Exploring climate-related risks to coastal infrastructure through the development and assessment of 'rich' storylines

Deliverable 7.1

climatestorylines.eu
RECEIPT_eu

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

RECEIPT project information	
Project full title	Remote Climate Effects and their Impact on European sustainability, Policy and Trade
Project acronym	RECEIPT
Grant agreement number	820712
Start date and duration	01/09/2019, 48 months
Website	www.climatestorylines.eu

Deliverable information	
Work package number	Work Package 7
Work package title	Sea level rise, infrastructure and coastal flooding
Deliverable number	D7.1
Deliverable title	Exploring climate-related risks to coastal infrastructure through the development and assessment of rich storylines
Description	Report
Lead beneficiary	Sayers and Partners
Author (s)	Paul Sayers (SPL), Elco Koks (VU-IVM), Sadhana Nirandjan (VU-IVM), Dewi Le Bars (KNMI), Arthur Hrast Essenfelder (CMCC)
Contributor (s)	
Revision number	2
Revision date	05 Sept 2020

Dissemination level of the document

X	PU	Public
	PP	Restricted to other programme participants
	RE	Restricted to a group specified by the consortium
	CO	Confidential, only for members of the consortium

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Versioning and contribution history			
Revision	Date	Modification	Author
v. 02	31-07-2020	First version	Elco Koks, Sadhana Nirandjan, Paul Sayers
v. 03	06-08-2020	Additions Dewi Le Bars and Arthur Hrast Essenfelder	Dewi Le Bars, Arthur Hrast Essenfelder, Elco Koks
v. 04	13-08-2020	Final review and edits	Paul Sayers
v. 05	21-08-2020	Final review and edits	Paul Sayers, Dewi Le Bars, Elco Koks, Sadhana Nirandjan
v.06		Submitted for review	As above
v.07	05-09-2020	Revised final	As above
V0.8	24/09/2020	Final revised submission	As above

Approvals			
	Name	Organisation	Date
Coordinator	Bart vd Hurk	Deltares	30 Aug 2020
WP Leader	Elco Koks	Amsterdam	30 Aug 2020

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Table of Contents

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Table of figures.

Index entries.

None

Glossary

No specific terminology introduced here that requires summary definitions in additional to those used across the consortium

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Executive summary

This report presents a strategy to develop and assess storylines about climate-related risks to coastal infrastructures for the coming century. These storylines are new tools developed in co-production with decision makers to include scientific inputs into practical planning. In particular storylines are used to map the inevitable deep uncertainty that arises when trying to imagine possible future states of coastal infrastructures. We present a myriad framework that considers a continuum of future states and focuses on three main aspects: (1) remote climate drivers, coastal infrastructure (2) adaptation and (3) expansion. The impact of three remote climate drivers are explored: (1) The melting of land ice in Antarctica and subsequent sea level rise, (2) the ocean warming in the tropical Atlantic and its consequences on tropical cyclone formation, in particular the 'Ophelia' type tropical cyclones that could directly reach the European coast, (3) the melting of Arctic sea ice that will open new shipping routes and potentially disrupt the European port operations. The myriad framework is complemented with a focus on a world 4°C warmer than in the preindustrial period in 2121 to provide a detailed storyline for a particular path of particular interest for the future coastal infrastructures.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

1. Introduction

Flooding is the most damaging natural disaster in the world, causing global losses more than ~USD100bn in 2017 alone (Munich RE, 2017). Global warming and the remote melting of the ice-sheets of Greenland and Antarctica will further increase the frequency and severity of flood hazards of European coastal regions, its people and economic assets. Moreover, flood risk will increase due to the continuous exposure of people and assets in Europe's coastal regions, which is expected to grow by a factor of two by 2050 (ECA, 2018).

When focusing on Europe's coastal infrastructure, a recent report by the European Environment Agency (EEA, 2017) notes port facilities and critical infrastructure networks are particularly vulnerable to flooding and erosion (Forzieri et al., 2017). General climate change losses to critical infrastructure are set to increase by more than 10 times present damage of €3.4 billion per year by 2100 (EEA, 2017). Critical infrastructure is important for the continuity of vital societal functions and is commonly associated with facilities such as the electricity grid, (tele)communication, transport, and water treatment plants. Ports are also important hubs for the economy and serve as a crucial link in global trade relations. Furthermore, protective infrastructures (levees, dams, and managed dunes and beaches) are essential to reduce the risk from flooding.

One of the major challenges in managing these risks is the large uncertainty that exists in sea-level rise (SLR) projections, the melting of large ice sheets and the temperature increase of our oceans alongside the future effort given to adaptation.

Over the period 1901-2010, global mean sea level has already increased by 0.19 ± 0.02 m (Church et al., 2013). In the last AR5 IPCC report, process-based models project a rise of 0.26-0.55m, and 0.52-0.98m for the RCP 2.6, and 8.5 scenarios, respectively. The melting of the Antarctic ice sheet and resulting SLR will exacerbate coastal flooding and the impacts to coastal infrastructure, and one of the scientific challenges is to provide more reliable estimations of the rate of SLR. At the same time, stakeholders may have different risk aversion levels which relate in considering or neglecting some sources of uncertainties in sea level projections. As such, tailored regional SLR projections are needed, also due to differences in coastal morphology, earth gravitational field, local meteorological conditions, among other factors. The melting of arctic sea ice may also initiate positive economic effects for European Ports and the related economy, since the length of trade and shipping routes between Asia and Europe may decrease. Finally, increased ocean temperatures may result in increased hurricane frequency and intensity.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

1.1. Report objectives and structure

This report builds upon the RECEIPT kick-off meeting and identifies climate 'hotspots[1]' within the coastal infrastructure sector (based on societal and scientific partner knowledge), a framework of associated storylines and associated illustrative micro stories and the models and data that will underpin the analysis.

The storyline framework set out here will be used as the basis for ongoing co-creation process (initiated at the RECEIPT kick-off in Delft) to help explore climate change impacts and the planning, performance and investment in coastal infrastructure.

The report is structured as follows:

- Decision drivers of our storylines
- Framework for developed of associated storylines
- Illustrative Micro-stories
- Quantification of the storylines

Note: This report focuses on coastal infrastructure. During the kick-off meeting the definition of infrastructure was discussed and in the context of RECEIPT 'coastal infrastructure' is considered to include the rail, ports, power infrastructure that provides a service directly to the infrastructure user. The impact on coastal flood defenses, beaches and other features (deterioration, increased maintained spend etc) that act to protect or enable these services, although important, are not considered here.

