The temporal dimension of coastal adaptation to climate change

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Abstract

While it is pretty obvious that actions for reducing the emissions of greenhouse gases into the atmosphere ("mitigation") need to be implemented as soon as possible for being effective, the time dimension of adaptive measures, for dealing the with consequences of non-avoided climate change, is considerably more complex.
A major factor is the uncertainty of the perspective of change; this depends on the efficiency of mitigation, but also on presently insufficient knowledge. This uncertainty will be reduced slowly and continuously in the future, when more data are available for analysis and constructing robust knowledge. Thus, for adaptation the predictive challenge is not only the prediction of, say, sea level, but also of the timing, when such predictions will be become robust.
However, even if the data base for determining the climate sensitivity and the speed of sea level increase will be better in 10 and more years, new so far overseen problems may be detected. Thus, likely new uncertainties will probably emerge, but postponed future decisions may take these into account.
The key temporal issue is the decision when to implement adaptive measures – in view of the steady improvement of technological and managerial options. Now, some options may be immature, and in some future, possibilities may be greatly improved. On the other hand, presently implemented measures for, say, improving coastal defense, should be designed in a manner so that future modifications are not ruled out.
These temporal dimensions will be discussed with the situation of the rising water levels in Hamburg port.

Keywords: Climate change, adaptation, Hamburg port, investment under uncertainty

I. Introduction: Which science is settled?

The frequently voiced assertion „The science is settled" is misleading, because of its lack to discriminate between those issues, which are really clarified, and those which are still subject to research and geophysical interpretation.

Beyond dispute is that the climate system is getting warmer – specifically: faster than what would be plausibly caused by natural processes ("detection"). An explanation of this faster-than-normal warming is successful only if increasing greenhouse gas concentrations in the atmosphere are considered dominant ("attribution"). Besides the intensifying anthropogenic greenhouse effect other drivers play a smaller role, such as land-use change and changing atmospheric aerosol loading.

Connected with the warming are changes in climate variables, which are directly associated with temperatures, such as heat-waves, snow cover or ice coverage on rivers and lakes. An ongoing intensification of the hydrological cycle, and embedded into it the formation of extreme precipitation events, is plausible, but the observational evidence is less commanding that that concerning temperatures.

Not yet resolved are questions on regional details, in particular concerning wind storms, the speed of sea level rise. Also, the quantitative role of reduced (Europe) and increased (China) aerosol loads on the regional climate is not yet clarified.

This is a selection of issues, which illustrate the level of uncertainty. Indeed – as common in science – the overall uncertainty is not reduced by more research but increased, simply because new questions are generated. But this general increase of open questions does not imply that the uncertainty related to the fundamental issues would also grow. Quite the contrary, the clarification of the fundamental questions (such as the reality of warming and the need of assigning greenhouse gases a dominant role in this warming) has been challenged for many years by many scientists, but all attempts for falsification have failed so far.

Of course, as with all scientifically constructed knowledge, some doubts remain. But in many cases these doubts are really miniscule and do not represent legitimate arguments for not recognizing this knowledge as conditioning in societal decision processes. On the other hand, scientific knowledge hardly determines which decisions are taken, but they are part of the spectrum of arguments entering the decision process.

II. Climate policy: Adaptation and Mitigation

The recent climate change, and the related impacts on societies and eco-systems, results from societal activity; as such it can be steered, at least in principle. Also the impacts of climate change can be cushioned by societal measures. A climate policy which will lead to the prevention of any change, will not be possible; in the same vein, adaptation to a completely unmitigated climate change seems hardly doable.

Thus, adaptation and "mitigation" (the reduction of greenhouse gas emissions) are the two options for dealing with the societal challenge of man-made climate change.

Quite some physicists have the perception that a good analysis of the dynamics would allow for an optimal mix of adaptation and mitigation, so that societal decisions would be limited to the provision of norms. However, this perception is inconsistent with societal reality, where socio-cultural constructions contribute, limit and condition societal decision processes – in competition with scientific constructions.

The *Conference of the Parties* (COP) has agreed in 2015 that measures shall be installed so that the warming will be limited below 2 K, for instance 1.5 K, at the end of the present century. Such a successful mitigation of anthropogenic climate change would, however, not lead to a halt of the rise of sea level. Irrespective of the scenario of future developments. This increase will go on, albeit with a possibly reduced speed.

