CONTRIBUTION TO SAFECOAST PROJECT (INTERREG IIIB NORTH SEA)

TRANSLATION OF "VERWAEST ET AL. 2005. DE ZEESPIEGELSTIJGING METEN, BEGRIJPEN EN AFBLOKKEN. DE GROTE REDE 15, DECEMBER 2005, P.15-25"

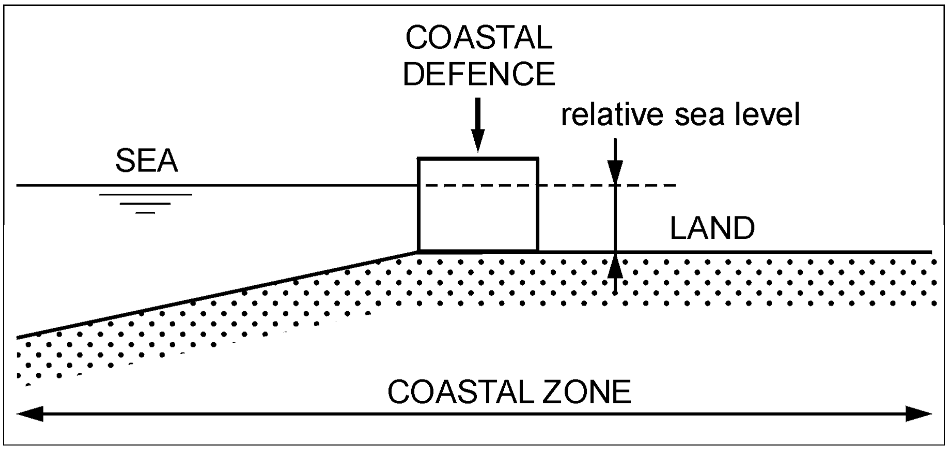
MONITORING, UNDERSTANDING AND BLOCKING SEA LEVEL RISE

It is sufficiently well known that the sea level is rising as a result of global climate warming. But how this rise is monitored and the problems arising with its interpretation are rarely discussed. In the following contribution, the competent Flemish experts take you to the coast for a lecture on "how to measure and interpret sea level rise and how to arm oneself against it?"

The Relativity of Sea Level Monitoring

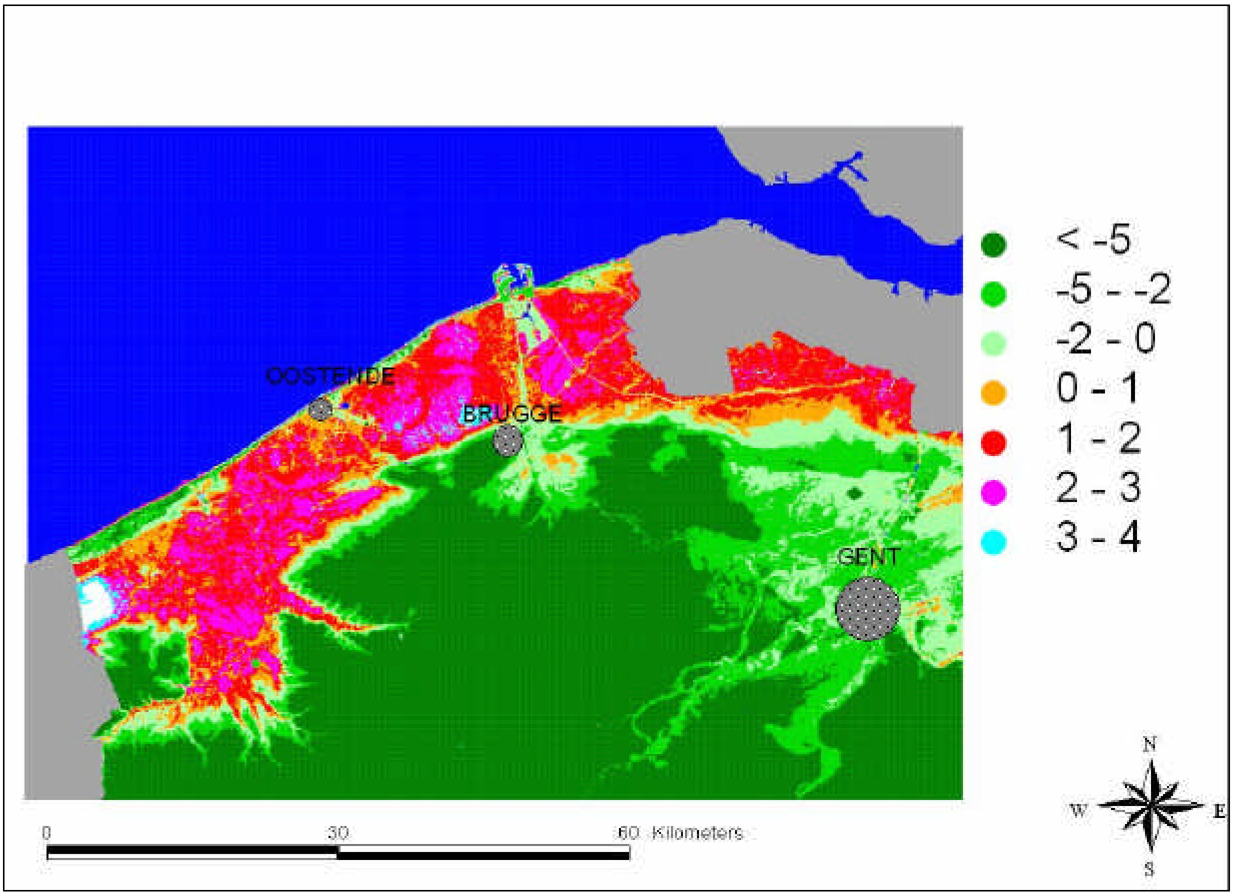
"Everything is relative", said Albert Einstein, probably the most famous scientist ever. This is also the case for the sea level. On the one hand, people are asking themselves where and when the sea level must be measured. On the other hand, talking about *the* sea level only makes sense when mentioning the zero level from which the sea level is measured. There appear to be at least three different prevailing approaches of the "relative sea level": you can measure the sea level from the current land level, from a fixed monitoring device on the seawall or from the level of an underground, geologically older layer or bedrock.