[1] Here climate change is assumed to a spatial process connections – for example climate change leads to remote changes (ice melt) than manifests as a climate change in Europe (sea level rise) with subsequent infrastructure, economic and social impacts. This is slightly different to interpretation in other WPs

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

2. Decision drivers of our storylines

Through the RECEIPT project we are aiming to present meaningful evidence that helps practical planning, operational and adaptation investment decisions. This will be done through asking questions such as:

- *What does climate change mean for the infrastructure we own/operate?*
- *Can I reduce the risks from climate change? And how much will it cost?*
- *If I invest will that give me a competitive advantage? Conversely if I don't invest how will this impact our profitability in the longer term?*
- *Does climate change lead to exploitable opportunities?*

Through exploring these stakeholder questions, RECEIPT seeks to promote a long-term perspective on future infrastructure investments and long-term resilience. This will be done by helping coastal infrastructure providers understand the scale of the potential impacts of climate change and how best to adapt and, in some instances, exploit new opportunities.

In developing storylines that respond to the remote climate drivers of interest, we recognize that the future is deeply uncertain and cannot be meaningfully described through a small set of (constrained) scenarios. Instead, we have adopted an approach based on a storyline framework that efficiently represents many future states that reflect three strands:

- Influence of remote (outside Europe) climate change drivers (land ice melt, sea ice melt and ocean warming)
- Approach to infrastructure adaptation (from no to high)
- Approach to infrastructure expansion (from no to high)

The decoupling of future states from time enables an assessment of the collection of futures and enables a post-hoc translation of the future states to a time-evolving story if desired (for example as the pace of adaptation to climate change become better known). The change in risk, in a particular future state, is described by a small number of metrics, including:

- Risk – Expected Annual Damage (EAD), Expected Annual Population Affected (EAPF) or Expected Annual Output Losses (EAOL).
- Hazard – Percentage are flooded and associated hazard footprints.
- Exposure – Percentage of infrastructure assets that are exposed within the coastal area
- Damage – per asset/region/country for different return periods, now and in the future.
- Losses – economic loss per region/country due to failure of infrastructure systems.

All of these aspects are discussed in more detail below.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

3. Storyline framework

Storylines are considered here in the context of a continuum of possible future system states (see Figure 1). We define these as 'rich' storylines because each reflects three aspects: (i) remote climate drivers; (ii) coastal infrastructure adaptation; and (iii) coastal infrastructure growth and are illustrated through micro-stories. A single storyline is determined by selecting a state for each aspect. This is illustrated by Figure 1 by the vertical pathways (1 to *n*). For purposes of practicality, each storyline component is selected from five discrete states as discussed in the following sections.

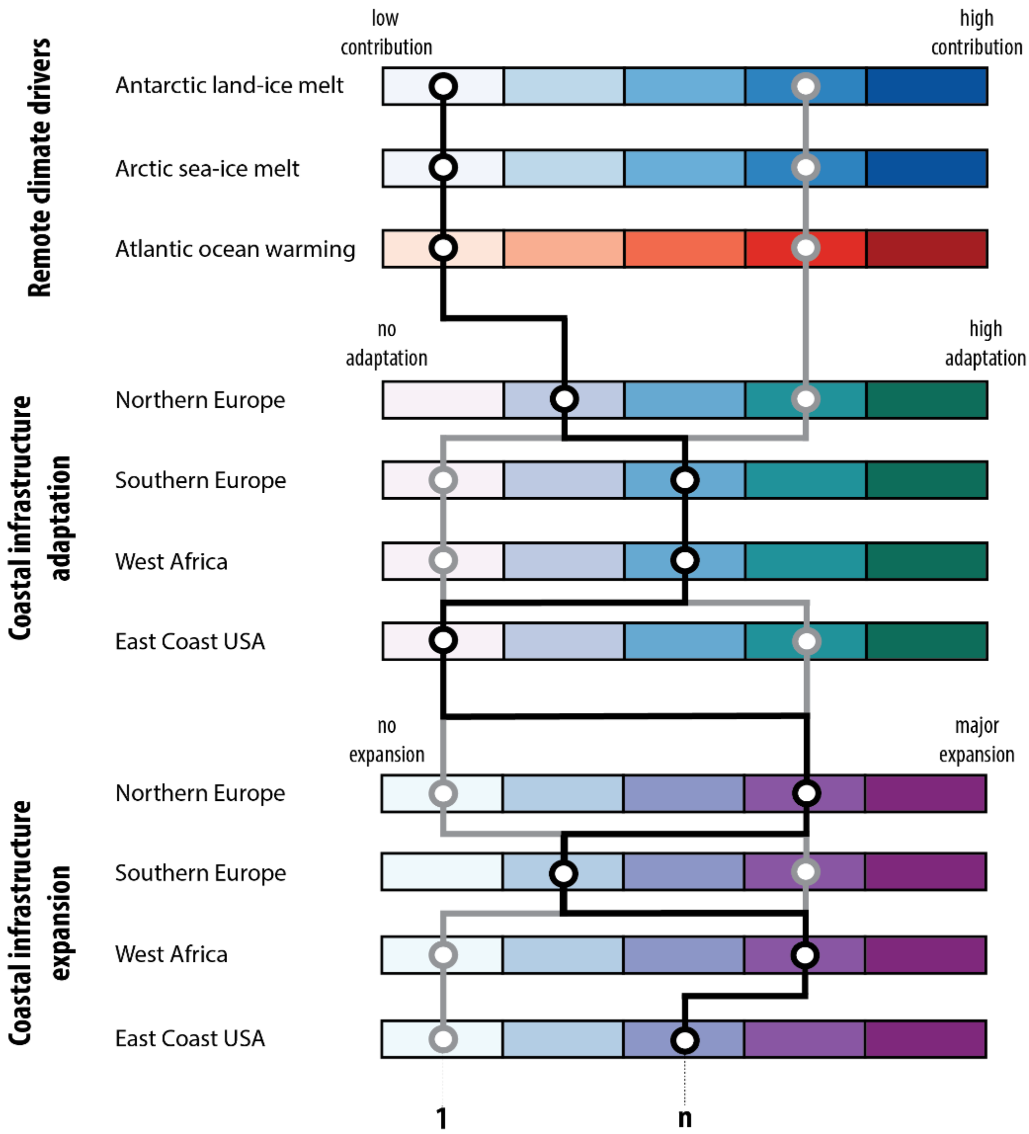


Figure 3-1 Future system state framework: a continuum of possible futures

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

3.1. Remote climate drivers

For the development of the storylines in this work package, we have identified three remote climate effects (see **Figure 2**): (i) melting of Antarctic land ice (driving sea level rise); (ii) reduced extent of Arctic sea ice (enabling new shipping routes); (iii) increased water temperature in the Atlantic ocean (driving changes in hurricanes).