It will be seen, if the goals of the Paris agreement will be reached. But, even if so, the ongoing climate change will not come to an end. The warming will go on, possibly double. Thus besides the efforts for ending net-emissions of greenhouse gases or the installment of large-scale negative emissions, adaptation will be a significant topic on the agenda of climate policy.

Such adaptation-policy will not replace mitigation policy; instead both will be pursued at the same time, but not by the same actors. **Adaptation will have priority for municipalities and regions**.

III The case of rising water levels

Global scenarios of future climate change announce the possibility for massive sea level rise in the coming century. The knowledge base is far from being settled, and the ranges of plausible sea level rises undergo significant changes from an IPCC report to the next (Figure 1, [1]). In any case, these plausible and consistent estimates (i.e., scenarios) hardly rise by more than 1 m at the end of the 21st century.

The IPCC expectations are not widely shared by the scientific community. In a survey international scientists were asked what they think about the numbers in the 4th report from 2007 (Figure 2; [2]). A small majority of 52% recognized the IPCC numbers as realistic, but almost 50% did not so. About 2/3 of these critical voices suggested higher numbers and 1/3 smaller ones.

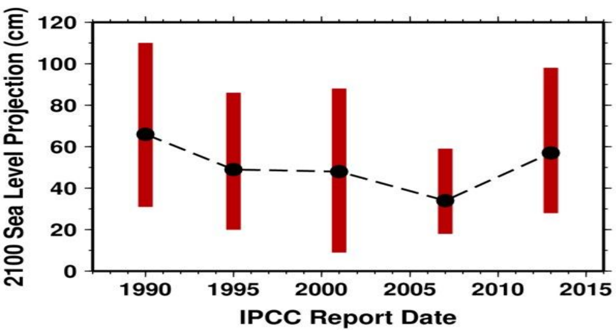

Figure 1: Expected ranges of possible future sea level rise and the end of the 21st century as estimated by the past five IPCC reports. [1]

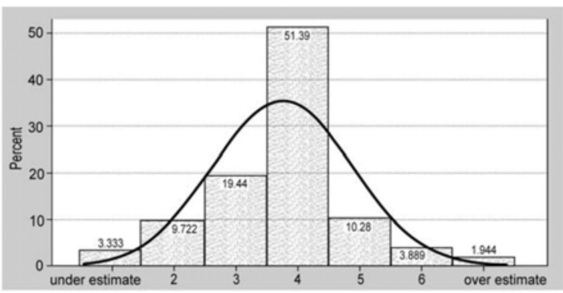

Figure 2: Assessment of climate scientists, if the ranges of expected sea level rise given in 2007 report of the IPCC is realistic (4), or if these numbers are too low (1-3) or too high (4-7). [2]

To first order approximation, the sea level rise is driving not by the air temperature change itself, but by the turbulent heat flux from the atmosphere into the ocean [3]. Given the increase in air temperature, the effect on the ocean is delayed, and will continue for decades or even centuries after the air temperature is no longer rising.

An ongoing linear trend since the 19th century would hardly be related to the anthropogenic warming, as a noteworthy warming has emerged only in the since the middle of the 20th century. Other drivers behind an extended linear trends should be sought, for instance the recovery from the so-called Little Ice Age.

The estimation of the changing global mean sea level is a challenge – reliable satellite-based data are available since 1993; tide gauges are in operation at many coastal locations since the 19th century. Analyzing the latter, a slow mostly linear increase of about 1.1 mm/year until 1993 was detected, and thereafter an acceleration to 3.3 mm/year [4].

Thus, the development of the global mean da level rise is consistent with the explanation that a major part of it may be traced to the ongoing emissions of greenhouse gases into the atmosphere.

In many port cities and coastal regions, an increase of sea level by one meter will represent a significant challenge, in particular when recognizing that the increase will not come to an end with the cessation of the warning. Measures to deal with the challenge, needs time. Installing new coastal defense is not only a costly but also a time-extensive effort with lengthy handling times.

