Assessing Changes in Coastal Hazards at Regional Level : Method and Case Studies

Marc Igigabel[1], Marissa Yates[1], Michalis I. Vousdoukas[2], and Youssef Diab[3]

[1]Cerema
[2]European Commission
[3]Université Gustave Eiffel

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Abstract

The evolution of coastal hazards in the context of climate change has been addressed at the regional scale by studying the height and frequency of extreme sea levels (ESL). However, sea level is not the only factor determining the hazard changes that can be used at this scale. Therefore, this article proposes an assessment method of coastal hazard changes integrating other determinants: geographical configurations (continental or island), tidal regimes and meteo-oceanic event types. This method, applied to the coasts of France (mainland and overseas), reveals significant differences in the evolution of coastal hazards: coasts subjected to high tidal ranges and storms (e.g., Atlantic, English Channel and North Sea) will experience a relatively moderate evolution of the hazard, thanks to ≪training≫ for the future conditions that present-day high variations constitute. Conversely, the microtidal shorelines of temperate latitudes (e.g., those of the Mediterranean) benefit from only a small variability generated mainly by storm surges, and are therefore poorly prepared for sea level rise. The situation of the small tropical islands is of particular concern: with the passage of cyclones these territories are subjected to very energetic sea states, but by their form, the surges remain moderate, which constitutes, as well as the low tidal ranges, a limiting factor for preparing for sea level rise. In addition to this approach at the regional level, geological, sedimentary and biological evolutions, as well as local hydraulic phenomena, should be considered to assess at a finer spatio-temporal scale the hazard changes.

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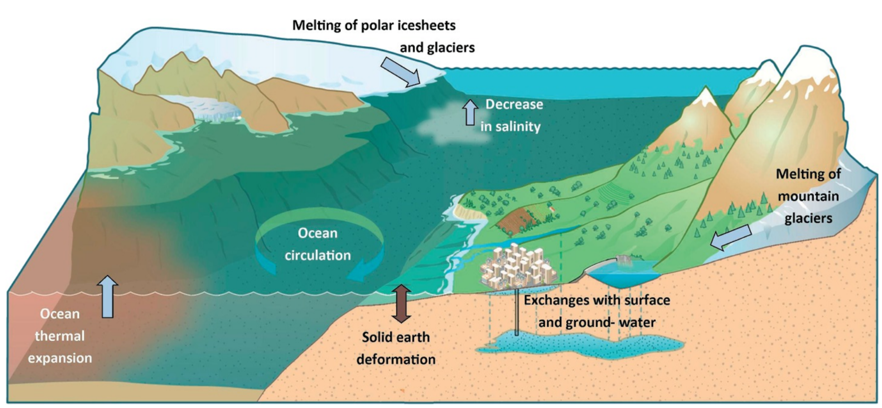

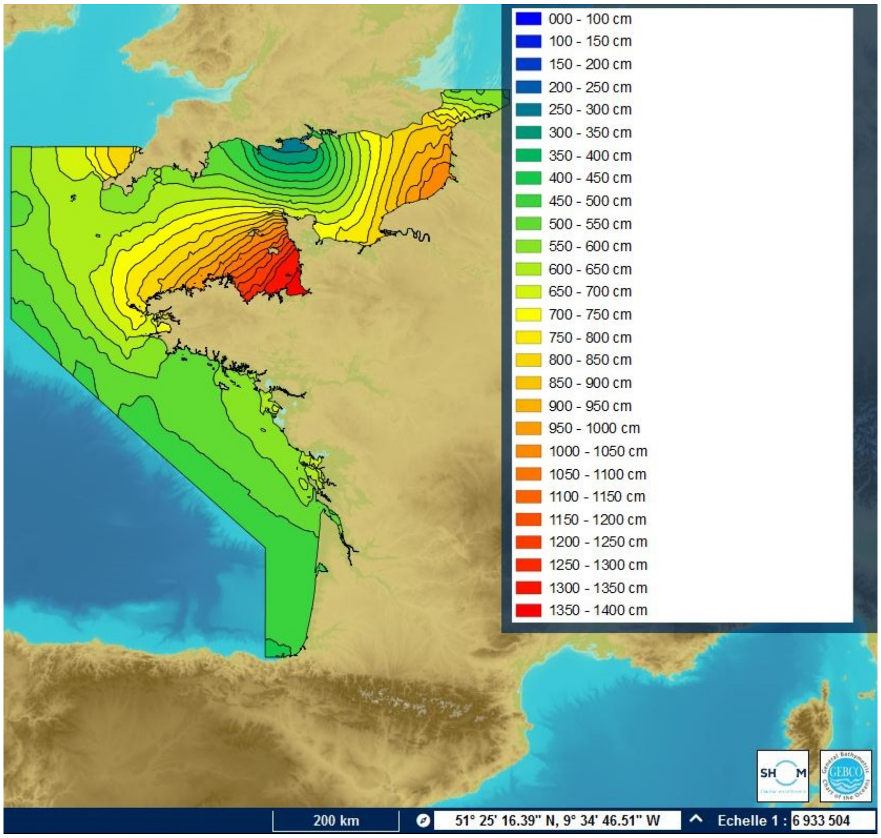
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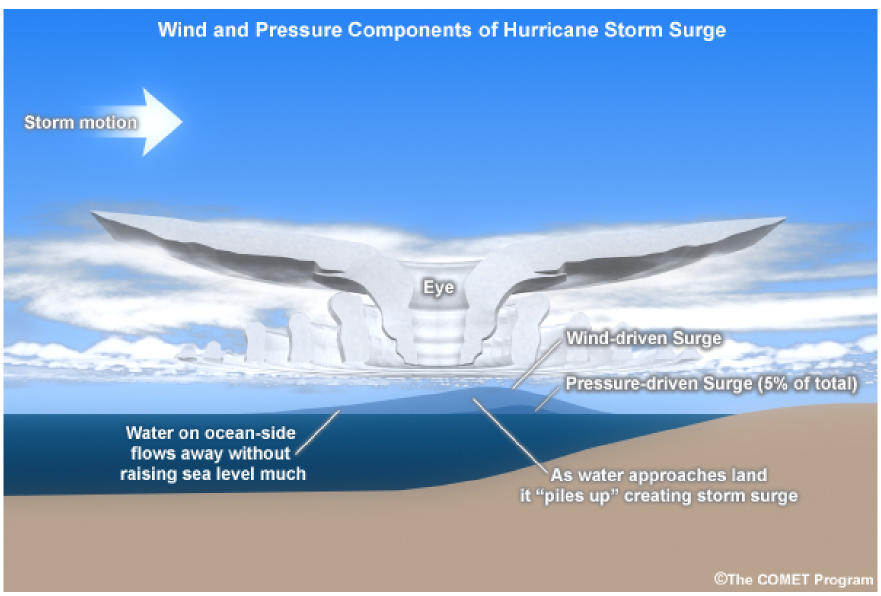
Wind and Pressure Components of Hurricane Storm Surge
Storm motion
Eye
Wind-driven Surge
Pressure-driven Surge (5% of total)
Water on ocean-side flows away without raising sea level much
As water approaches land it "piles up" creating storm surge
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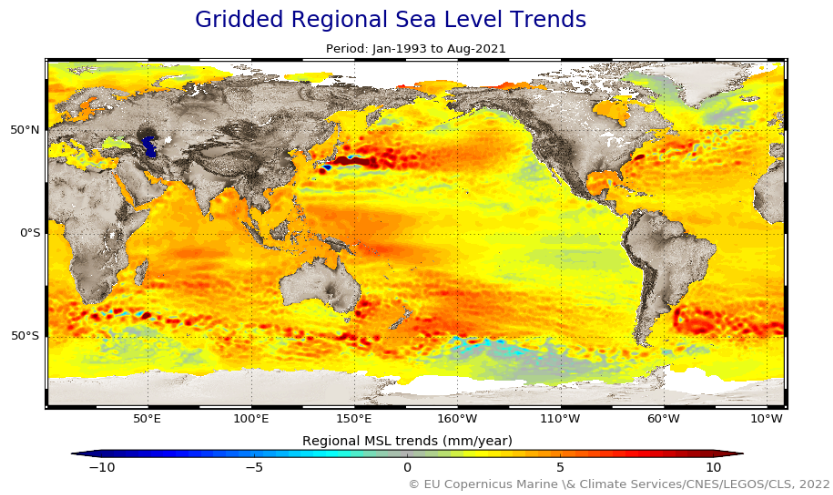
Gridded Regional Sea Level Trends
Period: Jan-1993 to Aug-2021
50°N
0°S
50°S
50°E
100°E
150°E
160°W
110°W
60°W
10°W
Regional MSL trends (mm/year)
−10
−5
0
5
10
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M. Igigabel[1], M. Yates[2], M. I. Vousdoukas[3], and Y. Diab[4]

[1] Cerema, Technopôle Brest Iroise, 155 rue Pierre Bouguer, BP5, 29280 Plouzané, France.

[2] Saint-Venant Hydraulics Laboratory & Cerema, 6 quai Watier, BP 49, 78401 Chatou, France

[3] European Commission Joint Research Centre, Via Enrico Fermi 2749, I-21027-Ispra, Italy.

[4] Université Gustave Eiffel, Lab'Urba, 5, Boulevard Descartes, 77430 Champs-sur-Marne.

Corresponding author: Marc Igigabel (marc.igigabel@cerema.fr)

Key Points:

- The assessment of coastal hazard changes at the regional level should not only consider sea level variations.
- This assessment should also integrate other determinants: geographical configurations, tidal regimes and meteo-oceanic event types.
- At a finer spatio-temporal scale, coastal hazard changes depend also on geological, sedimentary and biological evolutions.

Abstract

The evolution of coastal hazards in the context of climate change has been addressed at the regional scale by studying the height and frequency of extreme sea levels (ESL). However, sea level is not the only factor determining the hazard changes that can be used at this scale. Therefore, this article proposes an assessment method of coastal hazard changes integrating other determinants: geographical configurations (continental or island), tidal regimes and meteo-oceanic event types. This method, applied to the coasts of France (mainland and overseas), reveals significant differences in the evolution of coastal hazards: coasts subjected to high tidal ranges and storms (e.g., Atlantic, English Channel and North Sea) will experience a relatively moderate evolution of the hazard, thanks to «training» for the future conditions that present-day high variations constitute. Conversely, the microtidal shorelines of temperate latitudes (e.g., those of the Mediterranean) benefit from only a small variability generated mainly by storm surges, and are therefore poorly prepared for sea level rise. The situation of the small tropical islands is of particular concern: with the passage of cyclones these territories are subjected to very energetic sea states, but by their form, the surges remain moderate, which constitutes, as well as the low tidal ranges, a limiting factor for preparing for sea level rise. In addition to this approach at the regional level, geological, sedimentary and biological evolutions, as well as local hydraulic phenomena, should be considered to assess at a finer spatio-temporal scale the hazard changes.