In any given future the degree of climate change is described independent of time using a five-band qualitative scale of *very low* to *very high*, described as follows:

- Very low: Small global warming (1.5°C)
- Low: Global warming of 2°C as agreed in the Paris agreement and assuming that no tipping point is past
- Moderate: intermediate climate scenarios (RCP4.5)
- High: High-end climate scenario (following RCP8.5) without additional surprises from physical processes already included in state-of-the-art climate models.
- Very high: High-end climate scenario (RCP8.5) and destabilization of the Antarctic ice sheet.

Each remote climate effect is described briefly below.

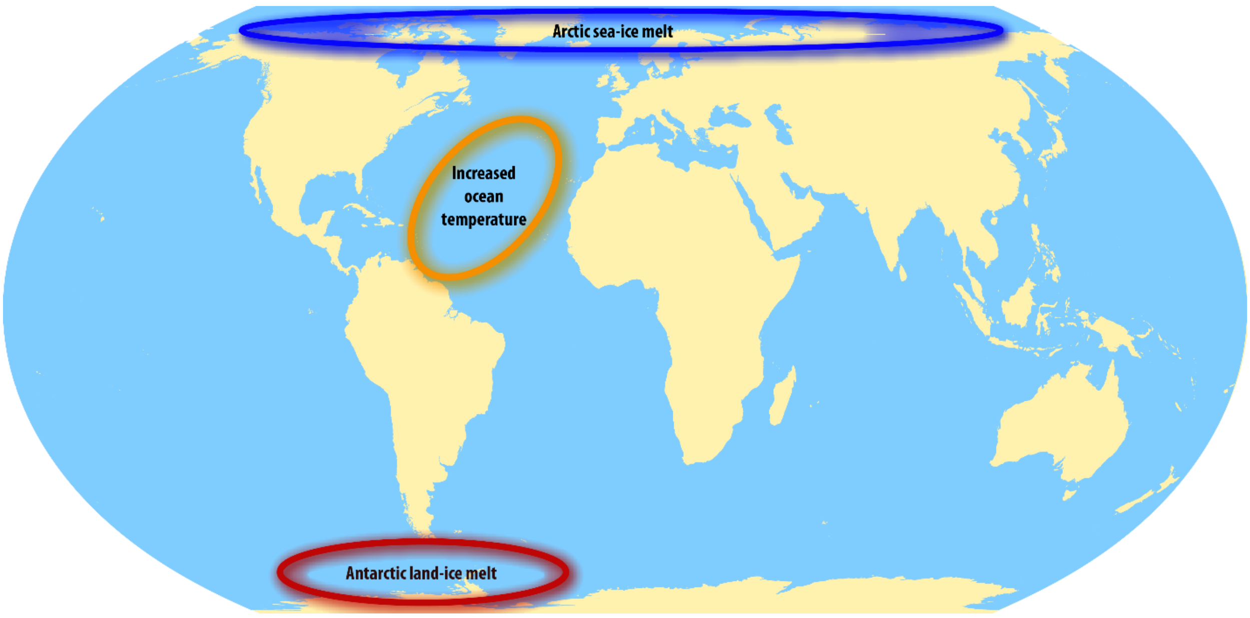


Figure 3-2 Remote climate effects

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

3.1.1. Melting of Antarctic land ice

The Antarctic ice sheet is important for three reasons:

- **Firstly**, if completely melted, it would raise global sea level by 58m. It would be 7m for the Greenland ice sheet and 0.3m for all the other glaciers on earth combined (Oppenheimer et al. 2019).
- **Secondly**, due to gravitational, rotational and earth elastic effects, when the Antarctic ice sheet loses mass it contributes more to sea level at the European coast than globally averaged, by a factor of between 1 and 1.2. This factor is called the fingerprint. In the meantime Greenland's fingerprint is around 0.1 (although significant variation across Europe exists), which means that if Greenland contributes to 1m of globally averaged sea level rise, Europe only gets 0.1m (Slangen et al. 2014).
- **Thirdly**, due to the relatively limited scientific understanding of ice sheet dynamics and polar climate, the uncertainties arising from the Antarctic ice sheet are much larger than those of ocean thermal expansion. This makes it a relevant candidate for the use of storylines.

Assessing different methods to measure Antarctic mass loss, a recent study found that mass loss accelerated between the periods 1992-1997 (49 Gt/year) and 2012-2017 (219 Gt/year) (IMBIE 2018). For the period 2012-2017 the loss contributes to a sea level rise of 0.6 mm/year. This contribution is relatively small compared to the 4.3 mm/year of total sea level rise during that period (WCRP 2018) but the acceleration is a source of concern. There is consensus that the Antarctic Peninsula and the West Antarctic ice sheet are losing mass, respectively because of ice shelves collapse and ocean basal melt under the ice shelves.

There is no consensus however on the behavior of the East Antarctic ice sheet where additional snow fall might compensate for the increase in basal melt from the ocean. But, a recent study argues that Wilkes land, a region of East Antarctica, has already contributed to sea level rise over the last 40 years for the same reason as West Antarctica: warmer ocean waters come in contact with the ice shelves (Rignot et al. 2019).

Due to the contradicting observations, the lack of knowledge concerning the ice dynamics, the future ocean and atmosphere temperature, and the resulting degree of mass loss, there is a large uncertainty in future sea level rise from the Antarctic ice sheet. Model projections vary from no future mass loss to more than one metre sea level rise in 2100 (Ritz et al. 2015; Deconto and Pollard 2016). This uncertainty is reflected in a recent structured expert judgment that suggests that anything between a few cm of mass accumulation and more than one meter

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

of mass loss is possible this century (Bamber et al. 2019). This situation is well suited for the use of storylines to explore the impacts of a range of mass loss scenarios.

3.1.2. Melting of Arctic sea ice

The surface temperature in the arctic increased by more than twice the global average temperature over the last two decades. Mainly due to exacerbating feedbacks from melt of sea ice and snow cover. Because of the increased atmospheric greenhouse gas concentrations artic sea ice thinned and the ice age distribution shifted to younger ice.

As sea ice extent reduced over the past two decades, shipping activity during the Arctic summer increased. Transit times shortened due to lighter ice conditions and the distance travelled by ships in the Arctic Canada nearly tripled during 1990-2015.

Further Arctic warming will result in continued loss of sea ice and snow on land and reduce the mass of glaciers. Depending on mitigation measures important differences in the trajectory of loss emerge from 2050 (IPCC SROCC report, Meredith et al. 2019).

The future of the Arctic sea ice mainly depends on the greenhouse gas emission scenario with less uncertainty from the natural system response itself. However, it seems that the new climate models simulations from the CMIP6 project have larger global mean surface temperature rise as well as a larger Arctic amplification than the ones of CMIP5. It is still unknown if this is realistic. If it is then it means that the Arctic sea ice will disappear faster than expected until now.