Also, since the sea level rise does not happen in surprising jumps but emerges as a continuous process, the timing of fortifying existing coastal defense measures may often not be a matter of very few years, but maybe a matter of a few decades. This makes adaptation very different from mitigation – in the latter case a postponement will degrade the chances for limiting the warming (and related changes).

Thus, for the decision process a number of conditions prevail:

a) **The knowledge about the timing and intensity of the sea level rise is uncertain. This uncertainty will be diminished in the coming decades.**

b) **The related risk is gradually increasing; in most cases immediate enhanced fortification for meeting climate change is not necessary.**

c) **The rise in sea level will not come to a halt at the time of ceasing warming, but will continue into the 22nd century.**

Installing and improving adaptive measures represent investments. A key element of the associated theory: "investment under uncertainty" [3] is the insight that the timing of the investment offers opportunities – for observing developments, or finding alternatives.

Building, say, a new dike now for the end of the 21st century will cost a certain amount now, but it would likely be too high, as it must consider pessimistic, possibly overly pessimistic expectations. An alternative would be postponing the fortification – then the sunk costs would be smaller, but there would be the risk that an unexpected strong sea level rise would lead to an inacceptable hazard before the originally postponed fortification is in place. Another alternative would be to fortify the existing defense in such a way that in future further fortifications may be installed with less efforts if needed. This leads to additional costs in near future, but less than building a new system now. And it goes with the option of investing later more, or not. When doing a cost-benefit analysis, the costs associated with this option has to be taken into account, according to the "Investment under uncertainty" theory [5].

Another complication is that other drivers may contribute to the relative movement of land and sea, such as gas extraction and groundwater extraction, land compactification [6] or coastal defense and river channeling [7]. Of course also natural geophysical processes such as movements of the crust may contribute to the changes in the coming decades of years. These effects may be significant but go with different time scales than the rise due to global warming [8]. Thus, a fourth insight has to be added to the above list

d) **The change in sea level rise may only be partly related to anthropogenic climate change; other factors, in particular local and regional ones, may at work – and subject to planning and future modification.**

For efficiently planning for the future, some bookkeeping is needed about the present uncertainties and how they may change:

- The geophysical state, which is for various reasons variable. With respect to sea level, we know that it is rising, but we there is high uncertainty about the speed of change.
- The knowledge about future changes of the geophysical state, in particular with respect to overseen risks or possibilities, and the contributions by different parts of the system. With respect to sea level, we may expect these uncertainties to shrink.
- The technological-organizational options for adaptation: Concerning sea level, we may expect that the set of options will increase, except if some options are made impossible because some presently available requirements are annihilated.
- The societal values and preferences. In case of sea level and the risk of flooding, such changes can hardly be envisaged.

Given these expected developments, adaptation decisions may be well advised to recognize the general recommendations:

e) Postponement of decisions to the extent possible.

f) All modernizations should be designed without limiting possible future additions in the adaptive system.

IV The case of Hamburg port

We discuss the issue of how to adapt to changing risk of flooding for the port of Hamburg. In this case climate change goes with a rise in sea level but not with significant change in storm-related water levels (see below). At least, until 2018 no systematic changes in regional storminess has been detected.

Hamburg is located at the tidal river Elbe, about 100 km inlands; at the mouth of the river, a tide gauge is operated in Cuxhaven since the 19th century. Until about 1960 the tidal high water in Hamburg (St. Pauli) was about 35 cm higher than in Cuxhaven (Figure 3); in the 1960s to the 1980s the difference gradually increased, until a new almost stationary difference of 70 cm emerged. Similar changes were observed in the other German estuaries. The cause of this change is attributed to water management efforts in the rivers, such as dredging shipping channels and straightening of costal defense lines [7].

Thus, the risk of flooding in Hamburg depends not only on the sea level of the North Sea but also on regional morphological conditions, which are subject to engineering modifications. Thus, such modifications may amplify the risk of flooding but may possibly also be exploited for mitigating it [9].

