STATE OF THE ART OF CLIMATE CHANGE IMPACTS ON OFFSHORE WIND

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Executive Summary

This report presents a comprehensive synthesis of the impacts of climate change on wind, sea level, and wave conditions, with a focus on both average and extreme values. The analysis distinguishes between historical trends and future climate projections, drawing primarily from European studies, with particular emphasis on France when relevant data are available.

The literature reviewed spans multiple generations of climate models and IPCC scenarios, from CMIP3 to CMIP6. As a result, discrepancies may exist between studies, and greater confidence should be placed in the most recent projections. The findings highlight that consensus is not always achieved, especially regarding extreme wind and wave conditions.

While some patterns appear well established—such as rising sea levels and decreasing mean wind and waves—results remain sensitive to temporal variability, geographic location, and the type of data used (observations vs. models). This is particularly true for future projections, which depend heavily on the selected scenario.

Given these uncertainties, it is recommended to refine climate impact assessments at the regional scale, using long-term observational datasets, high-resolution reanalyses, and state-of-the-art climate models. This approach will improve the reliability of projections and support better-informed decisions for offshore wind farm design and coastal planning.

1. Introduction

Climate projections of metocean parameters are of major importance for the offshore wind industry. Among other factors, maintenance conditions depend on metocean (weather and ocean) conditions. Likewise, the energy yield of wind farms is directly linked to wind resources. The design of the structures is determined by load cases associated with both normal and extreme wind speeds and wave heights. Sea level has a direct influence on wind turbine foundations and interface heights. Climate change, by affecting metocean parameters, could therefore alter the business plans for offshore wind farms (Deser *et al.*, 2012).

The impacts of climate change on wind, waves, and sea level have been investigated for several decades now (Suursaar & Kullas, 2006), and both historical data and climate projections need to be considered. A real lack of long-term observational datasets exists and only a few studies deal with in situ data only (Chang *et al.*, 2015); most studies use a combination of numerical reanalysis, climate models and in situ data (Maya *et al.*, 2023). Reanalysis enables exploring past data by reproducing, as accurately as possible, past observations over several decades. A reanalysis is a method that assimilates data from models covering multiple decades. To minimize uncertainties, so-called ensemble reanalysis, including data assimilation, should be favoured (Thorne & Vose, 2010). The main wind reanalyses that exist, from the oldest - 1871 - to the most recent – present date - are as follows: for the European reanalyses, ERA Interim, ERA 5 (latest global reanalysis – Hersbach *et al.*, 2020), and CERRA (latest regional reanalysis - Pelosi, 2023) from the ECMWF (European Centre for Medium-range Weather Forecasts), and for the American reanalyses, NCEP, MERRA2 (Gelaro *et al.*, 2017) and CFSR from the National Oceanic and Atmospheric Administration (NOAA). However, using reanalyses to determine trends can also be criticized as they are only interpretations of the observed data and differ from it sometimes (Krueger *et al.*, 2013).

The above-mentioned reanalyses are, by construction, dedicated solely to past periods. To anticipate future metocean conditions, climate models can simulate both past (historical) and future (projected) periods. Most climate projections come from global General Circulation Models known as GCMs or Regional Circulation Models, RCMs, at spatial scale inferior to 50 km (Eyring *et al.*, 2019), which can resolve large-scale atmospheric circulation of spatial extent around 100-200 km (Vrac *et al.*, 2012). GCMs/RCMs resolve the equations of fluid dynamics, physics, and chemistry for the atmosphere or the ocean (Flato *et al.*, 2013) and are valuable models for defining future climate projections (IPCC, 2001). The strengths and weaknesses of these climate models are expressed by Hausfather & Peters in 2020.

GCMs are constrained by scenarios based on an energy input represented by radiative flux forcings or by the evolution of greenhouse gases. The first scenarios covering the period 1985-2100 were studied by the Intergovernmental Panel on Climate Change (IPCC), starting with SA90 (IPCC, 1990), then IS92 (Leggett *et al.*, 1993; Pepper *et al.*, 1998) and finally the Special Report on Emission Scenarios - SRES (Nakicenovic *et al.*, 2000 - Fig. 1). Subsequently, scientific communities other than the IPCC developed scenarios for 2005-2100 (Moss *et al.*, 2010). In these new scenarios, after a community consensus on the atmospheric concentrations of greenhouse gases planned from now until the end of the century, climate projections are developed: these are the Representative Concentration Pathways - RCP type scenarios (van Vuuren & Edmonds, 2011 - Fig. 1). More recently, socio-economic conditions are taken into consideration in the scenarios; we then speak of Shared Socioeconomic Pathways - SSP type scenarios (O'Neill *et al.*, 2016 – Fig. 1). For example, the comparison between SRES and RCP indicates a similarity (Jacob *et al.*, 2014) between the SRES A1B scenario (rapid increase in CO2 until 2050 then decrease - IPCC, 2001) and RCP6 (increase from 2.8 to 4.2° - Rogelj *et al.*, 2012). An equivalence exists also between RCP and SSP scenarios, the most recent SSP1-2.6 and SSP5-8.5 scenarios are similar to RCP2.6 and RCP8.5, respectively (Carreno-Madinabeitia *et al.*, 2024). Main studies use the SSP1-2.6 scenario related closely to the Paris agreement international treaty with global warming below 1.5°C and a radiative forcing of 2.6 W m-2, and the scenario at the other extreme SSP5-8.5, corresponding to a radiative forcing of 8.5 W m-2, which is no longer seen as a possible trajectory (too high) for our planet but is still considered as a reference (Hausfather & Peters, 2020).

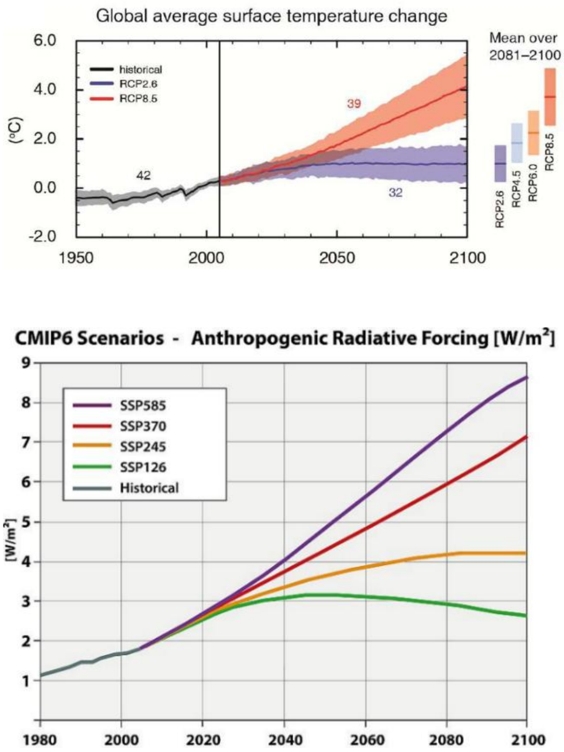

Fig. 1. Presentation of the main used scenarios with RCP scenarios on the top (from Laugel et al., 2014) and SSP scenarios at the bottom (from O'Neill et al., 2016)

The evolution of all scenarios mentioned over the last three decades can be found in Fig. 2. Future scenarios should be even more integrative, considering future climate change (RCP), socio-economic pathways (SSP) and associated policy responses (SPA - Shared Climate Policy) (Kriegler *et al.*, 2014). For the time being, global emissions have generally followed a moderately high trajectory, illustrated by "intermediate" scenarios (between SSP1 and 2) consistent with historical trends (Pedersen *et al.*, 2021). However, the prospect of creating scenarios adapted to regional or even local scales remains to be seen (Kriegler *et al.*, 2014).

