Fate of Mountain Glaciers in the Anthropocene
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Melting and Mystification
A Comparative Analysis of Mitigation and Adaptation Strategies

Hans Joachim Schellnhuber & Veronika Huber

Introduction

Who has not stood in awe gazing at a mighty mountain glacier? Worldwide, these white giants of high altitude are shrinking due to rising temperatures (Fig. 1).[1] Images of receding mountain glaciers have become as emblematic of climate change as are pictures of polar bears in search of solid ice. Climate impacts occurring at high altitudes and high latitudes also have in common that they provide early-warning signals. Where ice disappears temperatures are amplified beyond the global average,[2,3] allowing for a glance at the pace of change to be expected elsewhere.

This contribution is not meant to provide the most recent scientific findings on the implications and prospects of mountain glaciers under global

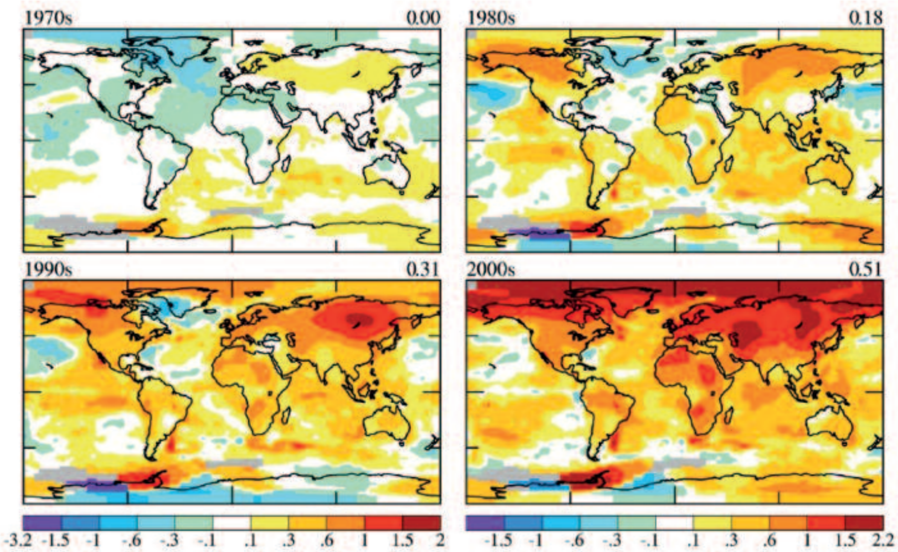

Figure 1. Decadal surface temperature anomalies relative to 1951-1980 base period. On average, successive decades warmed by 0.17°C. Source:[4]

warming. We leave this assessment to the glacial experts. Instead, we present a comparative analysis of mitigation and adaptation strategies interwoven with important fundamentals of climate change science. The fate of the mountain glaciers and of the people affected by their melting ultimately depends on whether the discussions about climate change will remain guided by scientific reasoning. In this paper we particularly address some of the myths related to adaptation that are increasingly emerging in the climate change debate.

Mitigation and adaptation constitute two different approaches for dealing with anthropogenic climate change. Human interventions that aim at reducing the sources and enhancing the sinks of greenhouse gases are commonly referred to as mitigation. The grand objective is to limit the extent of global warming. Adaptation is the adjustment of natural and human systems in response to actual or expected impacts of climate change. The intention here is to alleviate negative effects or to exploit potentially beneficial opportunities of occurring climatic changes.

Given the dire state of current international climate change negotiations and the poor prospects for coordinated global mitigation efforts a growing chorus – of scientists and politicians alike – calls for a new focus on adaptation.[5,6] Sure enough, addressing anthropogenic global warming requires a well-balanced mixture of "avoiding the unmanageable and managing the unavoidable".[7] Mitigation and adaptation are two sides of the same coin. This is especially true considering that the world is already committed to considerable warming that would unfold even if – against all expectations – ambitious mitigation actions were taken immediately.[8] Indeed, adaptation can no longer be the poor cousin of climate policy. However, many advocates of strengthening adaptation efforts and policies behave like besotted lovers. They praise the many positive aspects of adaptation strategies – to the point of mystification – but deny the difficulties becoming apparent when taking a closer look.

As one of many examples, Stehr and Storch, in an essay published in 2008, compliment adaptation for being easier to be legitimized and implemented than mitigation.[9] They assert that adaptation mostly takes place locally and regionally, and is easier to be adjusted to the wants and needs of different social and cultural groups. In their opinion, it is also easier to promote innovation and technology aimed at solving adaption problems than serving mitigation. Last but not least, they emphasize the many co-benefits arising from implementing adaptation measures, e.g., improving living standards, diminishing social inequalities, and fostering political participation. Towards the end of their essay they bluntly summarize their standpoint by concluding: "In the decades to come one must increasingly think about the feasible. And the feasible is precautionary adaptation – for the good of all".