A first approach measures the sea level from the level of the surface of the earth in the coastal zone, behind the coastal defence (see figure). This earth surface itself can also be in motion, e.g. when the ground has bedded down due to polder drainage. Therefore, this approach perfectly allows measuring a relative sea level rise while the actual sea level has remained the same and the land has "sunk". However, this relative level difference is important for the protection of coastal areas by means of coastal defence. Building and maintaining a sufficiently high and strong coastal defence, is the basis of coastal protection. Along the Belgian coast, sand dunes constitute the natural coastal defences. In seaside resorts and ports this natural defence has been replaced by constructions such as sea dykes and quay walls. Irrespective of the type of coastal defence, the height of the relative sea level is a determining factor to assess the risks of flooding.



There are different methods to measure the relative sea level. One of them is to estimate the height of an average sea level from the level of the earth's surface in the coastal zone.

By way of illustration: off the Belgian coast, the relative sea level during an average annual storm (with a storm level of +5,5 m TAW, i.e. the vertical level of reference in Belgium) rises up to a magnitude of 2 m above the land surface of the coastal area. This is shown in the figure below, calculated on the basis of the Digital Elevation Model (DEM) of Flanders.



The Flemish polder area and the Eastern Flemish creek area are located an average of 2 m below the level of an average annual storm (of +5,5 m TAW). Certain basins, such as the Moeren in Veurne and the Lege Moeren in Meetkerke are situated even another 1-2 m below this surrounding level. (DEM Flanders in raster format 100m, product of OC-GIS Flanders)

For a certain coastal area the relative sea level constantly varies in time resulting from a whole range of physical processes occurring on time scales from a few seconds to thousands of years and more, and on space scales from several tens of meters over thousands of kilometres to worldwide. The table below gives a survey of the most important processes influencing sea level with their indicative order and typical scales for the Belgian coast. This table especially illustrates how complex and relative the subject of “the sea level” actually is... Several processes, all with their own time and space scales and orders, interact and together they determine the final sea level measured.

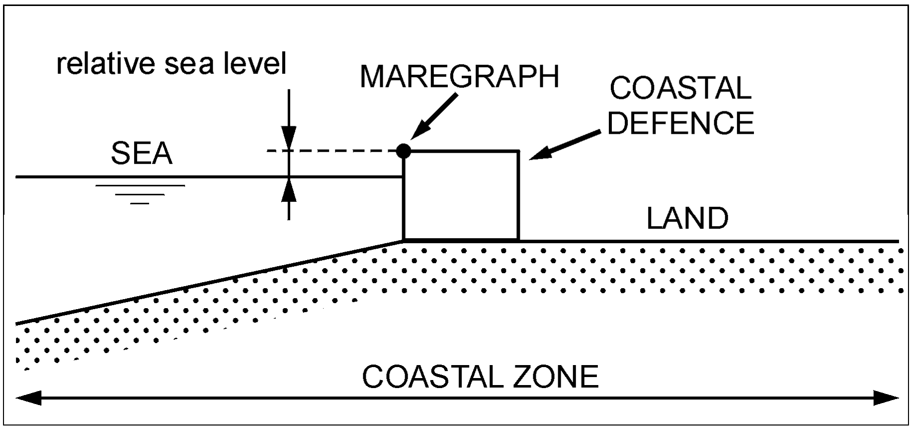
PROCESS	ORDER	TIME SCALE	SPACE SCALE
Waves	Cyclic with an amplitude of max. a few meters	Period of a few seconds	Several tens of meters
The effect of wind and atmospheric pressure	Cyclic with an amplitude of ~1 m	Period of hours, days	High and low pressure areas in Northwest Europe
Ebb tide and flood tide	Cyclic with an amplitude of ~4 m	Approx. every day 2 x high tide and 2 x low tide	Rotation around an amphidromic point in the Southern North Sea *
Spring and neap tide cycle in phase with the position of the moon	Cyclic with an amplitude of ~1 m	Period of approx. 2 weeks	Worldwide
The effect of the variable distance between earth and moon (due to the elliptic, non-circular orbit of the moon around the earth) on the tide amplitude	Cyclic with an amplitude of several dm	Period of approx. 4 weeks	Worldwide
The angle between the sun and the equator	Cyclic with an amplitude of a few dm	Period of 6 months (in March-April and September-October the biggest tide amplitudes of the year occur: this happens during the so-called equinoxes, when the sun passes over the equator)	Worldwide
Saros cycle **	Cyclic with an amplitude of several cm	Period of 18.61 years	Worldwide
Deformations and tilting movements of the earth plates (isostasy and tectonics)	Present trend with a magnitude of several mm per century	Trend continues for thousands of years	Continent

Increase of the ocean water volume (due to ice melting off, thermal expansion of water) (eustasy)	Present trend with a magnitude of several dm per century. In the future, might be dramatically increased due to the greenhouse effect.	Trend continues for thousands of years	Worldwide
Subsoil compaction = compression under own weight, reinforced by drainage	Present trend?	Hundreds of years	Coastal area
Regression-transgression Sedimentation-erosion	At present no evolution because the coastline is fixed by coastal defence	Period of 1000 years	Coastal area

** For an explanation in Dutch of “amphidromic point” and “tides”: see article in "De Grote Rede" 6, which can be consulted at: http://www.vliz.be/docs/groterede/GR06_mysterie.pdf*
*** Saros cycle: cycle determining the slow variation of the angle between earth, sun and moon*
For a certain coastal area the relative sea level continuously varies in time due to a whole range of physical processes occurring on time scales from a few seconds to thousands of years and more, and on space scales from several tens of meters over thousands of kilometres to worldwide. In this survey, the most important processes likely to influence sea level are displayed, together with their indicative order and typical scales for the Belgian coast.