3.1.3. Increase in sub-surface sea temperature of the Atlantic ocean

Although the global sea surface temperature (SST) has shown fluctuations over multiple time scales, from seasons to decades, there is a scientific consensus that an overall increasing trend of the depth-averaged 0-700 m ocean temperature from 1971 to 2010 is observed over the globe (Rhein et al., 2013). The estimated average warming on a global scale over the aforementioned 40-year period is "0.11 [0.09 to 0.13] °C per decade in the upper 75 m, decreasing to 0.015°C per decade by 700 m" (Rhein et al., 2013). SST datasets are based on a combination of (1) in situ data records (e.g. measured by ships and buoys) and (2) satellite data, of which the majority of the data has to be calibrated by in situ observations, but eventually provides information on global SST with a high spatial detail (Hartmann et al., 2013). The warming of the oceans is very likely to be the direct result of the influence of mankind on the radiative properties of the atmosphere and the heat budget of the Earth (Bindoff et al.,

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

2013). The increasing temperature of the upper sea layer is more pronounced in the Northern Hemisphere, especially in the North Atlantic (Levitus et al., 2009).

As the climate changes, observed patterns of tropical cyclones are expected to change as well. Tropical cyclones are generated by a combination of six climatological parameters, including SST that needs to exceed 26 °C to a depth of 60 m for hurricanes to develop (Gray, 1998). With the observed trend of increasing SST in mind, this leads to the question what changes in tropical cyclone activity are expected for future projections. Or more specific for our storyline: what changes in Atlantic hurricane activity are expected and how might this affect Europe's economy? This question also links to WP 4 within Receipt and we will maintain collaboration here.

Elsner (2006) has demonstrated evidence to support that the increase of Atlantic tropical cyclones is correlated with the 'late summer/early fall SST over the North Atlantic', and is thus caused by anthropogenic climate change. However, a recent study of Knutson et al. (2019) has shown that it is premature to conclude with high confidence that human activities have already had a detectable impact on hurricane activity, and that the relative contribution of natural variability to anthropogenic forcing is not clear yet. Note that these statements on Atlantic tropical cyclones differ from scientific evidence performed on global scale. Nevertheless, it is likely that hurricanes will have higher rain fall rates compared to current ones, and medium confidence that they will be more intense (Knutson et al., 2020). From this point, storylines can be created to explore the impacts on Europe and its economy.

3.2. Approach to adaptation

The approach to adaptation is considered in the context of four geographies (rather than sectors), including northern Europe, southern Europe, the west coast of Arica and the east coast of the USA. These four regions are a preliminary region classification for this work package, and are subject to change based on the on-going stakeholder consultation.

- **Northern Europe** is chosen due to several large and globally important ports (Rotterdam, Hamburg, London) and its densely populated low-lying coastal area with high value infrastructure (i.e. European entry of undersea data cables; dense electricity grids). Adaptation options could vary from hard infrastructure measures to land-use changes in a future with high levels of sea-level rise.
- **Southern Europe** is chosen as separate region for the significantly different consequences to sea-level rise compared to northern Europe. There are several high-value coastal areas as well (e.g. high-value horticulture in Almeria), but more sparsely located along the

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

coastline. This may require more tailored adaptation approaches instead of large-scale projects.

- **West coast of Africa** is primarily chosen as separate region due to linkages with other work packages (i.e. agriculture). The level of adaptation along the west coast of Africa may influence the reliability of supply of agriculture goods to Europe.
- **East Coast of the USA** is primarily chosen as separate region due to linkages with other work packages (i.e. manufacturing and financial sector). The level of adaptation along the east coast of the United States may influence the reliability of supply of chemical and manufacturing goods to Europe, and cost of insured damage recovery.

Within these regions, coastal infrastructure and related adaptation will include adaptation options at three levels: asset, network and regional level. On an asset level, we can think of structural design measures, such as wet or dry-proofing measures within an electricity substation. On a network level, it could be an investment in redundancy improvement of the system (e.g. building an additional power line to improve the stability of the system). On a regional level, this could be land-use development options, such as preventing new development of infrastructure in highly exposed areas.

3.3. Approach to infrastructure expansion

Infrastructure expansion is interpreted here as the investment and development of infrastructure within the coastal zone. An asset manager or regional authority may invest in new infrastructure, without considering any form of adaptation. For example, the port of Zeebrugge may decide to build an entire new dock, with or without taking sea-level rise into consideration. In other words, we only consider here how much infrastructure may be developed in the (near) future. In addition a region may “seize opportunities” due to climate change (i.e. port development in Norway due to new arctic sea trade).

The approach to infrastructure expansion is considered in the context of the same four geographies (rather than sectors): northern Europe, southern Europe, the west coast of Arica and the east coast of the USA. Again, these four regions are a preliminary region classification for this work package, and are subject to change based on stakeholder consultation.

RECEIPT has received funding from the European Union’s Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

4. Micro-stories

Micro-stories are used to illustrate how a given stakeholder may experience a given future. For example, Storyline ***n*** may be experienced by different stakeholders in different ways as illustrated in Figure 3.

