

# High-end climate change scenarios for flood protection of the Netherlands

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## Introduction

Sea level rise, especially combined with possible changes in storm surges and increased river discharge resulting from climate change, poses a major threat for a low-lying delta like the Netherlands. Future flood protection strategies need to take these possible changes into account. Therefore, high-impact, low-probability climate change scenarios for the Netherlands were developed<sup>1)</sup> at the request of the second Delta Committee<sup>2)</sup>. In this study, local sea level rise, changes in storm surge height and peak discharges of the river Rhine were considered. Such detailed information goes beyond the KNMI'06 climate change scenarios<sup>3)</sup> that span the range of most probable outcomes. The newly-developed high-end scenarios are discussed one-by-one below. The complex flood risk implied by the combination of these scenarios is illustrated by considering the situation near Rotterdam in the final section.

## Sea level rise along the Dutch coast

The high-end scenario for local sea level rise is constructed using the methodology developed for the KNMI'06 scenarios<sup>4)</sup>. First, separate high-end contributions for the processes that dominate the global mean changes were estimated: thermal expansion of the ocean, and mass changes of small continental glaciers and ice caps, the Antarctic Ice Sheet (AIS) and the Greenland Ice Sheet (GIS). Next, local effects are considered.

We assume that all contributions except that of AIS depend (partly) on the rise in global mean temperature, as for KNMI'06<sup>4)</sup>. A global mean rise of 2 to 6 °C in 2100 was assumed, akin to the range projected for the most severe emission scenario (A1FI) of the Intergovernmental Panel on Climate Change (IPCC)<sup>5)</sup>.

The contributions from global mean thermal expansion and from small glaciers were estimated by exploiting simple scaling laws for their relationship with atmospheric temperature rise derived from climate model results<sup>1,4)</sup>, as well as conceptual models and observations<sup>5)</sup> (Figure 1).

## Ice sheets

The contributions from AIS and GIS are the most uncertain components<sup>1,6)</sup>. The mass of ice stored on land in the ice sheets can change as a result of changes in surface mass balance (the net effect of snow accumulation, runoff and evaporation / sublimation) or by the flux of ice leaving the grounded ice sheet and entering the ocean (either as floating ice or melt water). The former is largely a response to changes in the atmosphere, while the latter is a complex response to atmospheric and oceanographic forcing and internal changes in the ice sheet of which we have limited understanding. Therefore, there is little confidence that the present generation of ice sheet models correctly

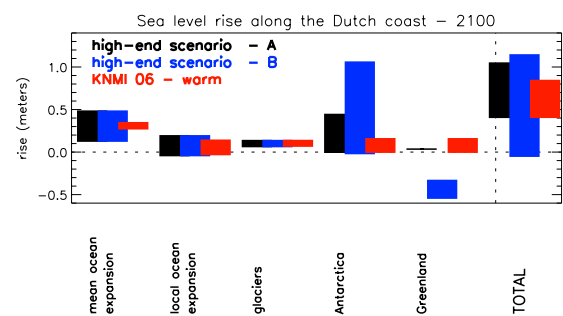


Figure 1. Individual contributions and total projected local sea level rise along the Dutch coast for 2100, for high-end scenarios A and B (black/blue) 1) and the KNMI'06 warm scenario 3).

simulates changes in ice flux in response to changing climate conditions. We therefore rely on recent observations and expert judgement to assess the possible contributions of GIS and AIS<sup>1</sup>.

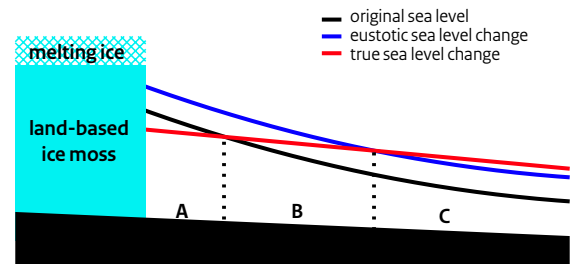
The most vulnerable parts of ice sheets are the so-called marine ice sheets (ice sheets that rest on bed rock that is below sea level and slopes downwards from the continental margin inland). Positive feedbacks in a marine ice sheet system can lead to a runaway collapse of the ice sheet, which would stop only where the retreat encountered a rising bed slope. The timescale over which such a collapse might occur is not well understood, but for large sections of an ice sheet it would probably be longer than a century. The largest marine ice sheet that exists today covers the majority of West Antarctica. The strongest inland bed slope, and hence the strongest tendency to instability, exists in that portion of the West-Antarctic Ice Sheet which drains into the Amundsen Sea (Pacific sector, near 100–110 W). In Greenland, only Jacobshavn Isbrae (on the west coast) contains a similar prominent inland slope, so that it could potentially display a sustained retreat<sup>6</sup>.