By way of contrast, we emphasize and explain here the strong symmetry between adaptation and mitigation strategies in terms of difficulties of implementation. We hold that adaptation is no smaller a challenge than mitigation – if addressed seriously. Considering the large-scale planning challenges and conflicts of interests involved, one realizes that coordinated adaptation is by no means the more easily feasible of the two. We develop our argument by undertaking a thought experiment, in which the response to climate change is either a pure strategy of adaptation or of mitigation. The two strategies are compared in terms of five characteristic dimensions illustrated with examples related to the melting of mountain glaciers where possible.

1. Losers and Winners

One of the great hurdles impeding ambitious mitigation is the huge amount of fossil fuels still waiting in the ground to be exploited. Recent estimates put the remaining conventional and unconventional oil, gas and coal resources and reserves at 60 (!) times the amount of carbon that has accumulated in the atmosphere since we started burning fossil fuels during the first Industrial Revolution.[10] Those who own these resources – countries and companies alike – organize strong resistance against losing the prosperity and power arising from these possessions in the current system. Their interests are in complete opposition to those who, e.g., by pioneering renewable energies, will greatly profit from decarbonizing our societies.

When it comes to adaptation, the conflicts of interest may appear – at a superficial glance – less fierce and clear-cut. Yet, large-scale adaptation will involve important trade-offs and will also divide societies into losers and winners. One obvious example concerns adaptation to sea-level rise in the meters-range (Fig. 2).[11] Since coastal protection matched to sea-level rise of this scale becomes very expensive, societies will need to decide which coastlines to hold and which to give up. In fact, managed realignment, i.e., deliberately retreating from part of the coast, is already today pursued as a strategy to deal with rising seas.[12] Considering that over one third of the human population lives within one hundred kilometers off an oceanic coast,[13] the decision-making about adaptive measures against inundation will certainly involve strong opposition by people threatened to lose their land. Depending on the location, the infrastructural assets standing on this land may easily equal in value some of the fossil fuel deposits that are so fiercely fought about in the mitigation debate.

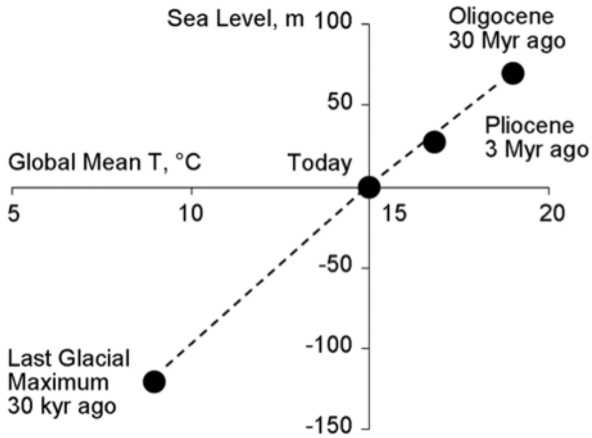

Figure 2. Estimates of changes in global mean temperature and corresponding changes in global mean sea level during Earth history. The global mean sea level was, e.g., approximately 120 meters lower than today at the height of the last ice age (around 30,000 years ago). And it was approximately 25 to 35 meters higher during the Pliocene (around 3 Mio years ago), when it was 2 to 3°C warmer than today. Thus, paleoclimatic data suggests that sea level rise on the order of 10 to 30 meter per degree of warming need to be expected – on equilibration time scales of hundreds to thousands of years. Source:[14]

At this point, we would like to make one short excursion from our comparative discussion. Many people who call for shifting the focus from mitigation to adaptation highlight the many win-win options arising when reducing the vulnerability of people to the impacts of climate change.[15] Truly, many adaptation measures improve people's livelihoods in various ways, very often serving development objectives as well. Yet, the many lose-lose risks inherent in an adaptation strategy are less often talked about. Lose-lose risks appear at the rigid limits of adaptation. Whatever the technological breakthroughs of the future, low-lying island states will not survive sea-level rise on the order of meters,[16] nor will coral reefs resist warming and acidifying oceans beyond certain thresholds (Fig. 3).[17]