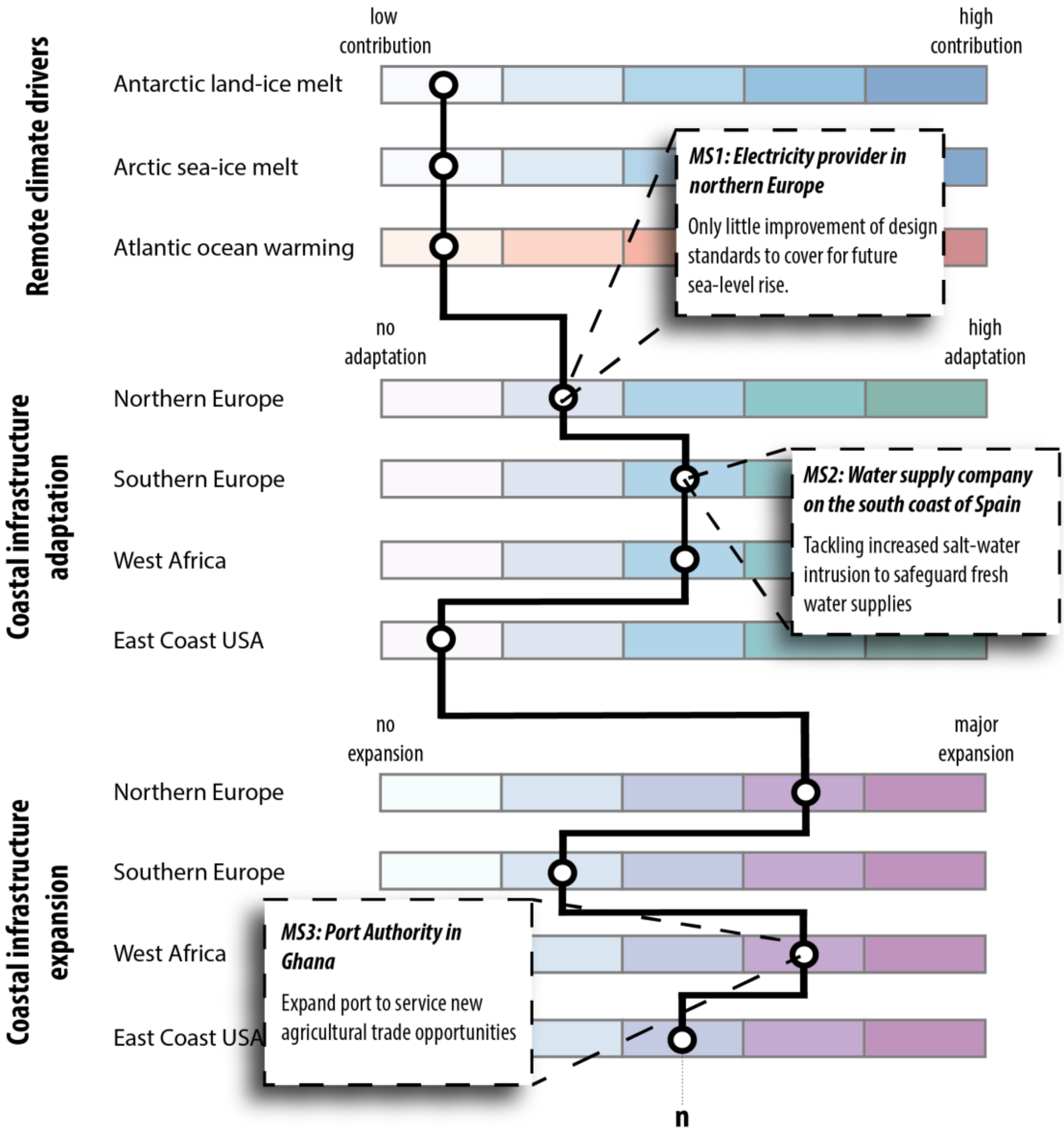


Figure 4-1 Micro-stories illustrative the storyline

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Through the stakeholder workshop (see **Section 5**) we propose to develop a small number of micro-stories to illustrate several storylines. It is anticipated this will include micro-stories from the perspective of:

- A port provider
- Rail provider
- Power provider
- Shipping company
- A community experiencing infrastructure disruption

In developing these micro-stories we will work with stakeholders to get a representation of the sectoral perspective (rather than an individual, or location specific stakeholder). This will broaden the relevance of storylines and avoid discussion of highly localized or organizational specific issues (issues that could be addressed through future work).

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

5. From concept to model

The next step is to translate our conceptual framework of a continuum of storylines into a small set of discrete storylines to further develop and assess. This chapter describes a first selection of storylines, the motivation behind their main assumptions, and the modelling approach.

Essential in the development of storylines is the documentation of the key assumptions. To start with, we consider a 4° warmer world as a substantial warming but still within plausible ranges (Smith et al. 2011). As it is difficult to analyze potential sea-level rise without a specific time-horizon, we assume that our future system state will be in the year 2121, 100 years from now. The year 2121 is not totally arbitrary. When it comes to large-scale infrastructure projects, these often have a notional life-span of 50 to 100 years (e.g high-voltage transmission lines and substations, storm surge barriers and locks).

There is still considerable uncertainty around Antarctic contribution to sea level in the coming 100 years (as discussed earlier). Our assumption is that the accelerated Antarctic mass loss observed over the past decades (IMBIE 2018) is forced by climate change and will continue in the future. There is no consensus in the scientific community about this assumption but the possible impacts are potentially large and hence ideal for exploration through a storyline approach.

We may not explicitly model an increase or decrease of extratropical cyclones (i.e. European winter storms), but assume these changes to be captured by the climate models that underpin our storylines as an example to illustrate the impact of higher sea levels (e.g. the 1953 North Sea flood affecting Netherlands, Belgium and UK).

In terms of adaption we consider a no additional adaptation (as defined conceptually in UKCCRA) case; this implies infrastructure owners make no further attempt to change their approaches, and consequently flood defence standards reduce in response to climate change. Although a plausible future, this storyline will also be used as a counterfactual for comparing risks under alternative storylines that do include adaptation. Through the 'no additional adaptation' storyline we will understand how the risk to Europe would change if infrastructure owners fail to response to climate change and experience and contrast this future with a storyline in which adaptation is continues to take place and opportunities (for port expansion) exploited. The detail of this second adaptation case will be developed in future work.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

5.1. Storyline choices and assumptions

Storyline 1: Storm Ophelia strikes again - Infrastructure owners fail to adapt to a 4˚C future

As outlined in the conceptual framework presented in Figure 1, the first step is to specify the climate boundaries. In our first set of storylines, we will assume a future world in which we have **four degrees of global warming** by 2121. Within this *four-degree world*, we will estimate the potential global sea-level rise, with an explicit contribution from melting of the west-Antarctic ice-sheet, and the possible increase in the Atlantic Sea Surface Temperature (SST). The increase in sea levels will result in a higher likelihood of coastal flooding, as a result of higher extreme water levels. The increase in SST may result in an increased frequency and intensity of hurricanes, with hurricanes more likely to reach Europe. The increased likelihood of coastal flooding will be exemplified through a winter storm hitting the coasts around the North Sea, whereas the occurrence of a hurricane hitting Europe will be exemplified through a future late summer hurricane remnant similar to 'Ophelia' (2017).

In this first storyline we assume no further population growth and no further adaptation.

Associated **micro stories** (to be developed further with stakeholders and others):

- Infrastructure owners: Power provider
- Communities disrupted: The impact on municipal infrastructure and the disruption to communities
- Public authorities: the impact on economic damage of the event and expected annual damages (impacting national investment demands)

Storyline 2: Storm Ophelia strikes again - Infrastructure owners continue to adapt (at present day rates) but GMST has risen by 4˚C

This storyline is similar to #1 but here we assume infrastructure owners have made some effort to adapt.