1 Introduction

Since 2001, the frequency and severity of extreme climate events, including marine submersions from tropical and other storms is identified by the Intergovernmental Panel on Climate Change (IPCC) as one of the five « reasons for concern » (IPCC, 2001, 2007). As part of analytical approaches, historical and future trends in sea level rise have been researched, considering the contributions of tides, waves and storm surges to Extreme Sea Level (ELS). Vousdoukas et al. (2017) presented a synthesis of these studies and assessed changes in the magnitude and frequency of occurrence of the present 100-year ESL (ESL_{100}) in Europe for Representative Concentration Pathways (RCP)4.5 and RCP8.5 by combining dynamic simulations of all the major components of ESL. Many territories around the world, including remote territories or developing territories that are more vulnerable to coastal hazards, do not have such studies. Above all, knowledge of the evolution of extreme sea levels is not sufficient to assess the evolution of coastal hazards that require the consideration of other factors, in particular the morphology of the coast, the tidal regime and meteo-oceanic event types. The objective of this article is therefore to propose an assessment method at a regional scale of coastal hazard changes integrating other determinants, a method applicable to territories that do not necessarily have high-resolution modelling of ESL changes. The French territories, mainland and overseas (cf. Figure 1), distributed in various latitudes (equator, tropics and temperate zones) and exposed to various climates, and characterized by various geographical configurations (island or continental) are chosen as case studies.

Figure 1. French territories considered in this study. Credit : Cerema, after Hoshie.

First, the definitions of absolute and relative sea levels and the factors determining the evolution of these parameters will be presented. Then the method for assessing the evolution of the hazard will be specified, indicating the factors that can be considered at the regional level on the long term and those that fall within finer spatio-temporal scales. This method will be applied to the sample of territories in order to arrive at a comparison of the evolution of coastal hazards at the regional level over the long term. Finally, the discussion will focus on the necessary extensions of studies at the local level to take into account the specific characteristics of each shoreline.

2 Absolute sea level and relative sea level: définitions and evolution factors

Understanding changes in sea levels requires a clear distinction between global average and local variations. The mean sea level changes, both globally and locally, vary according to seasonal, annual, or longer time scales. According to the IPCC (2019), these variations may be caused by changes in the mass of water in the ocean (*e. g.*, due to melting of glaciers and ice sheets), changes in ocean water density (*e. g.*, water volume expansion under warmer conditions), changes in the shape of the ocean basins and changes in the Earth's gravitational and rotational fields, and local subsidence or uplift of the land. These processes are represented schematically in figure 2.

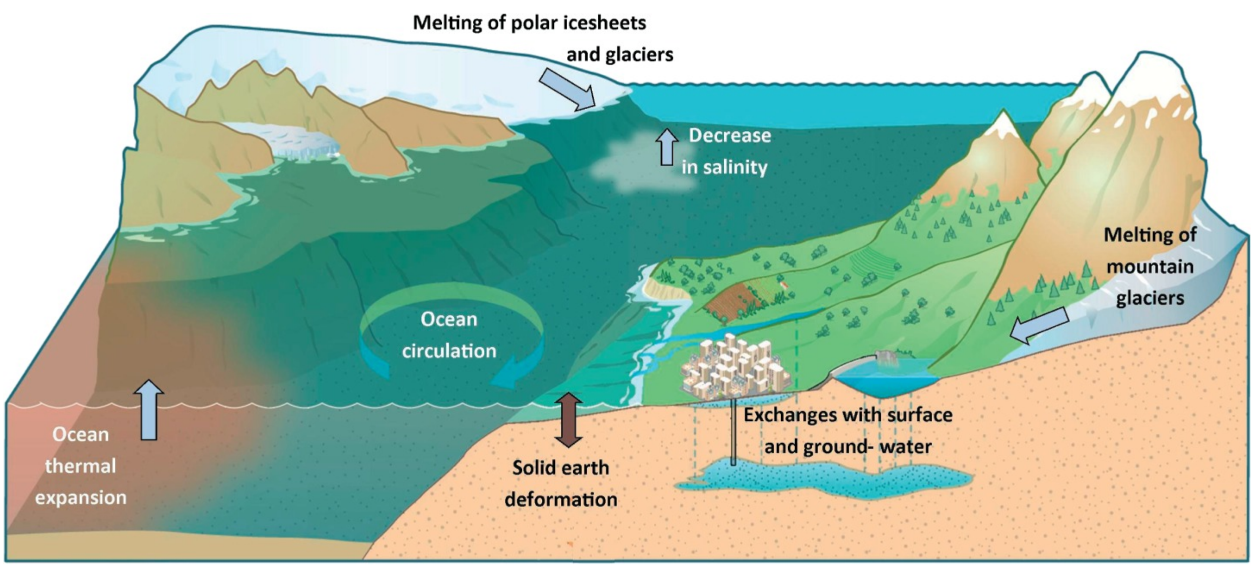

Figure 2. Schematic showing the main factors causing sea level changes (Cazenave and Le Cozannet, 2013).

Among the causes of sea level change identified by the IPCC (2019), a distinction is made between variations in the mass or volume of the oceans and vertical movements of the Earth's surface in relation to the surface of the sea. In the first case, a sea level change is defined as « eustatic »; and in the second case, it is defined as « relative » (Rovere et al. 2016).

The global mean sea level (GMSL) is defined as an average of the eustatic sea level at a global scale. Neither the eustatic level of the sea nor its global average, the GMSL, correspond to a physical level of the sea with reference to a point on the earth's surface (Rovere et al., 2016).

Since the early 1990s, sea level is routinely measured with quasi-global coverage by high-precision altimeter satellites that function with a revisit time of days or weeks (called « orbital cycle »). Compared to tide gauges that provide sea level relative to the ground, satellite altimetry measures « absolute » sea level variations in a geocentric reference frame. The GMSL is increasing with an acceleration in recent decades due to an increasing loss of ice from the ice caps of Greenland and Antarctica, in addition to the continuous loss of glacier mass and thermal expansion of the ocean. Observations show that GMSL is rising at an average rate of 3.53 mm/year over the period 1993-2022, with an uncertainty range of 90% estimated at 0.4 mm (Cazenave and Le Cozanet, 2013).

In addition to the knowledge of the evolution of the absolute level, it is important to know locally the evolution of the relative sea level (RSL). The Relative Sea Level (RSL) is defined as the sea level measured by a tide gauge with respect to the land upon which it is situated (IPCC, 2019). The rate of rise of the RSL exhibits strong regional variations on the order of plus or minus 10 mm per year as shown in Figure 3.

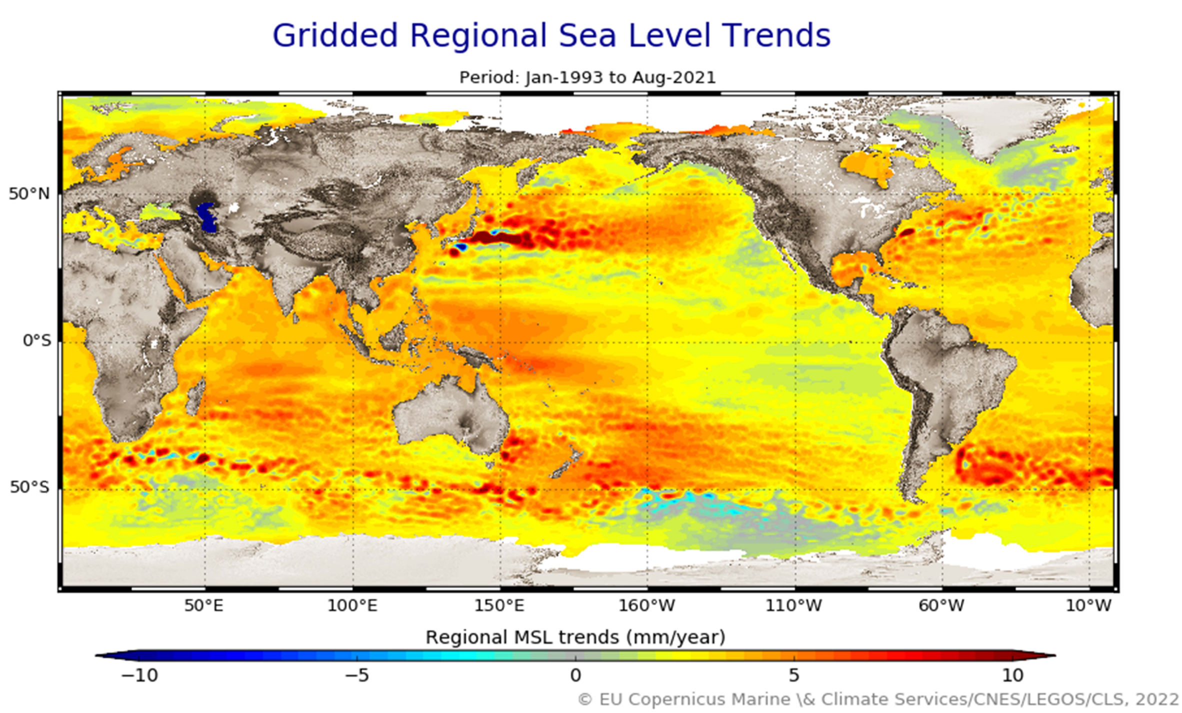

Figure 3. Regional variations in relative sea level trends from January 1993 to August 2021[1]

3 Method for assessing changes in coastal hazards at regional scale

To propose a method for assessing the evolution of coastal hazards, at regional and long-term scales, implies defining an appropriate conceptual framework. A major challenge is to combine a quantitative approach on the parameters characterizing the extreme marine levels and their different components and a qualitative approach on other factors determining the evolution of the hazard.

3.1 Conceptual framework for assessing the evolution of coastal hazards

The proposed conceptual framework states risk definitions that can be used in quantitative and qualitative approaches, and the determining factors which can be taken into account at regional level and those which can only be considered in the context of local studies.

3.1.1 Two definitions of risk

Flood risk, and more generally, all coastal risks, can be defined in at least two alternative ways (FLOODsite, 2009). The first definition considers risk to be the result of the exposure of a vulnerable stake to a hazard, which is reflected in the following formula:

(1) risk = hazard (meteo-oceanic event) * exposure * vulnerability (of the society/area/structure)

However, in an attempt to quantify risk, and considering that the word « risk » suggests a probability of occurrence, a second definition may be sought. To do this:

- the two terms « exposure » and « vulnerability » are substituted by « consequences », with the consequences being generally more quantifiable (for example, in number of fatalities and economic damage) than the previous two terms;
- the hazard can be represented by its probability distribution.

This yields the second definition:

[1] https://www.aviso.altimetry.fr/fileadmin/images/data/Products/indic/msl/MSL_Map_MERGED_Global_AVISO_NoGIA_Adjust.png

(2) risk = probability (of the hazard) * consequences

In the following, we will show that analytical approaches that aim to quantify the evolution of the hazard by focusing on the evolution of the marine levels lead to favour this second definition, but that to qualify more globally the evolution of the hazard and the risk, it is better to go back to the first definition.

3.1.2 Identification of the determining factors at regional level

Climate change through its multiple effects, as well as other anthropogenic changes, can create very diverse situations depending on the coasts. Many parameters should therefore be considered to understand the evolution of risks in a territory. In particular, slow changes, such as sea level rise, warming and ocean acidification, or geomorphological evolutions, should be studied in conjunction with extreme events, such as cyclones, storms, associated storm surges, and heavy precipitation (Igigabel et al., 2021). However, while some factors can be taken into account in the study at the regional level, others cannot be retained, because of the complex interactions between sea level rise and the evolution of coastal areas, that can be of various types. This conceptual framework must therefore establish a clear line between the factors that can be taken into account at the regional level (and will therefore be taken into account by the proposed method) and those that can only be taken into account by extensions of studies at the local level (the influence of these factors will be specified in the discussion).

