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Sea level rise and its spatial variations

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SEA LEVEL RISE AND ITS SPATIAL VARIATIONS

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This report was written at the request of Dirk Jan Sloot (Ministerie van Infrastructuur en Waterstaat, Directoraat-Generaal Water en Bodem). It aims at helping non-specialists understand recent the sea level rise science to make better decisions. The central question we try to answer is: why is sea level not rising at the same pace everywhere around the globe? To anwser this question we focus on explaining the basic physical processes at play in sea level rise and which ones dominate total sea level at different length and time scale. This report could also serve as a entry point into the specialised literature that is cited. It forms the basis for a presentation at the Ministry of Infrastructure and Water Management.

CONTENTS

1 KEY POINTS OF THE REPORT

- **Global sea level rise is accelerating because of global warming**. Sea level rise in the 20th century had an average speed of 1 to 2 $mm/year$. It was the fastest in the last 3000 years. Sea level rise continues to accelerate and reached 4.3 $mm/year$ on average over the last 10 $years$. The main drivers of sea level rise are thermal expansion, melting of small glaciers all around the world and more recently the melting of Greenland and Antarctica, the two large ice sheets.
- Sea level rise in the 21^{st} century will be larger than in the 20^{th} century. **The uncertainty in sea level projections has increased recently because the mass loss from Antarctica and Greenland could be faster than previously estimated**. There are now two main uncertainties in sea level rise projections: the total emissions of greenhouse gases and the speed at which the ice

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sheets adjust to a warming climate. **Projections range from 0.3 to 3 m over the 21^{th} century**. It could be possible to reach 0.3 m under small greenhouse gases emissions, small resulting global warming and slow adjustment of the ice sheets while 3 m could be reached for large greenhouse gases emissions, large global warming and fast adjustment of the ice sheets. Note that the present pace of sea-level rise has increased to 43 $cm/century$.

- **Many processes lead to differences between local and global sea level**. Because of changes in the gravity field of the earth a simple counter-intuitive rule is that when land ice melts sea level rise is larger far away from the melt area. This is why for the Netherlands the future of Antarctica is more important than the future of Greenland. However, other factors like the earth rotation and the deformation of the earth's crust also have an influence so this rule of thumb is not always valid.
- **At time scales of years to decades local sea level is mainly driven by natural climate variations**: the impact of wind on the ocean currents and its transport of heat and salt. A famous example is El Niño Southern Oscillation (ENSO). Therefore decadal sea level forecasts are not possible. Local sea level projections only become useful over longer time scales (more than a few decades) when the slow drivers of sea level, like land ice melt and global thermal expansion, become dominant.
- **Subsidence, the sinking of land due to ground water pumping or oil and gas extraction can have a magnitude of more than 10 cm/y locally**. This is a lot larger than climate change driven sea level rise and can greatly increase the risk of flooding.
- **Global sea level is a good indicator for local sea level only under a few conditions:** the region is far away from the ice sheets, the ground is not sinking locally due to anthropogenic effects like groundwater pumping, natural climate variability is small and the location is far away from the location of the old continental ice sheets of the last glacial maximum. It is therefore important to be careful when translating global sea level rise to local situations.
- Climate change will change the characteristics of storms and tides and the related extreme sea levels. However **it is expected that future increase in extreme sea levels will be mainly driven by sea level rise itself**.

2 INTRODUCTION

Sea level is a very important metric of the climate system because a large part of human activities take place close to the coast. The current acceleration of global sea level rise is observed using multiple instruments: tide gauges, satellite altimetry and geological proxies. It has and will have a growing impact on human societies around the world. Therefore understanding the processes leading to global and local sea level rise and recent evolution of the scientific understanding is important.

For simplicity in this report we focus on conclusions not on the evidence that allows to reach these conclusions. For the traceability or for the interested readers the original scientific literature that provides the foundations for these conclusions is always cited. To limit the use of technical terms we will use the terms "global sea level" to talk about the globally averaged sea level and local sea level to talk about the sea level relative to the land in a specific location (formally called "relative sea level").

The report starts with a section on past global sea level rise followed by a section on future global sea level rise. These help to provide context to the following section on processes that lead to a local sea level that is different from the global sea level. The small scale anthropogenic changes in land level is treated in a separate section called "subsidence". The following section deals with two related issues. First the notion of temporal variability which is very important to understand the meaning of local sea level measurements and how it should be interpreted. Second the notion of extreme sea levels which are the rare events during which sea level is very high and has the most impact. This report finishes with a short discussion section.

3 PAST GLOBAL SEA LEVEL RISE

Over the last 3000 years sea level rose at a slow rate of between 0 and 0.2 mm/yr caused by the transition from the last glacial period to the present interglacial (Holocene) [1, 2]. From the late 19th century or beginning 20th century this relatively slow rate accelerated to a larger rate of over 1 mm/yr [3, 4]. As a result 20th century sea level rise was the fastest in the last 30 centuries [4, 5]. This is mostly due to anthropogenic greenhouse gas emissions warming the earth [6]. Different reconstructions of sea level based on tide gauge measurements show that sea level during the 20th century was between 1 and 2 mm/yr with an acceleration during the century [7, 8, 9]. The mean rate of sea level rise since global satellite altimetry measurements started in 1992 is around 3.07 mm/yr [10] with also a clear acceleration during that period [11, 12, 13]. The average rate of sea level rise over the last 10 years was 4.3± 0.3 mm/yr [10]. Over the satellite altimetry period (1992-present) the drivers of sea level rise are known with a good accuracy: thermal expansion (1.3 mm/yr), glaciers (0.65 mm/yr), Greenland (0.48 mm/yr), Antarctica (0.25 mm/yr) which gives a total trend of 2.7 mm/yr. The discrepancy between this sum of contributors and the observed rate is 0.37 mm/yr. It is probably due to terrestrial water storage that is not included in the budget because it is highly uncertain [10] but it could also be due to an underestimation of past Antarctic mass loss [14].