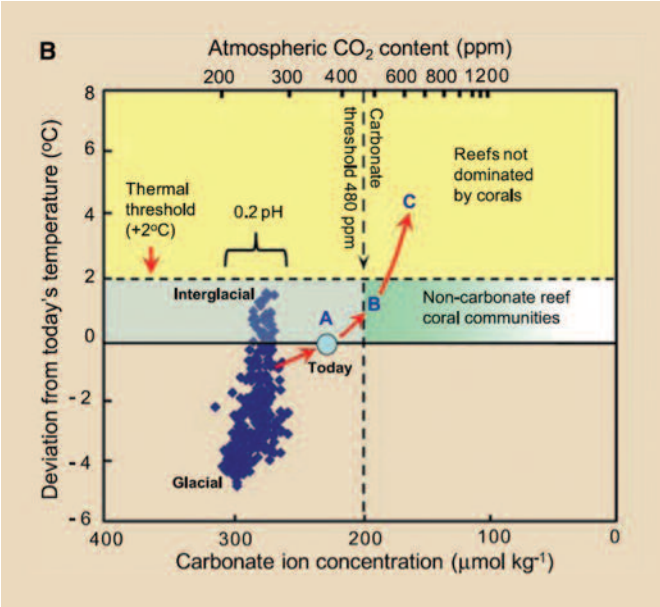

Figure 3. Deterioration of coral reefs (red arrows A to C) as temperature, atmospheric carbon dioxide content, and carbonate-ion concentrations in the ocean increase with climate change. Blue dots show reconstructions of ocean conditions for the past 420,000 years based on a Vostok Ice Core data set. The thresholds for major changes to coral communities are indicated for thermal stress (+2°C) and carbonate-ion concentrations ([carbonate] = 200 mmol kg–1; $[CO_2]$atm = 480 ppm). Source:[16]

2. Cooperation

A *conditio sine qua non* of successful mitigation is global cooperation. At the same time, since decarbonizing the energy system incurs significant costs, strong incentives to free-ride exist. Depending on the specific circumstances of a country, the optimal choice might be to profit from the reduced climate-change impacts brought about by the mitigation efforts of other countries while avoiding the costs of reducing emissions at home.[18] At first glance again, adaptation appears different in this regard. Following the prevailing misconception that adaptation happened mostly on a local scale and that those who implement adaptation measures profited from them alone, there would indeed be rather limited incentives for free riding. Yet, much of anticipatory adaptation cannot be done by individuals or small groups alone, e.g., farmers switching crop types or house owners installing air conditioning. It requires cooperative action on a regional to continental – if not global – scale.

For example, reducing the vulnerability of people to the melting of mountain glaciers requires the implementation of transnational water management in many regions. This is especially true in the parts of Asia bordering the Himalayas and the Tibetan plateau, where more than one billion people receive their freshwater supply from rivers seasonally fed by glacial and snow melt in the mountains.[19] Since irrigated agriculture is widespread in these regions, climate impacts on the so-called Asian water towers may also threaten regional food security. Recent estimates suggest that the food security of around 60 million people would be affected in the Brahmaputra and Indus basins if the melting of the glaciers were not accompanied by adaptive measures.[20] A smart system of water storage facilities, with the capacity to smoothen seasonal fluctuations in precipitation, will have to be constructed in a cooperative effort of the affected countries. However, past experiences with transnational river management, such as along the Euphrates crossing the arid regions of Turkey, Syria and Iraq or along the Nile between Sudan and Egypt, provide ample examples of the difficulties of establishing the trust required for effective cooperative schemes.[21]

3. Fair Burden Sharing

Both mitigation and adaptation come with massive financial and social burdens that need to be shared equitably. The question is whether the motives that make countries take on a fair share differ depending on whether the money is channeled into mitigation or adaptation efforts. So far, national wealth remains coupled to the carbon intensity of the respective economy. People in rich countries have emitted and still emit more carbon dioxide than people in poor countries (Fig. 4).[22] It is therefore easily argued that an equitable sharing of the costs of climate change contains significant and technological transfers from developed to developing countries. Regarding mitigation, this support should help developing countries to leapfrog to a low-carbon economy, allowing for economic growth decoupled from growth in emissions. As for adaptation, it is aimed at reducing vulnerabilities of those who have contributed least to climate change but are often disproportionally affected by its adverse effects.