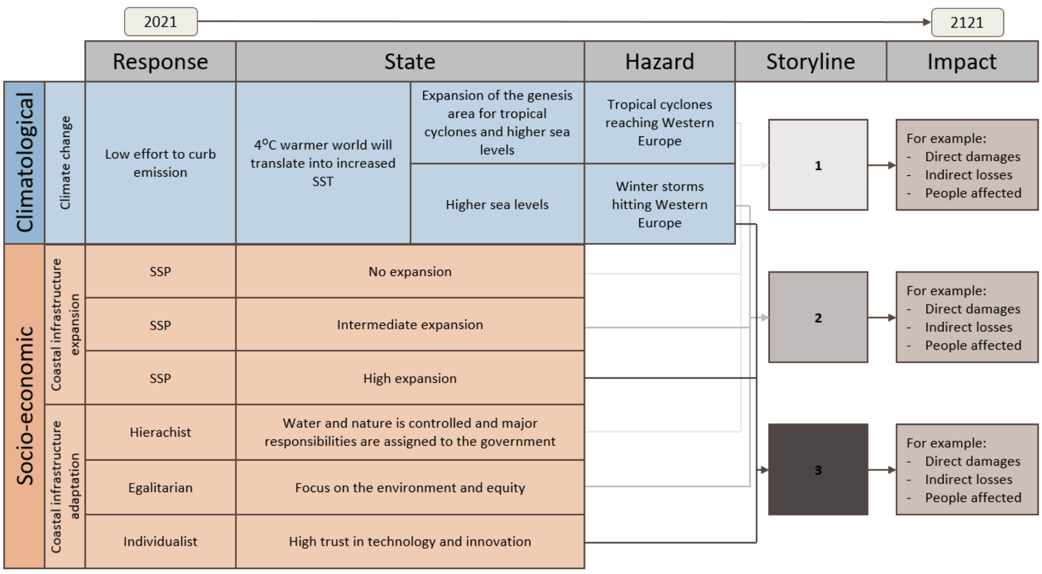
3 or 4 additional storylines will be developed to illustrate the framework.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

5.2. Assessment framework

Building upon the conceptual framework outlined in Section 3, figure 4 presents a more concrete visualization of the storylines. These storylines allow for the exploration of different possible futures in the context of fundamental future uncertainties. Near-time responses to the challenges associated with climate change and socioeconomic development may have long-term consequences. The response to these challenges in 2021 will translate in a climatological and socioeconomic state of the world in 2121. Transient adaptive/dynamic pathways between 2021 and 2121 will not be considered; instead the focus will be on discrete future states of the world. A storyline is built by combining the climatological future state with the socio-economic future states, and this storyline will then be used to assess the impacts of coastal flooding in a future four degree world.

For any given storyline, we first select a climate future and then consider multiple socioeconomic responses. This way, we can assess how a future climate state, caused by a remote climate effect, will play out under different socioeconomic futures (e.g. van Vuuren et al., 2014). Future socioeconomic states are based on the level of coastal infrastructure expansion and adaptation (see section 5.6). To illustrate the impact of rising sea levels and coastal flooding in a future warmer world with different socioeconomic states, the hazards considered are tropical cyclones and winter storms reaching Western Europe.



Illustrative only – to be made consistent numbering with narrative storylines as we progress

Figure 5-1 Storylines future coastal flooding in Western Europe

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

5.3. Modelling remote climate effects and extreme water levels

Sea level rise projections for the European coast will be developed using a process-based method. This method projects the future of individual sea level contributors (e.g. thermal expansion, Antarctic and Greenland ice sheets, glaciers, ocean circulation and land water storage). The impact of each contributor on regional sea level is then computed considering changes in gravitational attraction, change in the earth's rotation and deformation of the earth's crust deformation. The sensitivity of the projections to uncertainties in Antarctic mass loss will also be assessed. In particular a scenario with a large Antarctic contribution will be developed based on recent ice sheet model projections (Levermann et al. 2020) and Structured Expert Judgement (Bamber et al. 2019).

To support the specific case of Storyline 1 and 2 (introduced earlier in Section 5.1r) future local relative sea level rise will be combined with extreme sea level information. Wind and pressure from individual storms will be provided by a specific regional model study of Ophelia in a 2°C warmer world. The storm analysis will be performed at KNMI using the global HighRes MIP simulations that are currently being extended to 2100 from which the large storms can be selected. The model extension to 2100 using the RCP8.5 scenario will allow to find 4°C warmer worlds to use in our storyline. The simulations will not run up to 2121 but this is not a problem because for the atmospheric variables it is reasonable to assume that a 4°C warmer world before 2100 is the same as in 2121.

These wind and pressure fields will then feed into a barotropic ocean model that models storm surges and tides. This will be the Global Tide and Surge Model (GTSM, Muis et al. 2016) or specific WAQUA model simulations that focus on the North Sea (Ridder et al. 2018).

No explicit wave model will be used in this project. For the UK the Future Flood Explorer (Sayers et al, 2020) (recently used in support of the UK Climate Change risk Assessment) includes an emulation of the overtopping and breach response to changing sea levels in a way that includes wave influences. For other coasts some simple scaling relationship between changes in water depth due to sea level rise and wave heights changes will be investigated and used to drive the impact models.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

5.4. From extreme sea-levels to coastal inundation

In some countries across Europe open data enables us to understand the extent of coastal inundation as sea levels rise but this data does not exist for all European domains. In these areas we propose to fill in priority gaps to support the impact assessment within our storyline using the ANUGA model, developed by the Australian National University (ANU) in collaboration with Geoscience Australia (GA).

ANUGA is a 2D-Hydrodynamic model capable of simulating the free surface elevation of water flow over land areas. The model is free and open source. The model is suitable for the numerical modelling of hydrologic disasters such as riverine and coastal flooding (Roberts et al. 2015). ANUGA can be coupled with oceanic models by incorporating coastal boundary conditions, thus allowing the numerical simulation of the propagation of flood waves and inland inundation. An interesting characteristic of ANUGA is its capability of simulating the wetting and drying of land areas. This means that the model is suitable for simulating coastal inundation over dry land and around/above structures, such as buildings and flood defence structures. The model, however, is capable of providing the extent, depth, duration, velocity and momentum of a coastal flood event, thus being suitable for multivariate flood damage assessments. Indeed, this fits perfect within our storyline approach, in which we do deep dives into specific events.

5.5. Socio-economic development and exposure

The magnitude and extent of future impacts due to coastal flooding depends not just on the dynamics of the earth system, but also on socio-economic developments. These socio-economic developments will be developed in a way that has a line of sight to the SSP but also reflects the individual behavior of an infrastructure owner. The socio-economic development will be implemented in the storyline as an external change (increasing population) and an internal change by influencing the choices in the 'coastal infrastructure expansion' and 'coastal infrastructure adaptation'. As explained in section 3.3, coastal infrastructure expansion can be interpreted as the investment and development of infrastructure within the coastal zone. Over the past years, efforts of various initiatives and projects (e.g. OpenStreetMap) has led to (freely) available information on the spatial location of infrastructure assets situated in the current world. If possible we will update the FloPRO datasets (Scussolini et al, 2016).