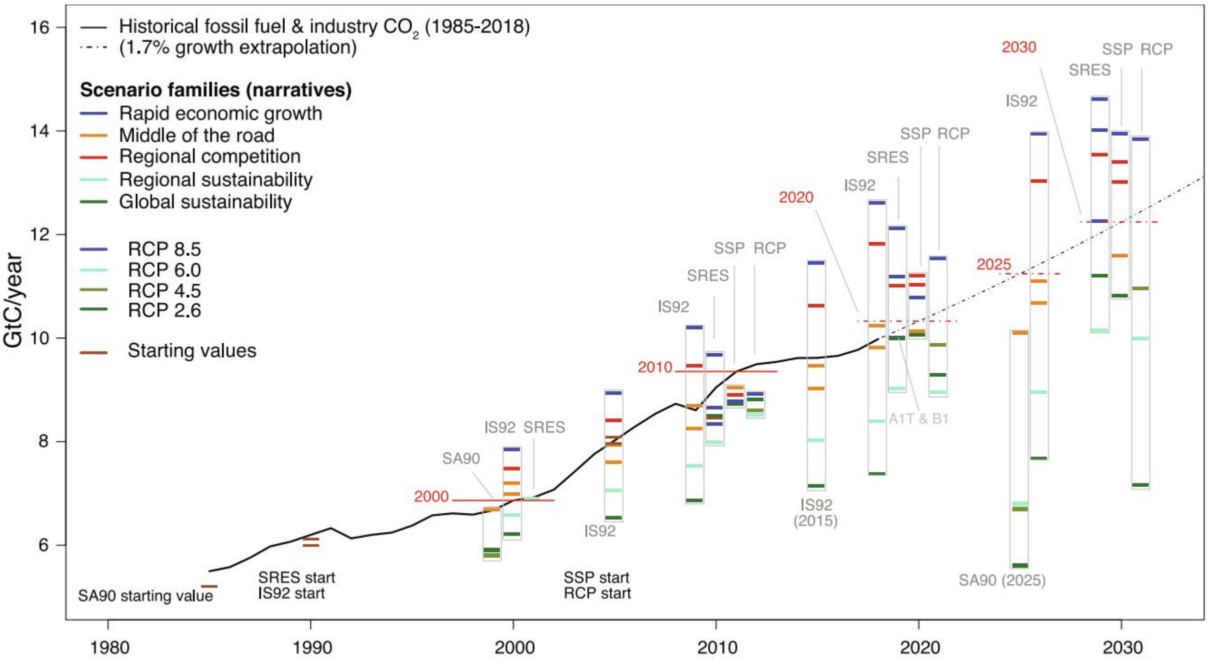

Fig. 2. Evolution over the past three decades of observed C02 emissions trends (black line) compared with main emission scenarios. The black dotted line shows extrapolation beyond 2018 of the 1.7% growth rates for 1990-2018 historical emissions (from Pedersen et al., 2021)

The best-known simulations encompassing these different climate scenarios are the Coupled Model Intercomparison Project (CMIP); the latest phase is called CMIP6, but CMIP5 also remains interesting to analyse on a global level (Costoya *et al.*, 2020). CMIP6 includes finer spatial resolution, improved parameterizations of some processes, and additional processes and components in the Earth system such as biogeochemical cycles and ice sheets (Eyring *et al.*, 2019) compared to CMIP5. At the regional level, the Coordinated Regional Climate Downscaling Experiment (CORDEX), based on CMIP5, provides regional projections around the world, with several scenarios that can be found on a European scale in the form of EURO-CORDEX (Giorgi, 2006). The number of models used in CMIP5 or CMIP6 can vary, and for example, only 3 models have been selected by C3S from Copernicus for the C3S-ENTSOE experiment 1 (Buontempo *et al.*, 2022), with a 100 km spatial resolution and an hourly output.

In these GCMs/RCMs, biases can exist due to model error and lack of assimilated data in the frequency and intensity of climate variables simulated by models (Maraun *et al.*, 2017). To reduce biases, considering several models is the most common option (Pedersen *et al.*, 2021).

As we can see, the choice of the used climate model and the considered scenarios is key to estimate the impacts of climate change and will generate associated uncertainties of greater or lesser importance. Uncertainties are generally linked to limited computing resources, model parameterization, simplified assumptions during model construction, insufficient spatial or temporal resolution to resolve climatic processes, lack of measurements, and, finally, future climate projections (models and scenarios). Natural climate variability can induce uncertainties in climate projections (Tebaldi & Knutti, 2007; Hawkins & Sutton, 2009; Wu *et al.*, 2022) and may even exceed anthropogenic variability in some parts of the globe (Deser *et al.*, 2012; Dobrynin *et al.*, 2015). Anticipating the impact of future climate change requires a holistic environmental approach to what drives climate and its variability, as well as the associated uncertainties (Dessai *et al.*, 2009). Uncertainties can also be kinked to downscaling methods, where fitting models and their parameters can increase the uncertainties of the results (Kim *et al.*, 2019; Wang *et al.*, 2020). Kim *et al.* in 2019 describes each source as stages which add up to a total uncertainty. Multiple methods exist to decompose it. A standard method (Kim *et al.*, 2019) quantifies the uncertainty at each stage, based on the average of all projection values. Lee *et al.* in 2016 first applies the uncertainty on all projection values, then takes the average, for each stage. Kim *et al.* in 2019, explains there are multiple approaches using the ANOVA method (Yip *et al.*, 2011; Bosshard *et al.*, 2013) which requires a gaussian distribution, and which is ‘vulnerable to outliers. Then, Kim *et al.* in 2019, depicts the cumulative uncertainty approach, based on the multivariate ANOVA method, to attribute the uncertainty to the different sources and consider their interactions. A different method is PAWN, of Dawkins *et al.* in 2023, which measures the differences in the empirical Cumulative Distribution Function (CDF) between sources, using the Kolmogorov–Smirnov test. A last approach from Wu *et al.* in 2022 suggests using linear regression model results, with the variance of the fitted values and their residuals. However, it assumes there is no interaction between the defined sources.

This report aims to present the state of the art of the literature concerning wind, wave, and sea level trends in the context of climate change as applied to offshore wind turbines. Both historical and future trends are considered. the next section, section III, is dedicated to the methods that are commonly used for the analysis of climate projection: downscaling, scores and extreme events calculations. Section 4 and 5 provide the state of the art of the impacts of climate change on wind, and waves and sea level, respectively, focusing on the characterization of trends in mean and extreme values, which will be linked to physical processes. Section 6 looks at the impact of these wind, wave and sea level trends on the offshore wind resource and design of offshore wind farms.