The ethical arguments that may induce developed countries to provide these financial and technological funds for either mitigation or adaptation purposes can be regarded equally convincing. On the one hand, the need to finance adaptation measures in developing countries can be justified with the widely accepted polluter-pays principle.[23] Damages need to be alleviated or

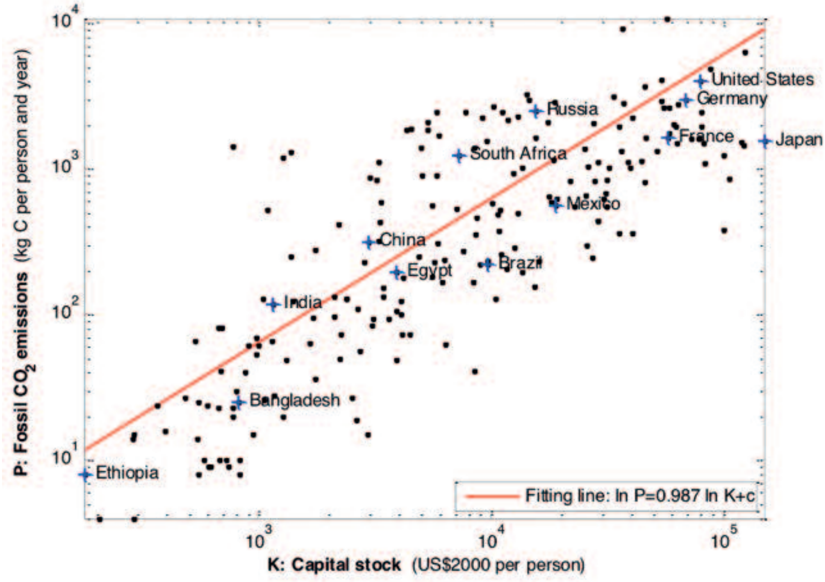

Figure 4. The relationship between national wealth and responsibility for climate change. Data was extracted from the CAIT data set as described in.[22] Source: Hans-Martin Füssel (PIK).

compensated for by those who have caused them. On the other hand, the need to finance mitigation measures follows from the legitimate claim to compensate developing countries for denying them the same access to the atmospheric carbon sink that the developed countries' wealth relies upon.[24] Ability to pay is another criterion to operationalize fair burden sharing:[25] Rich countries might be incentivized to support mitigation and adaptation in poor countries by what might be called the 'solidarity principle'.

Despite this multitude of motives the willingness of developed countries to provide mitigation and adaptation funds for developing countries remains sharply limited. Few of the funding promises given in the course of international climate negotiations have been fulfilled so far.[26] It is therefore helpful to also compare the direct incentives beyond normative considerations that make developed countries engage in mitigation and adaptation efforts in the developing world. And in this regard mitigation and adaptation are different.

Supporting adaptation abroad may indirectly serve a country's self-interest because it opens new markets for technologies manufactured at home and it reduces the risk of political instability triggered by massive migration from countries strongly affected by climate change. Yet, judging from the perpetual under-achievement of development aid targets, which are motivated by similar expectations, regarding indirect benefits, these incentives are obviously weak. By contrast, supporting mitigation abroad brings about direct advantages in the form of reduced climate change impacts at home. These may serve as much stronger incentives to take a fair share of the global mitigation cost burden – at least in countries that deem themselves vulnerable to global warming.

4. Time Dimensions

In recent years scientists have come to realize that, despite the extremely complex machinery of the Earth System, a surprisingly simple relationship exists between carbon dioxide emissions and the magnitude of global warming: In first-order approximation, the rise of global mean surface temperature is directly proportional to the cumulative amount of carbon dioxide that is added to the atmosphere.[27,28,29] It follows from this finding that the peak of global emissions needs to be reached in the coming decade for the world to have a fair chance to avoid dangerous climate change.[30,31] Any extra ton of carbon dioxide that reaches the atmosphere today takes a bite out of the global carbon cake left. If one waits too long the emissions reduction rates needed to stay within the given carbon budget are eventually so high that they become practically unfeasible (Fig. 5).

This enormous urgency of taking ambitious mitigation actions is often contrasted with the time it takes until serious impacts of global warming unfold. In the eyes of many, the comparatively slow rates of climate change give the world ample time to implement appropriate adaptation measures. For example, rates of sea-level rise are often considered slow enough to easily keep up by raising dikes and installing other coastal protection devices. It takes indeed several centuries – even under strong warming – until the additional heat from the enhanced greenhouse effect has penetrated into some of the largest ice masses on Earth, producing the sea-level rise they hold in store. For the Greenland ice sheet, recent model studies suggest that even when temperatures are eight degrees higher than during the pre-industrial era, it would take two thousand years until all of the water currently stored in the ice raised mean sea levels eventually by seven meters.[33]

