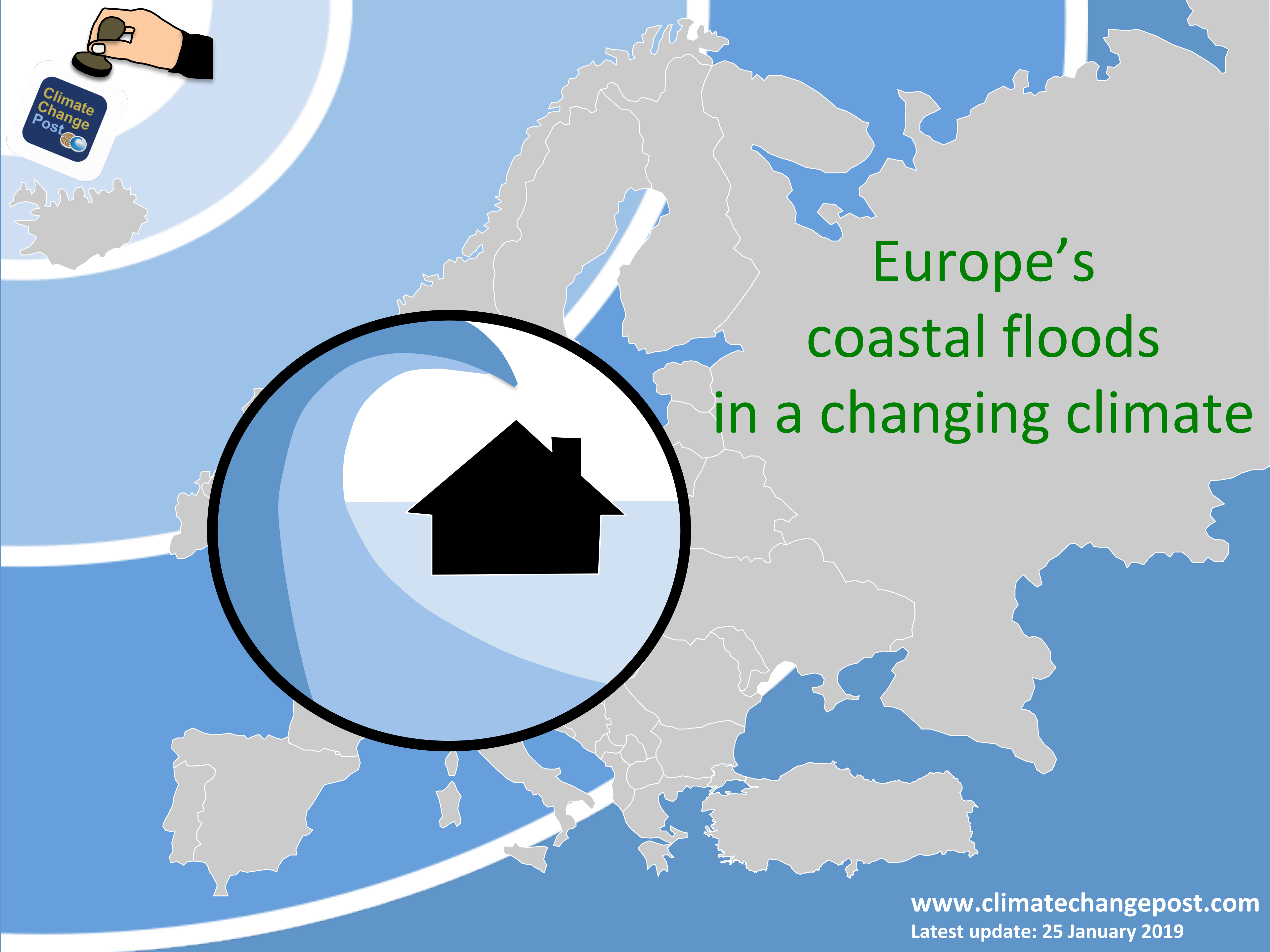


Europe's coastal floods in a changing climate

www.climatechangepost.com

Latest update: 25 January 2019

Coastal flood risk

What determines coastal flood risk?

Flood risk = probability X consequences

- Flood probability changes due to climate change
- Flood consequences change due to socio-economic developments

What determines flood probability?

Climate change affects flood probability because of
- Sea-level rise, and
- Changes in storm surges and extreme waves

Coastal floods

Sea-level rise

Sea level rise has 'two faces'

- Absolute sea-level rise and
- Relative sea-level rise: sea-level rise relative to the land surface

Absolute

Drivers that contribute to sea level rise are thermal expansion of ocean water, melting glaciers, mass loss of the Greenland and Antarctic ice sheets, and changes in water volumes stored on land (reservoirs behind dams and groundwater).

At the global scale, rate of sea level rise is accelerating:

- Tide gauge data 1901-1990: global mean sea level rise 1.1 ± 0.3 mm/year
- Satellite data 1993-2012: global mean sea level rise 3.1 ± 1.4 mm/year

However: at the local scale, in studies for specific parts of Europe, no significant acceleration in the rate of sea level rise has been detected during the 20th century.

Relative

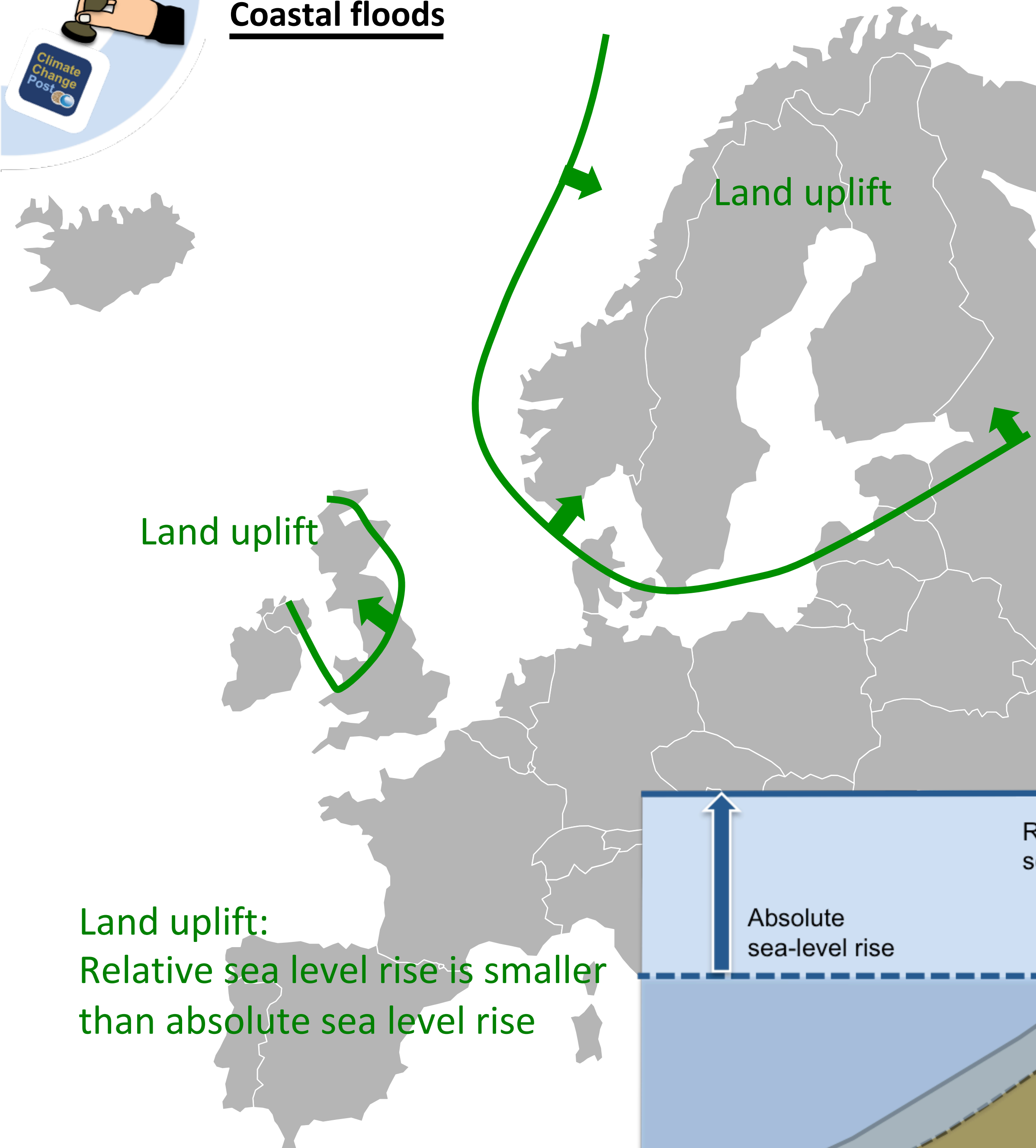
Because of land subsidence / land uplift relative sea-level rise can be higher / lower than absolute sea-level rise.

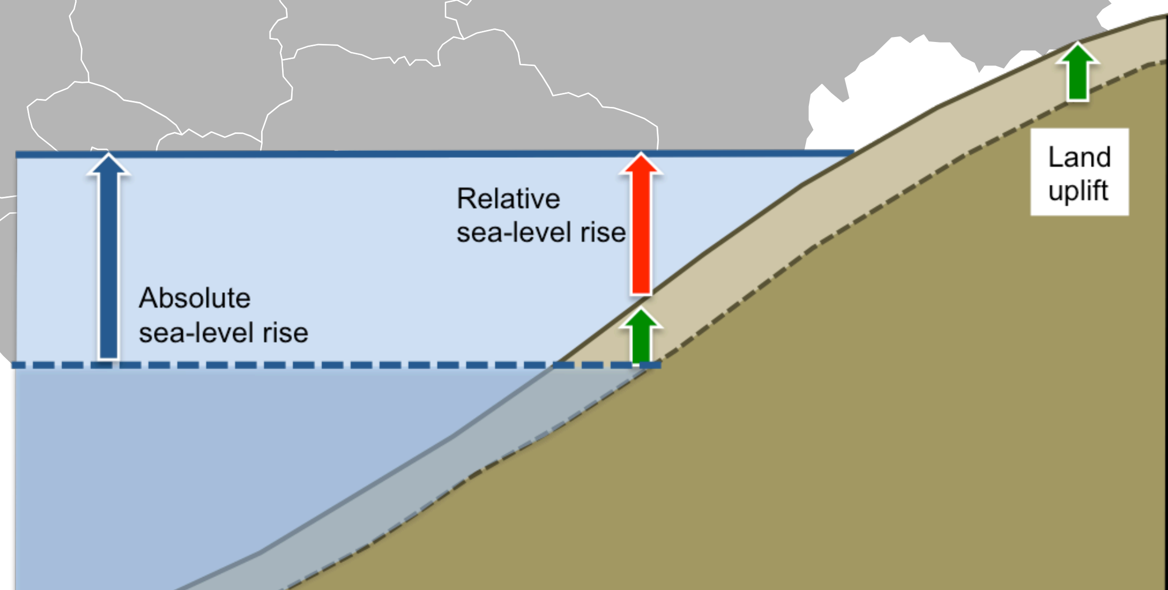
Vertical land movements occur due to the on-going adjustment of the Earth's crust to the deglaciation at the end of the last ice age, tectonic activity and localized sediment consolidation.