4 PROJECTIONS OF GLOBAL SEA LEVEL RISE

To know how much sea level we can expect in the future it helps to have an idea of the potential maximum contribution from the different sources of sea level: Antarctica 58 m [15], Greenland 7.4 m [16], glaciers and ice caps 0.4 m [17]. Thermal expansion does not have a maximum but a reasonable order of magnitude is that over long time scales (millennia) an increase of the earth surface temperature by 1°C is associated with a sea level rise of 0.4 m. We note here that sea ice, the thin ($<$5 m) layer of ice that forms at the surface of the ocean at the poles, does not contribute to sea level rise when it melts because it is already floating.

Sea level projections for the 21^{st} century depend on two major unknowns: (1) the amount of greenhouse gazes that will be emitted and (2) the speed at which the ice sheets will adapt to the warmer climate. This is why different scenarios are developed and used to help the users of sea level information make the best decisions. Assuming that the ice sheets will respond relatively slowly to global warming the IPCC AR5 report projected a sea level rise of 30 to 60 cm for a small emission scenario and 50 to 100 cm

for a large emission scenario [1]. The assumption of a slow adjustment of the ice sheets is increasingly being questioned since 2013 when the IPCC AR5 report was published. Observations of the Antarctic ice sheet show that the mass loss is accelerating faster than expected [18, 19, 14] and ice sheet models are undergoing a "paradigm change" [20] that could lead to much faster mass loss [21]. We therefore think that it is useful to investigate what would happen for scenarios with large Antarctic mass loss. For such scenarios sea level could rise between 1 and $3\,m$ this century [22, 23].

An important fact to keep in mind is that sea level will continue to rise for thousands of years even if the concentration of greenhouse gazes in the atmosphere does not increase. Current estimates are that over millennial time scale sea level rises by 2 to $10\,m$ per degree of global warming [1, 24]. This means that even if the world is successful in meeting the Paris agreement and limiting global warming to 1.5° to 2°C sea level will eventually rise by 3 to $20\,m$.

5 LOCAL SEA LEVEL

Globally averaged sea level changes are mostly driven by the melting of land ice and thermal expansion. However locally sea level is influenced by additional physical mechanisms that redistribute the water around the oceans. Even in the absence of storm the ocean surface is not a perfect sphere or ellipsoid. It depends mainly on four categories of physical processes:

1. **The earth gravity field** is not homogeneous because mass is not distributed homogeneously inside the mantle nor at the surface of the earth (figure 1). In location where gravity is stronger sea level is higher than where it is lower. The difference can be up to $150\,m$ for example between Sri Lanka where sea level is very low and Iceland where is it very high (figure 2). This physical mechanism is also relevant when land ice melts and goes into the ocean. A reduced ice sheet reduces the local gravity pull. In this case global sea level rises but within a distance of $2200\,km$ from the mass loss sea level drops. Between 2200 and $6700\,km$ sea level rises less than the global average and further than $6700\,km$ sea level rises more than the global mean (figure 3). This is the reason why the Netherlands is more sensitive to a melt of Antarctica than of Greenland while for Chile it is the opposite.

2. **The earth rotation** also has an effect on the ocean surface. Sea level is around $20\,km$ higher at the equator than at the poles, relative to a reference spherical surface, because of the centrifugal effect (figure 4). The centrifugal effect is also the reason why the earth itself has an ellipsoidal shape and not spherical. When mass is redistributed at the surface of the earth because of land ice melt the centre of rotation of the earth and the speed of rotation change. Land ice is generally closer to the poles so when it melts it reduces the speed of the earth rotation. The effect is a drop of sea level at the equator and a rise at the poles. Also the axis of rotation changes, for example recently because of mass loss from Greenland and West Antarctica the Netherlands became closer to the axis of rotation, which lead to slow down sea level rise [25].

3. **The deformation of the earth's crust** also plays a role. It can happen for two main reasons. **(1)** The long term effects of the disappearance of land ice from the last glacial maximum around 20.000 years ago. This type of adjustment is called Glacial Isostatic Adjustment (GIA). It leads for example to increased sea level rise at the Dutch coast and reduced sea level at the Norwegian coast. **(2)** When land ice melts there is also an elastic response of the earth's crust, that effect is faster than GIA, so it is already triggered by present day land ice mass loss [26].

4. **Climate dynamics effects** can also redistribute the ocean volume. The winds transfer a large amount of energy to the oceans and drive ocean currents. In turn the ocean currents transport heat and salt around the ocean. When an area becomes warmer or less salty sea level rises because its density decreases. These effects can be visualised in what is called the dynamic topography which is the sea level compared to the geoid. The geoid is the surface that the ocean would have under the influence of gravity and rotation alone, without ocean currents (figure 5).

The long term changes (century and longer) in spatial differences of sea level are mainly set by gravity and rotation. The unit in figure 2 is meter while the one in figure 5 is centimeter. For faster sea level

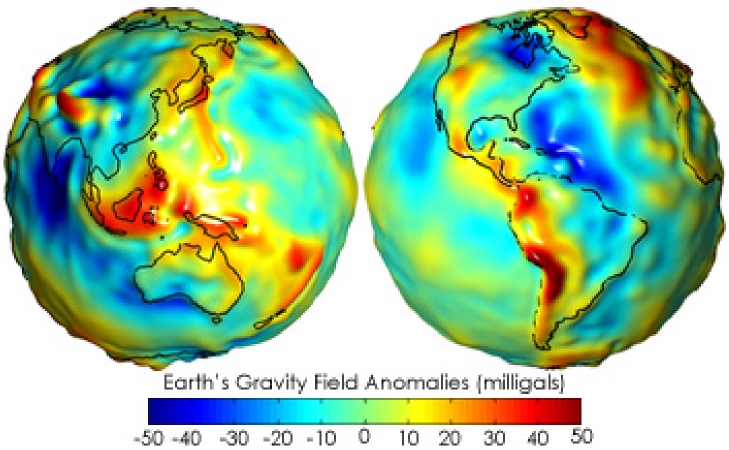

Figure 1: Earth's gravity showing deviations from the theoretical gravity of an idealized smooth Earth, the so-called Earth ellipsoid. From https://earthobservatory.nasa.gov/features/GRACE/page3.php