2 Methods: downscaling, scores and extreme events

As mentioned in the introduction, the estimation of metocean parameters modifications linked to climate change is done through the study of GCMs. These climate models may show deviations from observations (Kotlarski *et al.*, 2005; Kay *et al.*, 2006; Graham *et al.*, 2007). These differences might come from different sources:

- The numerical models that inherently make assumptions and approximations, especially regarding the nonlinearities of the equations of climate
- The temporal and spatial resolution of the models, which:
  - o necessitate representing phenomena at the sub model grid resolution with approximation (called sub-grid parameterization).
  - o cannot consider local effects such as the sea/land interface, which directly concerns the offshore wind industry, the projects being positioned on the continental shelf close to the coasts.

To try to overcome these differences between GCMs (or RCMs) and reality, so-called downscaling methods are used. These methods allow to obtain locally finer climatology based either on local numerical modelling, or on numerical reanalyses (Pryor *et al.*, 2005). In the second case, the choice of the best reanalysis at the location of interest is generally made based on statistical comparison metrics, called scores. Downscaling methods and scores are discussed in the rest of this section.

2.1 Downscaling

The process of downscaling (Bricheno & Wolf, 2018) involves deriving regional information from global data, or local information from regional results. Studies using downscaling methods are quite rare due to a lack of high-frequency (<= day) and spatially well-distributed *in situ* data (Kjellström *et al.*, 2018; Moemken *et al.*, 2018), with most studies considering a single measurement mast for wind, for example (Vrac *et al.*, 2012; Amengual *et al.*, 2012). Studies with downscaling methods are even more rare for sea state data, where the variability of metocean conditions is high and trends remain difficult to identify (Lobeto *et al.*, 2021; Hochet *et al.*, 2023).

The two main types of downscaling methods are statistical methods and dynamical methods (Michelangeli *et al.*, 2009). Dynamical downscaling consists in running a numerical model with a higher resolution than GCM over an area of interest, as reducing the spatial and temporal resolution often yields better results (Herrmann *et al.*, 2011). This model uses a GCM (lower spatial resolution) as boundary conditions and physical principles to reproduce local climate. Some studies apply this method only with an RCM (Deque *et al.*, 2007), others with a Statistical Downscaling Model (SDM) (Raje & Mujumbar, 2011) or with both (Segui *et al.*, 2010). The drawback of this method is that it is very expensive in terms of computation time, so studies are often limited in time and space. Statistical downscaling methods are more widely used and are described in the following paragraphs.

2.1.1 Introduction to statistical methods

Statistical methods have been regularly applied in studies due to their computational efficiency compared to dynamical downscaling methods. The main disadvantage of this method is that it relies on the assumption that predictor relationships remain unaltered under climate change (Wilby *et al.*, 2004).

Statistical methods involve deriving statistical relationships between observed variables on a small scale (often a measuring station) and variables on a larger scale (GCM), using regression models (for example weather typing, which is an efficient approach to study the relationship between large scale circulation and regional climate (Boe & Terray, 2008), linear (Busuioc *et al.*, 2008), or non-linear (Salameh *et al.*, 2009) or stochastic weather generators (Carreau & Vrac, 2011). When observations are available, the method is called Perfect Prognosis (PP), while when only the outputs from numerical models are available, the statistical approach is referred to as Model Output Statistics (MOS). PP is calibrated using observations from the local scale, and projections are produced using large-scale predictors simulated by GCM. The MOS approach is based on the estimation of the statistical relation between the GCM and the observed local variables, after correcting the error.

A method of downscaling using weather types was developed by Menéndez *et al.* in 2011, because waves, winds and sea levels are subject to global forcings called weather regimes. To achieve this classification into weather patterns, a first possibility is the k-means method - calculation of a point's distance from the average of all points in clusters. Other possibilities for classification are a Principal Component Analysis (PCA) – transforms linked variables into fewer decorrelated variables or a maximum dissimilarity algorithm – select points that are maximally dissimilar to each other, can be used.

2.1.2 Bias correction regarding statistical methods

Among the statistical downscaling methods examined above, two families of approaches related to the process of bias correction exist: regression and distribution approaches. Bias correction refers to the adjustment of raw model outputs to remove biases in summary statistics at a given location, such as the mean and variance (and potentially other statistics, depending on the method) compared to observation-based data (Maraun *et al.*, 2017).

Regression approaches are average based with linear scaling (Lenderink *et al.*, 2007), local intensity scaling (Schmidli *et al.*, 2006), variance scaling (Leander & Buishand, 2007) and power transformation (Chen *et al.*, 2013). Distributional approaches are more frequently used, as they operate on the whole distribution of a given variable. The 2 most well-known methods are Quantile Mapping (Deque *et al.*, 2007) and Cumulative Distribution Function transform - CDF-t (Michelangeli *et al.*, 2009), both described below.

Other parametric methods exist such as ISIMIP3 (Lange, 2019) or the Delta Change (DC) approach (Gleick, 1986; Hay *et al.*, 2000) which implement observed data series with projected future climate change like in the study of Middelkoop *et al.* in

2001. The disadvantage of DC is the inability to deal with covariance and variability of climate variables. Indeed, Distribution Based Scaling (DBS) is more sensitive to projections and preserves better the annual variability from GCM or RCM than DC. DBS fits a statistical distribution to the cumulative distribution function and uses those fitted distributions to conduct quantile-mapping. More complex methods exist considering the complete distribution of a variable (Piani *et al.*, 2010), multi-variate features, temporal resolution and spatial mismatch with observations (Nguyen *et al.*, 2016). The detrended quantile mapping, an Empirical Cumulative Distribution (EQM) with trends added to bias adjusted data (Cannon *et al.*, 2015) or the quantile delta mapping which is an EQM but instead of initiating the transformation by the value it originates from the quantile value (Cannon *et al.*, 2015). Finally, the new MIdAS method (Berg *et al.*, 2022) is a semi-parametric quantile-mapping method. In contrast to the fully parametric methods, it does not pre-assume a certain statistical distribution for the data but uses an empirical spline-fit to describe the distribution of the data. The MIdAS method of bias correction is rather new and is among others important for its use in the CMIP6 project (Berg *et al.*, 2022).

Quantile mapping

The method of bias adjustment or bias correction involves defining a mapping of the range of model values to an observed range of values. A well-known method is quantile mapping (Maraun *et al.*, 2017; Maurer & Pierce, 2014), the quantile distribution of climate model data is adjusted to become like the quantile distribution of the reference data over the common period of both datasets. So, instead of adjusting the mean of climate model data, the full distribution is therefore corrected and results especially for extreme events analysis are better. Practically, all values within one quantile are adjusted to the observation of similar quantile values. Two bias correction methods are applied to quantile mapping in the Costoya *et al.* study in 2020: bias correction (Amengual *et al.*, 2012) and frequency dependent bias correction which reduces errors in the variance of the model simulation as a function of frequency (Pierce *et al.*, 2015). The adjustment calibrated over the training period can then be applied to future projection of the climate model, to get bias adjusted projections.