Coastal flood risk changes because of: relative sea-level rise + changes in storm surge + changes in extreme waves

Coastal floods

Land uplift and relative sea-level rise





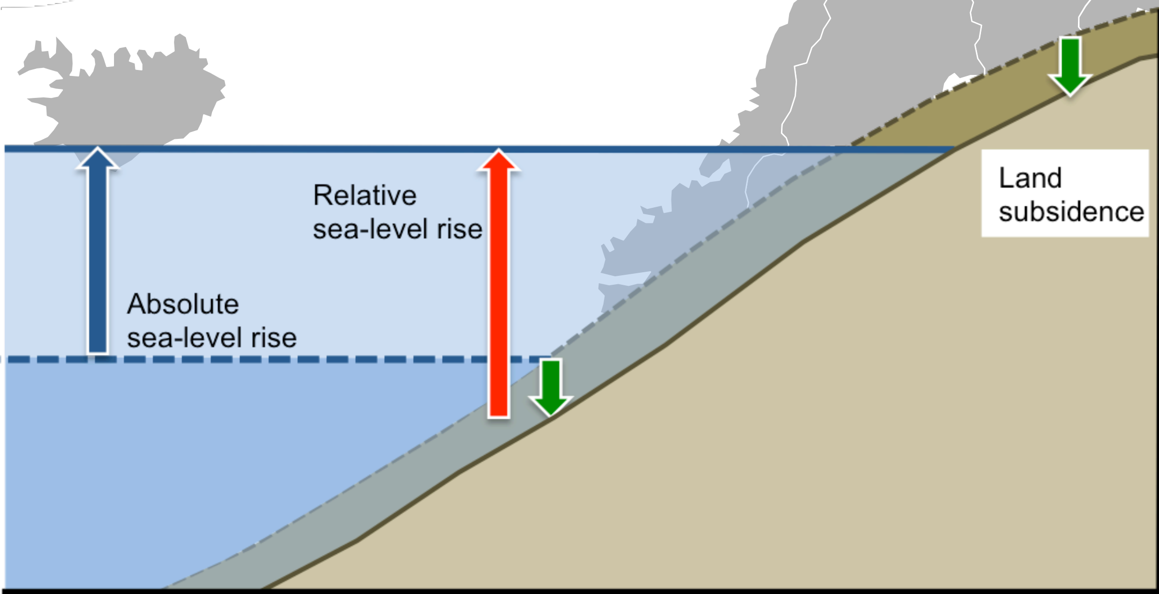
Northern Europe was covered with an ice sheet during the last glacial maximum. Vertical land movements occur due to the on-going adjustment of the Earth's crust to the deglaciation.

In Northern Europe, sea level rise with respect to the land (relative sea level rise) is the combination of absolute sea-level rise and postglacial land uplift.

At other locations, vertical land movements may result from tectonic activity and localized sediment consolidation.

Coastal floods

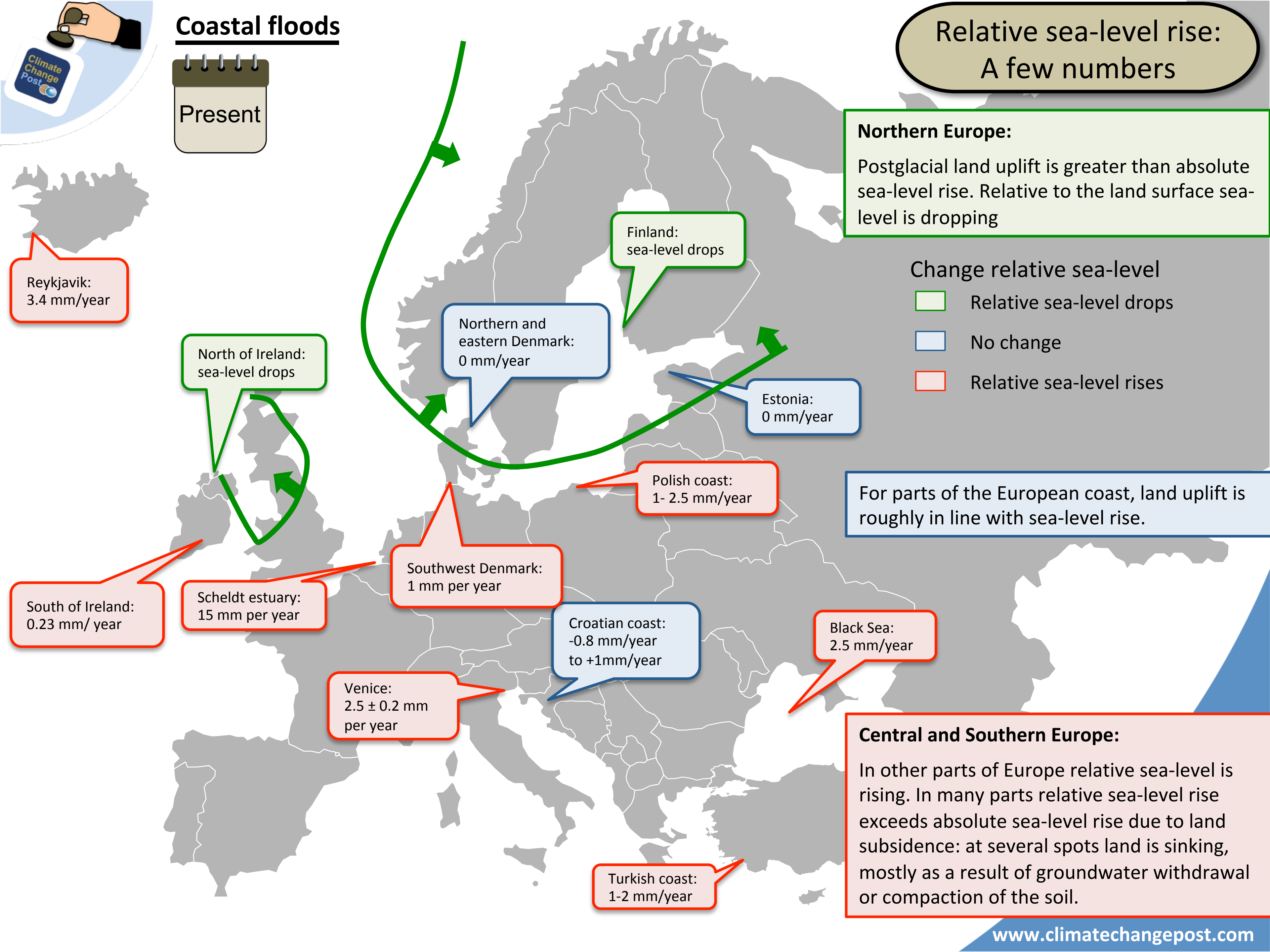
Land subsidence and relative sea-level rise



Land subsidence:
Relative sea level rise is larger than absolute sea level rise

An example:

Intense and extended groundwater extraction in the industrial area of Thessaloniki has resulted in a dramatic subsidence since the 1960s, up to 2.8 - 5 cm/year and reaching up to 3m from 1955 to 1980. This strongly impacted flood risk since the average height above sea level of this area is a+ 2.5 to + 3.0m in the north and 0 m in the south. Sea barriers that protect the deltaic plain were destroyed and catastrophic floods have occurred several times.


Coastal floods
Present
Relative sea-level rise: A few numbers
Northern Europe:
Postglacial land uplift is greater than absolute sea-level rise. Relative to the land surface sea-level is dropping
Change relative sea-level
Relative sea-level drops
No change
Relative sea-level rises
Reykjavik: 3.4 mm/year
North of Ireland: sea-level drops
Northern and eastern Denmark: 0 mm/year
Finland: sea-level drops
Estonia: 0 mm/year
Polish coast: 1- 2.5 mm/year
For parts of the European coast, land uplift is roughly in line with sea-level rise.
South of Ireland: 0.23 mm/ year
Scheldt estuary: 15 mm per year
Southwest Denmark: 1 mm per year
Croatian coast: -0.8 mm/year to +1mm/year
Black Sea: 2.5 mm/year
Venice: 2.5 ± 0.2 mm per year
Turkish coast: 1-2 mm/year
Central and Southern Europe:
In other parts of Europe relative sea-level is rising. In many parts relative sea-level rise exceeds absolute sea-level rise due to land subsidence: at several spots land is sinking, mostly as a result of groundwater withdrawal or compaction of the soil.
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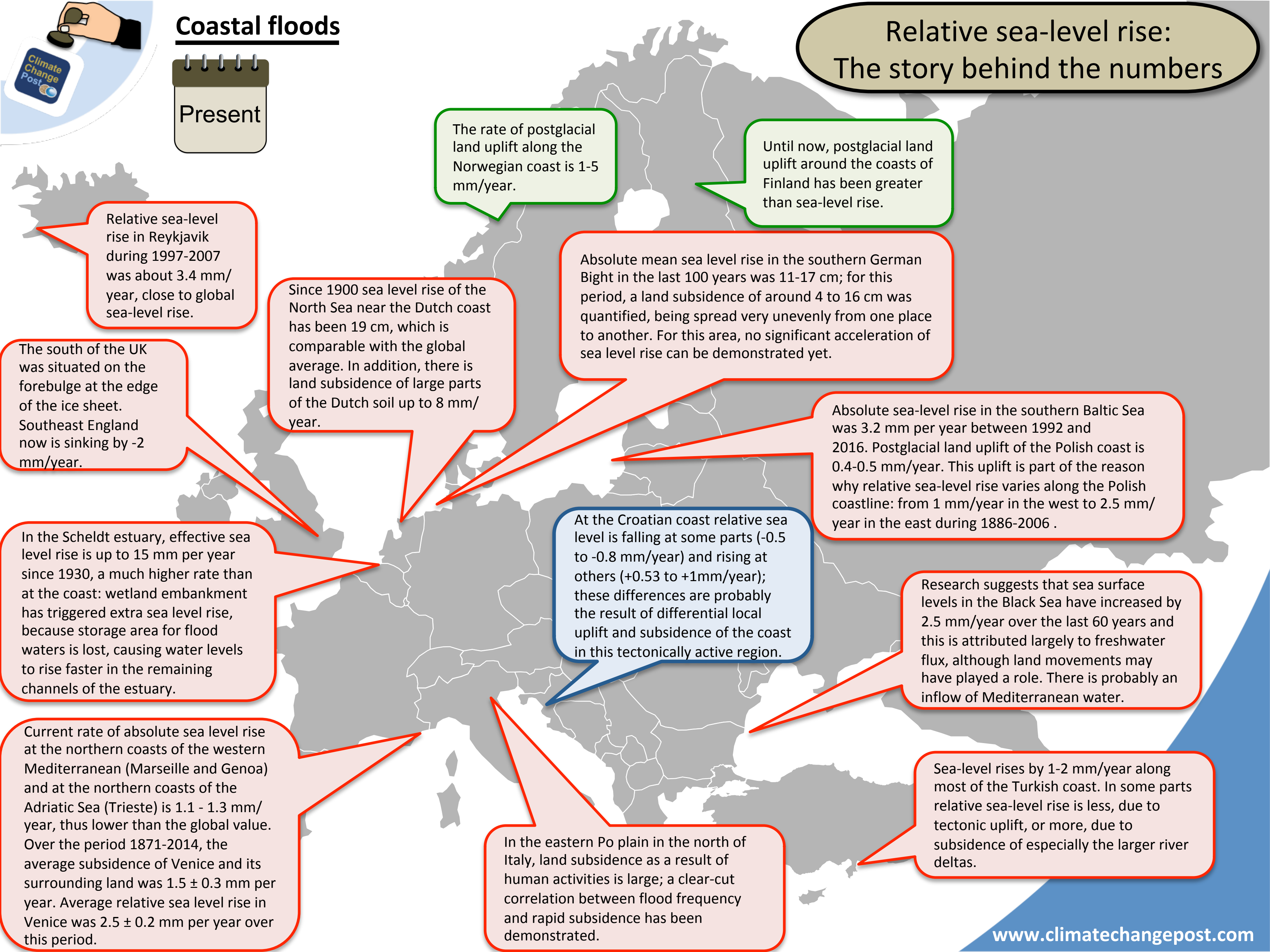
Climate Change Post
Coastal floods
Present
Relative sea-level rise: The story behind the numbers
The rate of postglacial land uplift along the Norwegian coast is 1-5 mm/year.
Until now, postglacial land uplift around the coasts of Finland has been greater than sea-level rise.
Relative sea-level rise in Reykjavik during 1997-2007 was about 3.4 mm/year, close to global sea-level rise.
Since 1900 sea level rise of the North Sea near the Dutch coast has been 19 cm, which is comparable with the global average. In addition, there is land subsidence of large parts of the Dutch soil up to 8 mm/year.
Absolute mean sea level rise in the southern German Bight in the last 100 years was 11-17 cm; for this period, a land subsidence of around 4 to 16 cm was quantified, being spread very unevenly from one place to another. For this area, no significant acceleration of sea level rise can be demonstrated yet.
The south of the UK was situated on the forebulge at the edge of the ice sheet. Southeast England now is sinking by -2 mm/year.
Absolute sea-level rise in the southern Baltic Sea was 3.2 mm per year between 1992 and 2016. Postglacial land uplift of the Polish coast is 0.4-0.5 mm/year. This uplift is part of the reason why relative sea-level rise varies along the Polish coastline: from 1 mm/year in the west to 2.5 mm/year in the east during 1886-2006 .
At the Croatian coast relative sea level is falling at some parts (-0.5 to -0.8 mm/year) and rising at others (+0.53 to +1mm/year); these differences are probably the result of differential local uplift and subsidence of the coast in this tectonically active region.
In the Scheldt estuary, effective sea level rise is up to 15 mm per year since 1930, a much higher rate than at the coast: wetland embankment has triggered extra sea level rise, because storage area for flood waters is lost, causing water levels to rise faster in the remaining channels of the estuary.
Research suggests that sea surface levels in the Black Sea have increased by 2.5 mm/year over the last 60 years and this is attributed largely to freshwater flux, although land movements may have played a role. There is probably an inflow of Mediterranean water.
Current rate of absolute sea level rise at the northern coasts of the western Mediterranean (Marseille and Genoa) and at the northern coasts of the Adriatic Sea (Trieste) is 1.1 - 1.3 mm/year, thus lower than the global value. Over the period 1871-2014, the average subsidence of Venice and its surrounding land was 1.5 ± 0.3 mm per year. Average relative sea level rise in Venice was 2.5 ± 0.2 mm per year over this period.
Sea-level rises by 1-2 mm/year along most of the Turkish coast. In some parts relative sea-level rise is less, due to tectonic uplift, or more, due to subsidence of especially the larger river deltas.
In the eastern Po plain in the north of Italy, land subsidence as a result of human activities is large; a clear-cut correlation between flood frequency and rapid subsidence has been demonstrated.
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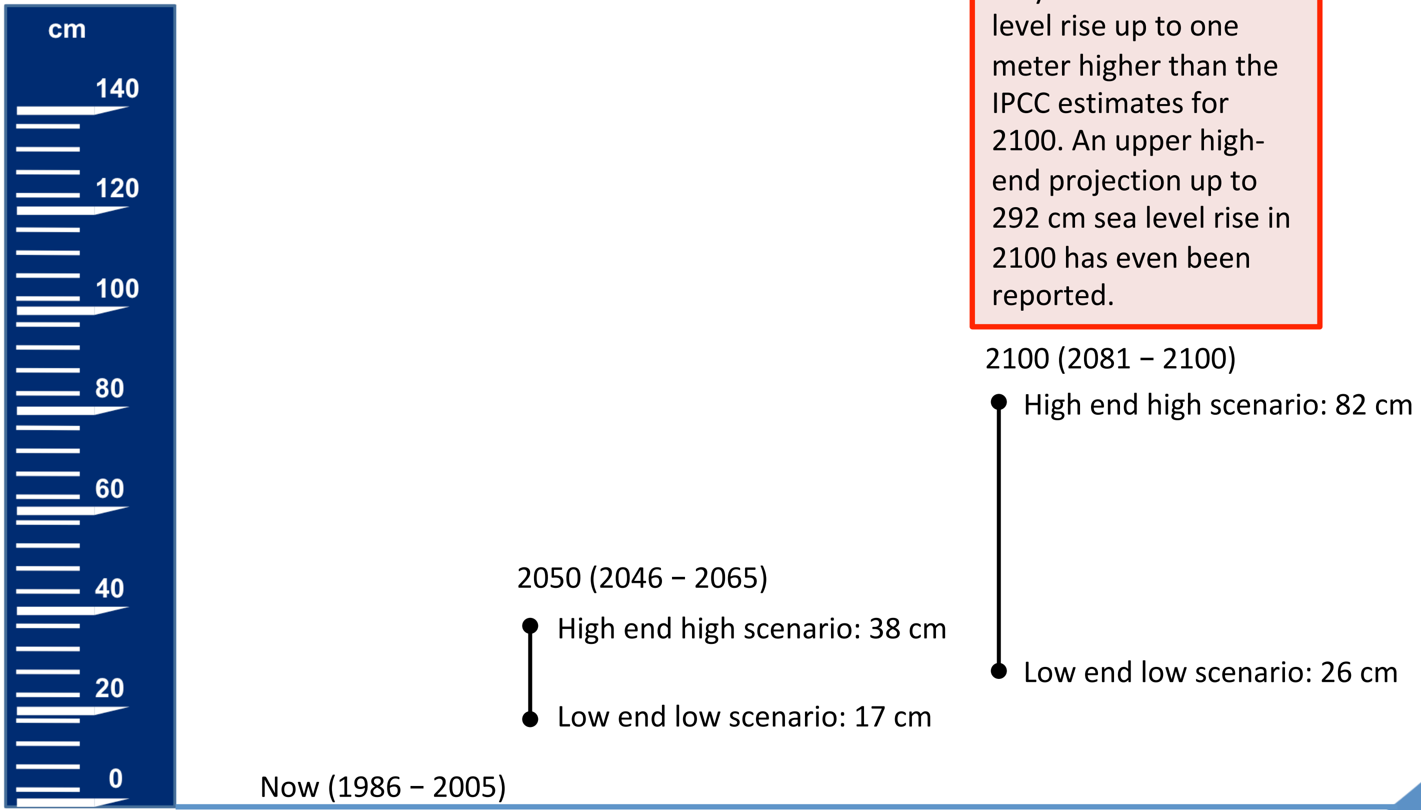
Coastal floods