How to Monitor the Relative Sea Level at the Belgian Coast?

The Flemish Hydrography (and its predecessors) has been monitoring the evolution of the relative sea level in time for almost 200 years. As a monitoring device the maregraph (from the Latin *mare* = sea, and the Greek *grafein* = to write) is used (maregraphs are also called tidal gauges). Along the Belgian coast, maregraphs are posted in Nieuwpoort, Oostende and Zeebrugge. These maregraphs register the relative sea level changes in relation to constructions which are part of the coastal defence structures in harbours, such as quay walls. Therefore, they make use of another "relative sea level" definition than the one mentioned above (i.e. in relation to land), as illustrated in the figure below. Since these constructions move together with the land, this approach is also subject to land level changes (e.g. by compaction of the subsoil on which the maregraphs are built).



There are different methods to measure the relative sea level. The height of an average sea level can, instead of to land level, also be compared to the level of the maregraph, i.e. a fixed monitoring device on the seawall.

Maregraphs are located in harbours because they provide shelter from the waves. After all, it is not the intention to measure high-frequency water level movements by the waves with these maregraphs. A damping tank, in which the registering float can move up and down, enables the influence of the waves on the monitoring data to be restricted as much as possible. The tide monitoring station in Oostende (see photo) presently has the longest monitoring series and is considered as the main monitoring station.

In the monitoring station in Oostende, which is located at the entrance of the Montgomery Dock, a maregraph is used to monitor the relative sea level by registration of the height of a float in the damping tank. The damping tank ensures that the water levels can be monitored without too much interference from waves or passing ships. The registered water level is regularly checked with a tape measure emitting a sound signal upon contact with water (Flemish Hydrography).

History of Water Level Monitoring in Oostende

In Oostende, the first known tide measurements go back to 1820-1834. Although these measurements were described in older publications, unfortunately no results have been preserved. A second series of measurements covers the period 1835-1852, of which only the monthly average high and low tide levels have been kept. From these data the water level corresponding to the average water level can be calculated with considerable accuracy. Between 1866 and 1871 tide monitoring also took place, but these results were lost too. Until that time, the water levels were read from a tide measuring rod.

Later a floating tide meter with automatic registration on paper was used for monitoring. This method gave a full registration of the entire tide graph, offering better possibilities for later analysis and further calculations.
The next monitoring period goes from 1878 to 1914. This first period of monitoring using floating tide meters is characterised by numerous interruptions. Furthermore, there is no documentation available mentioning the vertical reference level used for monitoring. Because of the numerous interruptions on the one hand, and the unknown reference level on the other hand, it is difficult to obtain a reliable interpretation of these data for the calculation of the average water level.

The most recent measurements cover the period from 1925 to 2005. These are qualitatively the best measurements. The continuity of the monitoring is, apart from a number of years (no data from 1941-1943; interruptions in monitoring from 1925-26 and in 1940), very good.

From Rough Monitoring to Useful Final Figures

For the calculation of an average water level you need a long series of monitoring data. Especially if you want to calculate the trends of an average water level over a longer period of time, a long series of monitoring data is necessary. Furthermore, these measurements must be adequately documented. For the interpretation of the results, it is of the utmost importance to know the precise vertical reference level used as well. Also the possible height variations (due to soil compaction or sinking landmass) to which the tide station is liable must regularly be measured by water levelling and corrected if necessary. In order to follow up the tide meter position in relation to the vertical reference level, since 1995 the Flemish Hydrography has also been using GPS-monitoring besides regular classical water levelling. Together with the regular check-up and maintenance of the tide meters, these measurements contribute to the guarantee of good quality data.

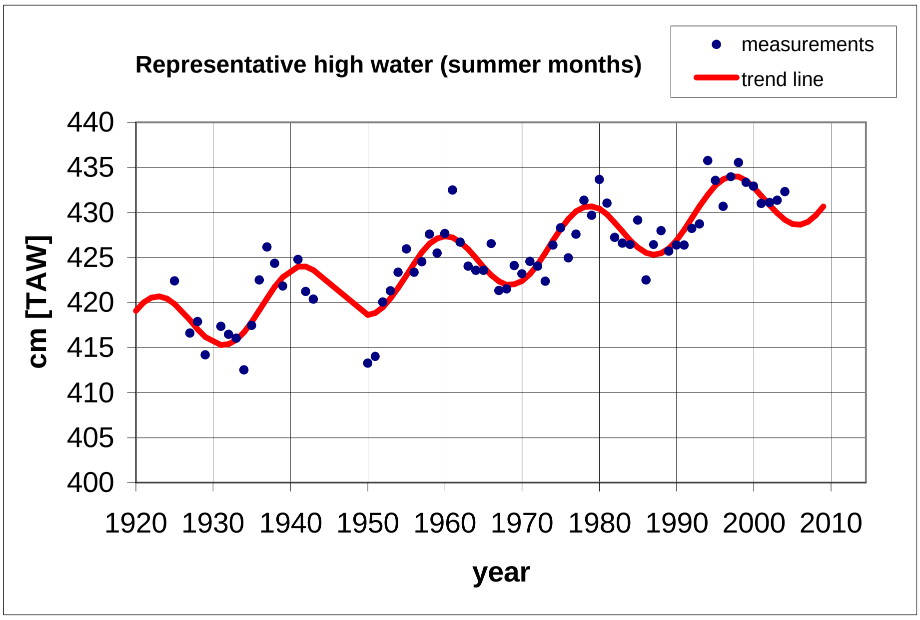
TAW as "Belgian" Vertical Reference Level

At present, “TAW” (Tweede Algemene Waterpassing) is used as vertical reference level for all tide monitoring along the Belgian coastline. In 1947, the National Geographical Institute determined the TAW reference height as vertical reference level for the whole area of Belgium.