The estimated contributions of AIS and GIS in the high-end scenario for sea level rise (Figure 1) combine the model-based assessment of surface mass balance changes<sup>5</sup> with a contribution due to fast ice dynamics, estimated from observations focusing on the vulnerable marine parts of the ice sheets<sup>1,6</sup>.

## Fresh water released by land ice melt is not distributed evenly over the oceans

### Local effects on sea level

To arrive at a local sea level rise scenario, the ocean circulation changes in the North East Atlantic Ocean and their effect on local sea level<sup>4,1</sup> are assessed by analyzing climate model simulations. In addition, we take into account that fresh water released by land ice melt is not distributed evenly over the oceans. Large land-based ice masses exert a gravitational pull on the surrounding ocean, yielding higher relative sea levels in the vicinity of the ice mass (Figure 2, black line). When the ice mass shrinks, global mean sea level rises (blue line). In addition, the gravitational pull decreases, so that the actual sea level (red line) will drop in the vicinity of the ice sheet (region A) as water is redistributed away from it. Farther away from the ice mass (region B in Figure 2), sea level



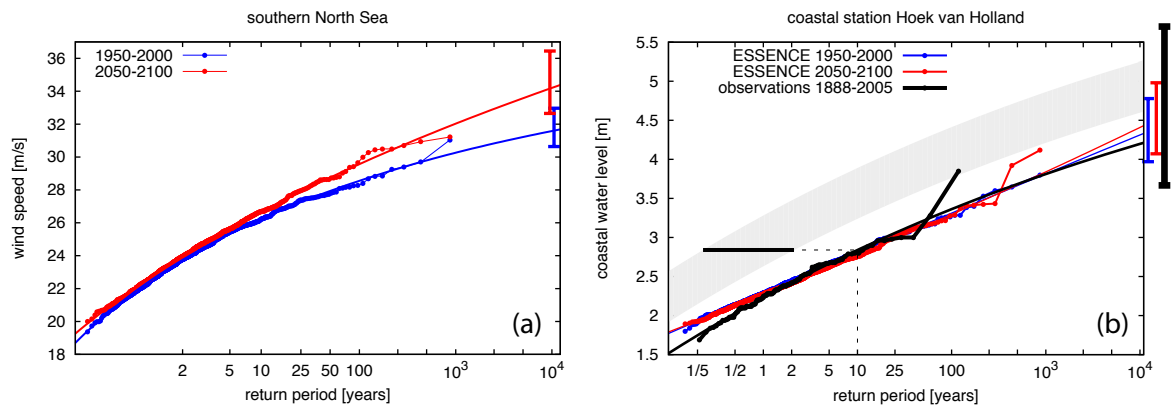
**Figure 2.** Schematic illustration of gravity effects on local sea level changes induced by land-ice melt (black line: original sea level, blue: sea level after ice melt assuming equal distribution of the melt water; red: true sea level after ice melt).

does rise, but this rise is smaller than the global mean rise that would result from equal distribution of the melt water. At even greater distances (region C), local sea level rise becomes larger than the global mean rise. Moreover, the solid Earth deforms under the shifting loads of ice and water and this deformation affects the gravity field and hence local sea level as well. As a result of these local gravitational and elastic changes, a shrinking land ice mass yields a distinct pattern of local sea level rise sometimes referred to as its fingerprint<sup>1,6</sup>. These effects can be incorporated by multiplying each of the global mean contributions from land ice melt by their respective relative fingerprint ratios. For GIS and AIS, there appear to be large (poorly understood) differences in the fingerprints published by various authors<sup>1,6</sup>. To cover the extremes, two scenarios were developed.

After summing the various components, we arrive at a plausible high-end scenario for sea level rise along the Dutch coast of 0.40 to 1.05 meters for 2100 (excluding local land movement) when quantifying the gravity-elastic effects for the one extreme (scenario A in Figure 1). Using the other extreme (scenario B), the range becomes -0.05 to +1.15 meters. Not surprisingly, this high-end scenario is substantially higher than the KNMI'06 scenario for local sea level rise of 0.35 to 0.85 meters for 2100. The main causes for the difference are the more extreme global mean temperature range that is used as the starting-point and the larger contributions of GIS and AIS due to fast ice dynamics that are included<sup>7</sup>.