As a starting point for this reflection, it seems natural to consider the increase in RSL, without which this study would not really have any purpose. The increase in the RSL is combined with the tides and the surges produced by the meteo-oceanic events to generate extreme sea levels (ESL). To understand the evolution of ESLs, it will be considered here that a meteo-oceanic event simultaneously generates a storm surge (caused by atmospheric depression and wind) and energetic waves, and that on the coast, waves also contribute to the elevation of the sea level by two phenomena:

- wave set-up : a time-varying wave-driven increase in the mean water level near the coast, resulting from wave shoaling and breaking processes (Bowen et al., 1968); and

- run-up : the height reached by a wave on a beach or a coastal structure, relative to the static water level, measured vertically (run-up may generate overtopping which, unlike overflowing, occurs intermittently).

In the context of our method, we will consider that all these hydrodynamic phenomena can be taken into account, with the exception of the run-up, which is a local phenomenon. In addition, we will consider that although geographic configurations, tidal regimes and weather-marine events types influence ESLs, these factors not only influence the evolution of coastal hazards across sea levels alone, but can have an additional influence, especially by the energy carried by waves. The two operational aspects of the method, presented below, are intended to clarify how, starting from a quantitative and analytical approach based on the assessment of sea levels and using the second definition of risk, the evolution of the hazard can be completed with a more global and qualitative approach based on the first definition of risk. This methodological approach, which, while taking into account the results obtained by modelling, leads to a return to the determining factors, also allows a better extrapolation of the results to the territories that could not benefit from these modelling.

3.2 Extreme Sea Levels change assessment method

To fully account for changes in sea levels, the analysis must include both changes in the average occurrence frequency of a certain extreme event and the increased height of the water level with a given return period. This is why the second definition of risk will be used here by studying the joint probabilities of the parameters determining sea levels, namely the RSL, the tidal range and the storm surge (including the effects of the waves). Although differences may exist between territories in the RSL rise, the predominant factor in the evolution of coastal hazards is the variability in sea levels generated by astronomical tides and storm surges (Buchanan et al., 2016). Great variability at present time is a form of training for future conditions. The situation is indeed very different for:

- a coastline for which the addition of the tidal range and the maximum storm surge is of the order of 1 m. In this case an increase in the mean sea level of 1 m results in a very frequent exceeding of the current ESL;

- a coastline with a very strong tidal range (regularly over 6 m) and strong storm surges (frequently over 2 m). On such a coastline, exceptional levels are reached only if the excess occurs at a time corresponding to a high spring tide. A rise in the mean sea level of 1 m will certainly lead to an increase in extreme levels, but extreme sea level situations (in reference to the present situation) will remain relatively infrequent.

The frequency of extreme sea levels will therefore vary significantly across coastlines. The combination of tide and storm surge phenomena requires a statistical approach to assess the evolution of the marine flood hazard. Thus, the change in ESL events is commonly expressed in terms of the amplification factor and the allowance. The amplification factor denotes the amplification in the average occurrence frequency of a certain extreme event, often referenced to the water level with a 100-year return period during the historic period. The allowance denotes the increased height of the water level with a given return period. This allowance equals the regional projection of RSL rise with an additional height related to the uncertainty in the projection (Hunter, 2012).

Amplification factors are strongly determined by the local variability in ESL events. Locations where this variability is large due to large storm surges and astronomical tides will experience a relatively moderate amplification of the occurrence frequency of extremes. In comparison, locations with small variability in ESL events will experience large amplifications even for a moderate RSL rise. Globally, this contrast between regions with large and small amplification factors becomes clear for projections by mid-century and considerable in the coming centuries (Vitousek et al., 2017). In particular, many coastal areas in the lower latitudes may expect amplification factors of 100 or larger by mid-century, regardless of the scenario. By the end of the century and in particular under RCP8.5, such amplification factors are widespread along global coastlines (Vousdoukas et al., 2018).

As for the amplification factor, the study of the allowance must be regionalized. To this end, we adopt the analysis principles and annotations used by Vousdoukas et al. (2017) in their study of the evolution of extreme levels along European coasts. In particular, we will focus on changes in the magnitude and frequency of occurrence of the present 100-year ESL (ESL_{100}). We consider that ESL are driven by the combined effect of Mean Sea Level (MSL), tides (η_{tide}) and water level fluctuations due to waves and storm surges (η_{w-ss}). As a result, ESL can be defined as:

(3) $$\text{ESL} = \text{MSL} + \eta_{\text{tide}} + \eta_{\text{w-ss}}$$

The climate extremes contribution η_{w-ss} from waves and storm surge can be estimated according to the following equation:

(4) $$\eta_{\text{w-ss}} = \text{SSL} + 0.2 \times H\text{s}$$

where SSL is the storm surge level, Hs is the significant wave height and 0.2 × Hs is a generic approximation of the wave set-up (U.S. Army Corps of Engineers, 2002). Remember that the run-up, as a local effect, is neglected.

These equations, of course, correspond to simplified approaches to reality, in that there are interactions between the various phenomena that produce non-linear effects which modelling at large scales cannot account for in the present state of knowledge (Vousdoukas et al., 2017).

3.3 Global Hazard Assessment Method

Given the high stakes associated with the rise of RSL in the 21st century, the global analysis considers the scenario RCP8.5 and the 2050 and 2100 horizons. Indeed, in terms of risk assessment, it seems more appropriate to consider the greenhouse gas emission trajectory currently followed (IPCC, 2019), rather than making the bet of a strong inflection of the curve. This hypothesis also has the advantage of better highlighting contrasting situations in the evolution of coastal hazards.

In addition, it is necessary to clarify that the data used for the variations in the RSL and the ESL are median values. The values obtained for the GMSL show how high the uncertainties remain: for this parameter and just for the RCP8.5 scenario, the median value is 0.84 m and the 17th to 83rd percentile range is 0.61 to 1.10 m (the high value is almost double the low value). Similar (or higher) uncertainties exist on the RSL and the centennial ESL. The analysis cannot therefore claim to a great precision on the figures. The research of precision on the variation of each of the factors at a well-defined time horizon would be moreover in vain since the sea levels continue to increase, meteo-oceanic events are highly variable. In addition, for long-term adaptations, a general description of the evolution of the hazard is more appropriate than a forecast (likely imprecise) of the evolution of a parameter at a given date. The objective must therefore be more to seek the effect of the RSL rise in each local context, by considering the concomitance of astronomical high tides, storm surges, and high energy waves. In particular, since wave exposure is a significant factor in increasing the hazard of extreme sea level events, the assessment must consider general geomorphological characteristics and the climate prevailing on each of the maritime facades, depending on whether they are (or not) subject to cyclones or storms.

4 Results

For the application of the method, the French mainland and overseas coasts will be studied. In addition to the qualitative or quantitative conclusions that can be obtained for each of them, the interest will be also on the comparison between them.

4.1 Analysis of extreme sea levels

In accordance with the principles set out above, the evolution of extreme sea levels depends mainly on three parameters: (1) the RSL, (2) tidal ranges and (3) waves and storm surges. The available data and projections on these parameters reveal very contrasting situations. The French coasts (mainland and overseas) are used as examples to illustrate these situations.

4.1.1 Absolute and relative sea levels: projections

The projection of marine levels is given by the IPCC (2019) in the 2050, 2100 and extended to the 2300 horizons to illustrate that even if the control of greenhouse gas emissions were to be achieved, warming would nevertheless result in a gradual rise in sea levels over several centuries (more or less strong depending on the scenarios).

The scenario RCP 8.5 of the IPCC is used to make these projections (see Table 1). However, accelerated and stronger developments could occur: in the event of a faster melting of the ice caps of Greenland and Antarctica, Bamber et al. (2019) estimate the increase of the GMSL above 2 m in the 21st century.

Table 1. *Sea Level Projections for 2050, 2100 and 2300 under RCP 8.5.*

Climate scenario	2050 Mean	2050 17-83% range	2100 Mean	2100 17-83% range	2300 Mean	2300 17-83% range

RCP 8.5	+ 32 cm	23 cm to 40 cm	+ 84 cm	61 cm to 110 cm	+385 cm	230 cm to 540 cm

Note. Median values and ranges for the 17th to 83rd percentiles are shown using the 1986-2005 period as a reference (IPCC, 2019).

Sea level rise is not globally uniform and varies regionally. Thermal expansion, ocean dynamics, and land ice loss contributions will generate regional differences of about ±30% of GMSL rise. Deviations from the global mean can be greater than 30% in areas of rapid vertical land movements, including those caused by local anthropogenic factors such as groundwater extraction (IPCC, 2019). Table 2 shows at various points along the French coastline the median values of the regional sea level rise projections for the period 1995-2014. For the scenario RCP8.5, the median values of the sea level rise on the French coasts are fairly uniform, between 0.16 m and 0.20 m in 2050, and between 0.76 m and 0.92 m in 2100.

Table 2. *Projections of Regional Sea Level Rise at Various Points along the French Coastline Compared to the Period 1995–2014 under RCP 8.5 (Vousdoukas et al. 2018)*

	2050	2100
Calais	0,19	0,86
Le Havre	0,19	0,87
Saint-Malo	0,19	0,87
Brest	0,19	0,83
La Rochelle	0,16	0,76
Saint-Jean-de-Luz	0,17	0,79
Port Vendres	0,16	0,76
Sète	0,16	0,76
Marseille	0,17	0,78
Saint-Pierre (Saint-Pierre-et-Miquelon)	0,19	0,83
Pointe-à-Pitre (Guadeloupe)	0,20	0,90
Cayenne (Guyane)	0,20	0,90
Pointe des Galets (La Réunion)	0,19	0,92
Papeete (Polynésie française)	0,20	0,91

4.1.2 Tidal range influence

The first discriminating parameter in the evolution of extreme sea levels is the tidal range. This parameter exerts a great influence on the amplification factor (strong amplification factor for low tidal ranges). It should be noted that tidal simulations show no significant control of the rise of the RSL on tidal amplitude throughout the 21st century at the regional level, although this does not exclude potential local effects (Haigh et al., 2020). We will therefore assume that the tides are in a steady state and that the tidal range does not change the allowance.

The French coasts can be represented in the three usual categories:

- microtidal coastline (tidal range < 2 m): the coasts of the Mediterranean with a tidal amplitude between 20 and 50 cm and the coasts of the West Indies, La Reunion, Mayotte and French Polynesia where the amplitude are less than 1 m; in addition, the coasts of Saint-Pierre-et-Miquelon, where the amplitude reaches 1.70 m;
- mesotidal coastline (tidal range between 2 and 4 m): the coasts of French Guiana (the maximum amplitude measured at the port of Degrad des Cannes reaches 2.90 m during the spring period);
- Macrotidal coastline (tidal range > 4 m): on the coasts of the Atlantic, English Channel and North Sea, with significant differences shown in Figure 4.