Marx – not Karl, but the American comedian Groucho – coined the sentence: "Why should I care about posterity? What's posterity ever done for me?" This quote nicely encapsulates – tongue-in-cheek – the benefit asymmetry between current and future generations inherent in any miti-

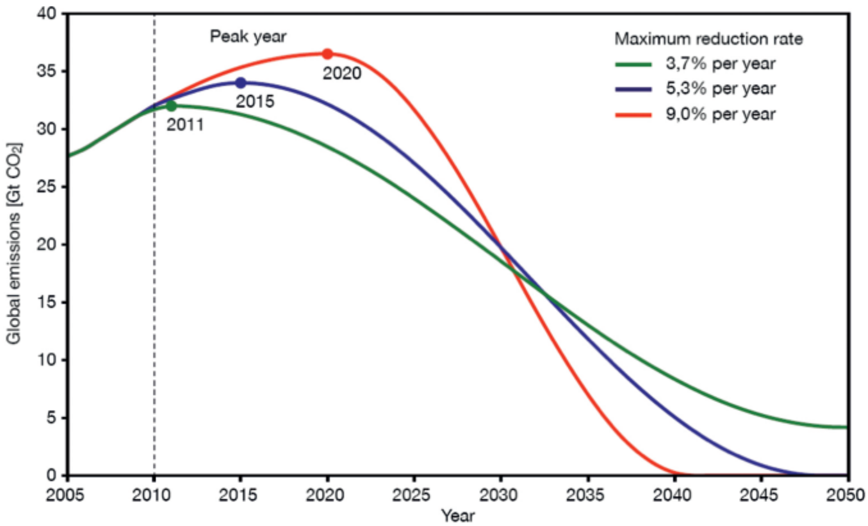

Figure 5. The urgency of mitigation. The three depicted global emission pathways comply with the same carbon budget yielding a probability of two thirds to confine global warming to 2°C. As the peak in emissions is further delayed (from 2011 to 2015 to 2020) the maximum rates of annual emission reduction to stay within the budget are magnified. Reduction rates at the order of >5% per year are extremely ambitious. For comparison, building power plants emission free from now on until mid-century would only result in mean annual emissions reductions of 0.7% per year.[29] Another yardstick is the Kyoto Protocol that foresaw emission reduction of 5.2% over a five (!) year period. Source:[32]

gation strategy. While current generations have to pay the costs of creating a low-carbon society, the advantage in terms of avoided impacts will be reaped by future generations. This time lag between incurring of costs and distribution of benefits arises from the inertia in both the climate and energy system, and because many impacts do not generate significant damages until global warming will have heavily progressed. Low-lying island states provide a particularly vivid example of current versus future generation trade-off. Very ambitious mitigation aimed at holding mean global temperature rise below 1.5°C increases the chance that these islands avoid disappearing in the rising sea.[34] Yet, the current inhabitants of these islands, whose economies are largely based on tourism, could be forced to pay a high price if stringent mitigation required abandoning long-haul air travel.

By way of contrast, the popular perception of adaptation implies no such clear trade-offs between the interests of current and future generations.

Adaptive measures are most often considered direct responses to immediate needs of people affected by climate change. According to this view, costs and benefits fall largely upon the same generation. In addition, climate change is thought to aggravate many problems that existed before.[35] In these cases, reducing the vulnerability of people in the face of climate change often requires addressing the multifactorial causes of these problems. Therefore, investments into anticipatory adaptation measures – implemented before serious climate change impacts become apparent – would not only pay-off in the future but would result in immediate co-benefits today. Malaria endemicity over the twentieth century, for example, has largely been determined by factors other than climatic influences.[36] An adaptation strategy would thus need to include investments in direct disease control, which would save lives today as well as under future climate change.

Based on the aforementioned arguments, mitigation and adaptation seem to differ substantially with regard to the urgency of action, and the time lag between arising costs and benefits. Yet, the difference becomes much smaller if one takes into account the following three aspects. First, the pace of climate change has often been underestimated in the past.[37,38] The urgency of taking adaptation measures may thus be much greater than often considered. This is especially true if one bears in mind that adaptation comprises more than local ad-hoc measures and rather requires long-term planning. Recent studies suggest, e.g., that under business-as-usual global mean sea-level is likely to rise around a meter until the end of this century[39] – despite the time it takes for the largest ice masses to melt. Also, it is often overlooked that due to ocean dynamics and gravitational adjustments some regions, especially around the Indian Ocean and Western Pacific coasts, will experience sea-level rise up to 45% higher than the global mean (Fig. 6). Coastal protection at the required scale is unlikely to be built in a few years – enhancing the urgency of taking action.