CDF-t

Traditional quantile matching methods assume that the distributions of models and observations will retain the same shape in the future. However, in the context of global warming, this stationarity assumption is no longer valid. The CDF-t for Cumulative Distribution Function – transform produces an estimation of the future reference distribution which is then applied for the adjustment (Michelangeli *et al.*, 2009). In this way it reduces the dependency of the stationarity assumption of most bias adjustment methods like the quantile mapping method. It is also used in the downscaling process (Kpogo *et al.*, 2016). Indeed, CDF-t considers that the large-scale bias between the GCM and the observations will be the same in the future period than from the historical period, which is called the transform function. On the other hand, quantile mapping projects large-scale simulated values onto historical data only to agree between quantiles. However, the CDF-t method involves constant correction (Deque *et al.*, 2007; Michelangeli *et al.*, 2009). CDF-t was originally developed for wind but can be applied to other parameters (Michelangeli *et al.*, 2009). Finally, results are best when the whole year is considered and not just one season (Michelangeli *et al.*, 2009). Validation involves calibration of the observed data, followed by downscaling.

The CDF-t can be translated as:

$$F_{o,f}(x) = F_{o,h}(F_{m\ h}{}^{-1}(F_{m,f}(x)))$$

where *Fo,h* is the CDF of observations in the historical period, *Fo,f* is the CDF of observations in the future period, *Fm,h* the CDF of one of the models in the historical period and *Fm,f* the CDF of the same model in the future period.

In addition to CDF-t and quantile mapping, two other methods exist: the unbiasing method (Deque *et al.*, 2007) where the difference between the observed and simulated variable is added to a common period of the projected value, and the delta method (Lehner *et al.*, 2006), where the same difference is added to an observed reference.

Bias adjustment methods can bring some problems such as introducing bias in one temporal resolution while adjusting another to correct. Some authors introduce the concept of cascade bias adjustment as proposed by Haerter *et al.* in 2011. Also, the CC signal can alter the modulation of bias adjustment as mentioned by Berg *et al.* in 2022.

Errors are frequent using multiple datasets with different spatial and temporal resolutions. Bias-correction of climate model simulations is important for impact studies, where absolute values and thresholds are considered. To not affect the magnitude of long-term changes using a bias-correction procedure, Bartók *et al.* in 2019 develop and assess a consistent ensemble (11 EURO-CORDEX) of high resolution (12 km in space and 3 hourly) climate projections for the European energy sector spanning the period 1971-2100.

2.2 Scores

As explained at the beginning of this section, statistical downscaling is usually performed by taking as reference a numerical reanalysis, also called hindcast. In order to choose the best reanalysis to use, comparisons are performed and are quantified using scores. Scores can also be used in dynamic downscaling to calibrate the numerical model used against measurements.

Statistical comparison metrics include usually explained variance, variance ratio (Vrac *et al.*, 2012), scatter index, symmetric slope (which corresponds to the sum of simulated data squared divided by the sum of observations squared), RMSE (Root Mean Square Error) or NMRSE (Normalized RMSE), overlapping percentage (Soares *et al.*, 2017), median difference, percentage of error (Santos *et al.*, 2018), Weibull peak difference (Costoya *et al.*, 2020) and Yule-Kendall skewness measure (Riahi *et al.*, 2017). Also, the Theil Sen regression (Theil, 1992) seems more favourable than the linear regression as exposed by Sy *et al.* in 2023. The study by Jiang *et al.* in 2023 compares, for example, historical data (1950-2014) with simulated waves (2015-2100) using CMIP6 and the SSP1-2.5, 2-4.5 and 5-8.5 scenarios, calculating mean bias, absolute error, Pearson correlation and RMSE. Finally, a recent study considers the skill score, squared correlation, conditional bias, and mean error to compare wave spectra (Lobeto *et al.*, 2021). In a new study on waves, the difference between simulated and observed Significant Wave Height - Hs (mean wave height of the highest third of waves) is quantified by the mean absolute error skill score (Maya *et al.*, 2023), the index of agreement (Jeong *et al.*, 2023) and the Kling-Gupta efficiency (Gupta *et al.*, 2009). Commonly used, the scatter index, the normalized mean bias and the normalized mean differences are calculated in Alday *et al.* study in 2023. Daily scorings are regularly used in recent studies such as the one of Srivastava *et al.* in 2022 but are still discussed of their representativity nowadays. The comparison metrics must be accurate, particularly regarding extremes, which may undergo changes greater than those seen in mean conditions (Schaeffer *et al.*, 2005; Trigo *et al.*, 2005).

Another statistical score widely used in the climate change community is the significance test, which is used in particular to determine whether a trend is significant or not. Various statistical tests for statistical significance of trends exist, such as the t-test (Tebaldi *et al.*, 2011; Aarnes *et al.*, 2017), which can be used to ascertain if the mean of a normally distributed variable is significantly different from a null hypothesis value, here zero; the Mann-Kendall test (Mann, 1945; Kendall, 1955), which can be used in temporal series data to identify if a trend exists. It is a non-parametric test, which means it can be used on any distribution type. Another non-parametric statistical test is the Kolmogorov-Smirnov test (Darling, 1957), which can be used to verify if a sample follows a particular distribution. The Mann-Withney test (Jacob *et al.*, 2014) can also be used to ascertain if two independent samples of ordinal values share a similar distribution. And finally, the Cramer von Mises test (Michelangeli *et al.*, 2009; Vrac *et al.*, 2012), which can be used to verify if the cumulative density function of a sample is similar to a given distribution.

Perkins *et al.* in 2007 have suggested the possibility of combining multiple statistical tests as cited above into a single metric, the skill score, which corresponds to the common area between two datasets based on the minimum cumulative value of the two distributions of each binned value.

3 Impacts of climate change on wind

Surface winds are one of the core elements of atmospheric circulation and climate change. The dynamic changes of surface wind speed (SWS) not only have important impacts on regional evapotranspiration (McVicar *et al.*, 2012), the hydrological cycle (Liu *et al.*, 2014), air pollution (Zhang *et al.*, 2020) and dust disasters (Wang *et al.*, 2017) but also lead to drastic changes in wind energy resources (Pryor *et al.*, 2020; Zhang *et al.*, 2019). SWS can vary at different time scales, ranging from small-scale turbulence to seasonal oscillations and up to long-term climate variability.