Global mean sea-level rise: Projections 2050 and 2100

Global mean sea-level rise according to the IPCC (2013): Projections for 2046 – 2065 and 2081 – 2100 relative to 1986 – 2005

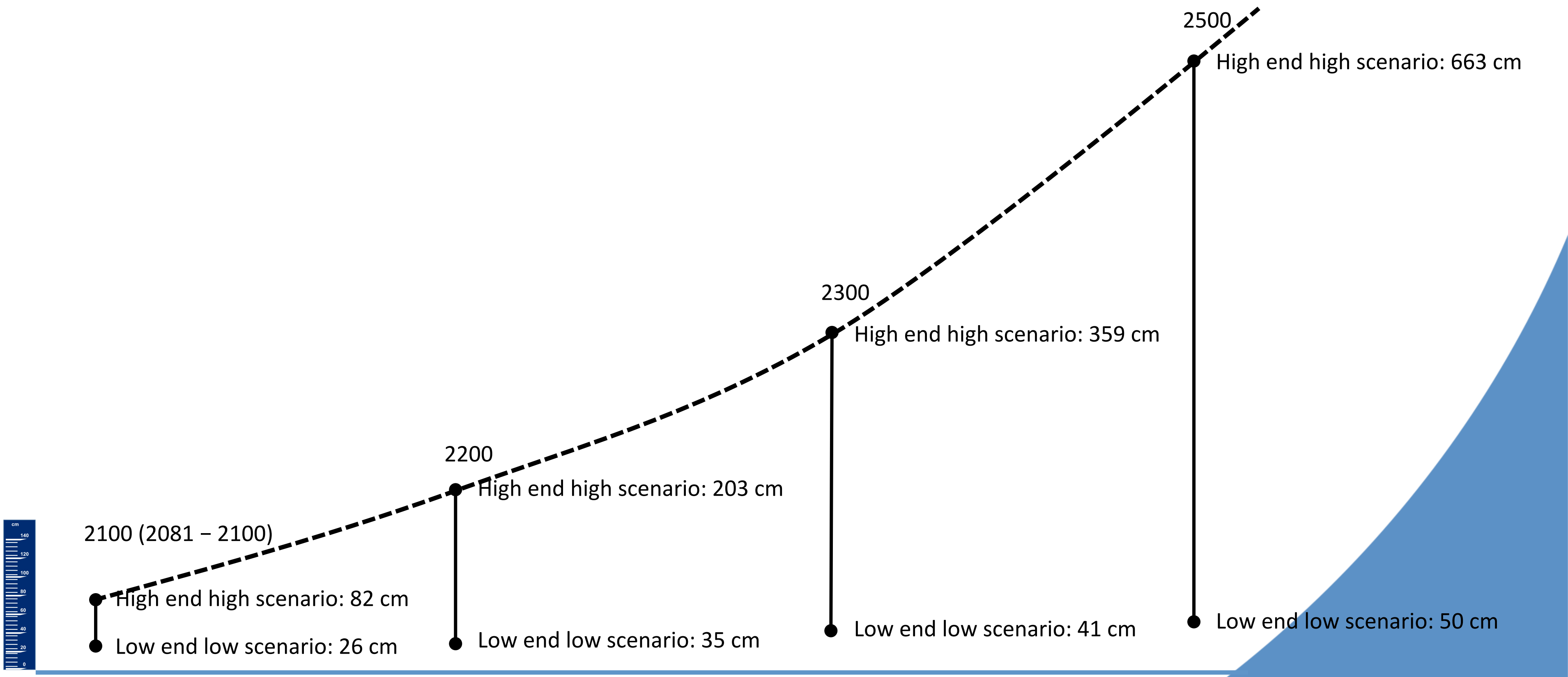
New insights point at future instability of the Antarctic ice sheet. This may accelerate sea level rise up to one meter higher than the IPCC estimates for 2100. An upper high-end projection up to 292 cm sea level rise in 2100 has even been reported.



Coastal floods

Global mean sea-level rise: Projections beyond 2100

Global mean sea-level rise according to the IPCC (2014): Projections for 2200 onwards



Coastal floods

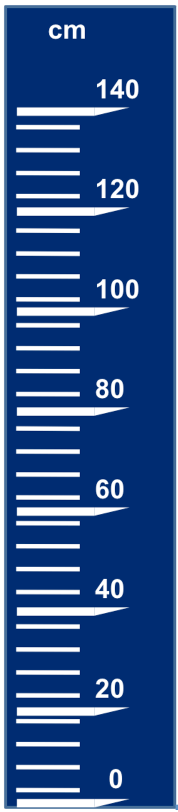
Relative sea-level rise in Europe: Projections 2050 and 2100

Average relative sea-level rise (Vousdoukas et al. 2017): Projections for medium and high-end scenarios of climate change

The dominant uncertainty in sea level rise is associated with the fate of Antarctica, followed by expansion of ocean waters due to warming and uncertainties in glacial isostatic adjustment.

In an assessment carried out for the Dutch Delta Programme, Dutch scientists concluded that under a worst-case scenario sea-level rise on the North Sea might be up to 2-3 metres in 2100, and up to 5-8 m in 2200.

Projected sea level rise is highest along the North Sea and Atlantic coasts, followed by the Black Sea, and smallest for the Baltic Sea due to land uplift in this area.



Now (2000)

2050

High-end: 24 cm
Medium scenario: 21 cm

2100

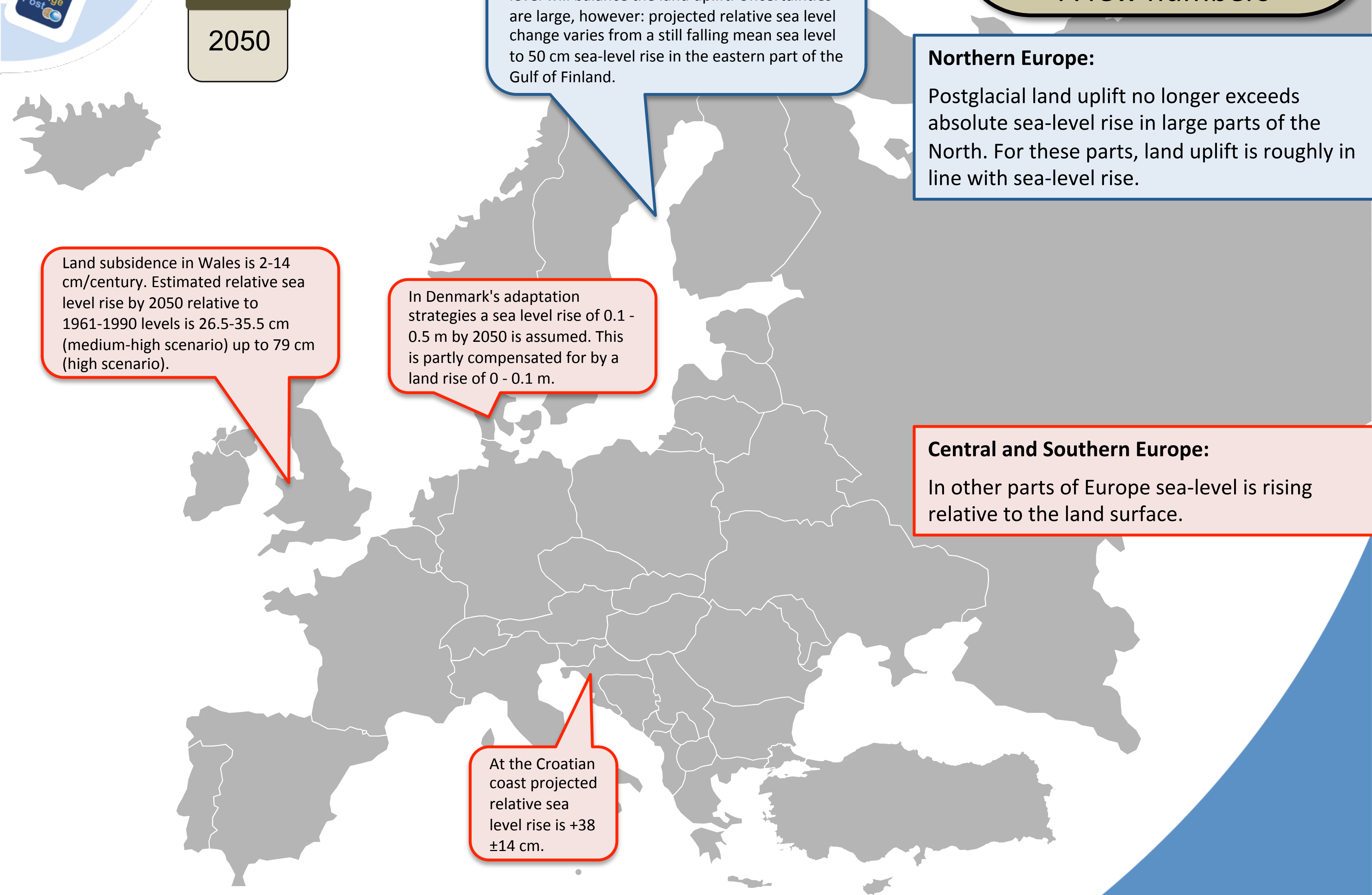
High-end scenario: 77 cm

Medium scenario: 53 cm

Coastal floods

2050

Relative sea-level rise: A few numbers



Sea level in the Gulf of Finland will remain roughly at the present level until the end of the century: the accelerating rise in the mean sea level will balance the land uplift. Uncertainties are large, however: projected relative sea level change varies from a still falling mean sea level to 50 cm sea-level rise in the eastern part of the Gulf of Finland.