Second, similar to the situation faced with mitigation projects, huge up-front investments are needed to realize large-scale adaptation measures – investments that would not necessarily pay-off in one generation. For example, water management infrastructure of the size of the Chinese Three Gorges Dam might be needed to deal with the increased flood risk after glaciers will have disappeared in the Himalayas and on the Tibetan plateau. While the construction of that dam took only around fifteen years, the first drafts existed since the 1940s but were put on hold due to political and economic reasons until the 1980s.[41] And if China were a democratic country the time between returning to the project in the 1980s and its completion would have probably been much longer – if the project had been

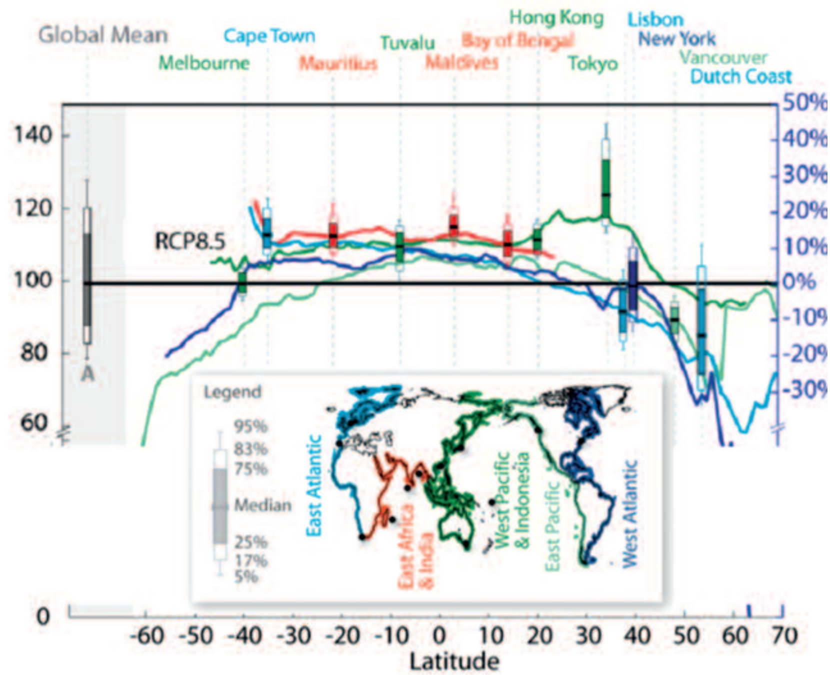

Figure 6. Projected sea-level rise along the world coastlines for the 21st century, based on a high-emission scenario (producing around 4.3°C warming until 2100). Coloured lines show regional sea-level projections, averaged over coastal areas, over latitude, and for various oceans (selected coastlines are highlighted on the map). They are presented as deviations from the global mean sea-level rise (cm), indicated by a horizontal black bar. Particular locations are also shown (black dots on the map, and vertical dashed lines with labels above). Source:[40]

realized at all. Another example is the idea of eco-migration corridors that would allow species to freely move to higher latitudes once adaption to higher temperatures was no longer possible. In our fragmented contemporary landscapes, which comprise mosaics of public and private land, establishing these corridors would most likely require decades of negotiations between landowners and conservationists.

Third, one should not forget the many co-benefits of mitigation efforts that (similarly to the much-debated positive side effects of adaptation) might arise immediately. There are, e.g., indications that many geopolitical conflicts were quickly resolved if countries depended less on fossil fuel imports. A more specific example involves black carbon (the main constituent of soot), which contributes significantly to the melting of ice caps and mountain glaciers.[42] Reducing black carbon emissions could therefore be an effective mitigation measure complementing efforts to reduce greenhouse gases. A large share of black-carbon emissions are produced by individual households burning biomass as their main or exclusive energy source.[43] Providing these households with cleaner forms of energy would not only result in long-term benefits by slowing the rate of glacier melt, but would also directly reduce indoor air pollution, which is a serious health problem in many developing countries.