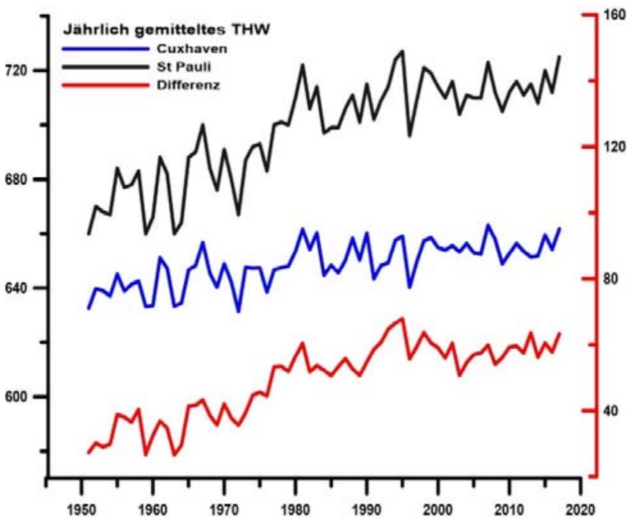

Figure 3: Changing annual mean tidal high waters in Hamburg (St. Pauli; top), in Cuxhaven (middle) and the difference (bottom) at the mouth of the tidal river Elbe since 1950. Data provided by WSA Cuxhaven and Hamburg Port Authority.

Obviously, the global sea level is an informative scientific construct, but it does not necessarily provide significant information for regional change. For Hamburg, the state of the open ocean manifests itself through the water level in Cuxhaven, which we analyze in Figure 4.

For each year the mean high tide is determined (upper curve) and also the intra-annual 95%-percentile of variations around the mean value (lower curve).

We find that the increase of the mean is almost linear, and even stagnating since about 1990. Thus, this increase can hardly be related to the accelerated rise in global mean water level. How this discrepancy may be explained is an open question for the time being. Maybe, the missing acceleration in Cuxhaven will take place with further delay.

The percentiles are a proxy for the storm activity in the region – the time series is stationary, so that no noteworthy trend in regional storminess exists (as mentioned before) – in consistency with other studies using different proxies.

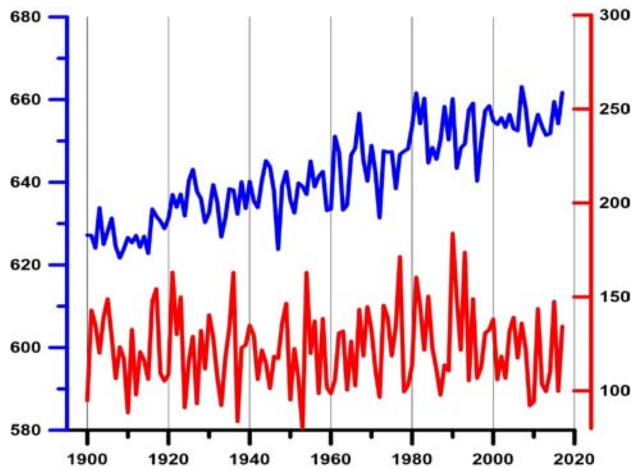

Figure 4: Annual times series of annual averages (top) and of intra-annual 95% percentiles (bottom; after subtraction of the annual mean) of tidal high waters.

V Recommendations for Hamburg port

1. Planning of infrastructure and building in a **flexible manner**, with the option to implement critical water levels at a late time of the project.
   This recommendation is motivated by the expected reduction of uncertainties between the time of planning and the time of actually building.
2. Determination of a **time horizon**, for which the critical level is stipulated. There is little doubt that the sea level will continue to rise beyond any time horizon in the 21st and even 22nd century. Thus, assuming the return of stationary conditions (in terms of geophysical states and of knowledge about it) is unrealistic. All future planning must recognize the fundamentally instationary character of risks and opportunities.
3. Using an approach like the Dutch Delta-Commissie for estimating maximum possible sea level increases [8] may allow limiting the extent of future additional strengthening of flowing defense measures. However, since the specification of such upper limits is uncertain to some extent, additional fallback plans should be prepared (such as sketched by [9]).

As an example, we have chosen 2070 as time horizon. The numbers of the Dutch commission have been modified slightly, concerning the non-change of storms, and the amplifying effect of the water in the estuary.