To be able to deduce long-term trends in the evolution of the relative sea level from maregraph monitoring, it is necessary to filter out the effect of the various cyclic processes (such as waves, wind, atmospheric pressure and tides) influencing time scales shorter than one year. After filtering, you obtain an average value for the relative sea level, which is representative for a certain year. We already explained how the influence of the waves can be undone by positioning the maregraph in harbours and using a damping tank. The influence of the astronomical forces can be filtered out by using the knowledge of the tide periods. After all, engineers can approach the effect of the astronomical forces relatively well as a summation of three sinusoidal variations with periods of 12h25m14s (high/low water cycle), 14.765 days (spring/neap tide cycle) and 27.322 days (elliptic orbit of the moon around the earth). The effect of the semi-annual and annual astronomical cycles can be eliminated by considering the same season each year for the calculation of an average sea water level. The effect of four-yearly leap years is negligible.
Filtering out the effect of the meteorological forces (wind, air pressure, waves) is the hardest. The simplest approach is only to consider the maregraph measurements of the summer months of May, June, July and August. During these months, the influence and variation of the meteorological forces is significantly smaller than in the remaining months of the year. Furthermore, for the sake of convenience, the average meteorological effect in the summer months is supposed to be equally big each year. A much more sophisticated approach consists in calculating the effect of the weather conditions on the sea water level by means of a hydrometeorological model. This method has not been used until today because of its complexity.

Sea Level Rise at the Belgian Coast in Straight Figures: +15 cm Over 85 Years

The diagram below shows the result of a simple analysis of the maregraph data in Oostende for the period 1925-2004, indicating that the relative sea level (at high water) in Oostende has risen by approx. 15 cm over 85 years.



The evolution of the relative sea level from 1925 to 2004, as monitored with the maregraph in Oostende. The dots indicate the filtered measurements. The undulating line is the trend line through these dots. This trend line is determined by the combination of an average linear rise of 18 cm per century with a sinusoidal fluctuation (of 3,5 cm over a period of 18.61 years) in accordance with the Saros cycle, i.e. the natural cycle determining the slow variation of the angle between earth, sun and moon. (Verwaest & Verstraeten 2005)

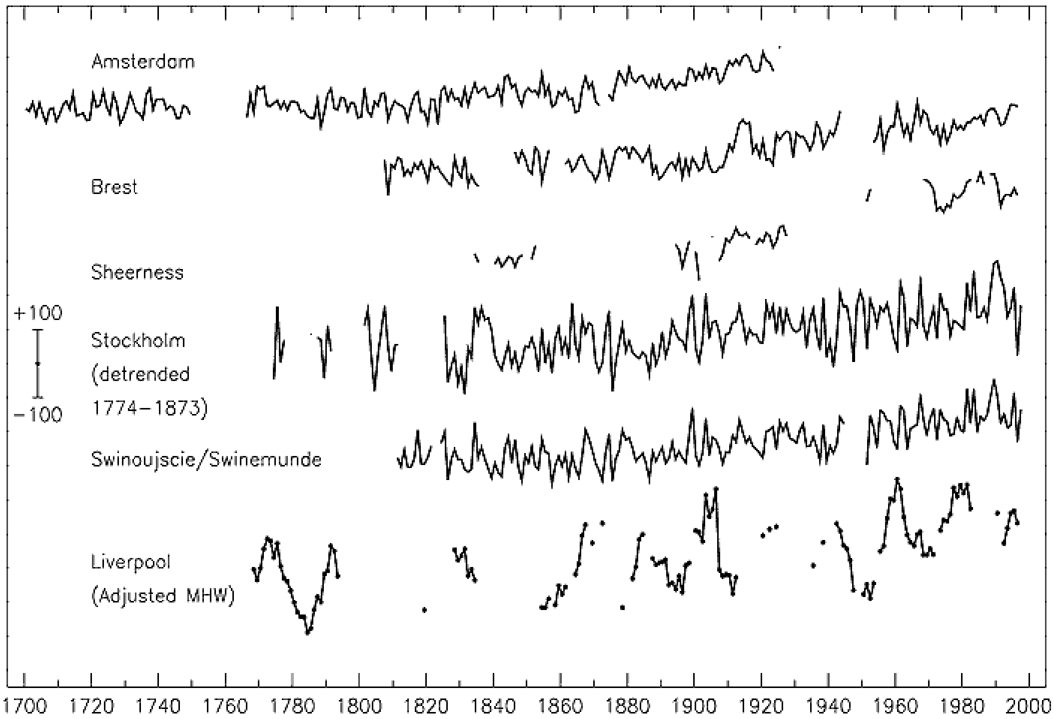
Yet, this evolution is not linear. After all, the evolution of the annual representative high waters during the observation period 1925-2004 consists of a superposition (= an “addition”) of an average linear rise of 18 cm per century and a sinusoidal fluctuation with an amplitude of approx. 3,5 cm and a period of 18.61 years (under the influence of the Saros cycle, which determines the slow variation of the angle between earth, sun and moon). The result of both is the undulating trend line globally indicating a rising pattern. Because of the simultaneity of these two phenomena, sea level (at high water) does not on average rise slightly each year. Periods of approx. 9.3 years of sea level rise do alternate with periods of approx. 9.3 years of less sea level fall, but with a rise as a net result. During rising years the sea level rises with a speed of approx. 10 mm per year and during falling years the sea level falls with a speed of approx. 6 mm per year. The net result of this trend is a rise with a net speed of approx. 2 mm per year.