The changes in SWS will affect the wind power density (WPD) and then significantly affect the development and utilization of regional wind energy resources. As the WPD varies with the cube of the wind speed, small changes in the wind speed can lead to significant changes in the wind resource. The WPD at hub height is computed from the wind speed (WS) following equation (1), where ρ is the air density (1.225 kg/m3 at 288.15 K and 1013 hPa) and WS is the wind speed at the selected hub height.

$$WPD = 0.5\rho(WS)^3 \quad (1)$$

SWS data is usually available for 10 m height only in climate projection models, so it needs to be extrapolated to hub height. This is most often done using the power law described by equation (2):

$$WS_{tb} = WS\left(\frac{Z_{tb}}{Z_s}\right)^{\alpha} \quad (2)$$

where WStb and WS represent wind speed at height Ztb and Zs (10 m), and α is a non-dimensional parameter usually assumed to be constant 1/7, which is generally applicable to low surface roughness and has been used in some studies involving wind power assessment (Islam *et al.*, 2011; Wang *et al.*, 2016, Liu *et al.*, 2019). However, recent work improved the estimation of α by considering the roughness/orography and gradients of the air column temperature over the surface at each grid-point as well as hourly and monthly variability. The Copernicus Climate Change Service for Energy (C3SEnergy) provides this 24 (hours) x 12 (months) gridded α matrices on a 0.25°x0.25°, which have been calculated from 10 years of ERA5 hourly data of 10 m and 100 m WS (not yet published).

With atmospheric flow patterns predicted to change due to increased GHG emissions, it is crucial to consider the impacts of climate change on the future development of wind energy. The first works addressing the evolution of wind under climate change in Europe are based on climate change scenarios A2 and B2 of cumulative GHG emissions (Räisänen *et al.*, 2004), developed by the IPCC in its Third Assessment Report (TAR). The first thorough assessments of wind speed and wind energy in Europe were presented for Northern Europe (Pryor *et al.*, 2005) and the Eastern Mediterranean (Bloom *et al.*, 2008), focusing on the long-term (2071–2100) evolution. Afterwards, ensembles of regional climate projections were calculated to investigate the impacts of climate change on the European wind energy resource (Hueging *et al.*, 2013) and the effects in wind power production (Tobin *et al.*, 2015). The evolution of the wind power density (Carvalho *et al.*, 2017) and the energy output of a benchmark turbine over Europe (Reyers *et al.*, 2016) under climate change are studied using an ensemble of Global climate models (GCM) available through the 5th phase of the Coupled Model Intercomparison Project (CMIP5), which uses the Representative Concentration Pathways (RCPs). The 6th phase of the Coupled Model Intercomparison Project (CMIP6) uses the Shared Socioeconomic Pathways (SSPs), as explained in the Introduction.

3.1 Historical part

To compute historical changes, climate models, observations or reanalysis data are usually applied. Specifically for the wind industry, the lack of long and homogeneous records of wind speed observations has favored the adoption of reanalysis data for assessing wind resources (Cannon *et al.*, 2015). For the case of climate models, by using a Multi-Model Ensemble (MME), individual uncertainties are reduced, therefore producing more reliable results than single-model approaches. Preconstruction wind resource assessment studies need to determine long-term mean wind speed (Tammelin *et al.*, 2013) and its probability distribution accurately at each turbine location to estimate wind power generation/wind energy production.

When we talk about wind energy production, we have the wind resource on one side and the wind turbine and its power curve on the other. To connect the two, the important parameters are the cut-in and cut-out wind speeds, that are considered to decide the classification criteria for categorizing the SWS in power generation. The cut-in wind speed refers to the minimum wind speed that results in the turbine to start rotating and generating electricity. The cut-out wind speed is the maximum wind speed to generate usable power. The cut-in and cut-out wind speeds refer to the wind speed at the hub height of the wind turbine. For modern turbines, the common range is of the order [3.5; 25] m/s. Outside of this interval, the turbines do not produce energy. However, we note that some of the most recent offshore turbines feature cutout wind speeds of 28m/s or even 30m/s and more. The potential wind power production (Wpot), according to the working regimes of a wind turbine, depends on the wind speed WS by the following relation (3):

$$W_{pot} = \begin{cases} 0 & if\ WS < WS_i\ or\ WS > WS_o \\ \frac{WS^3 - WS_i{}^3}{WS_R{}^3 - WS_i{}^3} & if\ WS_i \leq WS \leq WS_R \\ 1 & if\ WS \leq WS \leq WS_o \end{cases} \quad (3)$$

where WS_R is the rated speed, or speed at which the wind turbine produces its maximum or rated power, and WS_i and WS_o are the cut-in and cut-out speed, respectively.

Equation (1) can therefore be rewritten as:

$$WPD = 0.5\rho\, W_{pot}(WS)^3 \quad (4)$$

The cut-out speed is defined in order to avoid mechanical damage during extreme wind events, where turbines are parked or idled, and produce no power (Lydia *et al.*, 2014).

3.1.1 Mean conditions

Global annual mean near-surface wind speed (SWS) over land continuously declined over the past five decades before 2010, known as the period of stilling (Roderick *et al.*, 2007; Vautard *et al.*, 2010; McVicar *et al.*, 2012), with a decrease rate of −0.08 m s−1 decade−1 during 1978–2010 (Zeng *et al.*, 2019), and increase during 2010-2017 (+0.24 m s−1 decade−1), as computed using measurements from ground weather stations (at 10 m height) during 1978 - 2017. By reviewing 148 studies dealing with SWS trends from across the globe, McVicar *et al.* in 2012 reported an average decline of terrestrial SWS of −0.14 m s−1 decade−1 over a period of more than 30 years. Using wind data from *in situ* stations, Zeng *et al.* in 2019 illustrate that decadal-scale variations of near-surface wind are probably determined by internal decadal ocean–atmosphere oscillations, rather than by vegetation growth and/or urbanization, as hypothesized previously. Wu *et al.* in 2018 analysed a series of studies reporting SWS trends spanning the last 30 years from around the world (Tab. 1).

The most recent report of the IPCC (IPCC, 2021) agreed that since the 1970s a worldwide weakening of surface wind has likely occurred over land, particularly marked in the NH, with low confidence in a recent partial recovery since around 2010. Deng *et al*. in 2021 also confirmed the observed decrease in wind speed (−0.02 m s−1 decade−1) over land in the Northern Hemisphere (NH) using a reanalysis dataset. In contrast, over the ocean, wind speed increased (+ 0.09 m s^{-1} $decade^{-1}$) over the 1981-2010 period, specifically in the Southern Hemisphere (SH). The reversal in the Northern Hemisphere (NH) wind stilling/SH wind strengthening appears from around 2010. That is, SWS over the NH land (SH ocean) underwent increasing (decreasing) trends during 2010–19. Using an observed dataset (1038 stations) of surface wind speeds from 1979 to 2016 over the Northern Hemisphere, Tian *et al*. in 2019 reported decreasing trends. In conjunction with decreasing surface wind speeds, the wind power potential at the typical height of a commercial wind turbine was also declining in past decades for most regions in the Northern Hemisphere (Tian *et al*., 2019). Approximately 30%, 50% and 80% of the total number of stations studied, lost over 30% of the wind power potential since 1979 in North America, Europe and Asia, respectively.