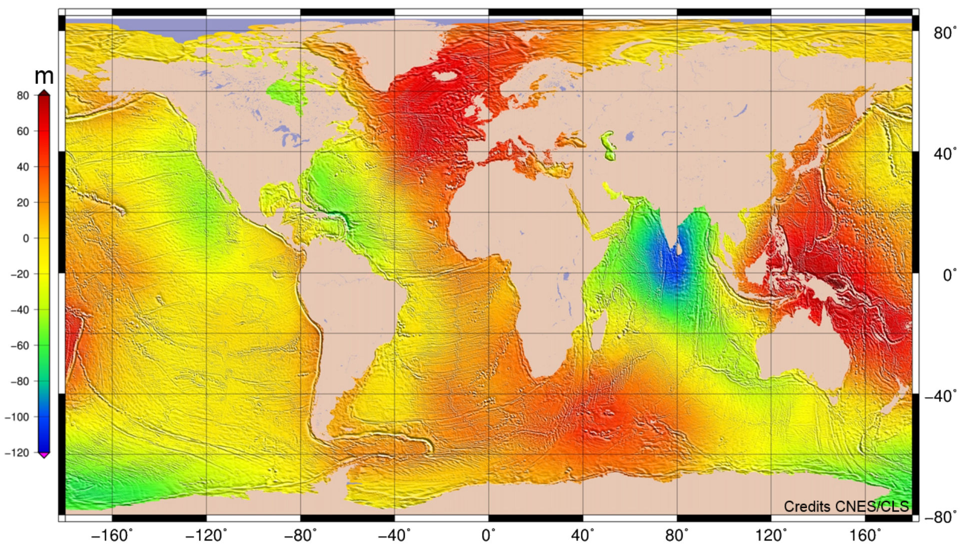

Figure 2: Mean Sea Surface compared to the reference ellipsoid. From https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/mss.html

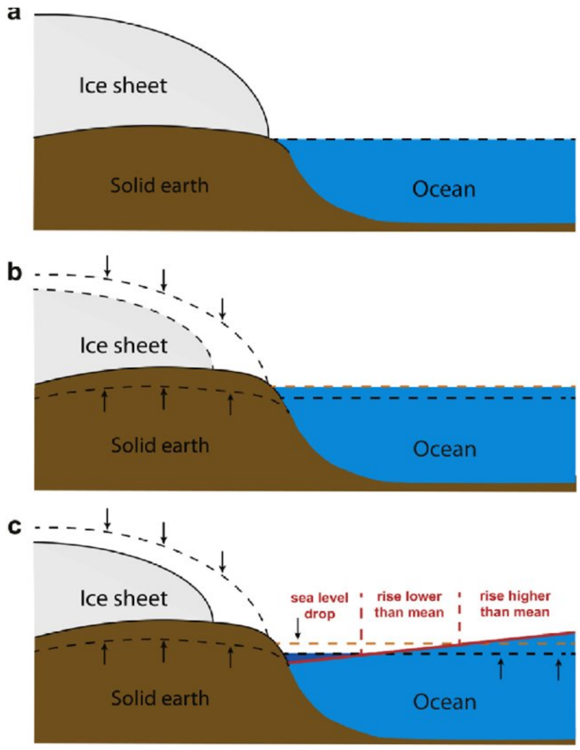

Figure 3: A schematic representation of the gravitational interaction between ice sheets, the solid Earth and the ocean. a) The initial state. b) A decrease in ice-sheet mass will result in rebound of the solid Earth beneath the ice sheet and an increase in ocean volume. In (b) we show the change in sea level as uniform, but in reality due to self-gravitation effects the sea surface will fall in close proximity to the ice sheet, it will rise by an amount less than the mean at mid-field locations, and it will rise by an amount greater than the mean at far-field locations as shown in (c) [27].

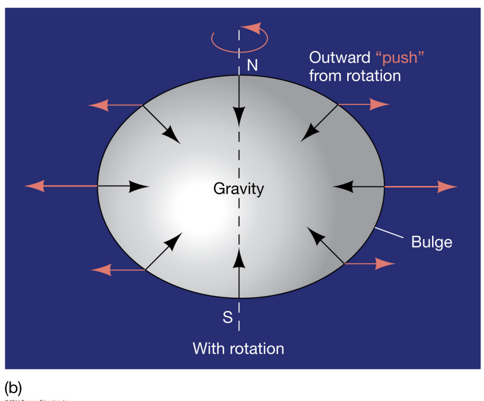

Figure 4: Effect of the earth rotation on the bulging of sea level at the equator.

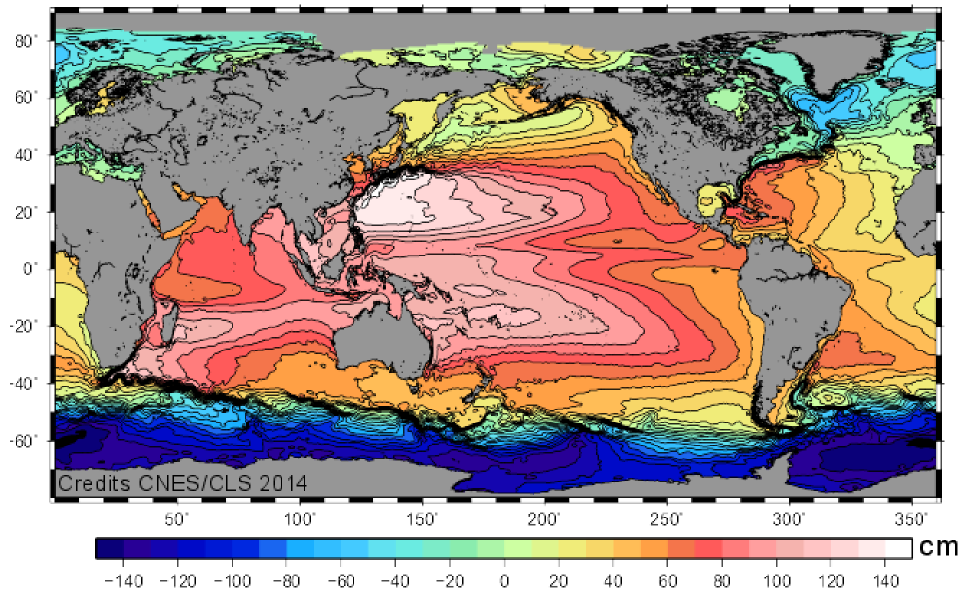

Figure 5: Climatic effects, like ocean currents and density, on mean sea level. This surface is called the Mean Dynamic Topography, it is the sea level compared to the geoid, the surface that the ocean would have under the influence of gravity and rotation alone. From https://www.aviso.altimetry.fr/en/data/products/auxiliary-products/mdt/mdt-description.html