The diagram indicates a relatively big unexplained variability of the annual representative high waters, with a standard deviation of approx. 2 cm (the “dots” in the diagram fluctuate a few centimetres around the continuous trend line). This "deviation" is mainly caused by the annual variability of the meteorological conditions the analysis did not take into account. Due to this remaining variability it is not possible to detect that the sea level rise might have accelerated in the past decades. To this day there is no proof that the sea level rise at the Belgian coast is accelerating. Neither is there proof to the contrary. Therefore, further research is required. A more sophisticated hindcast analysis (reconstructing historical conditions - the opposite of forecasting - by means of models and known conditions) using a hydrometeorological model might help clarify whether or not an acceleration of the sea level rise is occurring.

Belgium Compared to the Rest of the World

The Intergovernmental Panel on Climate Change (in short IPCC; http://www.ipcc.ch/) has charted that the sea level in the 20th century has risen on average approx. 1 to 2 mm per year. These conclusions are based on worldwide maregraph measurements corresponding with the findings for the Belgian coast.

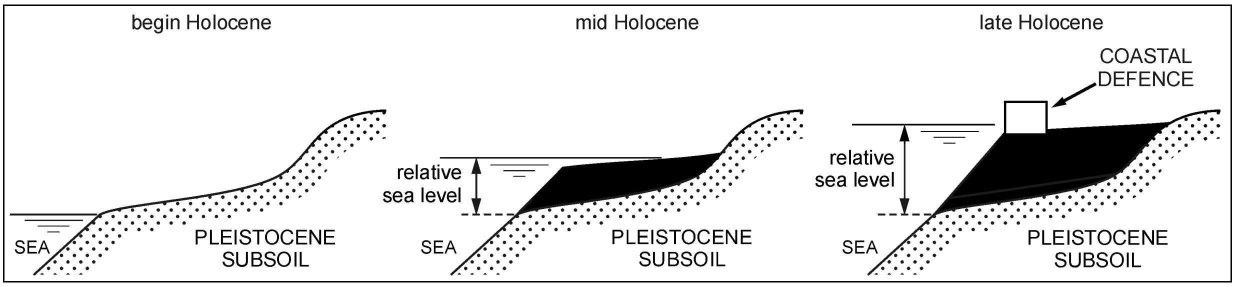
For a number of European monitoring locations, 300 years of monitoring results are available (see figure). Analyses of these long series of monitoring results show that during this entire period a sea level rise acceleration with a magnitude of a few tenths of a millimetre per year per century (0.3 - 0.9 mm per year per century) has occurred. Such small acceleration is very hard to detect. Until now, no solid evidence for acceleration in the past hundred years has been revealed.



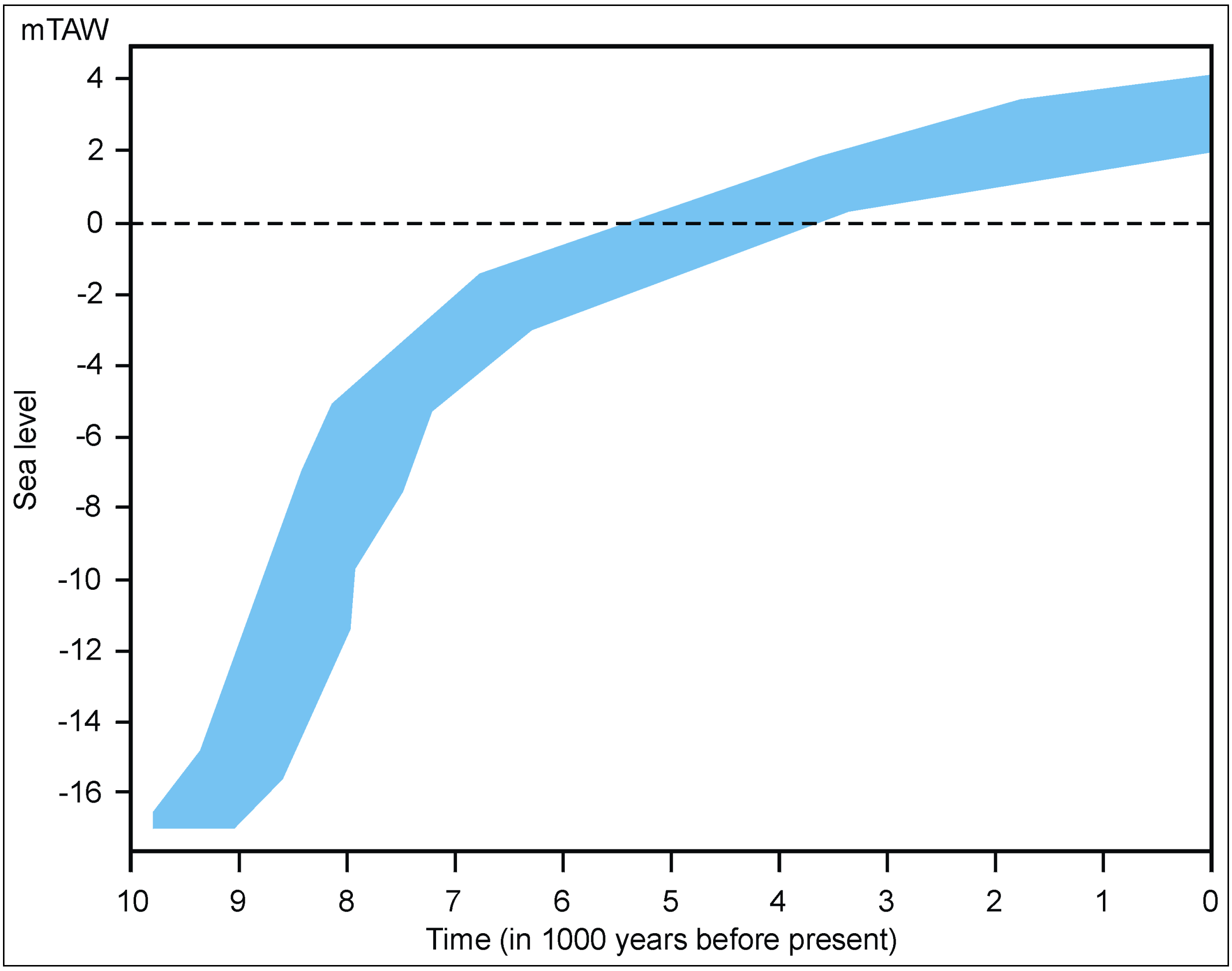
An analysis of sea level monitoring on various locations in Europe during the past 300 years not only indicates a sea level rise. An acceleration of this rise with a few tenths of a millimetre per year per century (0,3 - 0,9 mm per year per century) seems to have occurred too. (IPCC 2001)