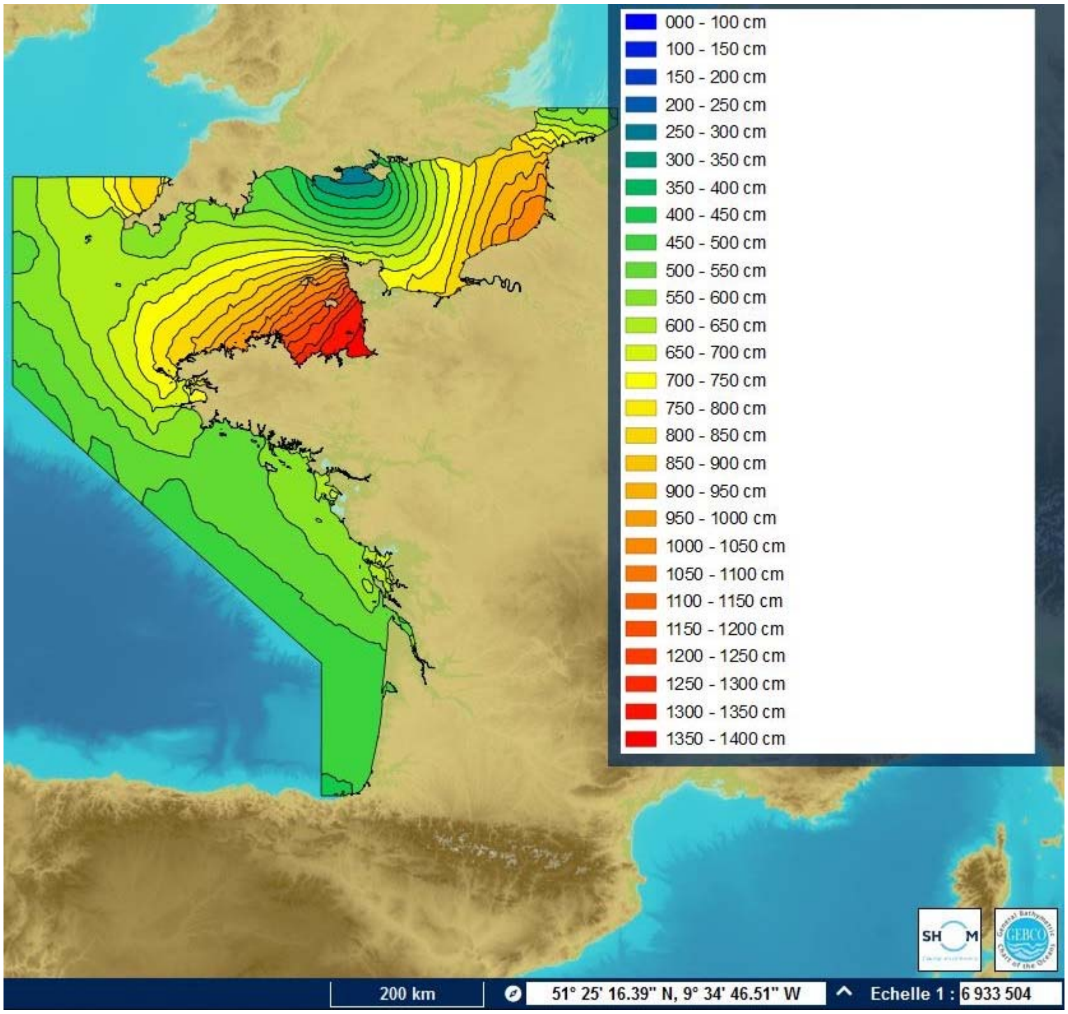

Figure 4. Maximum tidal range (source: Data.shom.fr)

4.1.3 Influence of waves and storm surges

The second discriminating parameter in the evolution of extreme sea levels is the surge due to storm and waves. This parameter influences the amplification factor (strong amplification factor for low surges) and can also influence the allowance. Indeed, through a statistical analysis of tide gauge observations, Calafat et al. (2022) have shown that trends in surge extremes and sea-level rise both made comparable contributions to the overall change in extreme sea levels in Europe since 1960.

Surges estimates are generally based on tide gauge measurements at places protected from waves. Therefore, these measurements are primarily of storm surges. Additional increases in the water level related to waves (e.g. set-up) can be more or less significant depending on the meteorological conditions and the sea states they generate, as well as on the geomorphological configuration of the coast.

Information on surges will be presented separately in mainland France and overseas to take account of differences between climates.

In Metropolitan France, there are significant variations along the coastline, as shown by the estimates of the 100-year return period surges (Cerema, 2018) presented in Table 3. The analysis of storm surges computed from the national REFMAR database reveals that they are controlled not only by storm tracks but also by the width of the continental shelf. Thus, during the studied period 1998-2018, storm surges hardly reach 1.0 m along the coastlines of the southern Bay of Biscay and the eastern Mediterranean Sea, but can exceed 2.0 m in the English Channel (Dodet et al., 2019). It should be noted that this last value is slightly higher than the centennial surge estimated on the basis of the measurements carried out in the metropolitan ports (Cerema, 2018).

Table 3. *Estimates in Meter of the 100-year Return Period Surges.*

Tide gauge	100-year return period surge (m)
Dunkerque	1,4
Calais	1,1
Boulogne-sur-Mer	1,2
Dieppe	1,4
Le Havre	1,4
Cherbourg	0,9
Saint-Malo	1,1
Roscoff	0,8
Le Conquet	1,0
Brest	1,0

Concarneau	1,0
Port Tudy	1,0
Crouesty	1,1
Saint-Nazaire	1,3
Saint-Gildas	1,1
Sables d'Olonne	1,0
La Rochelle	1,2
Port-Bloc	1,2
Arcachon	1,3
Bayonne	0,9
Saint-Jean-de-Luz	0,6
Port-Vendres	0,9
Sète	1,1
Marseille	1,3
Toulon	0,8
Nice	0,8
Monaco	0,8
Ajaccio	0,8

Note. Two estimates were made, respectively by statistical adjustment of a Pareto distribution (GPD) and an exponential law (Cerema 2018) on storm peaks. This table shows the average of these two estimates.

Vousdoukas et al. (2017) studied along European coasts the ESL allowance. They specified the influence on this parameter of the elevation of the RSL and of the waves and storm surges. Projections of waves and storm surges were based on hydrodynamic simulations driven by atmospheric forcing from six Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models. The results obtained under RCP8.5 are presented in Table 4. It appears first of all that the ESL increase in absolute value is relatively homogeneous on the various maritime facades of France: under the RCP 8.5 scenario in 2100, for the English Channel 0.89 to 1.00 m, for the Bay of Biscay 0.74 to 0.77 m and for the western Mediterranean 0.75 to 0.78 m. However, the percentage variations are very different: under scenario RCP 8.5 in 2100 for the English Channel between 16 and 22%, for the Bay of Biscay between 20 and 24% and for the western Mediterranean, between 52 and 63%. The increase will therefore be much more noticeable in the Mediterranean.

Table 4. *Table Summarizing the Projected Absolute and Relative Changes of the 100-year Event ESL (ΔESL and %ΔESL) under RCP8.5, during the Years 2050 and 2100 (Vousdoukas et al., 2018).*

	RCP8.5 - 2050		RCP8.5 - 2100	
	ΔESL (m)	%Δ ESL	ΔESL (m)	%Δ ESL
Calais	0.21	4,3	0.94	19,2
Le Havre	0.23	4,4	1.00	19,6
Saint-Malo	0.21	3,8	0.89	16,0
Brest	0.22	5,0	0.96	21,5
La Rochelle	0.16	4,3	0.77	19,9
Saint-Jean-de-Luz	0.16	5,3	0.74	24,1
Port Vendres	0.16	13,3	0.75	60,7
Sète	0.18	12,5	0.76	52,5
Marseille	0.18	14,6	0.78	63,2

The analysis of ESL height variation should be supplemented by a frequency analysis based on Table 5. These forecasts show that sea levels of centennial occurrence could occur on an annual basis by the end of this century in mainland France (except in the centre of the Atlantic facade). Some regions are projected to experience an even higher increase in the frequency of occurrence of extreme events, most notably along the Mediterranean, where the present day 100-year ESL is projected to occur about ten times a year (Vousdoukas et al. 2018). The higher increase in the Mediterranean is closely related to the low variability of sea levels on these microtidal coastlines.

Table 5. *Return Period of the Present Day 100-year ESL under RCP8.5 in the Years 2050 and 2100 (Vousdoukas et al., 2018).*

	2050	2100
Calais	22,81	0,75
Le Havre	26,56	0,87
Saint-Malo	27,69	0,81

Brest	20,61	0,73
La Rochelle	36,16	2,59
Saint-Jean-de-Luz	33,87	0,63
Port Vendres	27,89	0,10
Sète	30,02	0,56
Marseille	26,88	0,10

Overseas, the Cerema (2019, 2020, 2021) provides information on the surges measured, observed and modelled in La Reunion, Mayotte, French Guyana, Martinique, Guadeloupe, Saint-Martin and Saint-Barthélemy and Saint-Pierre-et-Miquelon. Surges measured by tide gauges commonly reach values of 0.5 to 1 m. These values are much lower than the values measured on continental facades exposed to hurricanes: for example, in the case of Katrina, which impacted the United States in 2005, surges in eastern Louisiana reached values between 3.05 m and 5.79 m (Graumann, 2006). During the same event, the surges exceeded 8 m at several locations along the Mississippi coast (Dietrich et al., 2010).

This difference between the surges observed on the continental and island coasts is explained by the fact that, in the case of a hurricane, the impact of the low pressure associated with the storm on surge is minimal in comparison to the water being forced toward the shore by the wind (cf. figure 5). But, in the case of small islands (e. g. West Indies or La Réunion), the surge is generally reduced by a dissipative effect (Durand, 1996). However, the maximum potential storm surge for a particular location is sensitive to the slightest changes in storm intensity, forward speed, size (radius of maximum winds), angle of approach to the coast, central pressure, and shape and characteristics of coastal features such as bays and estuaries[2]. In particular in shallow waters, the wind effect can significantly dominate the effect of the low-pressure surge and the surge can therefore be strongly amplified according to the bathymetry along the coast (Bertin, 2012). For example, during the passage of Cyclone Irma on September 6, 2017, an instantaneous surge of 2.0 m was measured at the Saint-Martin tide gauge[3]. The surge, modelled by Météo-France, was more than 3 m on the northern coasts of Saint-Martin (Marigot Bay, Grand Case) and Gustavia (Saint-Barthélemy), but hardly more than 1.2 m on the island's

[2] https://www.nhc.noaa.gov/surge/
[3] https://data.shom.fr/donnees/refmar/SAINT_MARTIN

almost straight coastline (De la Torre Y., 2017). Concordantly, in September 1989, during the passage of Cyclone Hugo on the Guadeloupe archipelago, there was evidence that the sea level would have increased by 2 to 3 m along the coasts (Pagney 1991).