variations this conclusion is not true because climate variations are faster than the slow land ice melt. We show the sea level trend over the last 25 $years$ observed with satellite altimetry on figure 6. In this figure we see that on top of the average $\sim 3\, mm/year$ global sea level rise there is a lot of spatial variability. This variability is mostly due to modes of natural climate variability [28]. A famous example being the El Niño Southern Oscillation (ENSO). When sea level trends are computed over longer time scales, the importance of these mechanisms reduces and the importance of gravity and rotational effects related to the melting of glaciers and ice sheets increases.

For sea level projections the climate dynamics effects associated with modes of natural variability are not taken into account. Because of the chaotic nature of ocean and atmospheric dynamics these modes are unpredictable for time scales longer than a few years. This situation can be compared with the impossibility to make reliable weather forecasts further than around 2 weeks.

If we now look at longer time scales, for example the end of the 21^{st} century. When all sources of change are added, regional variations in sea level projections have the pattern shown in figure 7. From this figure we can conclude that except for locations close to the ice sheet the majority of the world coastline is expected to have a sea level rise that lies within 20 cm of the global mean [29]. This can be explained by the fact that sea level regional pattern is composed of a few components that are sometimes compensating like the gravitational effects of Greenland and Antarctic melt. And also patterns that are uncorrelated like climate dynamics redistribution of the ocean water, glaciers and ice caps melt and GIA. We can therefore say that regional effects are important for detailed understanding and projections of sea level rise but global mean sea level rise is generally a good indicator for the local sea level rise except very close to ice sheets or in location of fast earth rebound from the last glacial maximum.

6 SUBSIDENCE

The conclusion of the previous section was that global mean sea level rise is a good indicator for local sea level rise for most coastlines on time scales of half a century or more, where the effects of natural climate variability are small. This is including large scale effects like climate dynamics, glacial isostatic adjustment, land ice melt and the related gravitational, rotational and elastic earth responses. However there are also some small scale anthropogenic effects that can lead to large subsidence, the sinking of

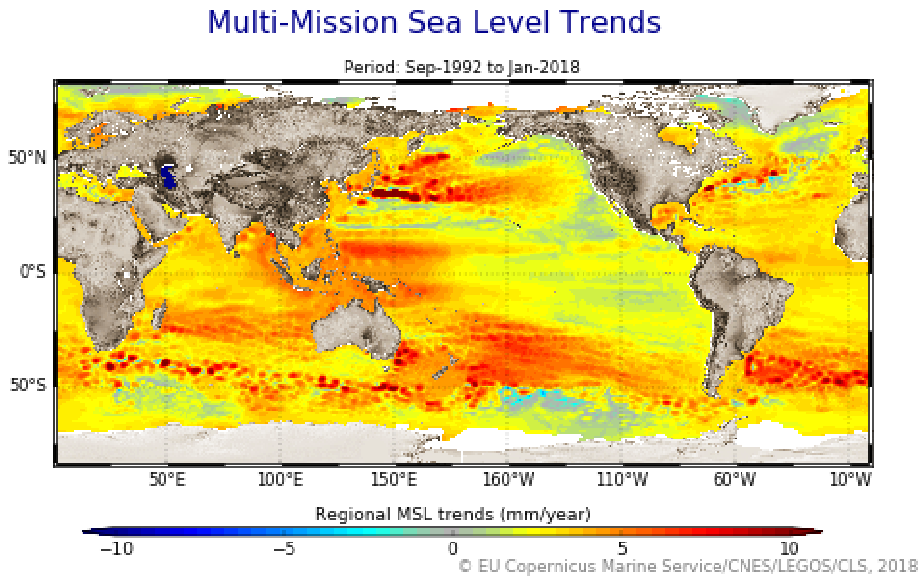

Figure 6: Sea level trend observed by satellite between 1992 and 2018. From https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html

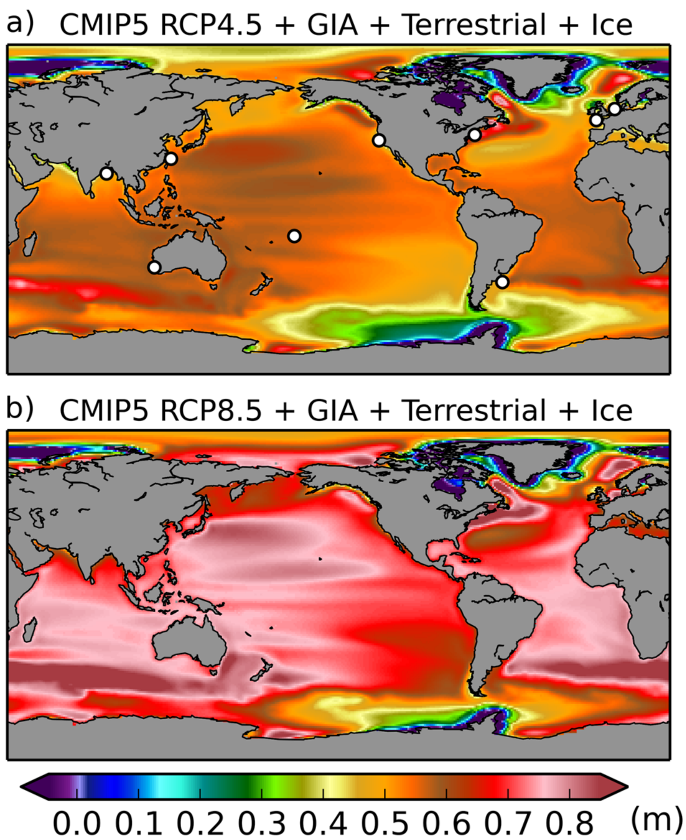

Figure 7: Regional sea-level change patterns of sea-level contributions over the period from 1986-2005 to 2081-2100, in meters, for two climate scenarios: a) RCP4.5 a medium emission scenario and b) RCP8.5 a large emission scenario. Note the similarity of the spatial pattern. Figure from [29].