Northern Europe:

Postglacial land uplift no longer exceeds absolute sea-level rise in large parts of the North. For these parts, land uplift is roughly in line with sea-level rise.

Land subsidence in Wales is 2-14 cm/century. Estimated relative sea level rise by 2050 relative to 1961-1990 levels is 26.5-35.5 cm (medium-high scenario) up to 79 cm (high scenario).

In Denmark's adaptation strategies a sea level rise of 0.1 - 0.5 m by 2050 is assumed. This is partly compensated for by a land rise of 0 - 0.1 m.

Central and Southern Europe:

In other parts of Europe sea-level is rising relative to the land surface.

At the Croatian coast projected relative sea level rise is +38 ±14 cm.

Coastal floods

2100

Relative sea-level rise: A few numbers

Coastal floods

Relative sea-level rise: The big picture

Present

Northern Europe:

Postglacial land uplift is greater than absolute sea-level rise. Relative to the land surface sea-level is dropping

Southern Scandinavia and Baltic States:

Land uplift is roughly in line with sea-level rise.

Central and Southern Europe:

In other parts of Europe relative sea-level is rising. In many parts relative sea-level rise exceeds absolute sea-level rise due to land subsidence: at several spots land is sinking, mostly as a result of groundwater withdrawal or compaction of the soil.

2050

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Central and Southern Europe:

In other parts of Europe sea-level is rising relative to the land surface.

2100

All along Europe’s coastline (except for the upper north) relative sea-level is rising.

Change relative sea-level

- Relative sea-level drops
- No change
- Relative sea-level rises

Storm surge, waves and tides

What causes extremely high water levels:

Coastal flooding is often the result of extremely high water level events due to the combined contributions of large waves, storm surge, high tides, and mean sea-level anomalies. Waves, storm surges, and tides in turn are influenced by the morphology of the coastal zone. The impact of sea-level rise on the risk of coastal flooding must be assessed as part of all these contributing factors. It is difficult, therefore, to predict the effect of sea level rise on episodic flooding events due to the unpredictable nature of coastal storms, nonlinear interactions of physical processes (e.g., tidal currents and waves), and variations in coastal geomorphology.

To what extent a certain amount of sea-level rise increases flood frequency may be completely different at different locations, because the combination of these factors is different from one place to another.

Coastal floods

Storm surge, waves and tides

Storm surge

At many coastal regions in Europe extreme storm surge level may increase by around 15%, and locally even up to 40%, of relative sea level rise for most of Europe's coastline. The combined effect of relative sea level rise and storm surge increase at the end of this century is projected to exceed 1 m for many regions in Europe.

Projected storm surge changes strongly vary for different parts of Europe, however. Especially there is a difference between the northern and southern half of Europe. Increase is highest along the eastern part of the North Sea coast, along the west-facing coastline of the Irish Sea, and at the Baltic Sea and the Norwegian Sea. Along the southern European coastline projected storm surges hardly change or even decrease.

Waves

Studies indicated that the height of extreme waves along the western European coast will increase. However, for the North Sea region reliable predictions concerning strongly wind-influenced characteristics such as local sea level, storm surges, and waves are still impossible; the large natural variability has a greater impact on the local North Sea wind field than potential anthropogenic-induced trends.

Tides

The projected change of tidal elevation between now and 2100 is negligible for the entire European coastline.

Coastal floods

Storm surge, waves and tides

Storm surge

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Tides

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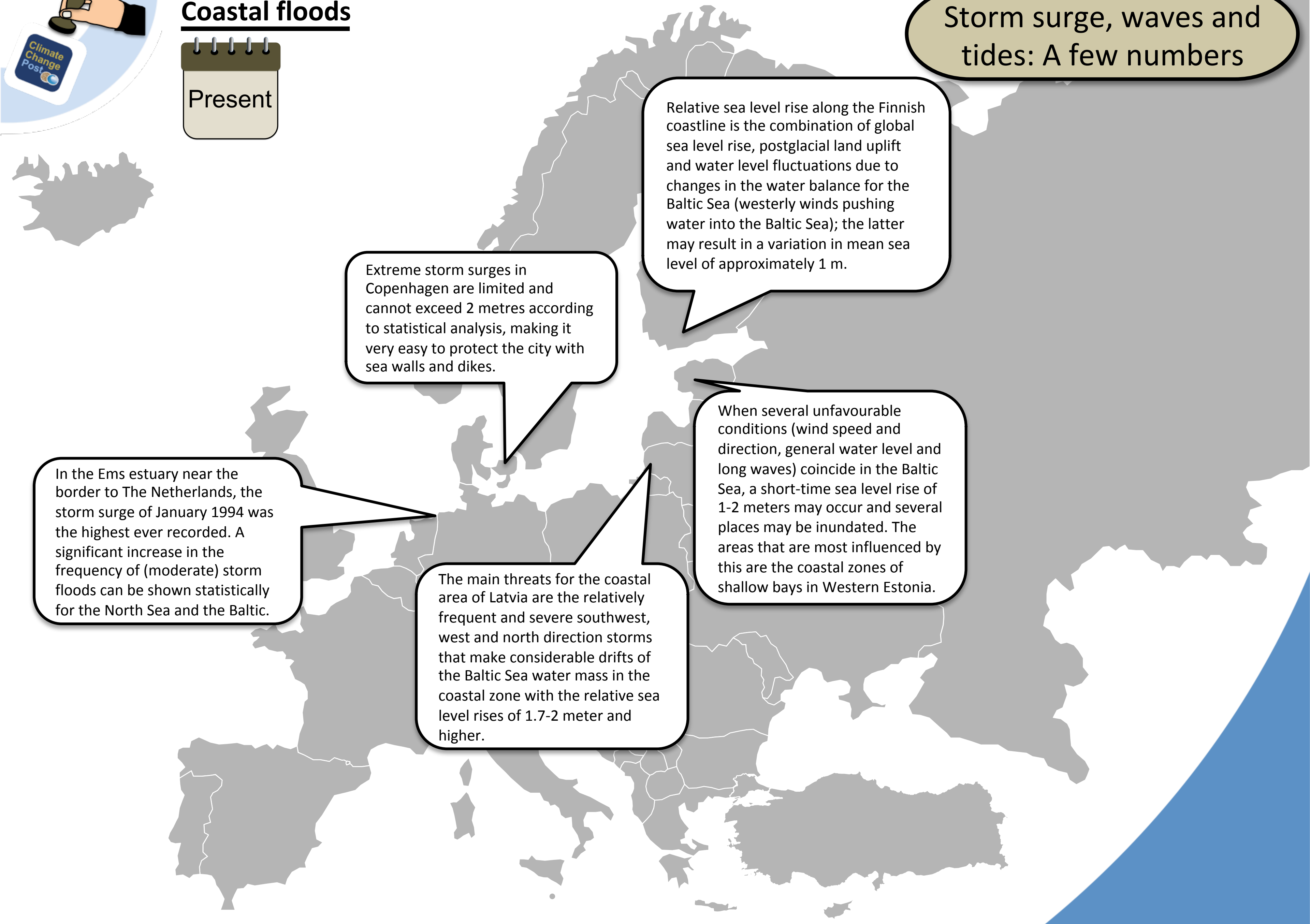
+

The combined effect of sea level rise, astronomical tide, and storm surges and wave set up on the once-in-a-hundred-years extreme sea levels along Europe's coasts is a rise by around 25 cm on average by 2050, and a rise by 57 - 81 cm by 2100. Strongest rise was projected for the North Sea region: up to 75 - 98 cm by 2100.

Coastal floods

Present

Storm surge, waves and tides: A few numbers



Relative sea level rise along the Finnish coastline is the combination of global sea level rise, postglacial land uplift and water level fluctuations due to changes in the water balance for the Baltic Sea (westerly winds pushing water into the Baltic Sea); the latter may result in a variation in mean sea level of approximately 1 m.

Extreme storm surges in Copenhagen are limited and cannot exceed 2 metres according to statistical analysis, making it very easy to protect the city with sea walls and dikes.

When several unfavourable conditions (wind speed and direction, general water level and long waves) coincide in the Baltic Sea, a short-time sea level rise of 1-2 meters may occur and several places may be inundated. The areas that are most influenced by this are the coastal zones of shallow bays in Western Estonia.

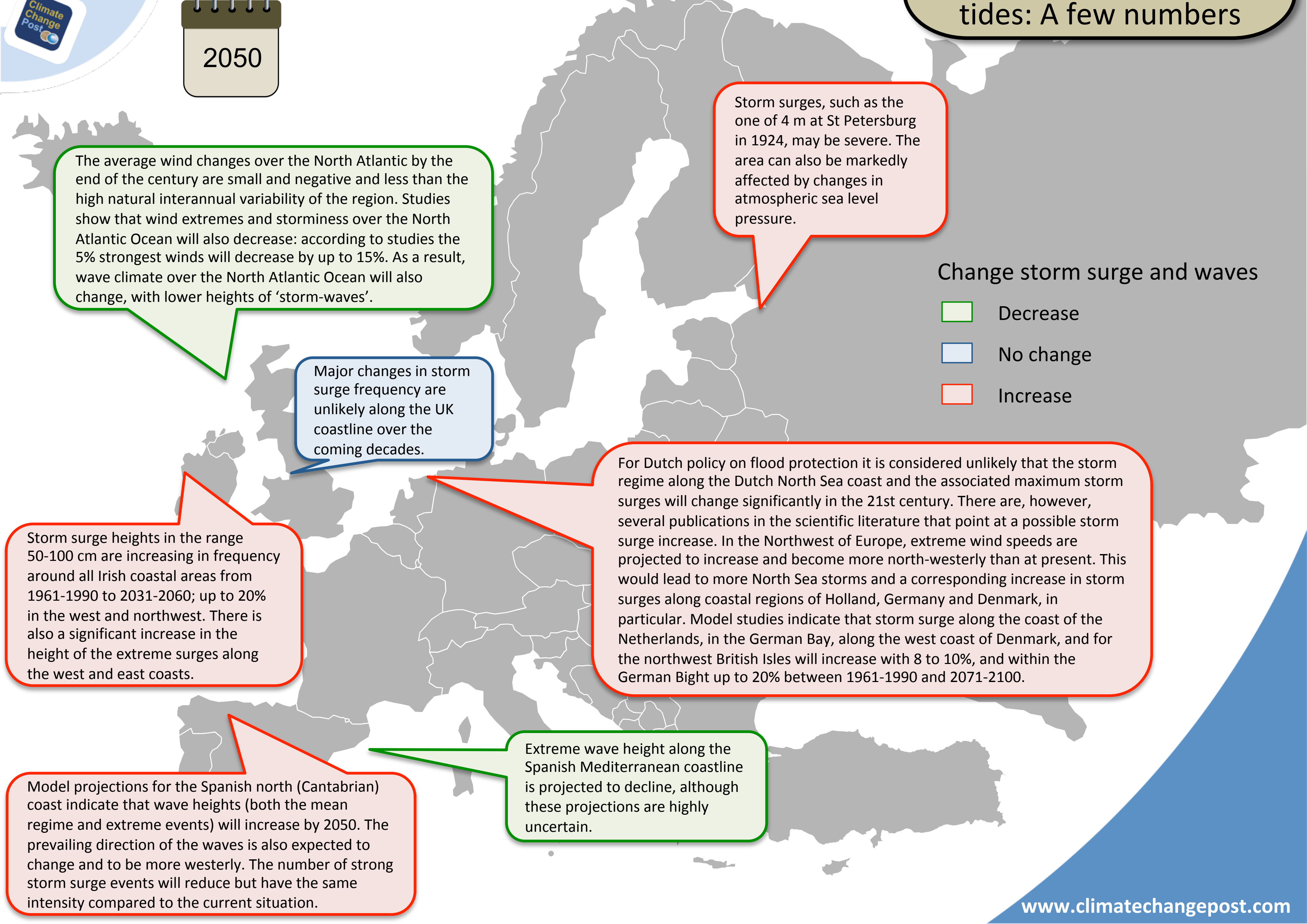
In the Ems estuary near the border to The Netherlands, the storm surge of January 1994 was the highest ever recorded. A significant increase in the frequency of (moderate) storm floods can be shown statistically for the North Sea and the Baltic.