Figure 5 sketches the estimate, by providing expectation for Cuxhaven, a lower and a upper limit of the most extreme developments, and another curve describing the amplification in the Elbe estuary leading to higher water levels in Hamburg. The blue dots represent the changes in global sea level in 2000 and 2017, and the points in 2100 the upper limits provided by the Delta Commissie work. The lines are simple geometrical interpolations. The numbers are coarsely specified, in recognition of the inherent uncertainties of this exercise.

The resulting upper limit for 2070 is an increase of the presently used critical level by 60 cm. If we use a time horizon 50 years later, in 2120, the upper limit is strongly increased, but the robustness of these values is reduced. For 2200 the numbers are even higher, but little faith can be given to them, among others because of the very uncertain development of the greenhouse gas accumulation in the atmosphere.

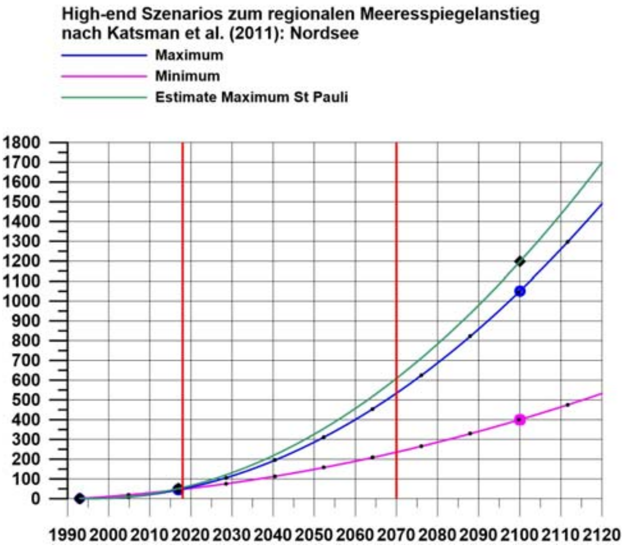

Figure 5: Ranges of expected maximum increases of water level in Cuxhaven (two lower curves; an optimistic and a pessimistic estimate, according to [8]) and in Hamburg (St. Pauli; upper curve). The red vertical bars mark the present time and the chosen time horizon of 2070. Vertical axis in mm.

If the pessimistic increases are valid, then we should expect in the coming decades strongly rising water level, with the need for significant adaptation measures to allow the usage of now planned infrastructure and buildings up to the time horizon of 2070. If no effective additional measure are possible, the continued usage of infrastructure and building would become challenging in 2070, if not impossible – and indeed in large parts of Hamburg massive adaptation measure would be needed.

If, however, the optimistic values turn out to be more realistic, the usage of infrastructure and buildings beyond 2070 seems possible.

When eventual decisions are delayed by, say 5 or 10 years, the observed changes in the future years will reduce considerably the uncertainty about the expected development. Any planning process should make sure that the empirical evidence of the latest available observations are taken into account.

Independent of climate change, further changes may take place concerning the morphology of the tidal river, or other measures which impact water levels in the port.

VI Summary and outlook

Planning future developments in the port of Hamburg have to recognize the need for adaption to changing geophysical conditions, be it due to climate change or other interventions. At the same time, the steady extension of knowledge, but also of uncertainty concerning details, must be taken into account

The key factor influencing water levels in Hamburg is the overall rise of water levels in the world ocean. The development found for the mean global sea level is not reflected in the time series assembled for Cuxhaven. This conflict must be resolved. The continuous monitoring of water level variations both in Hamburg and Cuxhaven must be continued.

High-End scenarios for the time horizon in 50 years (2070) suggest increases of 25 - 60 cm; for the time horizon +100 years, they amount to 60 – 120 cm. For 2200 increases by 100 - 135 cm are considered possible and plausible. The numbers for the 50-year horizon are robust, but for the other two horizons they become less and less robust.

A number of recommendations for the planning process have been made, among them

- Postponement of adaptation measures if possible;
- When improving adaptive measures now or in near future, this should be done to allow for future additional strengthening;
- An ongoing monitoring system must be operated to allow an assessment, to what extent the actual changes are consistent with the scenarios presented here (and elsewhere);
- Development and testing of alternative technological approaches, and of societal measures for public acceptance of adaptive strategies.

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