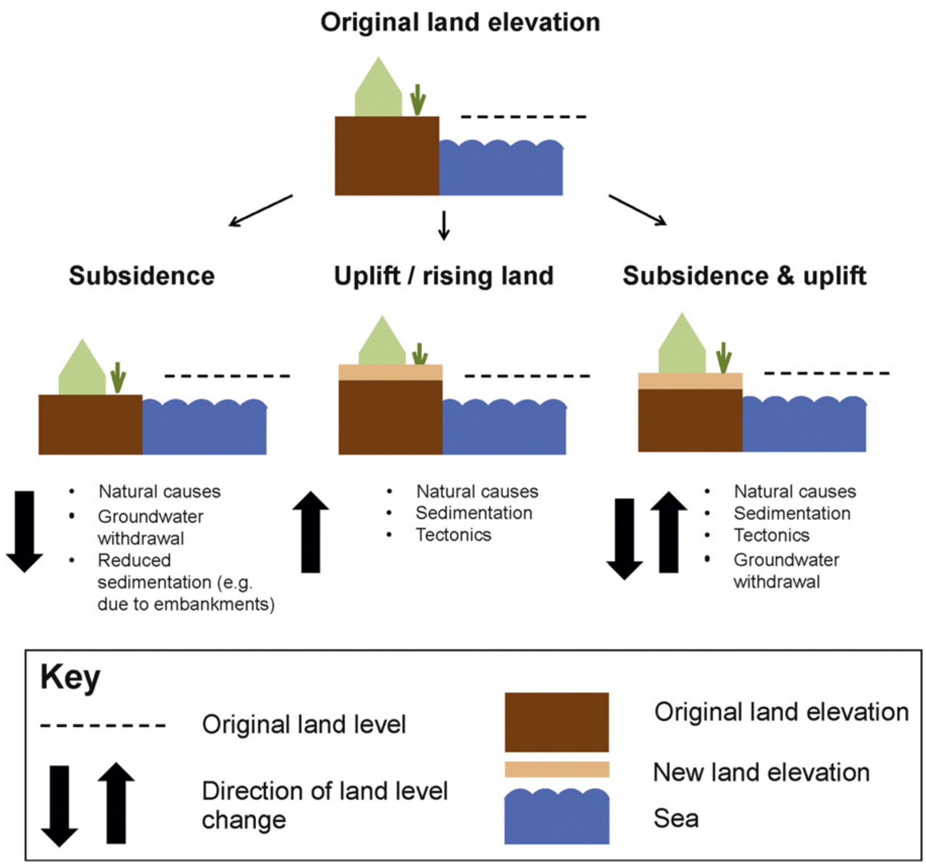

Figure 8: Illustration of land elevation changes [36]

the land surface, which have a magnitude a lot larger than large scale sea level rise in some places [30] (figure 8). Here are the major processes:

1. **The extraction of ground water and fossil fuel** is a very important threat for many coastal areas in the world. For example groundwater extraction results in subsidence rates of the order of 10 cm/y in Jakarta. A lot larger than rates of present day sea level rise. A few tide gauges at the Dutch coast have also been impacted by past oil and gas extraction. Around 20 cm at Delfzijl and 2 cm at Hoek van Holland over the period 1916-2016 [31].

2. **The oxidation of organic material** also leads to subsidence. It occurs especially in deltas when surface water is drained and the soil is in contact with oxygen (figure 9). This process is also seen in the Netherlands [32].

3. **Sediment input from rivers** is important for deltas to keep up with sea level rise. With the building of dams and reduction of the discharge due to intensive water use upstream the sediment input can reduce.

Other processes include mining and land compaction due to surface load. All of these local subsidence problems can be much larger than sea level rise from global warming but are in general also easier to solve because they only depend on local governance. If the cause of the subsidence is stopped, subsidence slows down very quickly but it is not reversible in general, meaning that the land does not rise back. A success story is the case of Kyoto where very large subsidence rates of up to 24 cm/y were reached in the late 1960th [33]. In the 1970th ground water extraction regulations were implemented and the rate of subsidence drastically reduced. The effects of subsidence is often lacking from global impact studies because there is no global subsidence map available yet [34, 35].

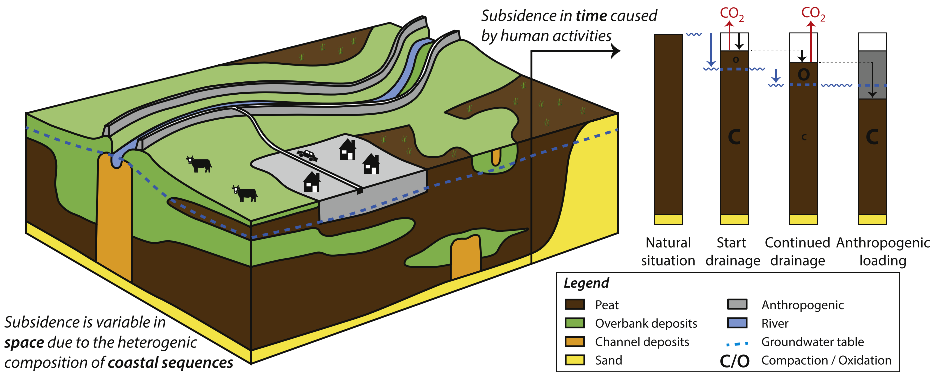

Figure 9: Schematic representation of temporal variations in the contributions of peat compaction and oxidation to land subsidence [32]