Tab. 1. Global and regional mean terrestrial SWS and decadal linear trends in published papers (from Wu et al., 2018)

Region	Mean wind speed (m s^{-1})	Decadal linear trend (m s^{-1} $decade^{-1}$)	Number of stations	Reference
Global average (except Australia)	3.5 (1981–2011)	− 0.078 (1981–2011)	1,100	Vautard *et al.*, 2012
	3.5 (1981–2010)	− 0.077 (1981–2013)	1,379	Tobin *et al.*, 2014
	3.5 (1981–2010)	− 0.082 (1981–2014)	1,423	Berrisford *et al.*, 2015
	3.31 (1981–2010)	− 0.087 (1979–2015)	2,264	Dunn *et al.*, 2016
Europe	-	− 0.09 (1979–2010)	276	Vautard *et al.*, 2010
	3.9 (1981–2011)	− 0.086 (1981–2011)	410	Vautard *et al.*, 2012
	3.8 (1981–2013)	− 0.072 (1981–2013)	488	Tobin *et al.*, 2014
	3.845 (1981-2014)	− 0.086 (1981–2014)	522	Berrisford *et al.*, 2015
	3.747 (1981-2010)	− 0.087 (1979–2015)	589	Dunn *et al.*, 2016

If we focus on ocean SWS, Sharmar *et al.* in 2021 showed increasing ocean wind speed trends from 1979 to 2000, which are consistent in ERA-Interim, ERA5 and MERRA-2 reanalyses, but disagree with CFSR trends for the same period. Young & Ribal in 2019 also analysed the ocean SWS trends over the 33-yr period from 1985 to 2018 using satellite altimeter observations and found that the largest increases in ocean SWS occurred in the Southern Hemisphere (SH). As for Europe, mean surface wind speeds have decreased, as in many other areas of the Northern Hemisphere over the past four decades (IPCC, 2013) (medium confidence), with a reversal to an increasing trend in the last decade (low confidence) although the robustness of this reversal is unclear given the short period and interannual variability (Kousari *et al.*, 2013; Kim & Paik, 2015; Blunden & Arndt., 2019).

If we look even more finely at the scale of France, Najac *et al.* in 2011 studied the impact of climate change on SWS using a statistical-dynamical downscaling method and comparing 2 periods: a historical period (1971-2000) and a future period (2046-2065); they conclude that there is an increase in SWS in the northern part of France and a decrease in the southern part, but especially on the fact that there is a large uncertainty with regard to the amplitude of the changes, which remain below 5.8%. Charles *et al.* in 2012 conducted a study on the impact of climate change on waves in the Bay of Biscay and showed a significant decrease in wind speed in this area, south of 46° (up to −0.9 m/s comparing the period 2061-2100 to the period 1961-2000), which then led to a decrease in significant wave heights.

3.1.2 Extreme conditions

In Europe, high-speed winds are mainly associated with the passage of extra-tropical storms (Froude *et al.*, 2007), especially in autumn and winter. Changes in the intensity and/or frequency of storms can cause changes in the occurrence of high- or low-speed winds events, with possible impacts on wind power. In a future scenario with more dependence on renewable energy sources, this might even lead to shortcomings in available electricity, with significant impacts especially on cities and urban areas. Contrariwise, if the weather regimes that cause extreme wind events differ from area to area, it would be possible to redirect the energy to the affected zones and thus avoid temporary shortcomings. However, Grams *et al.* in 2017 underline the lack of well-deployed installations and of an efficient European electric network that could handle electricity deficit periods. Therefore, installation of new capacity based on the meteorological understanding is crucial for a future stable renewable powered electricity system.

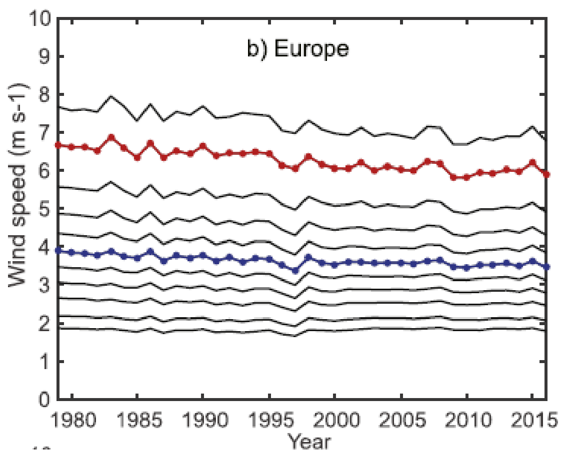

Fig. 3. Evolution of annual percentiles of wind speed in Europe (from Tian et al., 2019)

Tian *et al.* in 2019 reported on terrestrial wind speed trends from a low to high percentile of wind speeds based on observations (1979-2016). Globally, wind speeds exhibit sharper trends in higher percentiles (between 50th and 95th, Fig. 3), which is noteworthy because wind power generation is largely dictated by these percentiles of the wind speed distribution. In Europe, low percentile wind speeds show small negative trends, while higher wind speeds exhibit sharper downward trends. The average trend of high-speed winds (90th percentile: -0.2 m s-1 decade-1) is more than twice as large as median speed winds (50th percentile). This is also the case in Asia where high-speed winds slow down much more rapidly than median speed wind.

Rapella *et al.* in 2023 investigated the behaviour of extreme offshore winds over Europe, over the period 1950–2020 using ERA-5 reanalysis through the occurrence of wind events with the wind speed above the cut-out threshold (25 m/s at 100 m, “high wind”) and below the cut-in threshold (3.5 m/s at 100 m, “low wind”). In British Islands, North Sea and Bay of Biscay, a significant increasing trend has been observed for high winds, and a decreasing trend for low winds. In contrast, in Central Mediterranean and Balkan Peninsula, the number of low wind events has increased while the number of occurrences of high winds is almost identical (Tab. 2).

Zhao *et al.* in 2023 reported that the decrease of strong wind frequency (SWS > 5.0 m s−1) is a dominant cause of wind stilling before 2010, and the continuous increase of the low wind (0.1 m s−1 < SWS < 2.9 m s−1) after 2010 mainly contributes to wind speed reversal. They used the hourly surface wind speed (SWS) data provided by HadISD (Dunn *et al.*, 2016), which is a subset of the station data from the Integrated Surface Database (ISD) (Smith *et al.*, 2011).

Tab. 2.Number of wind events for the past period (1 January 1950–30 June 1985) and for the present (1 July 1985–31 December 2020) (from Rapella et al., 2023)

Area	Jan. 1950 > 30 June 1985		1 July 1985 > 31 Dec. 2020	
	High wind	Low wind	High wind	Low wind
British Island	176	552	281	382
North Sea	38	493	59	369
Bay of Biscay	29	585	56	389
Central Mediter.	32	531	31	513
Balkan Peninsula	9	477	10	561

The recent report of IPCC (IPCC, 2021) stated that the observed intensity of extreme winds is becoming less severe in the low to mid-latitudes, while becoming more severe in high latitudes poleward of 60 degrees (low confidence). In Europe, extreme near-surface winds have been decreasing in the past decades (Smits *et al.*, 2005; Tian *et al.*, 2019; Vautard *et al.*, 2019) according to near-surface observations.