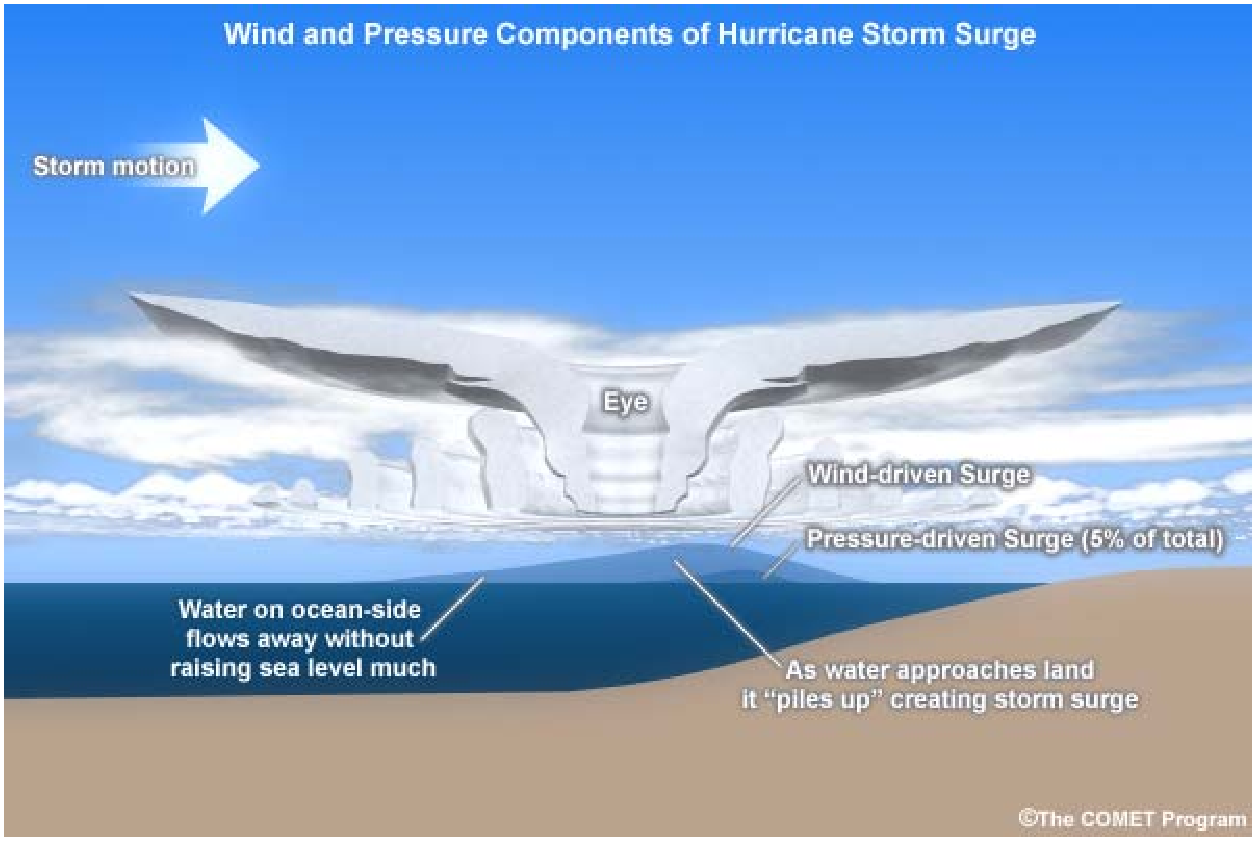

Figure 5. Wind and pressure components of hurricane storm surge. Credit: The COMET Program, UCAR and NOAA.

It can therefore be concluded that the surges measured by tide gauges present in the main ports are not representative of all the surges appearing on the coast. The surges generated by cyclones on the very small islands (maximum height of the order of 3 m) nevertheless remain much lower than those observed on the coasts of the continents (maximum height of the order of 8 m). However, depending on the trajectory and intensity of the cyclone, for islands of greater size, the dissipative effect may be less and it may therefore be considered that the surge can reach values greater than 3 m on the shore of the bays.

The framework developed by Vousdoukas et al. (2018) provides estimates of the ESL allowance along overseas coasts. Projections of waves and storm surges under RCP8.5 based on hydrodynamic simulations driven by atmospheric forcing from six Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models are presented in Table 6. It appears first of all that the ESL increase in absolute value is relatively homogeneous on the various overseas coasts between 0.16 and 0.24 m in 2050 and between 0.85 and 0.95 m in 2100. The percentage changes under the RCP 8.5 scenario are expected to be in the range of 8% to 18% by 2050, which should already be noticeable in terms of hazard intensity, particularly in the West Indies and French Polynesia, where the relative increases will be greatest. In 2100, under the same scenario, the increases should be around 50 to 75% (with the exception of Saint-Pierre-et-Miquelon where the increase should be of the order of 30%). These relative increases in extreme sea levels will necessarily lead to very strong intensification of the hazard associated with each meteocean event.

Table 6. *Table Summarizing the Projected Absolute and Relative Changes of the 100-year Event ESL (ΔESL and %ΔESL) under RCP8.5, during the Years 2050 and 2100 (Vousdoukas et al. 2018).*

	RCP8.5 - 2050		RCP8.5 - 2100	
	ΔESL (m)	%Δ ESL	ΔESL (m)	%Δ ESL
Saint-Pierre (Saint-Pierre-et-Miquelon)	0,24	8,4	0,92	31,8
Pointe-à-Pitre (Guadeloupe)	0,22	14,1	0,91	58,1
Cayenne (Guyane)	0,18	10,6	0,85	49,2
Pointe des Galets (La Réunion)	0,16	9,3	0,88	52,5
Papeete (Polynésie française)	0,23	17,8	0,95	74,7

As for metropolitan France, the analysis of ESL height variation should be supplemented by a frequency analysis based on Table 7, which forecasts show that on all overseas coasts, under RCP8.5, in 2100, the present day 100-year ESL is projected to occur about ten times a year, except for Saint-Pierre-et-Miquelon where this frequency would be about three times a year (Vousdoukas et al. 2018). The increase in frequency should already be noticeable in 2050, especially in French Guiana, French Polynesia and Saint-Pierre-et-Miquelon where the return periods of the present day 100-year ESL should be only 7 years, 16 years and 18 years respectively.

Table 7. *Return Period of the Present Day 100-year ESL under RCP8.5 in the Years 2050 and 2100 (Vousdoukas et al., 2018).*

	2050	2100
Saint-Pierre (Saint-Pierre-et-Miquelon)	17,69	0,31
Pointe-à-Pitre (Guadeloupe)	35,14	0,10
Cayenne (Guyane)	7,54	0,10
Pointe des Galets (La Réunion)	57,53	0,10
Papeete (Polynésie française)	15,86	0,10

4.2 Global analysis of the evolution of the hazard on the different coasts

The evolution of the hazard on the coasts can be assessed according to the principles presented in section 2.3, that is to say by taking into account more globally, the general geomorphological characteristics and the climate prevailing on each of the maritime facades, in order to better appreciate the influence of waves without going through the prism of sea levels. Conclusions will be drawn from the analysis of data summary tables, first for mainland France's coasts, then for the overseas territories. Finally, a synthesis will be presented.

4.2.1 Evaluation of wave influence

Sea level rise can greatly increase the hazard, because by increasing water depths, and assuming no changes in bathymetry, it allows locally more severe wave conditions to attack the shoreline. Thus, the coastal impacts of ESLs are largely due to the fact that waves impact the coast with considerable amounts of energy, potentially driving morphological changes and erosion, as well as coastal protection failure and overwash/inundation (CIRIA et al. 2013, Vousdoukas et al. 2017). By combining a global digital surface elevation model (30 m spatial resolution) with extreme coastal water levels derived from a combination of satellite altimetry, tide and surge models, and wave reanalyses, Almar et al. (2021) found that the globally aggregated annual overtopping hours have increased by almost 50% over the last two decades. Their assessment indicates that globally aggregated annual overtopping hours will accelerate faster than the global mean sea-level rise itself, with a clearly discernible increase occurring around mid-century regardless of climate scenario. Under RCP 8.5, the globally aggregated annual overtopping hours by the end of the 21st-century is projected to be up to 50 times larger compared to present-day.

The increase in wave damage can be assessed, considering local changes in significant wave height (average height of the highest one-third of the waves in a given sea state). Trends in coastal swell climates are reported in the IPCC (2019) report: projections of future extreme significant wave height are consistent in projecting an increase over the Southern Ocean and a decrease over the northeastern Atlantic and Mediterranean Sea. On the selected coasts, this means that the significant swell associated with extreme events would tend to decrease in the Mediterranean, the West Indies and Saint-Pierre-et-Miquelon, while it would tend to increase on La Reunion and Mayotte. These indicative trends will not, however, be explored in detail: the focus will be on the strong differences that already exist (and that will remain globally) between the swell climates of the maritime facades.

4.2.2 Evolution of the hazard in the European territory of France

The data available for the mainland France’s coasts are presented in Table 8.

Table 8. *Summary of the Main Factors Influencing the Hazard Evolution on the Mainland France’s Coasts.*

	Tidal	Reference	100-year	ΔRSL (m)	ΔESL (m)	%ΔESL	Return period of

	range	meteocean event	surge (m)	under RCP 8.5	under RCP 8.5	under RCP 8.5	the present day 100-year ESL under RCP 8.5 (year)
English Channel – North Sea	Macrotidal (7 to 14 m)	Storm	0,8 to 1,4	In 2050 : 0,19 In 2100 : 0,83 to 0,87	In 2050 : 0.21 to 0.23 In 2100 : 0.89 to 1.00	In 2050 : 3.8 to 5 In 2100 : 16 to 21.5	In 2050 : 20 to 28 In 2100 : 0.73 to 0.87
Bay of Biscay	Macrotidal (5 to 7 m)	Storm	0,6 to 1,3	In 2050 : 0,16 to 0,17 In 2100 : 0,76 to 0,79	In 2050 : 0,16 In 2100 : 0.74 to 0.77	In 2050 : 4.3 à 5.3 In 2100 : 19.9 to 24.1	In 2050 : 33 to 36 In 2100 : 0.63 to 2.6
West Mediterranean	Microtidal (< 2 m)	Storm	0,8 to 1,3	In 2050 : 0,16 to 0,17 In 2100 : 0,76 to 0,78	In 2050 : 0,16 to 0.18 In 2100 : 0.75 to 0.78	En In 2050 : 12.5 to 14.6 In 2100 : 52.5 to 63.2	En In 2050 : 26 to 30 In 2100 : 0.10 to 0.56

Note. The data refer to a 100-year ESL event. The reference period for the RSL projection is 1995-2014. The reference period for the ESL projection is 1980-2014.

By 2100, on the three maritime façades of France, the variations in the centennial ESL are largely dominated by the RSL rise. Although the surge evolution may have contributed significantly to the increase of ESLs since 1960 in Europe (Calafat et al., 2022), the study by Vousdoukas et al. (2017) shows that this factor will gradually lose its importance in the course of the 21st century due to the strong increase in RSL, which is becoming predominant. Thus, by 2100, for the RCP 8.5 scenario, the increases in RSL and ESL on the three maritime facades are rather close in absolute terms, with median values between 0.74 and 1.0m. On the other hand, the effect of these increases is significantly different for each maritime facade, depending on the tidal range, the surges and the type of meteo-oceanic event to which these coasts are subject:

- In the English Channel and the North Sea, the very high tidal ranges and the passage of storms produce a high variability of sea levels. The increase of 0.9 to 1.0 m of the 100-year ESL represents in percentage only a variation of 16 à 22%. The allowance is therefore relatively low. On the other hand, the increase in the RSL is sufficient for a present day 100-year ESL event to have a return period of less than one year (amplification factor greater than 100);

- In the Bay of Biscay, the situation is quite similar, but with lower tidal ranges and surges (especially on the coast of the Atlantic Pyrenees where the maximum tides are in the order of 5 m and the centennial surge in the order of 0.6 m). Under these conditions, the 0.75 m increase in the centennial ESL corresponds to a relative increase of 20 to 24%, and above all, a current centennial event will occur on average once or twice a year (amplification factor between 50 and 100);
- In the Mediterranean, the situation is clearly aggravated by the very low variability of the sea level (microtidal regime and rather low surges). As a result, the 100-year ESL increase of 0.77 m corresponds to a large relative increase (greater than 50%) and the present day 100-year event will occur between 2 and 10 times per year (amplification factor between 500 and 1000).