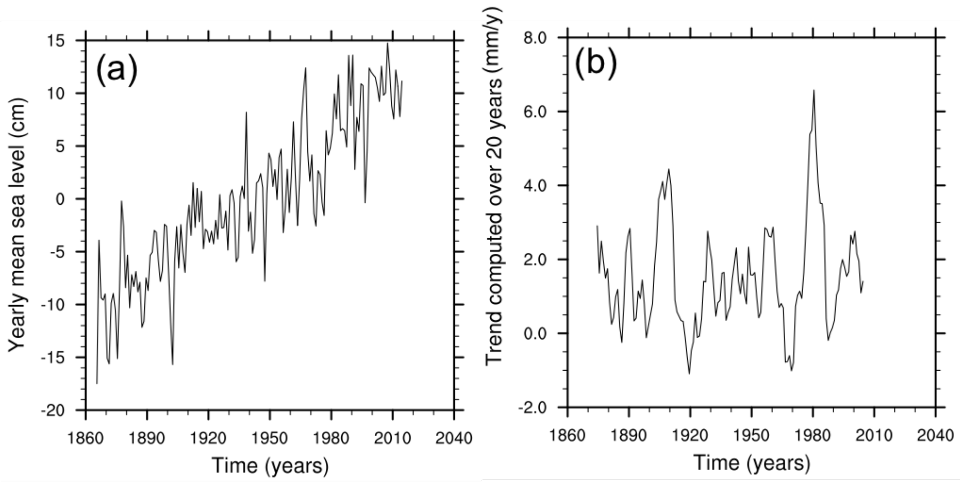

Figure 10: (a) Yearly mean sea level observation from the tide gauge of Den Helder. (b) Sea level rise computed over 20 *years* periods. Data from `http://www.psmsl.org/`.

7 SEA LEVEL VARIABILITY AND EXTREME EVENTS

From our experience we noticed that coastal managers and policy makers imagine sea level rise as a slow continuous process. This image is rather accurate when it comes to changes in large scale drivers of sea level like the loss of land ice and thermal expansion. However when sea level is measured at the coast many other processes come into play and the signal is not slowly varying. As an example we plotted yearly averaged sea level observations from the tide gauge of Den Helder on figure 10a. Besides the long term sea level rise trend a large variability is clear with some years up to 10 cm higher than the previous year and some 10 cm lower than the previous year. As a result computing the speed of sea level rise is difficult. An example is given on figure 10b where the trend is computed over periods of 20 $years$. We see that even over this relatively long period the trend ranges from $-1\,mm/y$ to $6.5\,mm/year$.

This large inter-annual and decadal variability is due to many physical processes. We already mentioned natural climate variability where winds drive ocean currents and heat and salt is redistributed in the ocean resulting in changes in density and in sea level. Also short time scale processes have an impact on this variability. For example if a storm rises sea level by 1.5 m for one day then it will also rise yearly mean sea level be around 4 mm.

The impacts of sea level rise like floods, erosion and salt intrusion are mostly felt during extreme events. Highest sea levels at the coast are reached during storms, when wind set-up, inverse barometer effect, high tide and large waves combine. See for example figure 11 for a summary of time and space scales of relevant physical processes. Given the sparsity of tide gauges, the short duration of observations

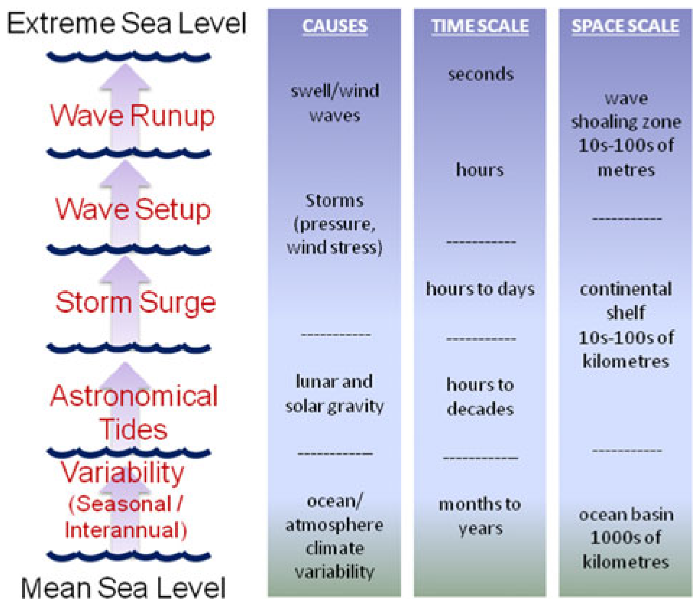

Figure 11: Oceanic phenomena that contribute to the total water levels at the coast during an extreme sea level event, their causes and the time and space scales over which they operate. Figure from [39].

and the shortcomings of physically and/or statistically based models, there is a large uncertainty in the present state of possible extreme events [37]. In fact incomplete knowledge about present day extreme events stays the largest uncertainty in predicting future extreme events of the coming decades. Sea level rise uncertainties only becomes dominant after 30 to 50 years [38].

As climate changes and sea level rises extreme events also change. For example high tide levels at the western european coast will increase or decrease by up to 15% of the sea level rise itself [40]. The characteristics of extreme storms might also be different in a warmer climate but there is still large uncertainty about this change [41]. Only recently, projections of future extreme sea levels that also include changes of winds, tides and waves have been performed [42]. The conclusion is that sea level rise is the main driver of the increase in extreme events but other physical processes can either compensate or worsen it locally [43]. This is for instance visible in a country like the UK where coastal protection is low and often absent and as a result, the coast is regularly flooded. There is a significant rise in flooding events over the last 100 years, which can only be explained by rising sea level, as storminess has not altered [44].

8 THE SITUATION FOR SELECTED COUNTRIES

We select now a few countries that collaborate with the Netherlands and compare sea level projections in these countries compared to the global mean sea level. One city is selected in each country, see map on figure 12. We look at a climate scenario called RCP4.5 that leads to a global warming of between 1.7° and 3.2°C at the end of the 21^{st} century. For this scenario the global sea level rises by $52\,cm$ during the 21^{st} century. There is an uncertainty attached to this number but we will not discuss it here since we focus on regional differences. The sea level projections compared to the global mean are shown in figure 13. Sea level projections for most cities are close to the global average. There is however one exception that is Punta Arenas in Chile because of large earth rebound resulting from the loss of ice from the last glacial maximum (see GIA component on the figure). Since each contributor has a different spatial variation some cities for example Amsterdam and Da Nang in Vietnam have similar total sea level projections but Amsterdam is more affected by ocean expansion and change in circulation while Da Nang is more affected by Greenland mass loss.