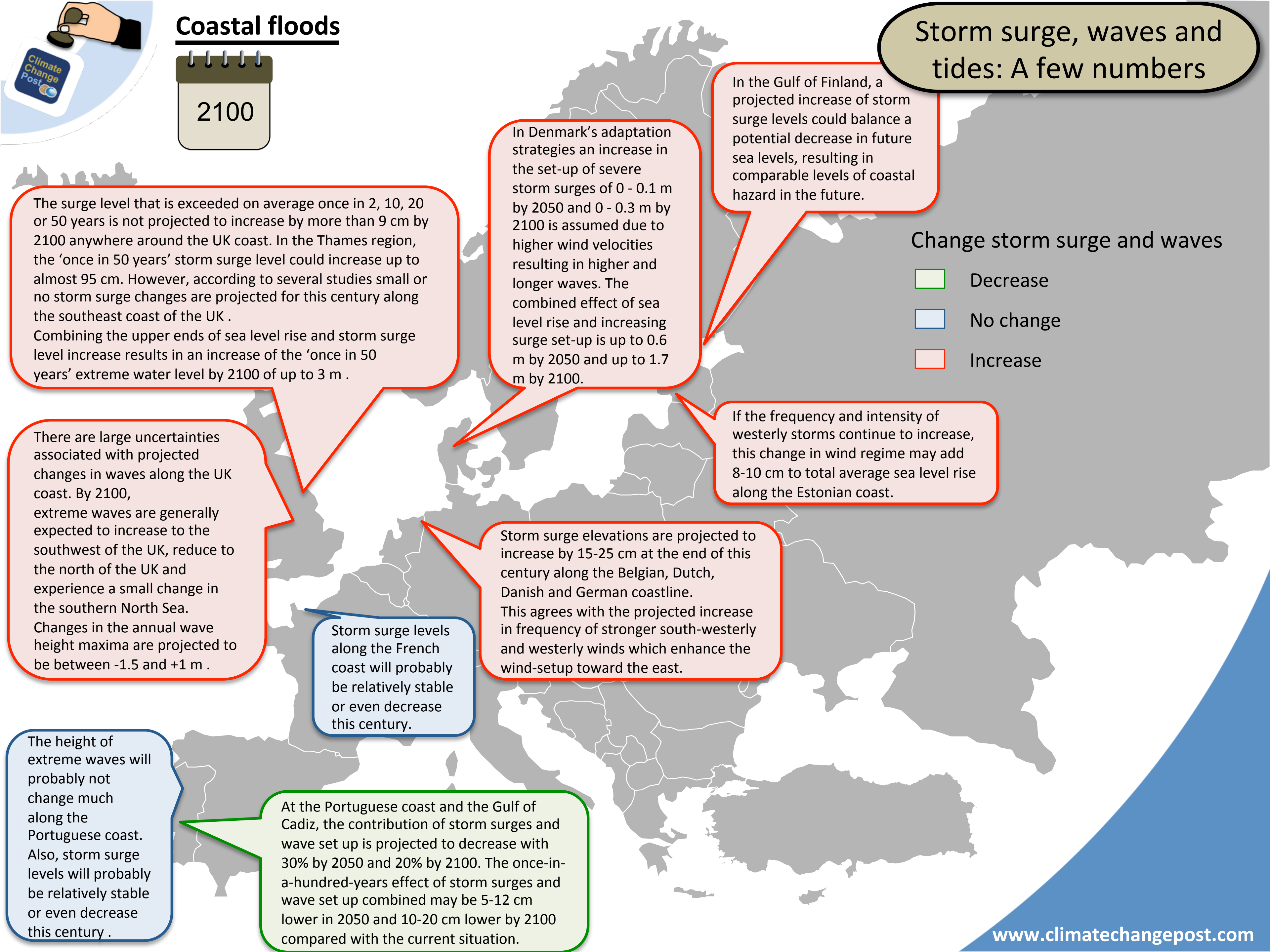
The main threats for the coastal area of Latvia are the relatively frequent and severe southwest, west and north direction storms that make considerable drifts of the Baltic Sea water mass in the coastal zone with the relative sea level rises of 1.7-2 meter and higher.

Coastal floods

2050

Storm surge, waves and tides: A few numbers




Climate Change Post
Coastal floods
2100
Storm surge, waves and tides: A few numbers
In the Gulf of Finland, a projected increase of storm surge levels could balance a potential decrease in future sea levels, resulting in comparable levels of coastal hazard in the future.
In Denmark's adaptation strategies an increase in the set-up of severe storm surges of 0 - 0.1 m by 2050 and 0 - 0.3 m by 2100 is assumed due to higher wind velocities resulting in higher and longer waves. The combined effect of sea level rise and increasing surge set-up is up to 0.6 m by 2050 and up to 1.7 m by 2100.
The surge level that is exceeded on average once in 2, 10, 20 or 50 years is not projected to increase by more than 9 cm by 2100 anywhere around the UK coast. In the Thames region, the 'once in 50 years' storm surge level could increase up to almost 95 cm. However, according to several studies small or no storm surge changes are projected for this century along the southeast coast of the UK . Combining the upper ends of sea level rise and storm surge level increase results in an increase of the 'once in 50 years' extreme water level by 2100 of up to 3 m .
Change storm surge and waves
Decrease
No change
Increase
There are large uncertainties associated with projected changes in waves along the UK coast. By 2100, extreme waves are generally expected to increase to the southwest of the UK, reduce to the north of the UK and experience a small change in the southern North Sea. Changes in the annual wave height maxima are projected to be between -1.5 and +1 m .
If the frequency and intensity of westerly storms continue to increase, this change in wind regime may add 8-10 cm to total average sea level rise along the Estonian coast.
Storm surge elevations are projected to increase by 15-25 cm at the end of this century along the Belgian, Dutch, Danish and German coastline. This agrees with the projected increase in frequency of stronger south-westerly and westerly winds which enhance the wind-setup toward the east.
Storm surge levels along the French coast will probably be relatively stable or even decrease this century.
The height of extreme waves will probably not change much along the Portuguese coast. Also, storm surge levels will probably be relatively stable or even decrease this century .
At the Portuguese coast and the Gulf of Cadiz, the contribution of storm surges and wave set up is projected to decrease with 30% by 2050 and 20% by 2100. The once-in-a-hundred-years effect of storm surges and wave set up combined may be 5-12 cm lower in 2050 and 10-20 cm lower by 2100 compared with the current situation.
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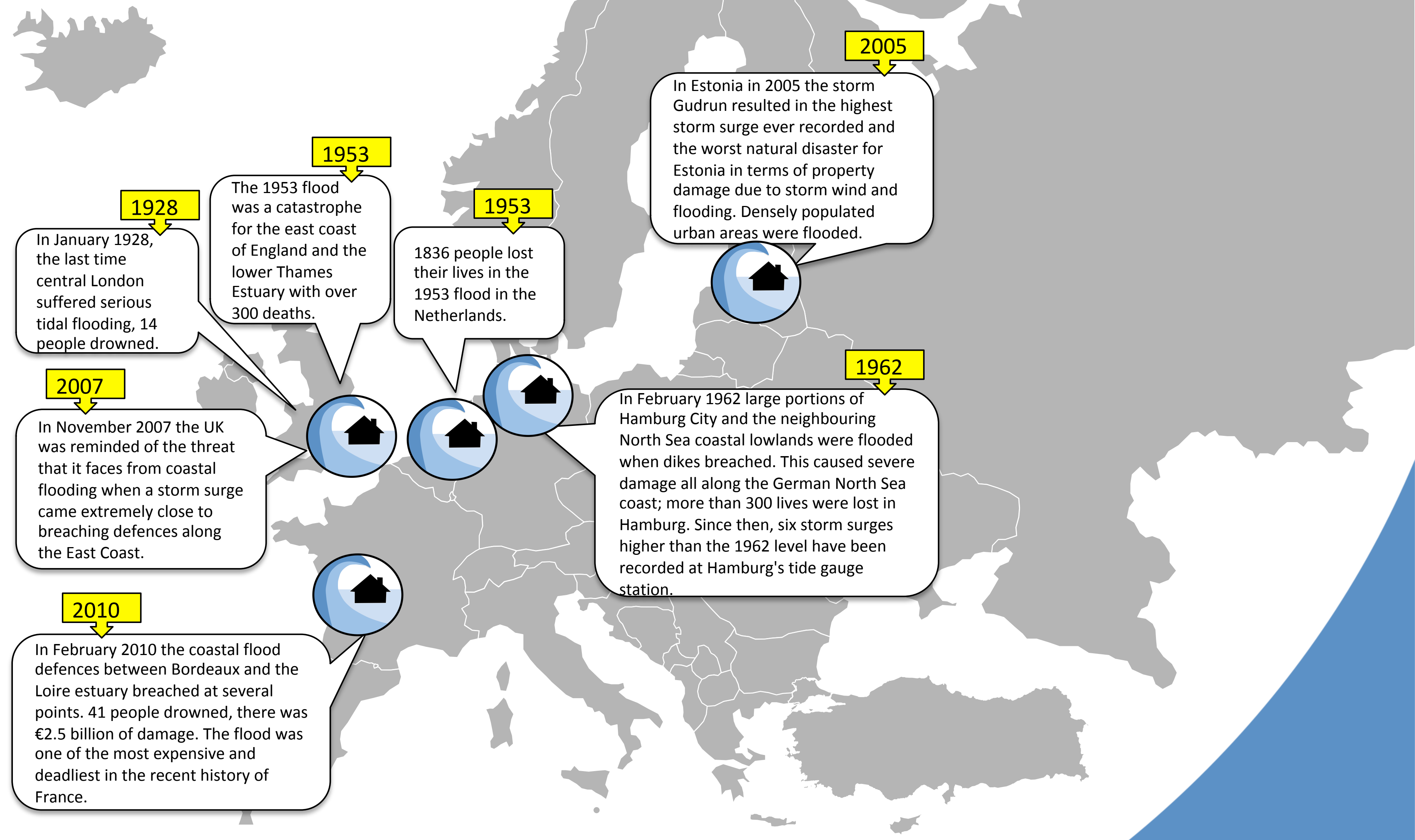
Coastal floods