However, no information is available on the spatial distribution of critical infrastructure in a future world while such input is needed for the impact assessment (figure 4). To fill this gap, a

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

set of future states of coastal infrastructure expansion will be developed by using Shared Socioeconomic Pathways (SSPs) as a set of reference scenarios. SSPs are defined as 'reference pathways describing plausible alternative trends in the evolution of society and ecosystems over a century timescale, in the absence of climate change or climate policies' (O'Neill et al., 2014). Based on the conditions described by the SSPs, specific assumptions can be made regarding coastal infrastructure expansion. This will be translated into spatial information on infrastructure assets representing the future state of coastal critical infrastructure, which will serve as an input for the storylines.

Whereas climate change and climate policies considering mitigation are part of the climatological component of the assessment framework[2] (section 5.3), coastal infrastructure adaptation will be part of the socio-economic development. Hereby, three perspectives will be considered representing active stereotypical perspectives on the future and preferential responses to control the environment. The preferred strategy of a *hierarchist* is to control water and nature, assigning major responsibilities to the government (e.g. building dikes, channeling); the center of attention of the *egalitarian* is the environment and equity (e.g. room for the river, relocation); and the *individualist* has high trust in technology and innovation, resulting in a preferred strategy focusing on cost efficiency and innovation (e.g. living on water, building offshore islands). Depending on the assumptions made on the basis of the SSPs, the coastal infrastructure adaptation will be either reflected as an independent state (as shown in figure 4) or incorporated in the coastal infrastructure expansion state.

5.6. Vulnerability and impacts

Flood hazards and exposure data will feed into an appropriate damage function – for example as in the Dutch DamageScanner (Klijn et al., 2007) or embedded in the Future Flood Explorer (FFE, Sayers et al, 2016) in UK. The original land-use classes were based on the Land-Use Scanner in order to evaluate the effect of future land-use change on flood damages. The current DamageScanner is able to assess damages using either objects or grids. Infrastructure damages will be estimated using a variety of sources of replacement cost data and damage curves. Damage estimates are calculated by relating the intensity of the hazard to a damage probability using predetermined damage functions, such as depth-damage curves used in

[2] Although it is noted that the rise in global mean surface temperature are given assumptions here, i.e no enough is may to focus on the relationship between mitigation and future temperature rise),

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

flood risk literature. For each asset in each storyline, this damage probability is multiplied by our assumed reconstruction cost for the respective asset.

To establish the regional impacts (rather than local depth-damages) in a subsequent simulation, the flood events (for different storylines) will be used as forcing for the economic Multi Regional Impact Assessment model (henceforth MRIA, Koks and Thissen, 2016) model and coherent risks in the UK using the FFE for comparison. This is a multiregional supply and use model, which estimates a new economic equilibrium in the short-term disaster aftermath to assess the economy-wide consequences of a natural disaster. Economic impacts of the European level (NUTS2) will be presented.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

6. Concluding remarks

We have described:

- **A framework to construct a continuum of futures** – this provides a structured approach to considering the elements of the future to be considered
- **A means of establishing discrete 'rich' storylines within this continuum of potential futures** – these provide a means of connecting the climate and adaptation aspects of the future
- **A means of illustrating a discrete storyline through micro-stories** – these bring to life the future world and how it may be experienced by individual or group stakeholders

We have started to outline a method of assessment to realize this framework. This assessment approach will be detailed as the research progresses.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

References

Bamber, Jonathan L., Michael Oppenheimer, Robert E. Kopp, Willy P. Aspinall, and Roger M Cooke. 2019. "Ice Sheet Contributions to Future Sea-Level Rise from Structured Expert Judgment." *Proceedings of the National Academy of Sciences* 116 (23): 11195–200. https://doi.org/10.1073/pnas.1817205116.

Bindoff, N.L., P.A. Stott, K.M. AchutaRao, M.R. Allen, N. Gillett, D. Gutzler, K. Hansingo, G. Hegerl, Y. Hu, S. Jain, I.I. Mokhov, J. Overland, J. Perlwitz, R. Sebbari and X. Zhang (2013), Detection and Attribution of Climate Change: from Global to Regional. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/CBO9781107415324.022.

Church, J.A., P.U. Clark, A. Cazenave, J.M. Gregory, S. Jevrejeva, A. Levermann, M.A. Merrifield, G.A. Milne, R.S. Nerem, P.D. Nunn, A.J. Payne, W.T. Pfeffer, D. Stammer and A.S. Unnikrishnan (2013), Sea Level Change. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi: 10.1017/CBO9781107415324.026

Deconto, Robert M, and David Pollard. 2016. "Contribution of Antarctica to Past and Future Sea-Level Rise." *Nature* 531 (7596): 591–97. https://doi.org/10.1038/nature17145.

ECA (2018) Floods Directive: progress in assessing risks, while planning and implementation need to improve. Special Report 25 by the European Court of Auditors. https://op.europa.eu/webpub/eca/special-reports/floods-directive-25-2018/en/#A30

EEA (2017) Climate change, impacts and vulnerability in Europe 2016; An indicator-based report. EEA report nr1. 2017. file:///C:/Users/jas700/Downloads/Climate%20change%20impacts%20and%20vulnerabilities%202016%20THAL17001ENN.pdf

Elsner, J. B. (2006). Evidence in support of the climate change – Atlantic hurricane hypothesis. *Geophysical Research Letters. 33*(16). doi:10.1029/2006GL026869.

Forzieri, G., Bianchi, A., Batista e Silva, F., Marin, M., Leblois, A., Lavalle, C. Aerts, J.C.J.H., Feyen, L. (2017) Escalating impacts of climate extremes on critical infrastructures in Europe. Global Environmental Change, 48, pp 97–107.

Gray, W.M. (1998). The formation of tropical cyclones. *Meteorology and Atmospheric Physics, 67,* 37-69. https://doi.org/10.1007/BF01277501.

Hartmann, D.L., A.M.G. Klein Tank, M. Rusticucci, L.V. Alexander, S. Brönnimann, Y. Charabi, F.J. Dentener, E.J. Dlugokencky, D.R. Easterling, A. Kaplan, B.J. Soden, P.W. Thorne, M. Wild and P.M. Zhai (2013), Observations: Atmosphere and Surface. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi: 10.1017/CBO9781107415324.008

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Jongman B, Hochrainer-Stigler S, Feyen L, Aerts JCJH, Mechler R, Wouter Botzen WJ, Bouwer LM, Pflug GC, Rojas R, Ward PJ (2014), Increasing stress on disaster-risk finance due to large floods. Nature CC, 4(4):264-268

Klijn, F., Baan, P., & Bruijn de K, K. J. (2007). Huidige en toekomstige over-stromingsrisico's in Nederland in een veranderend klimaat. WL Delft Hydraulics, Delft.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. & Wu, L. (2019). Tropical Cyclones and Climate Change Assessment: Part I: Detection and Attribution. *Bull. Amer. Meteor. Soc.*, *100*(10), 1987–2007. https://doi.org/10.1175/BAMS-D-18-0189.1.