By 2050, the 100-year ESL will rise by 5% in the North Channel and the Bay of Biscay. In the Mediterranean, this increase will already be of the order of 20%. However, the evolution of the situation will be especially noticeable in the frequency increase of ESLs, since the frequency will be multiplied by a factor between 3 and 4.

4.2.3 Evolution of the hazard in the overseas territories of France

The data available for the overseas coasts are presented in Table 9.

Table 9. *Summary of The Main Factors Influencing the Hazard Evolution on Coastlines of French Overseas Territories.*

	Tidal range	Reference meteocean event	100-year surge (m)	ΔRSL (m) under RCP 8.5	ΔESL (m) under RCP 8.5	%ΔESL under RCP 8.5	Return period of the present day 100-year ESL under RCP 8.5 (year)
Saint-Pierre (Saint-Pierre-et-Miquelon)	Microtidal (< 2 m)	Storm	1 to 2	In 2050 : 0,19 In 2100 : 0.83	In 2050 : 0.24 In 2100 : 0.92	In 2050 : 8.4 In 2100 : 31.8	In 2050 : 18 In 2100 : 0.3
Pointe-à-Pitre (Guadeloupe)	Microtidal (< 2 m)	Storm and cyclone	1 to 3	In 2050 : 0,20 In 2100 : 0,90	In 2050 : 0.22 In 2100 : 0.91	In 2050 : 14.1 In 2100 : 58.1	In 2050 : 35 In 2100 : 0.1
Cayenne (French Guyana)	Mesotidal (2 to 4 m)	Trade winds (without storm)	0.4	In 2050 : 0,20 In 2100 : 0,90	In 2050 : 0.18 In 2100 : 0.85	In 2050 : 10.6 In 2100 : 49.2	In 2050 : 7,5 In 2100 : 0.1
Pointe des Galets (La Réunion)	Microtidal (< 2 m)	Storm and cyclone	1 to 3	In 2050 : 0,19 In 2100 : 0,92	In 2050 : 0.16 In 2100 : 0.88	In 2050 : 9.3 In 2100 : 52.5	In 2050 : 58 In 2100 : 0.1
Papeete (French Polynesia)	Microtidal (< 2 m)	Storm and cyclone	1 to 3	In 2050 : 0,20 In 2100 : 0,91	In 2050 : 0.23 In 2100 : 0.95	In 2050 : 17.8 In 2100 : 74.7	In 2050 : 16 In 2100 : 0.1

Note. The data refer to a 100-year ESL event. The reference period for the RSL projection is 1995-2014. The reference period for the ESL projection is 1980-2014.

From the data collected in Table 9, it appears that **by 2100** for the scenario RCP8.5:

- on the coasts of the West Indies, Reunion Island, and French Polynesia, the tidal ranges are less than 2 m. On the other hand, the passage of the cyclones generates larger surges (up to 3 m), which generates greater sea level variability than in the Mediterranean. We can consider that the situation of these coasts is rather close to that of the Mediterranean in terms of allowance (50-75% increase) and amplification (increase in the frequencies of the current centennial ESL by about 1000). However, the change in the intensity and frequency of the hazard must be considered more carefully in these territories because of the greater damage that hurricanes can cause compared to storms that reach the European territory of France;

- on the coast of Saint-Pierre-et-Miquelon, the tidal range is less than 2 m. While the strong winds that regularly blow on these islands can produce large surges, the variability in sea levels remains low because of the microtidal regime. The situation is therefore close to that of the Mediterranean, with however a slightly less rapid increase in ESLs as evidenced by the factors of elevation (about 32%) and amplification (about 300);
- on the coast of French Guyana, the maximum tidal range is 2.9 m, and the maximum surge recorded in the bibliography is only 0.4 m. The increase in the amplitude and frequency of ESLs will be of the same order of magnitude as on the coasts of the Mediterranean, the West Indies and Reunion Island. However, this coast close to the equator is not exposed to meteo-oceanic events that generate strong swells. The increase in coastal hazards will therefore be less than in other overseas territories.

By 2050, the evolution of the hazard will be perceptible primarily because of the increase in the frequency of ESLs: frequency multiplied by 2 for Réunion Island, 3 for the West Indies, 5 for Saint-Pierre-et-Miquelon, 6 for French Polynesia, and 13 for Guyana. The most damaging changes are for the territories with low variability in sea levels that are subject to storms (Saint-Pierre-et-Miquelon whose centennial ESL will increase by 8%) and to cyclones (Reunion Island, the West Indies and French Polynesia, with ESL increases of 9, 14 and 18% respectively). In this comparison, French Polynesia shows both the greatest increase in frequency and intensity of the 100-year ESL event. Guyana is also expected to experience negative changes in the ESL by 2050, but thanks to its storm-free climate, this territory will not be exposed to catastrophic meteocean event.

5 Discussion

The coastal zone is a buffer zone where a multitude of processes and feedback effects can take place, what needs to be considered in the assessment of hazard changes and the definition of adaptation measures:

- in estuaries, changes in coastal morphology (bathymetry, shoreline topography, and anthropogenic development) can influence (positively or negatively) extreme events, including changes in the spread of tidal waves and storm surges (Talke et al., 2020);
- along most sandy coasts, coastal morphology is also likely to change. The reaction of each shoreline would therefore require to study locally the geomorphological characteristics, the height of the waves, but also the frequency of events, which also has an impact on the ability of systems to recover between energy events (Masselink et al., 2016). In addition, wave direction is also an important parameter related to long-shore sedimentary transport effects, which can change the state of equilibrium of the coasts at present (Ruggiero et al., 2010; Casas-Prat and Sierra, 2010);
- on many coasts, accelerated sea level rise is likely to result in permanent flooding of unprotected lowlands. More frequent and intense episodic coastal flooding could also occur with climate change that alters wave conditions and storm surges. This may also result in a chronic coastline erosion (Ranasinghe, 2016).

Other phenomena induced by climate change can increase the intensity and the frequence of extreme events or increase their impact:

- ocean acidification combines with ocean warming and deoxygenation to impact ecosystems (*e. g.*, coral reefs and oyster beds) and the associated services benefiting human societies, including coastal flood protection (Albright et al., 2018; Hoegh-Guldberg et al., 2018);
- in the polar regions, accelerating permafrost thaw is promoting rapid erosion of ice-rich sediments (Lantuit et al., 2011). Melting of ice and associated thaw subsidence may induce instability of various infrastructure components. Arctic SLR and sea surface warming have the potential to substantially contribute to this thawing (Lamoureux et al., 2015). Moreover, the decrease in seasonal sea ice extent in the Arctic, together with a

lengthening open water season, provide less protection from storm impacts, particularly later in the year when storms are prevalent (Forbes, 2011).

Lastly, it should be remembered that local subsidence can be a particularly aggravating factor, especially on deltas (Syvitski, 2008).

6 Conclusions

The review of knowledge on the evolution of marine levels in the context of climate change has made it possible to identify the predominant factors in the evolution of the height and frequency of extreme marine levels. This is mainly the tidal and the surge generated by the atmospheric depression, the wind and the waves. However, in order to correctly understand the evolution of coastal hazards at the regional level over the long term, it is necessary to complete this analytical approach by considering the morphology of the coast, the tidal regime and meteo-oceanic event types, which are particularly important for wave characteristics and the amount of energy transferred to the coast.

The application of these principles to a sample of coastlines of various geographical configurations and subject to various tidal regimes and meteo-oceanic event types reveals significant differences in hazard changes. There appears to be a greater increase in territories with low tidal range affected by cyclones (e.g. the West Indies, Réunion Island, French Polynesia) and a smaller increase in areas not subject to storms, even if in microtidal regime (e.g., Guyana). In metropolitan France, where all coasts are subject to storms, the Mediterranean by its low tidal range will experience a greater increase in the hazard in comparison with the coasts of the Atlantic Ocean, the English Channel and the North Sea. The situation of the small tropical islands is of particular concern because, exposed to cyclones, they can undergo energetic sea states, without, however, benefiting from the high variability of ESL that is conferred by the very large storm surges on the continental maritime façades, even if they are microtidal.

The results exposed in this paper can be considered as robust due to the fact that the hazard evolution is mainly determined by the factors on which the uncertainty in the projections is lowest: the gographical configuration of the coast, the tidal conditions and general meteorological conditions. However, locally, knowledge of the evolution of the hazard requires considering other biophysical parameters, in particular geomorphological evolutions and the evolution of natural formations (including coastal wetlands), under the influence of climatic and non-climatic factors.

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Open Research

Code availability.

The Delft3D-FM code is currently being made available in http://oss.deltares.nl. The WW3 model description is available in : https://polar.ncep.noaa.gov/waves/wavewatch/. The code applied for the non-stationary extreme value statistics (Mentaschi et al., 2016) is available in: https://github.com/menta78/tsEva.

Data availability.

The global ESL data that support the findings of this study are available in the LISCoAsT repository of the JRC data collection (http://data.jrc.ec.europa.eu/collection/LISCOAST) though this link: http://data.jrc.ec.europa.eu/dataset/jrc-liscoast-10012, with the identifiers: https://doi.org/10.2905/jrc-liscoast-10012; PID: http://data.europa.eu/89h/jrc-liscoast-10012

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Figure 1.

Metropolitan France
Saint Pierre and Miquelon
Saint Martin
Saint Barthélemy
Guadeloupe
Martinique
French Guiana
Mayotte
La Réunion
French Polynesia

Figure 2.