### Storm surges

The height of extreme storm surges is also important for flood protection of the Netherlands. Hence, it needs to be assessed whether and how climate change affects the heights of extreme surges, and in particular the statutory once-in-10,000 years storm surge height. To this end, the



**Figure 3.** Present (blue, 1950–2000) and future (red, 2050–2100) wind speed in the southern North Sea (a) and water level at coastal station Hoek van Holland (b), as a function of the return period. In (b), also the observed values for the period 1888–2005 are shown (black). Adding the high-end scenario for sea level rise to the surge height yields a coastal water level indicated by the grey band by 2100. It implies that the Maeslant barrier (Figure 5) will need to be closed five to fifty times more often than at present.

wind fields from a 17-member ensemble climate-change simulation, in combination with an operationally-used surge model for the North Sea area were used to analyze<sup>9)</sup> surge heights at the Dutch coast for two periods (1950–2000 and 2050–2100). Wind speeds in the southern North Sea are projected to increase (Figure 3a), due to an increase in south-westerly winds. However, the highest surges along the Dutch coast are caused by north-westerly winds because of their long fetch and the geometry of the coastline. As a result, local extreme surge heights are expected to be largely unaffected by the increase in wind speed (Figure 3b), as was found in earlier climate model studies<sup>1)</sup>.

### Peak river discharge

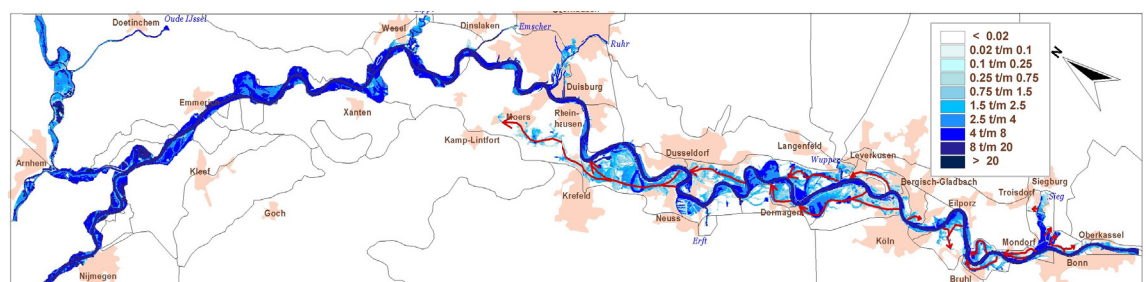
The Netherlands also faces possible flooding from the river Rhine. Several studies using climate models in combination with hydrological models indicate that the peak discharge with a 1250-years return period (statutory safety level for the major rivers) may increase by about 5 to 40% over the twenty-first century<sup>1)</sup>. In most studies,

the increase in peak discharge is caused by an increase in mean winter precipitation combined with a shift from snowfall to rainfall in the Alps. In addition, some studies project a considerable change in the multi-day precipitation variability in winter (decreases as well as increases have been reported), which in turn has a substantial effect on the peak discharge.

Another relevant factor is that the flood defence guidelines in Germany are currently less strict than in the Netherlands, and probably will remain so in the near future. As a consequence, uncontrolled flooding in Germany is anticipated in case of extreme discharges, preventing these extreme discharges to reach the Dutch part of the Rhine delta (Figure 4). Taking this constraint into account, the high-end scenario for the 1250-year peak discharge for the Netherlands for 2100 is estimated to increase by about 10%<sup>1,6)</sup>.

### Possible combined impacts: Rotterdam

The possible consequences of the combined impacts of



**Figure 4.** Example of a simulation of flooding along the lower Rhine (dike situation 2020). Given are maximum water depths [m, in blue] and main streams behind the dikes<sup>9)</sup>.



Figure 5. The Maeslant storm surge barrier near Rotterdam during a test closure (source: [www.BeeldbankVenW.nl](http://www.BeeldbankVenW.nl)).

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*The possible consequences of the combined impacts of local sea level rise, storm surges, and peak river discharge become apparent when considering the situation near Rotterdam*

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local sea level rise, storm surges, and peak river discharge become apparent when considering the situation near Rotterdam. Its harbour is protected by the Maeslant storm surge barrier (Figure 5), which closes automatically when the local water level reaches a prescribed criterion; an event that nowadays is expected to occur on average every 10 years. If the high-end projection for sea level rise presented here becomes reality, the storm surge barrier is expected to close five to fifty times more often (Figure 3b). This would severely hamper the accessibility of Rotterdam harbour, resulting in large economic losses<sup>2)</sup>. In addition, the projected increases in sea level and peak river discharge will significantly enhance the probability that the storm surge barrier needs to be closed while the river discharge is large. During closure,

the river system behind the barrier rapidly fills, increasing the local flood risk. It remains to be quantified exactly how large this risk will become. It depends among other things on the duration of the closure (which in turn depends on the duration of the storm and its timing with the tidal phase) and on the temporal storage or re-routing of the river discharge through the interacting distributaries in the lower Rhine-Meuse delta.

### Conclusion

The plausible high-impact, low-probability scenarios<sup>1)</sup> described here form the basis for updated flood protection strategies for the twenty-first century recently proposed by the Dutch Delta Committee<sup>3)</sup>. While such high-end scenarios inevitably have rather large uncertainties, the example of Rotterdam shows that evaluation of the complex, combined risks of sea level rise, storm surges and peak river discharge is crucial to updating flood management strategies.

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# Appendices