Given the large uncertainty concerning the Antarctic ice sheet we compare the IPCC AR5 projections, for which the Antarctic ice sheet remains relatively stable during the 21^{st} century [1], with another

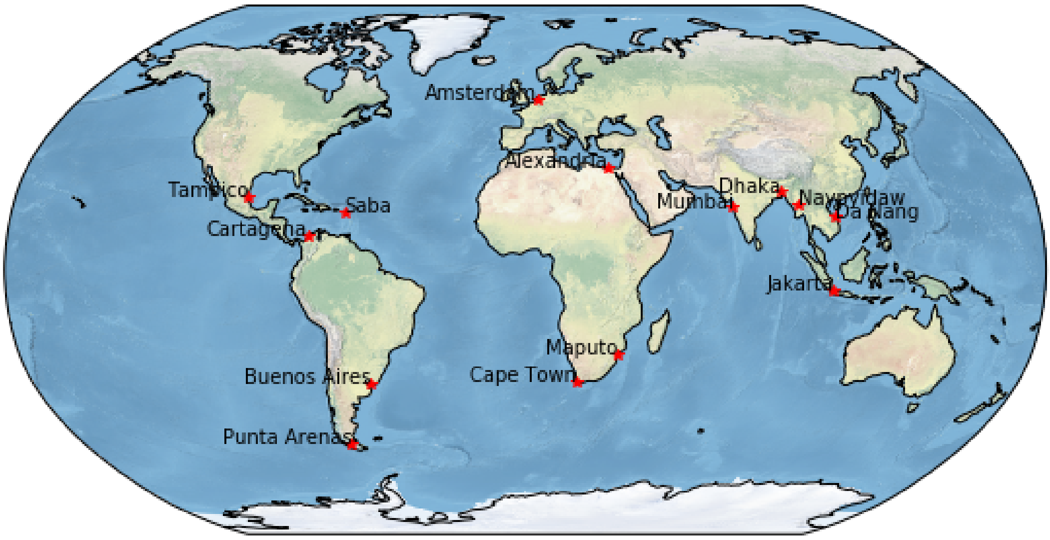

Figure 12: Cities of interest.

projection where the Antarctic ice sheet collapses due to a fast warming of the ice shelves and some ice dynamical instabilities [21, 22] (see figure 14). For that Antarctic collapse scenario the global mean sea level rises by 105 *cm*. Once again most cities have a sea level projection that is close to the mean except for Punta Arenas that is very close to the Antarctic ice sheet and therefore due to gravitational effects the Antarctic contribution to sea level rise is very small there.

These figures show relative sea level changes but do not include subsidence because even within a city the rates can vary a lot. However, as we have seen subsidence should not be neglected so for practical applications some local observations should be used.

9 DISCUSSION

For simplification in this report we did not elaborate on the uncertainties associated with current sea level science and sea level projections in particular. It is however important to keep in mind that there are still important gaps in our knowledge. For example there are still discrepancies between past sea level reconstructions from climate models and observations based products, especially locally [45, 46]. Also there is a lot of work on which sea level contributors contribute the most to the uncertainties associated with future projections [38] and how there dependencies contribute to the total uncertainty [47]. Therefore decisions that involve sea level science and climate science in general are always done under uncertainty. Many different frameworks were developed to do so [48, 49] .

10 POSSIBLE FOLLOW UP STUDIES

We identified a few possible subjects for future collaborations with the Ministry of Infrastructure and Water Management. One could be a focus on the temporal variability of sea level variability. In particular the notion of natural climate variability is not well understood by non-specialists who still need to use sea level knowledge. It has large consequences for the expectation about future sea level rise. If at a location sea level rise has been observed to be faster than global sea level over the last 20 years and the reason for this is natural variability it means that it will be slower than the global average in the coming 20 years. If however the reason can be traced to the fingerprint of a sea level contributor, described in this report, then one can expect sea level to continue at a faster pace than globally. The variability of sea level at higher frequency could also be the focus of future work. For example future changes in extreme events that are the result of storm surges, tides and sea level rise.