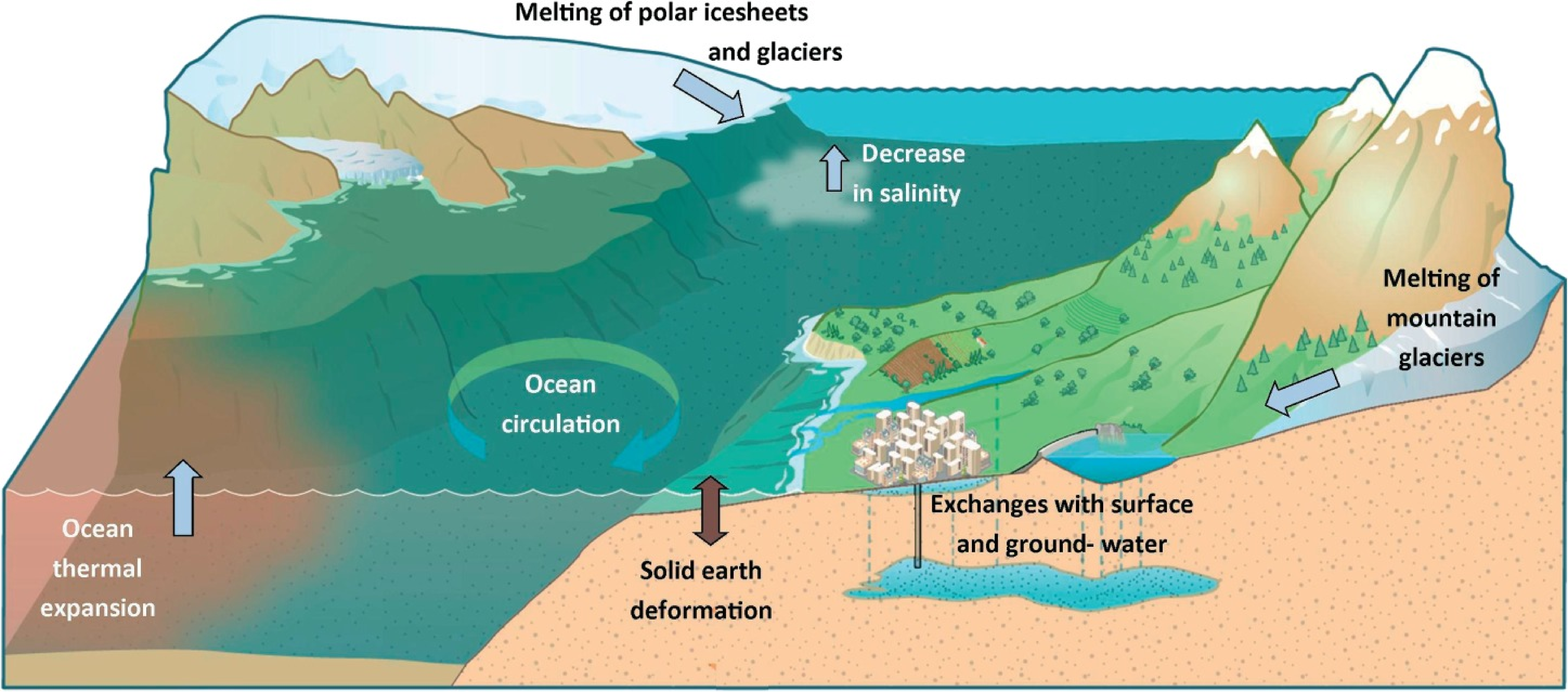
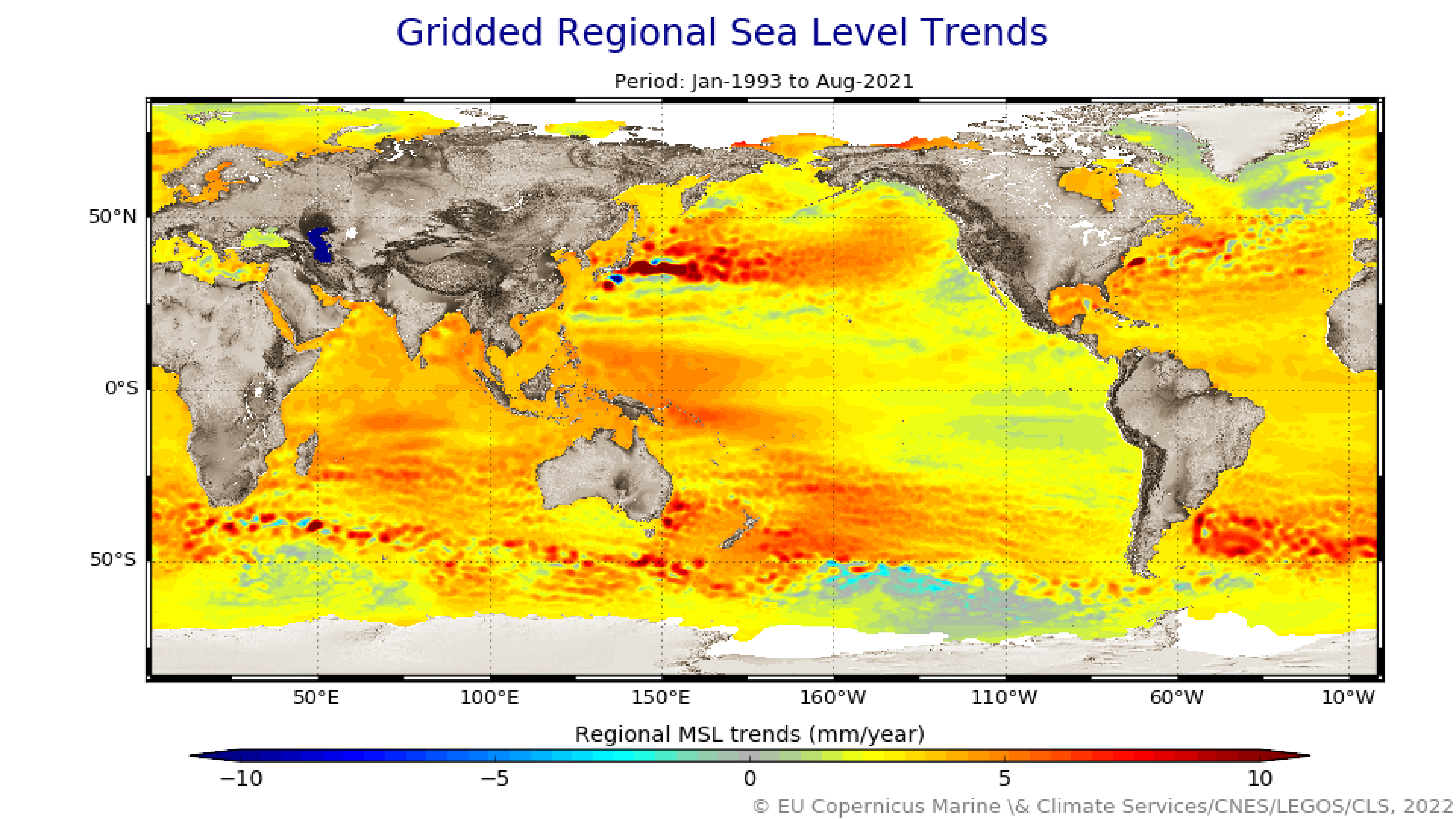

Melting of polar icesheets
and glaciers
Decrease
in salinity
Melting of
mountain
glaciers
Ocean
circulation
Ocean
thermal
expansion
Solid earth
deformation
Exchanges with surface
and ground- water

Figure 3.



Gridded Regional Sea Level Trends
Period: Jan-1993 to Aug-2021
50°N
0°S
50°S
50°E
100°E
150°E
160°W
110°W
60°W
10°W
Regional MSL trends (mm/year)
−10
−5
0
5
10
© EU Copernicus Marine \& Climate Services/CNES/LEGOS/CLS, 2022

Figure 4.

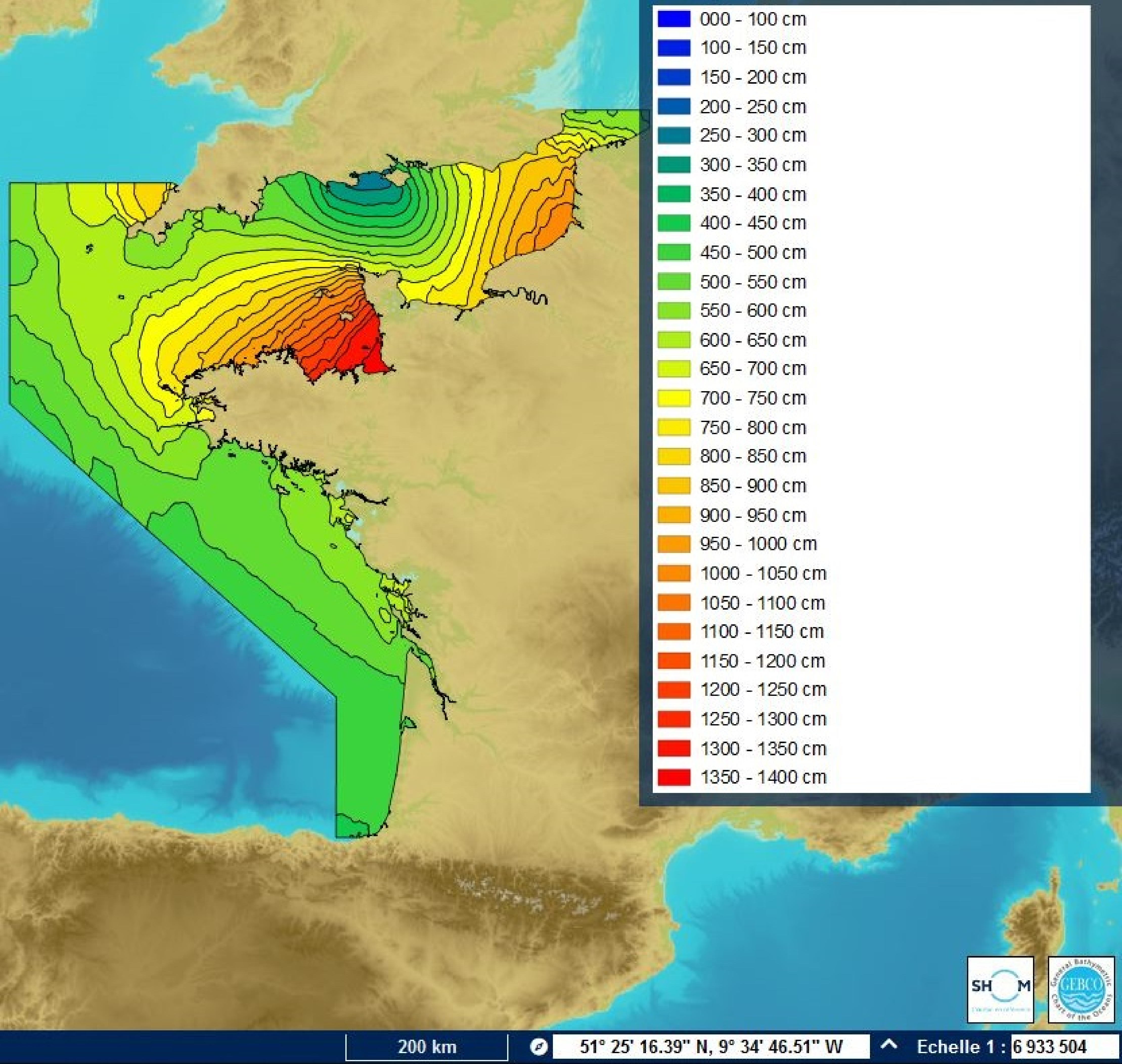
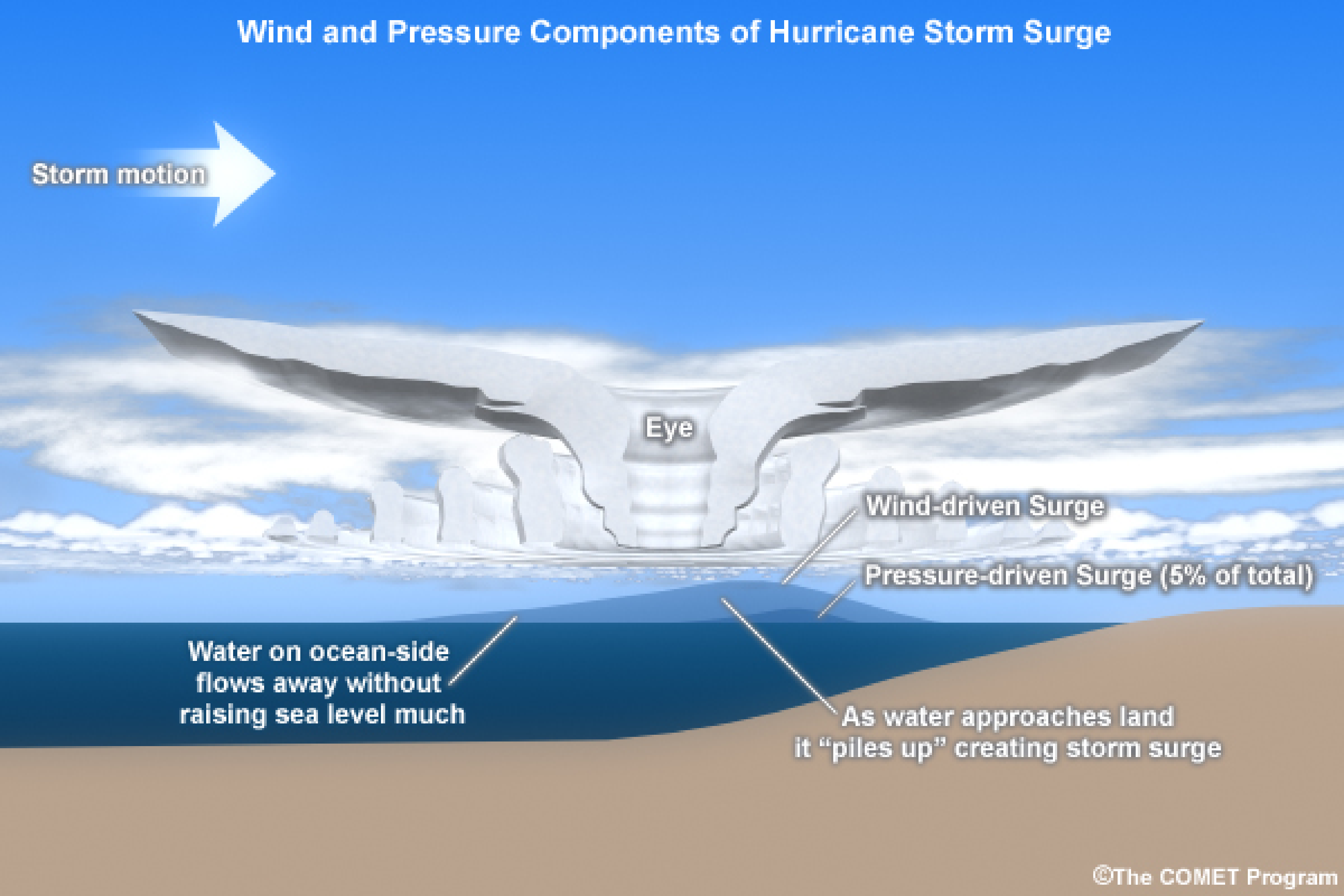