5. Uncertainty

The climate-change problem can be appropriately described as a cascade starting with socio-economic developments, running through carbon dioxide emissions, carbon dioxide concentrations, global and regional mean temperature rise, and ending at impacts of all kinds. Moving from one level of the cascade to the next, the characteristic uncertainties one encounters do not all have the same nature. Some aspects simply keep sitting in the haze because they are strongly under-researched. Others, such as many socio-economic factors and climate-change impacts, involve complex dynamics that engage a virtually endless number of variables and are extremely difficult to decipher. Some of the involved uncertainties are irreducible altogether – irrespective of the intensity of the pertinent research effort. It has been shown, for example, that the long tail of the probability density function of climate sensitivity – in other words the possibility that a relatively small amount of extra carbon dioxide in the atmosphere causes a relatively strong global-warming effect – is a fundamental characteristic of the climate-change problem. More observations and more models would not permit to significantly constrain the range of possible climate sensitivities.[44,45] Last but not least, besides all of these 'known unknowns' one should not forget the 'unknown unknowns' – responses of the Earth System that nobody has thought about yet.

To what extent do the involved uncertainties affect mitigation and adaptation strategies differently? For simplicity, we neglect uncertainties about socio-economic development, in particular uncertainties about economic costs, and consider the truncated cascade from carbon-dioxide emissions to climate impacts only. While adaptation and mitigation are equally affected by the uncertainties about carbon sensitivity (linking emissions with concentrations) and climate sensitivity (linking concentration with temperature rise), the largest differences between mitigation and adaptation arise at both ends of the cascade.

Clearly, a pure adaptation strategy would need to be adjusted to the whole suite of potential impacts. The better the impacts are known the more effectively adaptation measures can be designed. Mitigation is different in this respect – at least if mitigation targets are set according to the 'precautionary principle' instead of a cost-benefit-analysis.[46] The target is determined as to avoid impacts that – based on the present knowledge – are deemed dangerous. In fact, limiting the increase in global mean temperatures to less than 2°C – a goal acknowledged by all states at the last international climate summit in Cancun – is gauged particularly at the vulnerable large-scale features of the Earth System (so-called tipping elements; Fig. 7) that were at risk of undergoing abrupt or irreversible change if warming progressed unabated.[47] One could also say that the 'precaution-

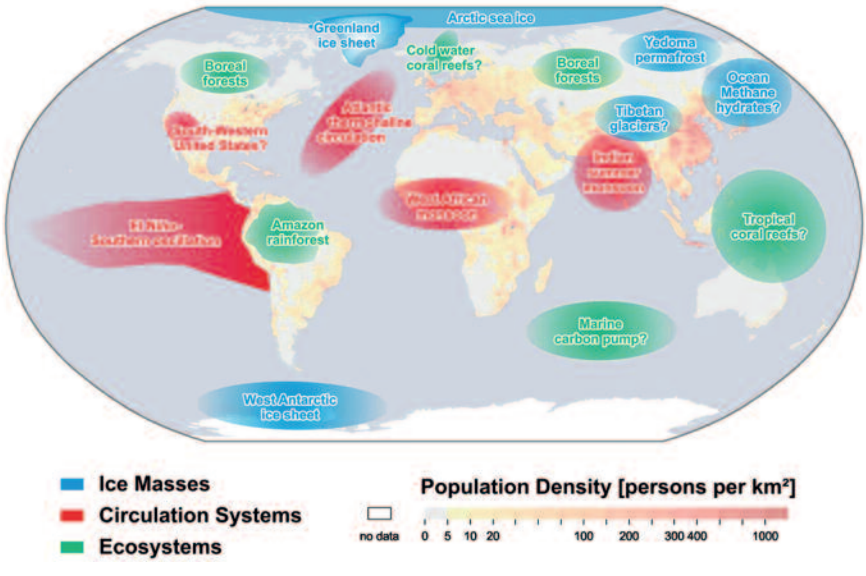

Figure 7. Map of the most important tipping elements in the Earth System overlain on global population density. Tipping elements are components of the Earth System that are sub-continental in scale and could be tipped into qualitatively different states by small external perturbations. The environmental impacts would be profound and could endanger the livelihoods of millions of people. There are three groups of tipping elements: disappearing ice bodies, changing circulations of the ocean and atmosphere, and threatened large-scale ecosystems. Question marks indicate systems whose status as tipping elements is particularly uncertain. Source: updated by Potsdam Institute for Climate Impact Research based on[47]

ary principle' aims at steering clear off the realm of exploding uncertainties. It does not matter that we don't know how each of the dangerous impacts would exactly play out as long as we know how to avoid them.

And here – as pointed out in the preceding section – the Earth System renders us an undeserved service. When a set temperature target is translated into allowable emissions, the temporal emissions profile is irrelevant as long as the determined budget of cumulative emissions is respected.[48] In other words, we can ignore the time dimension since all that counts is where the dangerous impacts are located in temperature space. Temporal characteristics of emissions and impacts, by contrast, matter for adaptation. The speed of emissions increase and the pace of unfolding impacts are critical for planning and implementing adaptation measures in time. For mitigation there is one simple safe bet: The more emissions are reduced, the more impacts are avoided. Emission reduction is the obvious lever. By contrast, following an adaptation strategy involves inherently larger uncertainties because the lever needs to be placed on the frayed, fuzzy end of the emission-to-impacts cascade.