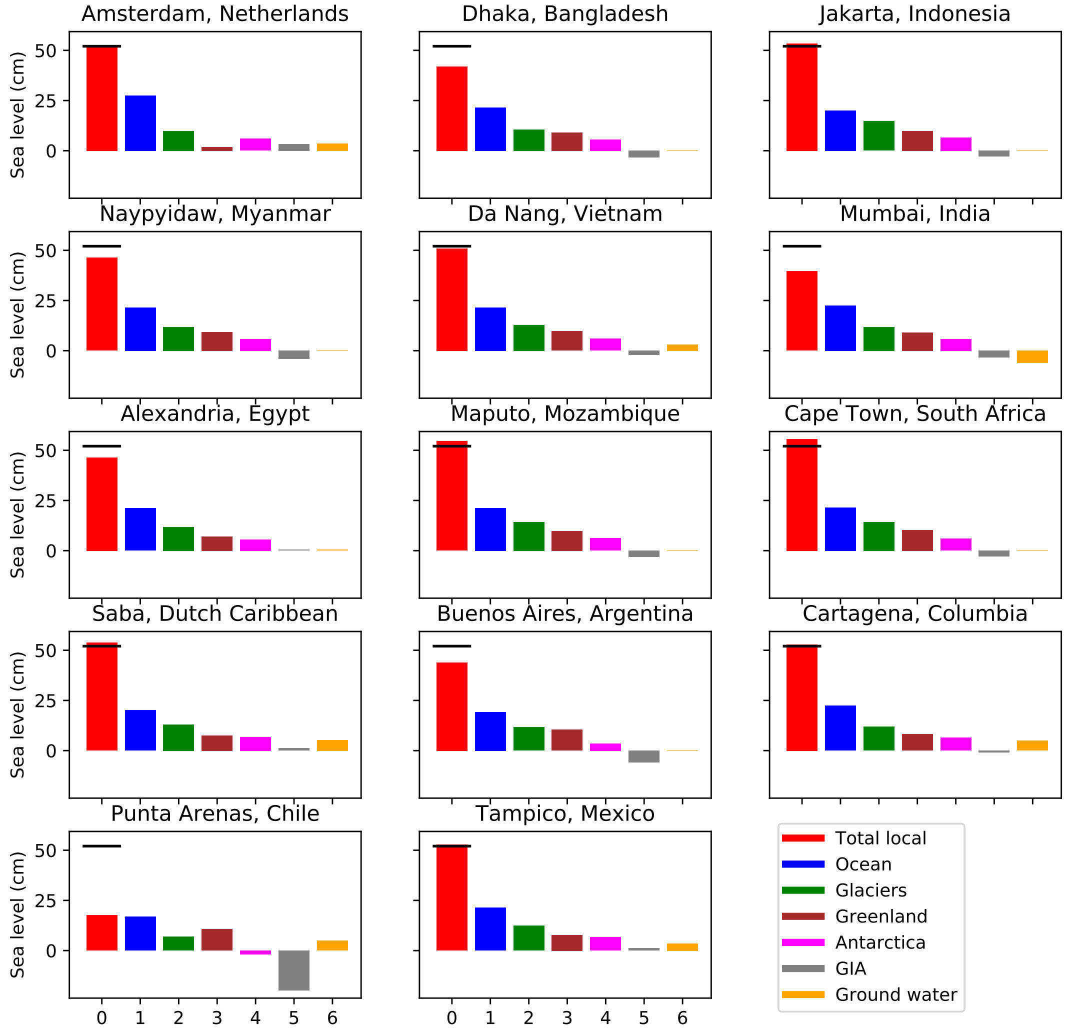

Figure 13: Projection of sea level in 2100 compared to the period 1986-2005 for a selection of cities, assuming a stable Antarctic ice sheet as in the IPCC AR5 report [1]. The total sea level projection of each city (red bar) is decomposed between the main contributors. The global average sea level is shown as a black bar in each panel for comparison. Subsidence is not included because there are no global subsidence projections avialable.

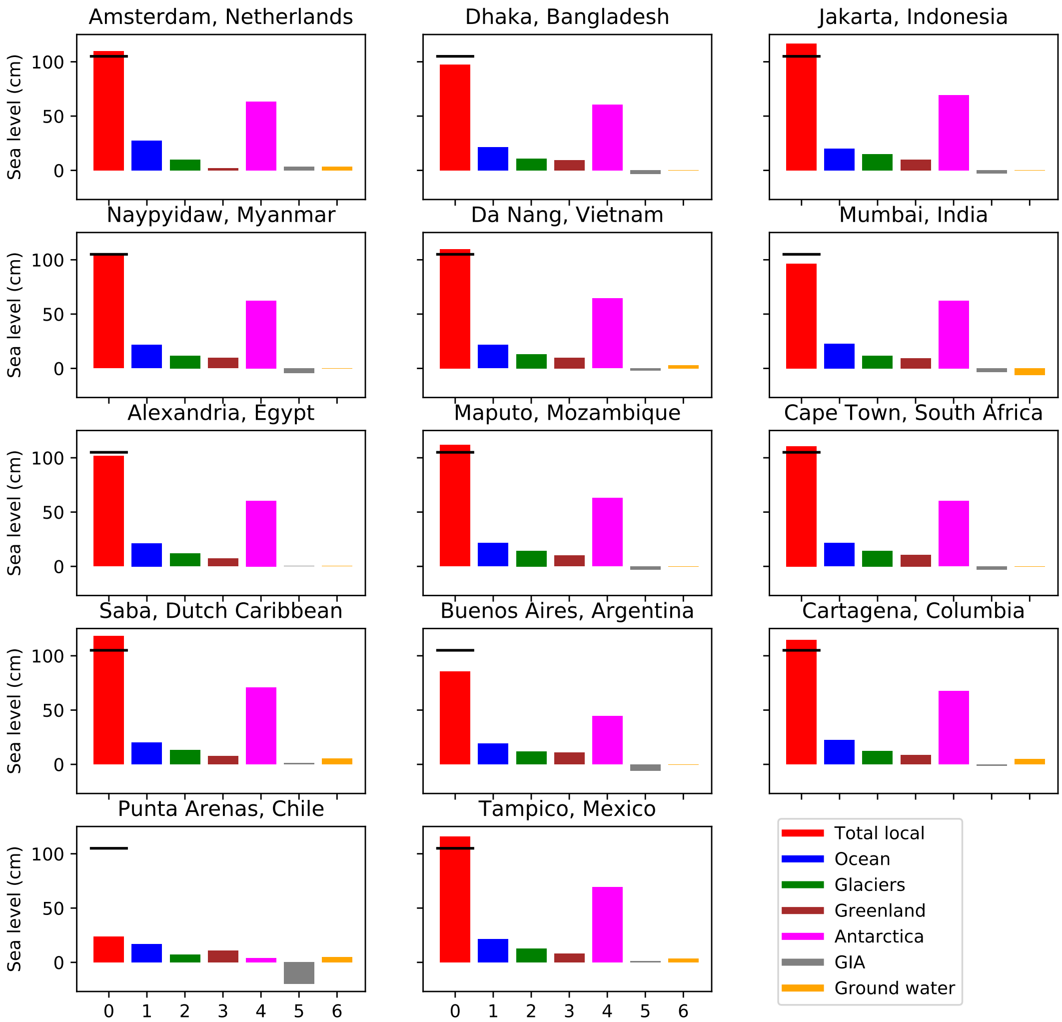

Figure 14: Same as figure 13 but assuming a collapse of the Antarctic ice sheet as proposed by [21].

Out of all the different scientific domains that are relevant for sea level, the domain in which knowledge is the most fragile and in which it is advancing the fastest is glaciology. Therefore, we could also focus on summarising the lastest developments in this field. The melting of Antarctica is the focus of recent research that we performed [22] and we are in the process of writing grant applications to increase the involvement of KNMI in this scientific domain.

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