3.2 Future part

This part of the report is dedicated to “future” periods and is mainly based on studies which use the projection parts (scenarios) of GCMs and RCMs from the CMIP experiments.

3.2.1 Mean conditions

In the early IPCC assessments, the most widely used and referred-to family of emissions scenarios were the so-called SRES scenarios. Using the SRES scenarios (used in CMIP3 models), Michelangeli *et al.* in 2009 showed a decrease in 10 m wind speed anomalies for most weather stations in France, ranging from less than 1% (in the South) to nearly 9% (in the North) in 2071-2100 with respect to 1958-2005, with a maximum in the Brittany region using IPSL-CM4 climate simulations of the 21st century under the SRESA2 scenario (Fig. 4).

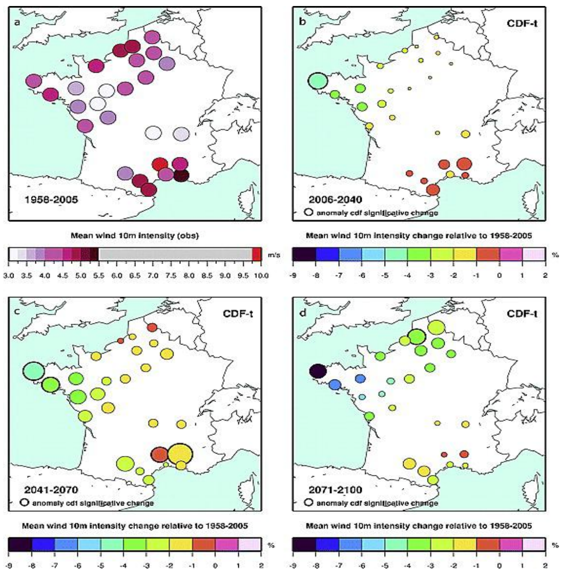

Fig. 4. (a) The 10m wind climatology for 1958–2005, and the other panels the change between 1958–2005 and the future time periods (b) 2006–2040, (c) 2041–2070 and (d) 2071–2100: colours correspond to the change in the mean 10m wind intensity relatively to 1958–2005; the radius of the circles is proportional to the CvM ("integrated" squared error) value between 1958–2005 wind anomaly CDF and future time period wind anomaly CDF; and bold lined circles correspond to stations where the future anomaly CDFs are significantly different from 1958–2005 CDFs (α = 0.05 significance).(from Michelangeli et al., 2009)

For the Fifth IPCC Assessment Report, Representative Concentration Pathways (RCPs) scenarios were developed. For RCP scenarios, Moemken *et al.* in 2018, using the ensemble mean of nine GCM-RCMs, reveal (for RCP8.5) a decrease of average annual wind energy output (Eout) for most of Europe in future decades, while increases are found for the Baltic and Aegean Seas. The ensemble mean projection shows only small changes of mean annual and winter Eout for large parts of Europe in future decades, but a considerable decrease for summer Eout. Both intra-annual and inter-daily variability of Eout are projected to increase over northern, central, and parts of eastern Europe. More frequent occurrence of 100 m wind speeds below the cut-in velocity (here 3 m/s) is also expected for all of Europe, except over the Baltic Sea. Due to a combination of higher annual mean Eout and lower intra-annual variability, climate change could be beneficial for regions the Baltic and Aegean Seas. For large parts of Germany, France, and Iberia, a lower mean Eout and increased intra-annual variability may imply larger temporal/spatial fluctuations in future wind energy production. For France and its offshore regions, increased seasonal/ intra-annual variability and increased frequency of low wind events (< 3m/s) will have a negative impact on wind power potential. The IPCC AR6 report stated that daily and interannual wind variability is projected to increase under RCP8.5 (only) for Northern Europe (low confidence), which can influence electrical grid management and wind energy production (low confidence) (IPCC, 2021). In particular, an enhancement of the intra-annual variability would affect a wind-driven energy system in a future climate due to a higher irregularity of wind energy production within a year.

de Castro *et al.* in 2019 performed a review of climate change impacts on European offshore wind energy resources analysing a wealth of published literature that used a wide range of future climate projections, including CMIP5 and CORDEX. They reported that there is a consensus on the decrease of the offshore wind energy resource over Europe, except for some areas (northern Europe, the northwestern part of the Iberian Peninsula, the Gulf of Lion, the Strait of Gibraltar and the northwest coast of Turkey) that show no change or even an increase in wind power (Fig. 5).

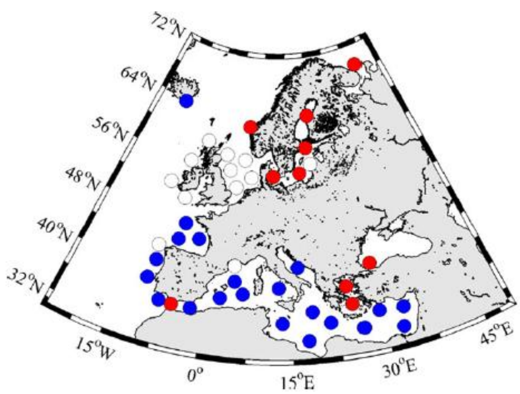

Fig. 5. Conceptual map showing the main results obtained from studies of future ocean wind energy resources under the less favourable greenhouse gas scenario for the 21st century. Red (blue) points mark the regions where a wind energy increase (decrease) is projected, and white points mark the regions where no changes are expected (from de Castro et al., 2019)

Pryor *et al.* in 2020 listed research projecting wind resources for the coming decades (Tab. 3). In Europe, there is some evidence for an emerging consensus that the mean annual energy density will increase in the north (for example, over Denmark and the UK) and slightly decrease in the south (including the Mediterranean).

In Carvalho *et al.* paper in 2021, 100m WS is projected to decrease between 0.6 and 1 m/s over Mediterranean, Poland, western Ukraine, northern Norway, British Isles and surrounding Atlantic areas, for SSP5-8.5 in 2081-2100 with respect to 1995–2014. CMIP6 MME SSP5-8.5 projects a strong decrease of the wind resource (10–20 %) over all of Europe, particularly towards the end of the current century. For 2045–2065 (2081-2100), SSP2-4.5 projects wind resource increases in eastern Ukraine and Turkey of around 10–20 % (15–30%), and of around 5–10 % for both future periods in localized areas in southern Finland and Sweden. SSP2-4.5 projects a decrease for the rest of Europe.

SSP2-4.5 does not project marked seasonality in WPD future changes, except for the Iberian Peninsula and adjacent Atlantic offshore area. For SSP2-4.5 there is also substantial uncertainty in seasonal changes particularly towards the end of the century, where MME spreads are high practically all over Europe (Carvalho *et al.*, 2021).

An increase is found in the intra-annual variability of the wind resource in the British Isles and adjacent ocean areas, Turkey, Balkans, Iberia and Northeast Europe, being more significant towards the end of the century and under stronger radiative forcing scenarios.