Past

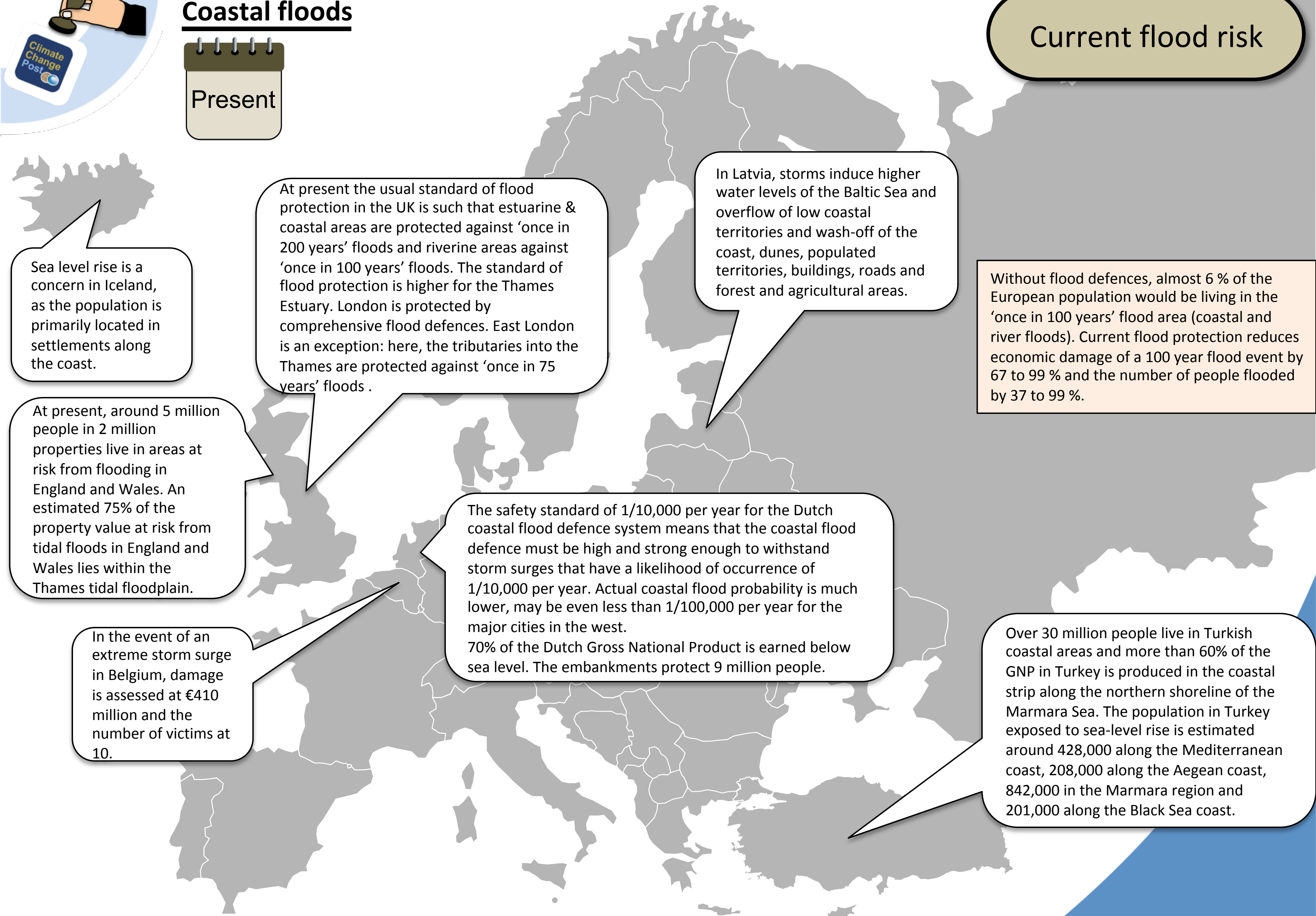
Recent examples



Coastal floods

Present

Current flood risk



Sea level rise is a concern in Iceland, as the population is primarily located in settlements along the coast.

At present the usual standard of flood protection in the UK is such that estuarine & coastal areas are protected against 'once in 200 years' floods and riverine areas against 'once in 100 years' floods. The standard of flood protection is higher for the Thames Estuary. London is protected by comprehensive flood defences. East London is an exception: here, the tributaries into the Thames are protected against 'once in 75 years' floods .

In Latvia, storms induce higher water levels of the Baltic Sea and overflow of low coastal territories and wash-off of the coast, dunes, populated territories, buildings, roads and forest and agricultural areas.

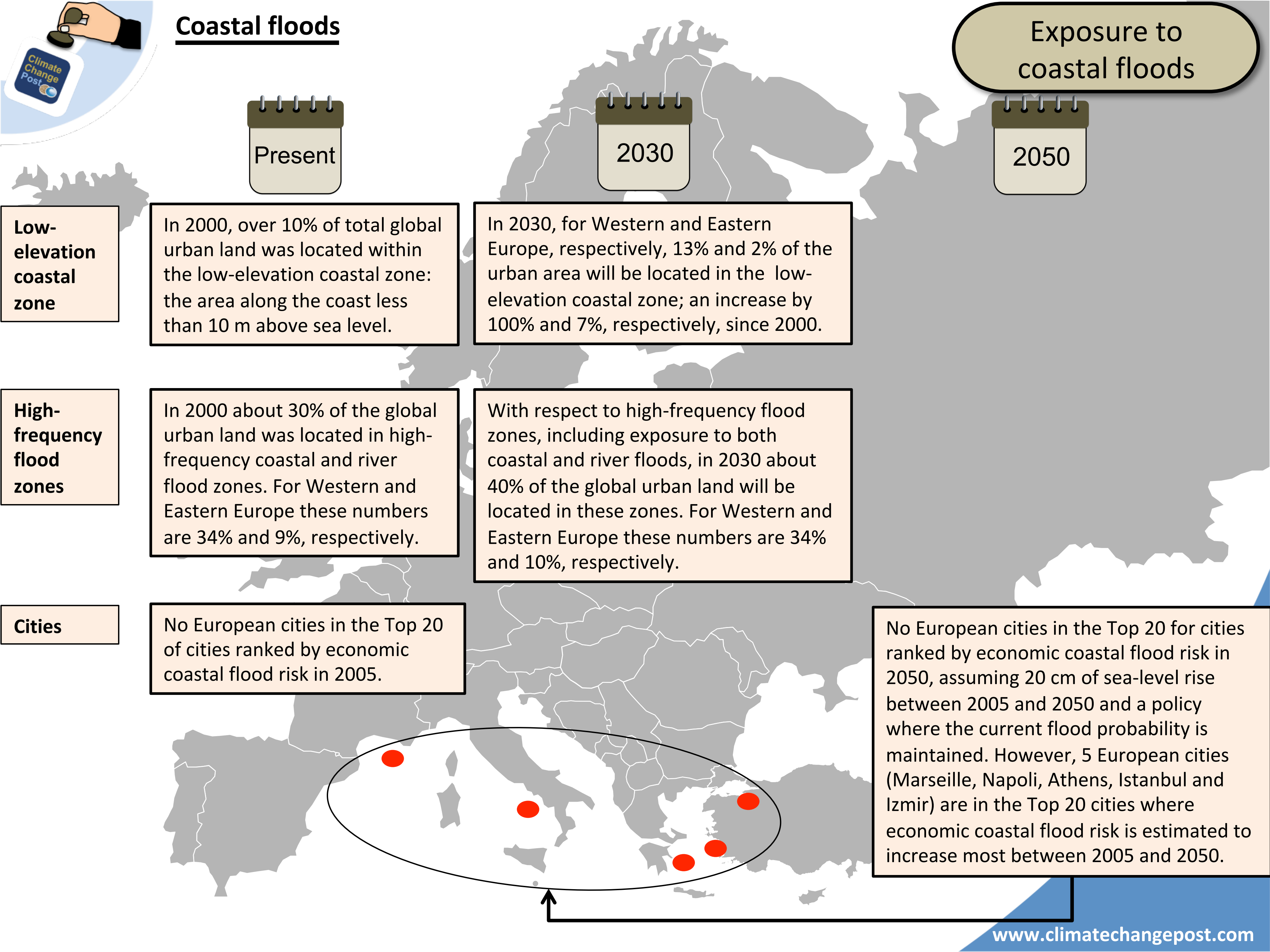
Without flood defences, almost 6 % of the European population would be living in the 'once in 100 years' flood area (coastal and river floods). Current flood protection reduces economic damage of a 100 year flood event by 67 to 99 % and the number of people flooded by 37 to 99 %.

At present, around 5 million people in 2 million properties live in areas at risk from flooding in England and Wales. An estimated 75% of the property value at risk from tidal floods in England and Wales lies within the Thames tidal floodplain.

The safety standard of 1/10,000 per year for the Dutch coastal flood defence system means that the coastal flood defence must be high and strong enough to withstand storm surges that have a likelihood of occurrence of 1/10,000 per year. Actual coastal flood probability is much lower, may be even less than 1/100,000 per year for the major cities in the west.
70% of the Dutch Gross National Product is earned below sea level. The embankments protect 9 million people.

In the event of an extreme storm surge in Belgium, damage is assessed at €410 million and the number of victims at 10.

Over 30 million people live in Turkish coastal areas and more than 60% of the GNP in Turkey is produced in the coastal strip along the northern shoreline of the Marmara Sea. The population in Turkey exposed to sea-level rise is estimated around 428,000 along the Mediterranean coast, 208,000 along the Aegean coast, 842,000 in the Marmara region and 201,000 along the Black Sea coast.



Coastal floods

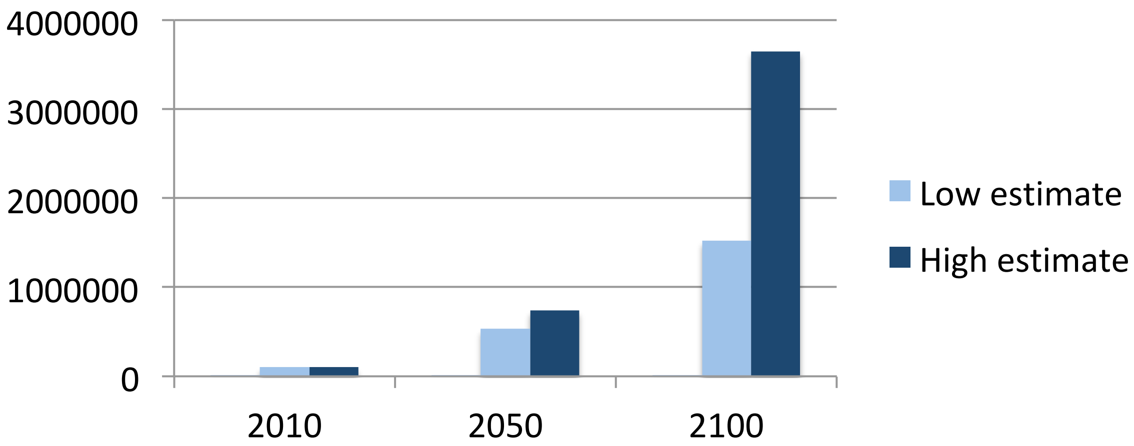
Exposure to coastal floods

	Present	2030	2050
Low-elevation coastal zone	In 2000, over 10% of total global urban land was located within the low-elevation coastal zone: the area along the coast less than 10 m above sea level.	In 2030, for Western and Eastern Europe, respectively, 13% and 2% of the urban area will be located in the low-elevation coastal zone; an increase by 100% and 7%, respectively, since 2000.	
High-frequency flood zones	In 2000 about 30% of the global urban land was located in high-frequency coastal and river flood zones. For Western and Eastern Europe these numbers are 34% and 9%, respectively.	With respect to high-frequency flood zones, including exposure to both coastal and river floods, in 2030 about 40% of the global urban land will be located in these zones. For Western and Eastern Europe these numbers are 34% and 10%, respectively.	
Cities	No European cities in the Top 20 of cities ranked by economic coastal flood risk in 2005.		No European cities in the Top 20 for cities ranked by economic coastal flood risk in 2050, assuming 20 cm of sea-level rise between 2005 and 2050 and a policy where the current flood probability is maintained. However, 5 European cities (Marseille, Napoli, Athens, Istanbul and Izmir) are in the Top 20 cities where economic coastal flood risk is estimated to increase most between 2005 and 2050.

