surprises. *Biodiversity and Conservation*, 5, 1109–1119.

Schulze, D.E., C. Wirth and M. Heimann (2000). Climate Change. Managing Forests After Kyoto. *Science*, 289, 2058–2059.

Steinberg, M. (1997). The Carnol Process System for CO_2 Mitigation and Methanol Production. *Energy*, 22(2–3), 143–149.

UNFCCC (1992). United Nations Framework Convention on Climate Change (UNFCCC). Downloaded from and available on the Internet: http://unfccc.int/resource/conv/index.html.

Walters, C.J. (1986). *Adaptive Management of Renewable Resources*. McGraw Hill, New York, USA.

Walters, C.J. (1997). Challenges in Adaptive Management of Riparian and Coastal Ecosystems. *Conservation Ecology*, 1(2), 1. Downloaded from and available on the Internet: http://www.consecol.org/vol1/iss2/art1.

Watson, R.T. (2001). Climate Change. Presentation given at Auckland University Aquatic and Atmospheric Science Institute, New Zealand, 3 May.

WBGU (2000). *World in Transition: Strategies for Managing Global Environmental Risks*. German Advisory Council on Global Change (WBGU), Springer Verlag, Berlin, ISBN 3-540-66743-1.

Zartman, W. (2001). Risk and Preventive Negotiations. School of Advanced International Studies, The John Hopkins University, USA. Unpublished report.