This difference is probably also one of the reasons – besides the asymmetry in research efforts devoted to mitigation and adaptation in the past – why the costs, technologies and tools of adaptation have never been spelled out like those of mitigation. For example, climate economics is today in a position to characterize the changes in the global energy mix that are required over the coming century to comply with a chosen climate target (Fig. 8A). A relatively solid knowledge base has accumulated about technologies that are interchangeable in the mix (e.g., renewables and nuclear energy) and/or irreplaceable (e.g., carbon capture & storage and biomass for ambitious mitigation).[49] As of today, no such comprehensive analysis exists for adaptation tools. Figure 8B depicts an illustrative mix of adaptation technologies to deal with water shortages in Asia as mountain glaciers continue to melt. For the time being such a figure remains the product of educated fantasy. Neither the necessary technologies nor their respective shares in the mix have been identified through scientific procedures. Thus it is not exaggerated to say that at the current stage we know very little of what and even less of how to adapt to in a world that is several degrees warmer than today.

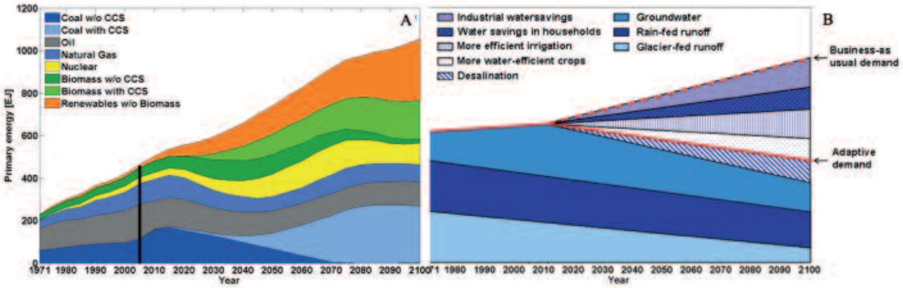

Figure 8. Exploring mitigation and adaptation pathways in terms of resources and measures to fulfill (A) global energy and (B) Asian water demands until 2100. While panel A is based on actual observations and model results panel B is an illustrative sketch only. To our knowledge adaptive capacities have not yet been investigated comprehensively enough to construct the figure of panel B based on actual calculations. Sources: panel A produced by Jan Steckel (PIK) based on IEA Data (1971-2005) and REMIND results for 450ppm-eq (ADAM); panel B produced by Veronika Huber.

Conclusion

While adaptation may seem more feasible than mitigation at the first glance (e.g., regarding the reduced need for international cooperation and the lesser urgency of action), major challenges and impediments become apparent at a second glance. In view of the ever more discouraging prospects for stringent mitigation – while climate change is incessantly proceeding – the world cannot rely on adaptation miracles to happen. Mitigation needs to remain a cornerstone of dealing with climate change.

At present, a peculiar 'horse trading' takes place on the international stage. The rich countries buy the right to continuously emit large amounts of greenhouse gases in exchange for vague promises to support adaptation in developing countries. Yet, the truth of the matter is that the poor short-sightedly give away their rights of atmospheric access[32] – like Esau sold his birthright for a mess of pottage. On the one hand, large portions of the financial flow from developed to developing countries still risk ending up in the pockets of ruthless potentates leaving the penniless and weak no less vulnerable to the impacts of climate change. On the other hand – and this is our message here – the true scale of adaptation measures is left out of the bargain. If adaptation were traded for what it really is, the rich would probably no longer agree to the deal currently on the table.

Clearly, adaptation cannot be taken lightly but requires serious efforts, in particular at the level of international governance and within the scientific community. Our comparative analysis has shown that, inter alia, new initiatives and ideas are needed to i) resolve conflicts between potential losers and winners; ii) foster international cooperation on adaptation projects; iii) incentivize fair burden sharing beyond national self-interest; iv) encourage planning of large-scale adaptation projects that will only pay-off in the long run; and v) fill the enormous knowledge gaps about the exact targets and tools of adaptation.

These efforts will not help to keep the mountain glaciers intact. Yet they will increase the chance that the children and grandchildren of those who marvel at these mighty masses of ice and snow today will be able to live a decent life after all.

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