Coastal floods (assumption: no upgrade flood protection)

Future projections for Europe

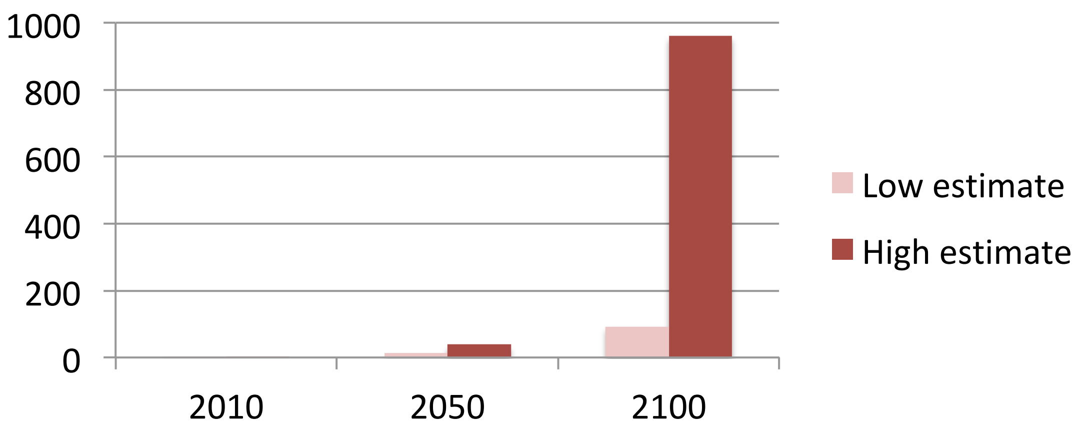
Number of people exposed to coastal floods in Europe annually



Currently, under the present climate conditions (reference year 2010), Europe's expected annual damage from coastal flooding is €1.25 billion. By 2050, this damage is projected to increase to €12.5 - 39 billion a 10- to 30-fold increase. In the second half of this century, the projected damage even increases to €93 - 961 billion, a staggering increase of 75 to 770 times.

The current expected annual number of people exposed to coastal flooding equals 102,000. By 2050 this number is projected to rise to around 533,000 – 742,000, further climbing to 1.52 - 3.65 million people by the end of the century.

Economic damage by coastal floods in Europe annually (billion Euros)



Source:
Vousdoukas et al. (2018)

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Coastal floods (assumption: no upgrade flood protection)

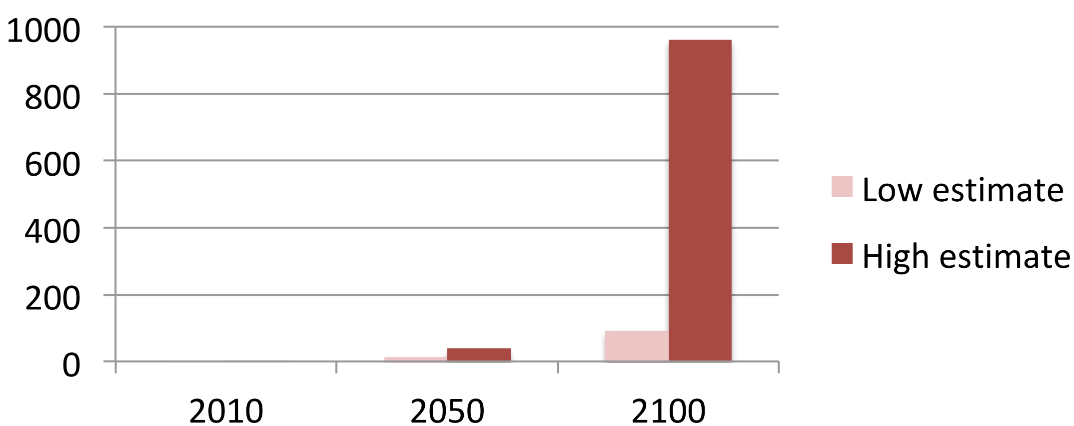
Future projections for Europe

Previous estimate Brown et al. (2015, in: EEA, 2017):

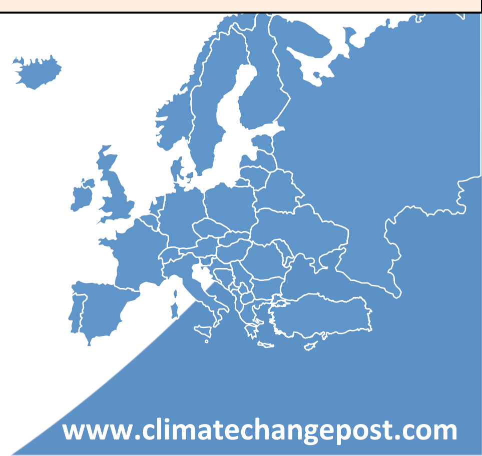
Mid-century:
Without adaptation the estimated costs of climate change to coastal zones in the EU in the 2060s are €6 to 19 billion per year for a low-end scenario of climate change, €7 to 27 billion per year for a moderate scenario and €15 to 65 billion per year for a high-end scenario (climate and socio-economic change combined, current prices, no discounting).

End century:
Without adaptation the estimated costs of climate change to coastal zones in the EU in the 2080s are €18 to 111 billion billion per year for a low-end scenario of climate change, €40 to 249 billion per year for a moderate scenario and €153 to 631 billion per year for a high-end scenario (climate and socio-economic change combined, current prices, no discounting).

Economic damage by coastal floods in Europe annually (billion Euros)



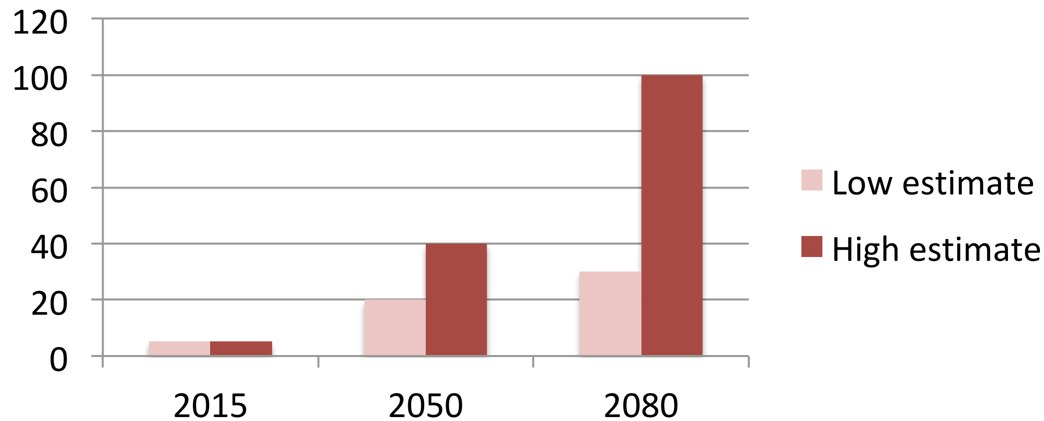
Source:
Vousdoukas et al. (2018)



Coastal floods compared with river floods

Future projections for Europe

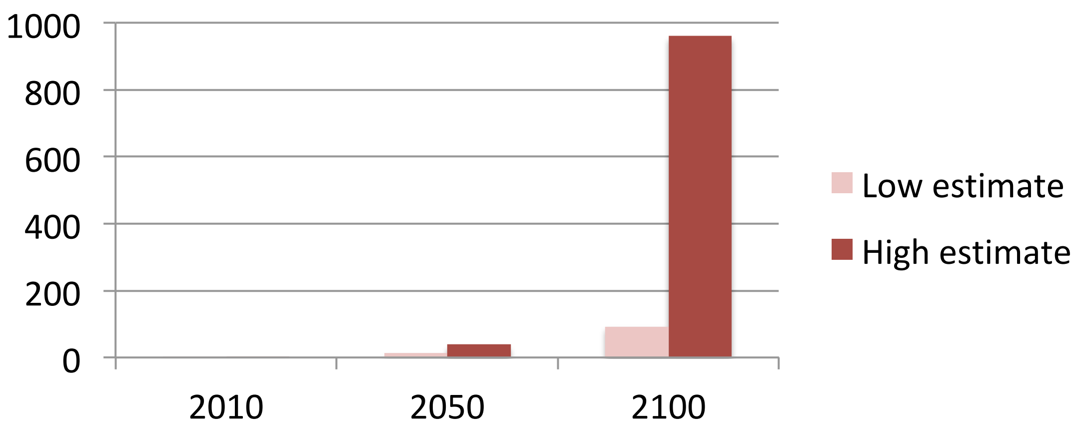
Economic damage by river floods in Europe annually (billion Euros)



Source:
Alfieri et al. (2015)

Expected annual damage from coastal flooding is currently around 0.01% of GDP for Europe, compared to nearly 0.04% (approximately €6 billion per year) for river flooding. This share is projected to grow in the coming decades to range between 0.29 and 0.86% of GDP by the end of this century for the scenarios considered, which is far larger than the share of future river flood risk to GDP in high-income countries.

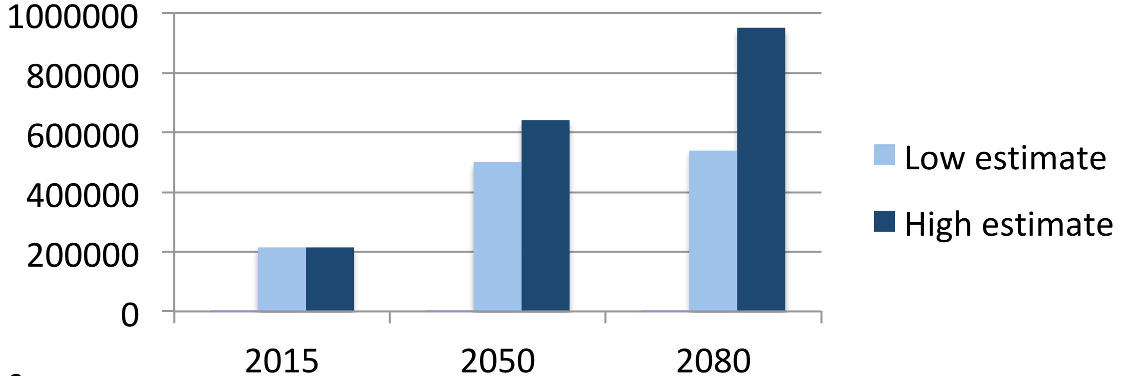
Economic damage by coastal floods in Europe annually (billion Euros)



Source:
Vousdoukas et al. (2018)

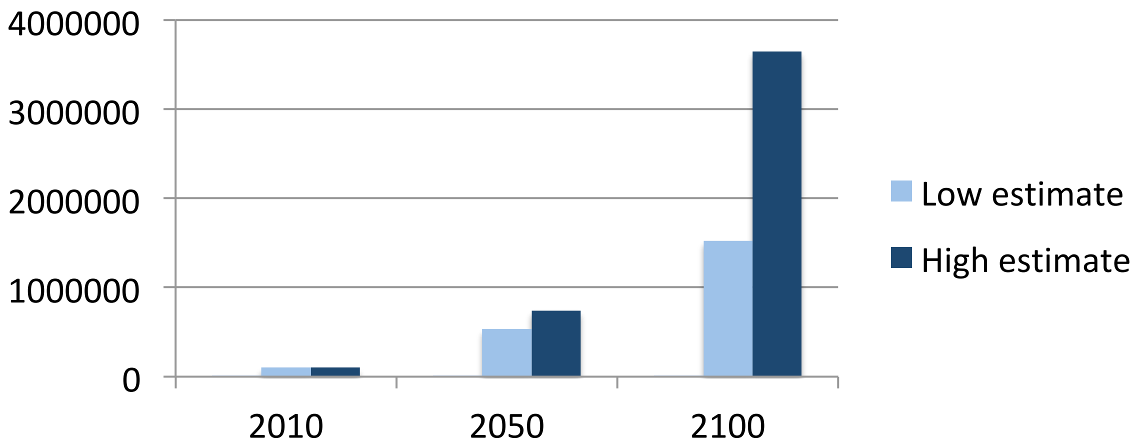
Coastal floods compared with river floods

Number of people affected by river floods in Europe annually



Source:
Alfieri et al. (2015)