Other Methods Exist: How Geologists Discover the History of the Sea Level Rise

We already mentioned that the sea level can be monitored in relation to the land lying behind or to a fixed monitoring device on the seawall, called the maregraph. The Quaternary geologist on the other hand uses sea level indicators from the subsoil. The transition from the last ice age (Pleistocene) to the Holocene (last 10,000 years) is characterised by a global sea level rise due to ice cap melting and thermal sea water expansion. Following the sea level rise, the land groundwater level rose too, even to the extent that freshwater swamps developed in which peat accumulated. This peat is called the basal peat. As sea level, and therefore also the groundwater level, kept on rising, the basal peat developed increasingly higher and more and more landward on top of the Pleistocene subsoil. Within the scope of extensive geological research in the Belgian coastal plain, this basal peat, covered by Holocene deposits, was dated by means of radiocarbon and on various depths. Geologists also tried to discover the then sea level by examination of diatoms in the ground. This resulted in a sea level curve (see diagram below from Baeteman & Declercq, 2002). The basal peat constitutes an ideal sea level indicator because it is still at its original level since the Pleistocene subsoil in the western coastal plain, contrary to the Holocene deposits, is not liable to bedding down.



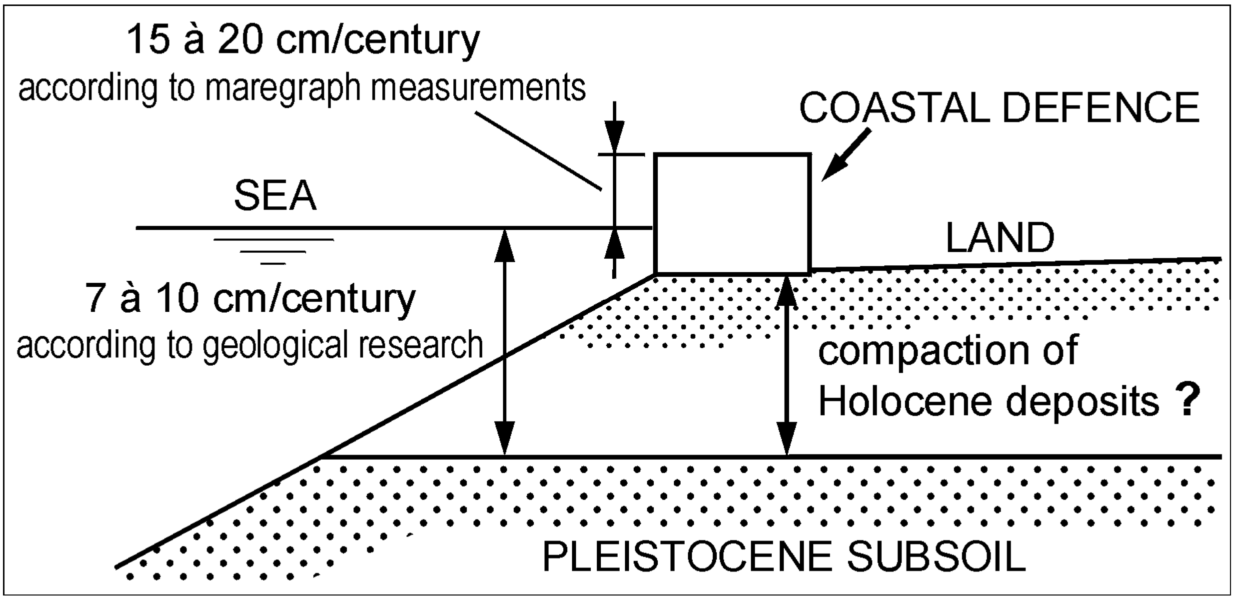
The Quaternary geologist uses sea level indicators which are present in the subsoil in order to draw up a sea level curve. Especially basal peat constitutes an ideal sea level indicator because it is still at its original level. Within the scope of extensive geological research in the Belgian coastal plain, this basal peat, covered by Holocene deposits, was dated by means of radiocarbon and on various depths. Geologists also tried to discover the then sea level by examination of diatoms in the ground.



The sea level curve, as calculated by Quaternary geologists for the last 10,000 years, indicates a global rise of 20 meters. A gradual deceleration of the sea level rise can be clearly determined as well. In the past millennia the sea level rose with a speed of only 7 to 10 cm per century, while between 10,000 and 7,500 years ago the speed still amounted to 70 cm per century. (Baeteman & Declercq, 2002)

The sea level curve indicates that during the last 10,000 years the relative sea level rise amounted to approx. 20 meters. The curve however clearly indicates a gradual deceleration of the sea level rise. In the past millennia, the sea level rose with a speed of only 7 to 10 cm per century, while between 10,000 and 7,500 years ago the rise - of approx. 70 cm per century - increased much faster.