000 - 100 cm
100 - 150 cm
150 - 200 cm
200 - 250 cm
250 - 300 cm
300 - 350 cm
350 - 400 cm
400 - 450 cm
450 - 500 cm
500 - 550 cm
550 - 600 cm
600 - 650 cm
650 - 700 cm
700 - 750 cm
750 - 800 cm
800 - 850 cm
850 - 900 cm
900 - 950 cm
950 - 1000 cm
1000 - 1050 cm
1050 - 1100 cm
1100 - 1150 cm
1150 - 1200 cm
1200 - 1250 cm
1250 - 1300 cm
1300 - 1350 cm
1350 - 1400 cm
200 km
51° 25' 16.39'' N, 9° 34' 46.51'' W
Echelle 1 : 6 933 504

Figure 5.


Wind and Pressure Components of Hurricane Storm Surge
Storm motion
Eye
Wind-driven Surge
Pressure-driven Surge (5% of total)
Water on ocean-side
flows away without
raising sea level much
As water approaches land
it "piles up" creating storm surge
©The COMET Program

Climate scenario	2050 Mean	2050 17-83% range	2100 Mean	2100 17-83% range	2300 Mean	2300 17-83% range
RCP 8.5	+ 32 cm	23 cm to 40 cm	+ 84 cm	61 cm to 110 cm	+385 cm	230 cm to 540 cm

	2050	2100
Calais	0,19	0,86
Le Havre	0,19	0,87
Saint-Malo	0,19	0,87
Brest	0,19	0,83
La Rochelle	0,16	0,76
Saint-Jean-de-Luz	0,17	0,79
Port Vendres	0,16	0,76
Sète	0,16	0,76
Marseille	0,17	0,78
Saint-Pierre (Saint-Pierre-et-Miquelon)	0,19	0,83
Pointe-à-Pitre (Guadeloupe)	0,20	0,90
Cayenne (Guyane)	0,20	0,90
Pointe des Galets (La Réunion)	0,19	0,92
Papeete (Polynésie française)	0,20	0,91

Tide gauge	100-year return period surge (m)
Dunkerque	1,4
Calais	1,1
Boulogne-sur-Mer	1,2
Dieppe	1,4
Le Havre	1,4
Cherbourg	0,9
Saint-Malo	1,1
Roscoff	0,8
Le Conquet	1,0
Brest	1,0
Concarneau	1,0
Port Tudy	1,0
Crouesty	1,1
Saint-Nazaire	1,3
Saint-Gildas	1,1
Sables d'Olonne	1,0
La Rochelle	1,2
Port-Bloc	1,2
Arcachon	1,3
Bayonne	0,9
Saint-Jean-de-Luz	0,6
Port-Vendres	0,9
Sète	1,1
Marseille	1,3
Toulon	0,8
Nice	0,8
Monaco	0,8
Ajaccio	0,8

	RCP8.5 - 2050		RCP8.5 - 2100	
	ΔESL (m)	%Δ ESL	ΔESL (m)	%Δ ESL
Calais	0.21	4,3	0.94	19,2
Le Havre	0.23	4,4	1.00	19,6
Saint-Malo	0.21	3,8	0.89	16,0
Brest	0.22	5,0	0.96	21,5
La Rochelle	0.16	4,3	0.77	19,9
Saint-Jean-de-Luz	0.16	5,3	0.74	24,1
Port Vendres	0.16	13,3	0.75	60,7
Sète	0.18	12,5	0.76	52,5
Marseille	0.18	14,6	0.78	63,2

	2050	2100
Calais	22,81	0,75
Le Havre	26,56	0,87
Saint-Malo	27,69	0,81
Brest	20,61	0,73
La Rochelle	36,16	2,59
Saint-Jean-de-Luz	33,87	0,63
Port Vendres	27,89	0,10
Sète	30,02	0,56
Marseille	26,88	0,10

	RCP8.5 - 2050		RCP8.5 - 2100	
	ΔESL (m)	%Δ ESL	ΔESL (m)	%Δ ESL
Saint-Pierre (Saint-Pierre-et-Miquelon)	0,24	8,4	0,92	31,8
Pointe-à-Pitre (Guadeloupe)	0,22	14,1	0,91	58,1
Cayenne (Guyane)	0,18	10,6	0,85	49,2
Pointe des Galets (La Réunion)	0,16	9,3	0,88	52,5
Papeete (Polynésie française)	0,23	17,8	0,95	74,7

	2050	2100
Saint-Pierre (Saint-Pierre-et-Miquelon)	17,69	0,31
Pointe-à-Pitre (Guadeloupe)	35,14	0,10
Cayenne (Guyane)	7,54	0,10
Pointe des Galets (La Réunion)	57,53	0,10
Papeete (Polynésie française)	15,86	0,10

	Tidal range	Reference meteocean event	100-year surge (m)	ΔRSL (m) under RCP 8.5	ΔESL (m) under RCP 8.5	%ΔESL under RCP 8.5	Return period of the present day 100-year ESL under RCP 8.5 (year)
English Channel – North Sea	Macrotidal (7 to 14 m)	Storm	0,8 to 1,4	In 2050 : 0,19 In 2100 : 0,83 to 0,87	In 2050 : 0.21 to 0.23 In 2100 : 0.89 to 1.00	In 2050 : 3.8 to 5 In 2100 : 16 to 21.5	In 2050 : 20 to 28 In 2100 : 0.73 to 0.87
Bay of Biscay	Macrotidal (5 to 7 m)	Storm	0,6 to 1,3	In 2050 : 0,16 to 0,17 In 2100 : 0,76 to 0,79	In 2050 : 0,16 In 2100 : 0.74 to 0.77	In 2050 : 4.3 à 5.3 In 2100 : 19.9 to 24.1	In 2050 : 33 to 36 In 2100 : 0.63 to 2.6
West Mediterranean	Microtidal (< 2 m)	Storm	0,8 to 1,3	In 2050 : 0,16 to 0,17 In 2100 : 0,76 to 0,78	In 2050 : 0,16 to 0.18 In 2100 : 0.75 to 0.78	En In 2050 : 12.5 to 14.6 In 2100 : 52.5 to 63.2	En In 2050 : 26 to 30 In 2100 : 0.10 to 0.56

	Tidal range	Reference meteocean event	100-year surge (m)	ΔRSL (m) under RCP 8.5	ΔESL (m) under RCP 8.5	%ΔESL under RCP 8.5	Return period of the present day 100-year ESL under RCP 8.5 (year)
Saint-Pierre (Saint-Pierre-et-Miquelon)	Microtidal (< 2 m)	Storm	1 to 2	In 2050 : 0,19 In 2100 : 0.83	In 2050 : 0.24 In 2100 : 0.92	In 2050 : 8.4 In 2100 : 31.8	In 2050 : 18 In 2100 : 0.3
Pointe-à-Pitre (Guadeloupe)	Microtidal (< 2 m)	Storm and cyclone	1 to 3	In 2050 : 0,20 In 2100 : 0,90	In 2050 : 0.22 In 2100 : 0.91	In 2050 : 14.1 In 2100 : 58.1	In 2050 : 35 In 2100 : 0.1
Cayenne (French Guyana)	Mesotidal (2 to 4 m)	Trade winds (without storm)	0.4	In 2050 : 0,20 In 2100 : 0,90	In 2050 : 0.18 In 2100 : 0.85	In 2050 : 10.6 In 2100 : 49.2	In 2050 : 7,5 In 2100 : 0.1
Pointe des Galets (La Réunion)	Microtidal (< 2 m)	Storm and cyclone	1 to 3	In 2050 : 0,19 In 2100 : 0,92	In 2050 : 0.16 In 2100 : 0.88	In 2050 : 9.3 In 2100 : 52.5	In 2050 : 58 In 2100 : 0.1
Papeete (French Polynesia)	Microtidal (< 2 m)	Storm and cyclone	1 to 3	In 2050 : 0,20 In 2100 : 0,91	In 2050 : 0.23 In 2100 : 0.95	In 2050 : 17.8 In 2100 : 74.7	In 2050 : 16 In 2100 : 0.1