Number of people exposed to coastal floods in Europe annually



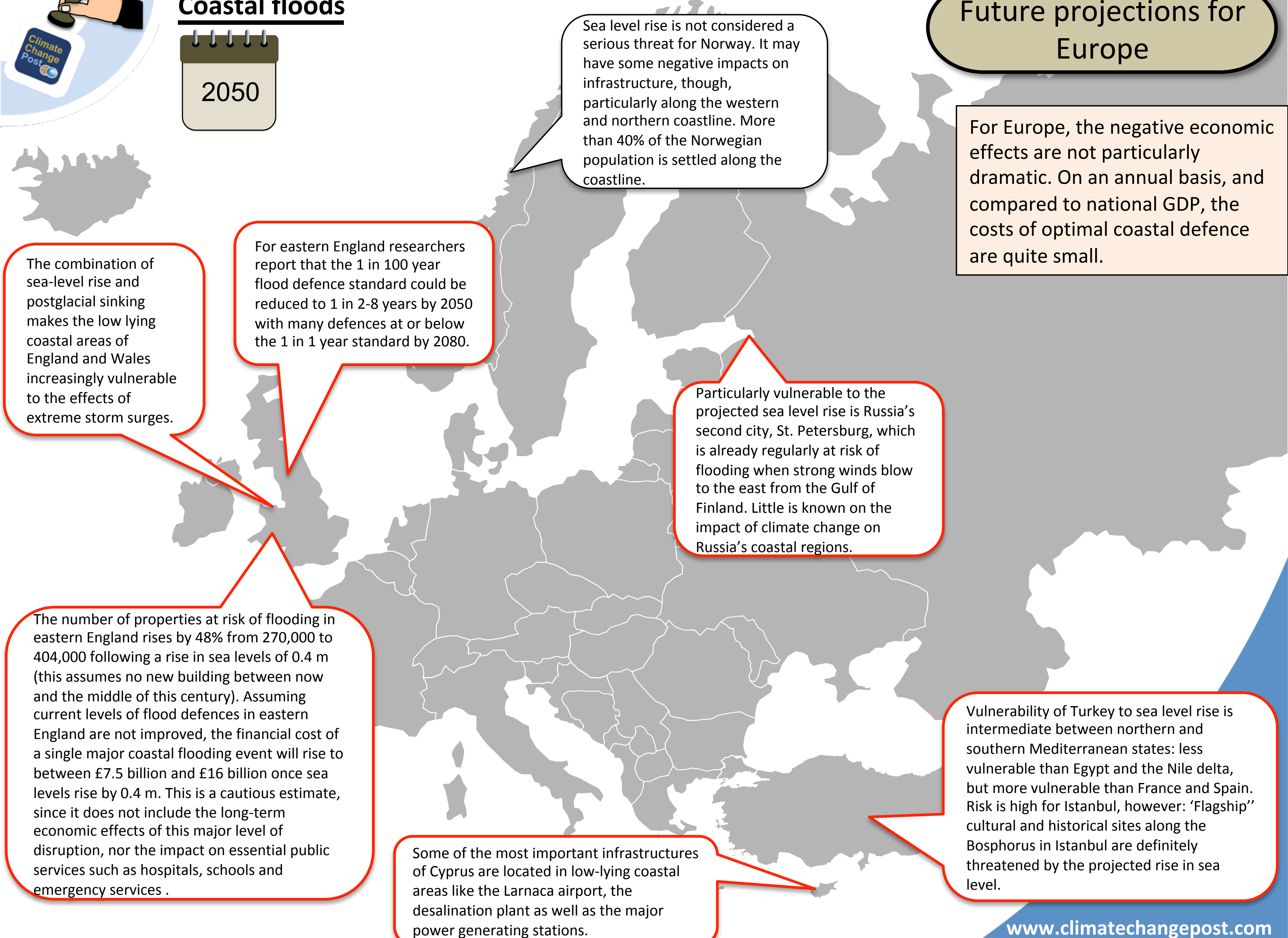
Source:
Vousdoukas et al. (2018)

Coastal floods

2050

Future projections for Europe

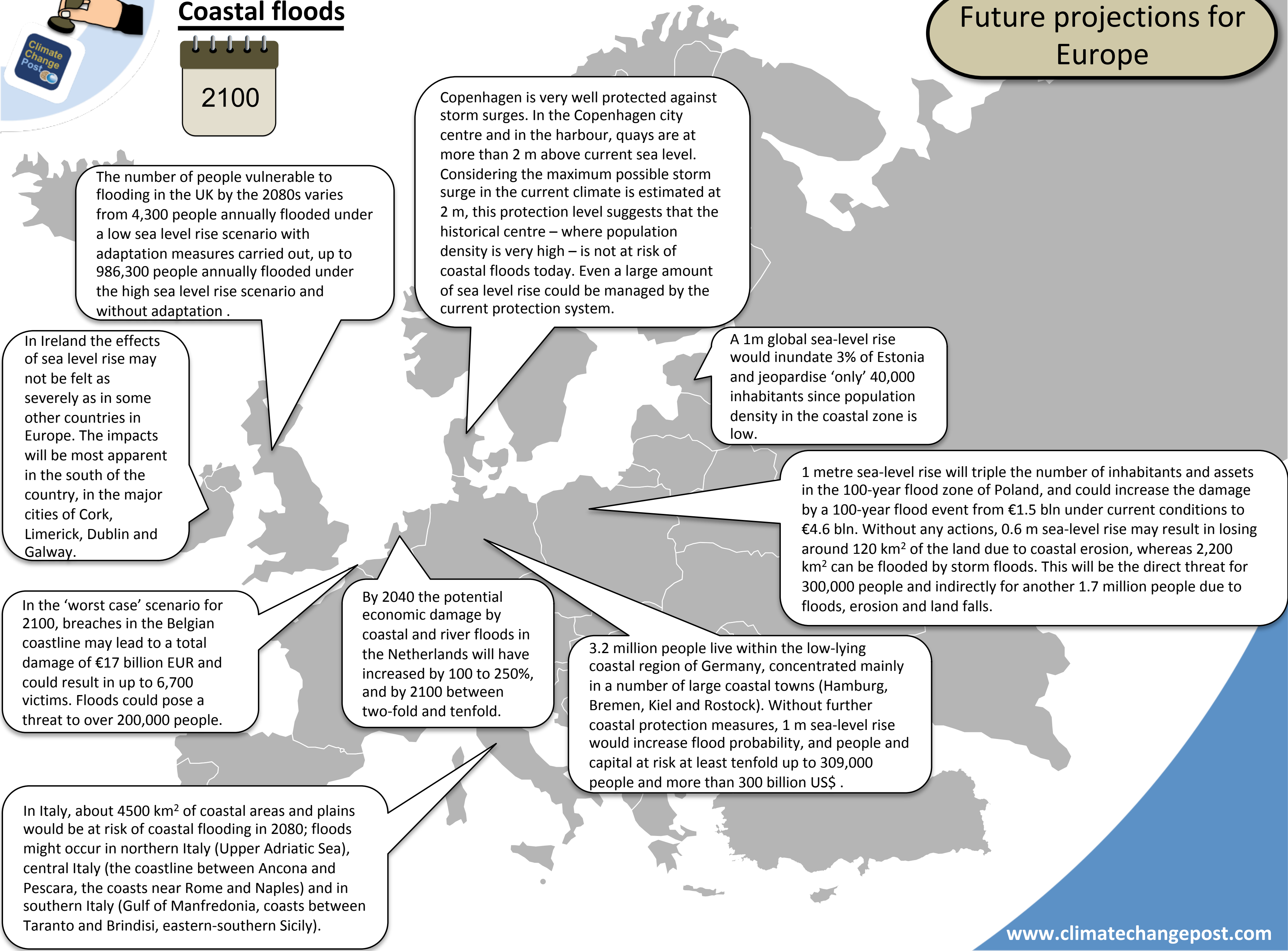
For Europe, the negative economic effects are not particularly dramatic. On an annual basis, and compared to national GDP, the costs of optimal coastal defence are quite small.



Coastal floods

2100

Future projections for Europe



The number of people vulnerable to flooding in the UK by the 2080s varies from 4,300 people annually flooded under a low sea level rise scenario with adaptation measures carried out, up to 986,300 people annually flooded under the high sea level rise scenario and without adaptation .

Copenhagen is very well protected against storm surges. In the Copenhagen city centre and in the harbour, quays are at more than 2 m above current sea level. Considering the maximum possible storm surge in the current climate is estimated at 2 m, this protection level suggests that the historical centre – where population density is very high – is not at risk of coastal floods today. Even a large amount of sea level rise could be managed by the current protection system.

In Ireland the effects of sea level rise may not be felt as severely as in some other countries in Europe. The impacts will be most apparent in the south of the country, in the major cities of Cork, Limerick, Dublin and Galway.

A 1m global sea-level rise would inundate 3% of Estonia and jeopardise ‘only’ 40,000 inhabitants since population density in the coastal zone is low.

1 metre sea-level rise will triple the number of inhabitants and assets in the 100-year flood zone of Poland, and could increase the damage by a 100-year flood event from €1.5 bln under current conditions to €4.6 bln. Without any actions, 0.6 m sea-level rise may result in losing around 120 km^2 of the land due to coastal erosion, whereas 2,200 km^2 can be flooded by storm floods. This will be the direct threat for 300,000 people and indirectly for another 1.7 million people due to floods, erosion and land falls.

In the ‘worst case’ scenario for 2100, breaches in the Belgian coastline may lead to a total damage of €17 billion EUR and could result in up to 6,700 victims. Floods could pose a threat to over 200,000 people.

By 2040 the potential economic damage by coastal and river floods in the Netherlands will have increased by 100 to 250%, and by 2100 between two-fold and tenfold.

3.2 million people live within the low-lying coastal region of Germany, concentrated mainly in a number of large coastal towns (Hamburg, Bremen, Kiel and Rostock). Without further coastal protection measures, 1 m sea-level rise would increase flood probability, and people and capital at risk at least tenfold up to 309,000 people and more than 300 billion US$.

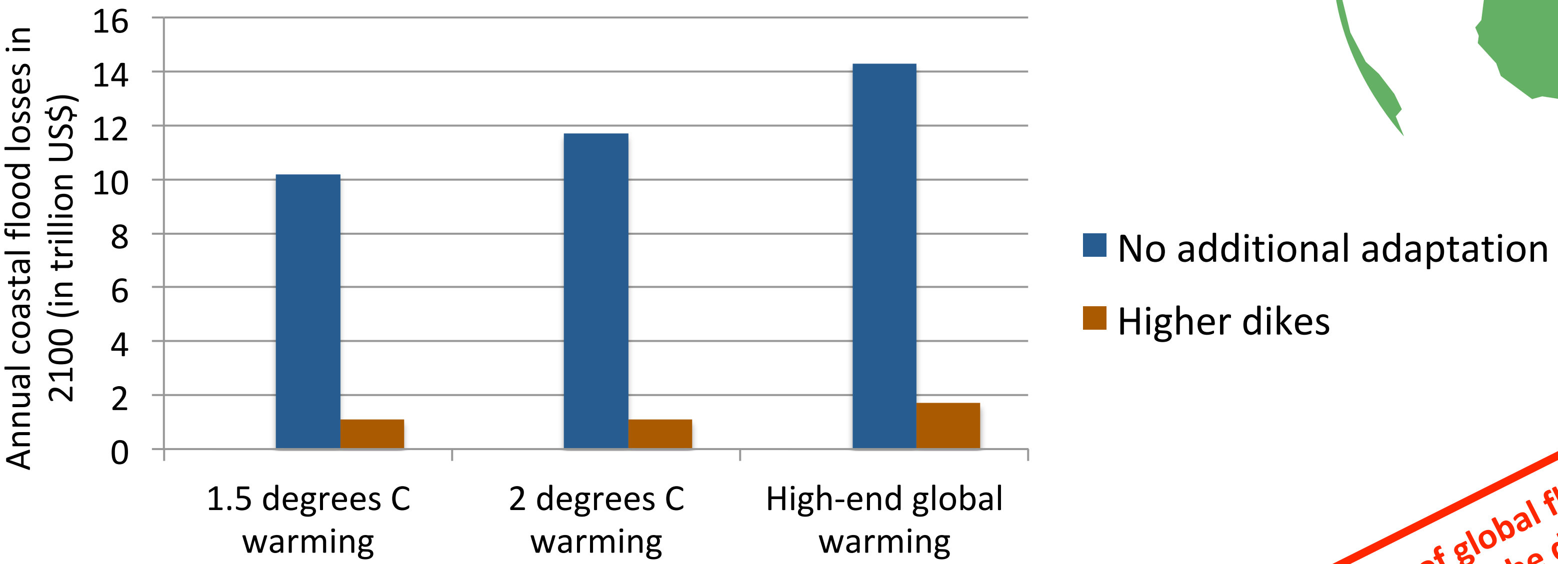
In Italy, about 4500 km^2 of coastal areas and plains would be at risk of coastal flooding in 2080; floods might occur in northern Italy (Upper Adriatic Sea), central Italy (the coastline between Ancona and Pescara, the coasts near Rome and Naples) and in southern Italy (Gulf of Manfredonia, coasts between Taranto and Brindisi, eastern-southern Sicily).

Coastal floods

2100

Future flood risk: the global picture

Effect raising dikes to cope with rising sea levels



Tenfold reduction of global flood risk: it pays of to raise the dikes!

Median sea level rise:	52 cm	63 cm	86 cm

The Paris Agreement sets out actions to limit global warming well below 2°C, and preferably below 1.5°C compared to preindustrial levels.

Source:
Jevrejeva et al. (2018)

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