According to the IPCC, in the 21st century - for an average expected scenario - due to the greenhouse effect, a worldwide acceleration of the sea level rise will take place with a magnitude of on average 2 mm per year per century. This would mean that the current net sea level rise of approx. 2 mm per year will gradually increase to approx. 3 mm per year towards 2050. Such small acceleration is very hard to detect. When the relative sea level rise, as indicated by the maregraph data (approx. 15 to 20 cm per century), is compared to the relative sea level rise deduced from coastal plain geology (approx. 7 to 10 cm per century for the most recent period), the Belgian coast seems to experience an acceleration of the sea level rise. But to be able to compare the geological figures on the relative sea level rise above the Pleistocene subsoil to the maregraph figures on the relative sea level rise above the current surface of the earth (the upper layer of the Holocene deposit), also the Holocene compaction must be considered, especially the compaction of the subsoil on which the maregraphs are positioned (see figure below). Unfortunately no uniform figures concerning the latter phenomenon are available, leaving a lot of uncertainty.

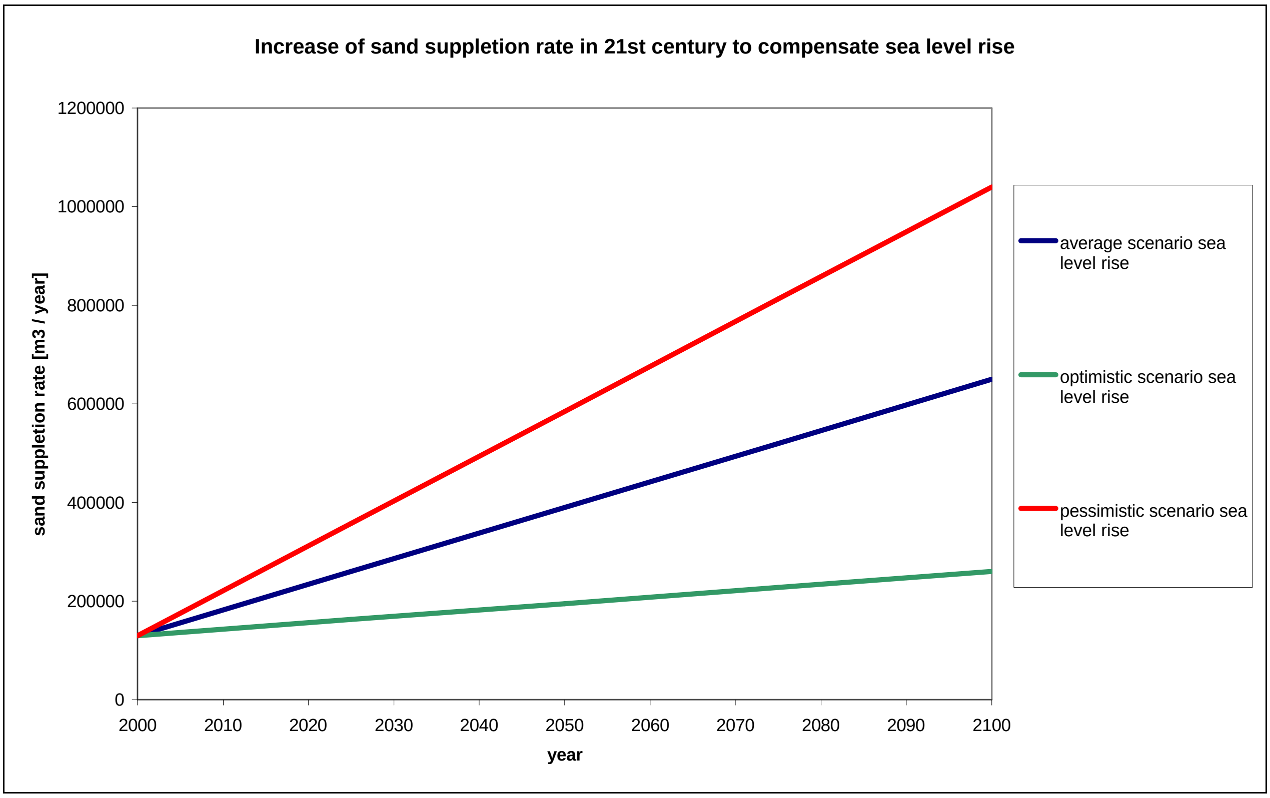


To be able to compare the geological figures on the relative sea level rise above the Pleistocene subsoil to the maregraph figures on the relative sea level rise above the current surface of the earth (the upper layer of the Holocene deposit), also the Holocene compaction must be considered. Unfortunately no uniform figures concerning the latter phenomenon are available.

Consequences for Our Safety?

The extent to which the relative sea level rise will continue in the 21st century has important consequences for coastal defence. For a relatively small sea level rise can strongly increase the risks of sea damage during storms. Calculations have shown that the risks increase with a factor 10 when the sea level rises by half a meter, which obviously is totally inadmissible. Hence the Flemish Region will compensate the sea level rise by structurally raising and strengthening the natural seawall. This is best achieved by beach and foreshore sand suppletion. To protect one kilometre of coast so that the flooding risks do not increase, a suppletion volume of 100,000 m^3 sand per 10 cm of sea level rise is required. In an average sea level rise scenario (+60 cm towards the year 2100) this means that our 65 km long sandy coast must be structurally strengthened with a volume of 40 million m^3 in the 21st century.

This corresponds with an average yearly supply of 400,000 m^3 sand, the equivalent of the loading capacity of approx. 40,000 trucks (so-called dumpers) or 3 times the current sand suppletion rate. For the different sea level rise scenarios, the figure below gives an indication of the required suppletion volume in order to compensate 21st century sea level rise.