Knutson, T., Camargo, S.J., Chan, J.C.L., Emanuel, K., Ho, C., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K. & Wu, L. (2020). Tropical Cyclones and Climate Change Assessment: Part II. Projected Response to Anthropogenic Warming. *Bull. Amer. Met. Soc.*, *101*(3), 303-322. https://doi.org/10.1175/BAMS-D-18-0194.1.

Levermann, Anders, Ricarda Winkelmann, Torsten Albrecht, Heiko Goelzer, Nicholas R. Golledge, Ralf Greve, Philippe Huybrechts, et al. "Projecting Antarctica's Contribution to Future Sea Level Rise from Basal Ice Shelf Melt Using Linear Response Functions of 16 Ice Sheet Models (LARMIP-2)." Earth System Dynamics 11, no. 1 (February 14, 2020): 35–76. https://doi.org/10.5194/esd-11-35-2020.

Levitus, S., Antonov J.I., Boyer, T.P., Baranova, O.K., Garcia, H.E., Locarnini, R.A., Mishonov, A.V., Reagan, J.R., Seidov, D., Yarosh, E.S. & Zweng, M.M. (2012). World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010. *Geophysical Research Letters*, 39(10). doi:10.1029/2012GL051106

Meredith, M., M. Sommerkorn, S. Cassotta, C. Derksen, A. Ekaykin, A. Hollowed, G. Kofinas, A. Mackintosh, J. Melbourne-Thomas, M.M.C. Muelbert, G. Ottersen, H. Pritchard, and E.A.G. Schuur, 2019: Polar Regions. In: *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate* [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

Koks, E. E., & Thissen, M. (2016). A multiregional impact assessment model for disaster analysis. Economic Systems Research, 28(4), 429-449.

Muis, Sanne, Martin Verlaan, Hessel C. Winsemius, Jeroen C. J. H. Aerts, and Philip J. Ward. "A Global Reanalysis of Storm Surges and Extreme Sea Levels." Nature Communications 7, no. 1 (September 2016): 11969. https://doi.org/10.1038/ncomms11969.

Munich RE (2017) https://www.munichre.com/en/media-relations/publications/press-releases/2017/2017-01-04-press-release/index.html

O'Neill BC, Kriegler E, Riahi K, Ebi K, Hallegatte S, Carter TR, Mathur R, van Vuuren DP (2013). A new scenario framework for climate change research: The concept of shared socio-economic pathways. *Clim Chang, 122,* 387-400. doi:10.1007/s10584-013-0905-2

IMBIE. 2018. "Mass Balance of the Antarctic Ice Sheet from 1992 to 2017." *Nature* 558 (7709): 219–22. https://doi.org/10.1038/s41586-018-0179-y.

Oppenheimer, M., B.C. Glavovic , J. Hinkel, R. van de Wal, A.K. Magnan, A. Abd-Elgawad, R. Cai, M. Cifuentes-Jara, R.M. DeConto, T. Ghosh, J. Hay, F. Isla, B. Marzeion, B. Meyssignac, and Z. Sebesvari, 2019: Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. In press.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

Rhein, M., S.R. Rintoul, S. Aoki, E. Campos, D. Chambers, R.A. Feely, S. Gulev, G.C. Johnson, S.A. Josey, A. Kostianoy, C. Mauritzen, D. Roemmich, L.D. Talley and F. Wang (2013). Observations: Ocean. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. doi:10.1017/CBO9781107415324.010.

Ridder, Nina, Hylke de Vries, Sybren Drijfhout, Henk van den Brink, Erik van Meijgaard, and Hans de Vries. “Extreme Storm Surge Modelling in the North Sea: The Role of the Sea State, Forcing Frequency and Spatial Forcing Resolution.” Ocean Dynamics 68, no. 2 (February 2018): 255–72. https://doi.org/10.1007/s10236-018-1133-0.

Rignot, Eric, Jérémie Mouginot, Bernd Scheuchl, Michiel van den Broeke, Melchior J. van Wessem, and Mathieu Morlighem. 2019. “Four Decades of Antarctic Ice Sheet Mass Balance from 1979–2017.” *Proceedings of the National Academy of Sciences*, January, 201812883. https://doi.org/10.1073/pnas.1812883116.

Ritz, Catherine, Tamsin L Edwards, Gaël Durand, Antony J Payne, Vincent Peyaud, and Richard C A Hindmarsh. 2015. “Potential Sea-Level Rise from Antarctic Ice-Sheet Instability Constrained by Observations.” *Nature* 528 (7580): 115– 18. https://doi.org/10.1038/nature16147.

Sayers et al (2016). The analysis of future flood risk in the UK using the Future Flood Explorer (FFE). Proceedings of Floodrisk2016. DOI: http://dx.doi.org/10.1051/e3sconf/20160721005

Sayers et al (2020). UK Climate Change risk Assessment – future flood projections. An assessment using the Future Flood Explorer

Scussolini, P., Aerts, J. C., Jongman, B., Bouwer, L. M., Winsemius, H. C., de Moel, H., & Ward, P. J. (2016). FLOPROS: an evolving global database of flood protection standards. Natural Hazards & Earth System Sciences, 16(5).

Slangen, A. B. A., M. Carson, C. A. Katsman, R. S. W. van de Wal, A. Köhl, L. L. A. Vermeersen, and D. Stammer. “Projecting Twenty-First Century Regional Sea-Level Changes.” Climatic Change 124, no. 1–2 (May 2014): 317–32. https://doi.org/10.1007/s10584-014-1080-9.

Smith, Mark Stafford, Lisa Horrocks, Alex Harvey, and Clive Hamilton. “Rethinking Adaptation for a 4°C World.” Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 369, no. 1934 (January 13, 2011): 196–216. https://doi.org/10.1098/rsta.2010.0277.

van Vuuren, D.P., Kriegler, E., O’Neill, B.C., Ebi, K.L., Riahi, K., Carter, T.R., Edmonds, J., Hallegatte, S., Kram, T., Mahtur, R. & Winkler, H. (2014). A new scenario framework for Climate Change Research: scenario matrix architecture. *Climatic Change, 122*, 373–386. https://doi.org/10.1007/s10584-013-0906-1.

WCRP. 2018. “Global Sea-Level Budget 1993–Present.” *Earth System Science Data* 10 (3): 1551–90. https://doi.org/10.5194/essd-10-1551-2018.

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712

RECEIPT has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant agreement No. 820712