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The head of the Coastal Division will amplify on these aspects in the insert below “Growing with the Sea”.

Growing with the Sea

“That is what we will do to counterbalance sea level rise. As the people responsible for coastal protection, we take into account the different scenarios, whether or not with an acceleration of the sea level rise. Even in the most pessimistic scenario of climate specialists, sea level rise remains a rather slow process. In the worst-case scenario the sea level would have been risen with almost 1 m by the end of this century. This would mean a fivefold increase of the speed at which the sea level is currently rising. Even such strongly accelerated sea level rise, could be compensated by strengthening the coastal defences. This requires indeed reservation of considerable additional financial means.”

“Our strongest weapon is sand suppletion, with which we can raise beaches and foreshores wherever necessary. The result of raising the beaches and foreshores by means of sand suppletion simultaneously with the rising sea level, is that the flooding risks do not increase. In the past decades we have already achieved splendid successes with the sand suppletion technique. Note for example the structural raising of beach levels realised along the entire coastline of Knokke-Heist, in the centre of De Haan, and now recently also in the centre of Oostende. It is true that these beaches need maintenance, but compared to the complexity to manage constructions such as dykes, this isn't so bad. Because there is a lot of uncertainty among climatologists about the extent to which we can expect a sea level rise acceleration in the future, we today have adopted a wait-and-see attitude towards the realisation of sand suppletions. Since a big advantage of sand suppletion is that it is a very flexible technique. The raising and broadening of the natural coastal defences (consisting of our beaches, foreshores and dunes) is structurally a simple operation: applying sand on top of sand. On the other hand, the strengthening of constructions such as sea dykes is much more complex and thus more expensive. You can safely compare suppletion with a new housing project, of which we all know that it is not necessarily more expensive than the renovation or extension of an existing house. Moreover, structurally strengthening a seawall infrastructure is much more difficult on account of all limiting conditions regarding integration in the urban and ecological environment."

Interview with Peter De Wolf, head of the Coastal Division

How Does the Coast Itself React to a Sea Level Rise?

An important question is to what extent the "soft" coastal defences will automatically grow or erode due to natural processes together with a certain sea level rise. For each sea level change can change the pattern of the currents and the impact of the waves, causing an evolution in the deposition of sand on the beach or its erosion. The more foreshores, beaches and dunes will grow naturally, the less intervention by means of coastal defence measures to stagnate flooding risks will be necessary.

European research carried out on behalf of the Dutch-German-Danish Wadden region shows that the natural growth of the soft coastal defences strongly depends on the speed of the sea level rise. Researchers came to the surprising conclusion that - if the sea level will rise according to the plausible scenario of a 25 cm rise within the next 50 years - this coastal system will not undergo any substantial changes in the next fifty years, not from morphological nor ecological point of view! In this case, the efforts required for coastal defence would only increase by approx. 10 %. Whereas the scenarios which are at present considered likely for the last decades of the 21st century (i.e. a 50 cm rise within 50 years) would actually cause dramatic morphological and ecological changes to the coastal system of the Wadden islands. This could also double the budget required for coastal defence. This example of the Wadden Sea shows that, if the speed of the sea level rise exceeds a certain critical value, it can lead to a trend break in coastal management.

And What in Belgium?

How do we expect that the Flemish coast will react morphologically to a faster sea level rise? The morphology of the Flemish coast differs greatly from that of the Wadden Coast. Consequently, you can expect that the reaction to a faster sea level rise will differ correspondingly. Our sandy coast is characterised by a shallow seabed with sandbanks, relatively wide foreshores and beaches, and dunes cut off from the beach on many places by human intervention. The sand exchange between beach and (the remnants of) dunes is as good as non-existent in the seaside resorts where constructions have been built almost onto the beach.

During the past decades the morphological evolution of the beaches and foreshores was monitored in great detail. In this period the sea level rose with an average of 1,5 to 2 mm per year. The morphological evolution in this period was different for the west coast, the middle coast and the east coast. Roughly speaking, the west coast (French border to Nieuwpoort) remains rather stable: in general there is little erosion of the foreshore and little growth of the beaches, both with a magnitude of 1 million m^3 sand per decade that almost compensate each other. The middle coast (Nieuwpoort to Blankenberge) is rather erosive: it suffers from an average erosion of approx. 10 million m^3 of sand per decade. The east coast (Zeebrugge to the Dutch border) is growing at a rate of approx. 10 million m^3 sand per decade. It is generally assumed that this is the result of the expansion of the Zeebrugge breakwaters which extend 3,5 km into the sea.

Little is known about what will be the natural morphological response of the different areas at the Belgian coast to an accelerated sea level rise. This question will be worth investigating during the coming years. Many of these questions are also of international importance. That is why Belgium participates in international projects looking for an answer to these questions, such as the European SAFECoast project considering the question: "How to Manage our North Sea Coasts in 2050?" (See insert). Will undoubtedly be continued!

safecoast

The SAFECoast project was started up this year as the successor to the COMRISK project. In COMRISK (2002-2005) several authorities of the North Sea states (the UK, Germany, Belgium, Denmark and the Netherlands) dealt with common strategies to reduce the flooding risk in low-lying coastal areas. The common mission of SAFECoast is to exchange knowledge about coastal flooding risks. The Belgium-based Coastal Division and Flanders Hydraulics Research are the participating partners for the Flemish Region. The SAFECoast project focuses on anticipating future climate changes and spatial developments in the 21st century. This will increase pressure on the low-lying coastal areas of the North Sea. Because of its transnational character, the European Regional Development Fund has granted subsidies to the project. The SAFECoast project will continue until mid 2008.

Interreg North Sea Region

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