For France and the surrounding seas, the decrease is relatively small (within 0.3 m/s) for SSP5-8.5. However, for the Brittany region, a stronger decrease (around 0.8 m/s) is projected for SSP2-4.5 scenario for both 2046–2065 (near-term future) and 2081–2100 (long-term future). The projected wind power density (WPD) at 100m height shows a decrease (> 10%) for both SSP2-4.5 and SSP5-8.5 at both the middle (2045–2065) and the end of 21st century (2081-2100) with respect to 1995-2014.

Tab. 3. Wind resources projection for the coming decades (from Pryor et al., 2020)

Region	Variable	Model	Projected Change	Period	Reference
Europe	Energy density (80 m)	1GCM 2RCM	• Increases in northern and central Europe	(2061–2100) (1961–2000)	Hueging *et al.*, 2013
Europe	Energy density	21GCM (1.125–2.8°)	• Increases < 30% over Baltic region • Declines over western Europe	(2081–2100) (1986–2005)	Carvalho *et al.*, 2017
Europe	Energy density (80 m)	22GCM 1RCM (25 km)	• Increases in ensemble mean over northern and central Europe (2061–2100) • Decreases over southern Europe in both periods	(2021–2060) and (2061–2100) (1961–2000)	Reyers *et al.*, 2016
Europe	Energy density (Hub height)	6GCM 10RCM (25 km)	• 15-member ensemble exhibits changes of between − 20% and + 20% • Changes aggregated over Europe < 2%	(2071–2100) (1971–2000)	Tobin *et al.*, 2015
Europe	Annual energy production (78 m)	5GCM (36 realizations) (1.4–2.8°)	• Near-future spatially varying differences • Ensemble mean change of between − 12% and + 8%	(2020–2049) (1979–2005)	Devis *et al.*, 2018
Northern Europe	Energy density	1GCM 2RCM (25 km)	• Increase over Denmark and Baltic Sea	(2070–2099) and (2036–2065) (1961–1990)	Pryor *et al.*, 2012
Northern Europe	Energy density	1GCM statistical downscaling	• Small declines (< 5%) but remains within historical interannual variability	(2046–2065) and (2081–2100) (1961–1990)	Pryor *et al.*, 2012
United-Kingdom	WS, Energy density, Capacity factor (80 m)	1GCM (2 × 2.5°)	• Small increase in interannual variability • + 2% increase in capacity factor in Scotland	(2071–2090) (1981–2000)	Hdidouan *et al.*, 2017
Germany	Energy density (80 m)	1GCM	• Statistical downscaling • No change at annual scale • Increases in winter (< 6%) • Declines in summer (< 4%)	(2061–2100) (1961–2000)	Reyers *et al.*, 2015
Black Sea	Energy density (120 m)	5GCM 1RCM (12 km)	• No change in resource or seasonality	(2061–2090) (1979–2004)	Davy *et al.*, 2018

When compared with CMIP5, CMIP6 does not project an increase in wind resources for Northern Europe, showing a strong decline for practically all of Europe by the end of the century (SSP5-8.5). CMIP6 projects a strong increase in wind resource in future summers in some areas of southern Europe, whereas CMIP5 projected the opposite (decrease in southern Europe during summer). Unlike CMIP5, in CMIP6 stronger radiative forcing scenarios not only enhance the differences when compared to milder scenarios but also change the spatial patterns of changes in the wind resource (Carvalho *et al.*, 2021).

Martinez & Iglesias in 2021 reported a remarkable increase in mean wind power density for West Finland, but considerable decreases in the Central Mediterranean (centred in the Italian Peninsula and Tyrrhenian Sea), the northernmost regions of Continental Europe (centred in the Finnish Lapland) and the upper European Atlantic Ocean – in latitudes above 45°N, including Ireland, Britain and Iceland, for both SSP5-8.5 (highest emissions scenario) and SSP2-4.5 (intermediate emissions scenario). For Western and Central Europe (France, Belgium, the Netherlands, Germany, Czech Republic), the SSP2-4.5 scenario predicts a significant increase in wind power density, whereas slight decreases are predicted in the SSP5-8.5 scenario. These discrepancies indicate that some regions are highly sensitive to the climate change scenario, which may well be the reason behind the discrepancies found in the literature on the evolution of wind energy in Central Europe. The SSP5-8.5 scenario predicts a widespread increase in the COV (coefficient of variation) of over 10% in offshore and Central Europe. A notable reduction in variability (of around 10%) is predicted in the northern most regions of Continental Europe – Norway and, especially, the Finnish Lapland. For intra-annual variability, increases in the available wind energy that are consistent throughout the year are projected in the SSP2-4.5 scenario in Central Europe and parts of Western Europe – especially in France, Germany, the Netherlands and Belgium. While for SSP5-8.5, no regions maintain a consistent evolution throughout the year. However, this study doesn't perform any robustness measure in contrast to Carvalho *et al.* in 2021.

In more recent studies, Jung & Schiendler in 2022 analysed 75 papers published between 2017 and 2021 and concluded to a decrease in wind resources in Europe for RCP8.5 projections (Tab. 4). Ibarra-Berastegui *et al.* in 2023 selected marine areas located less than 200 km offshore, with depths below 1000 m and average wind speeds at a hub height (90 m) of more than 5 m/s as candidate locations for WTs (with a 5 MW power ranking). Using two CMIP6 climate model simulations (EC-Earth3 and ACCESS-CM2), they showed negative annual electricity production trends for the 2015-2100 period over the coastal areas of Northern Europe, the Eastern seaboard of US, northern Japan, Italy, southwestern Australia and the Yellow Sea. They stated that the negative trend in electricity production in those areas even under the worst-case scenario (SSP5-8.5), is moderate (1-2% per decade) and unlikely to involve major long-term changes or compromise economic feasibility through 2100. The recent IPCC report (IPCC, 2021) concluded that mean surface wind speeds are projected to decrease in the Mediterranean areas under RCP4.5 and RCP8.5 by the middle of the century and beyond, or for global warming levels of 2 degrees and higher (high confidence), with a subsequent decrease in wind power potential (medium confidence) (Hueging *et al.*, 2013; Tobin *et al.*, 2015, 2018; Davy *et al.*, 2018; Karnauskas *et al.*, 2018; Kjellström *et al.*, 2018; Moemken *et al.*, 2018).

Tab. 4. Future wind resource changes. The requirement for listing is the use of at least ten GCMs or RCMs for a period beginning after 2060. (from Jung & Schiendler, 2022)

Reference	Scenario	Statistical test	Change	Area and Description
Carvalho *et al.*, 2017	RCP8.5	Yes	Increase and decrease	• Major part Europe: decrease (up to -40% in Mediterranean) • Baltic Sea and surrounding areas: increase
Santos *et al.*, 2018	RCP8.5	No	Increase and decrease	• Iberian Peninsula: decrease over most parts with some exceptions
Soares, 2017	RCP8.5	No	Increase and decrease	• West Iberian coast: decrease of less than - 5% except for northwest where it increases
Carvalho *et al.*, 2017	RCP4.5	Yes	Increase and decrease	• Major part Europe: less pronounced tendencies than under RCP8.5 Eastern Europe: stronger reduction than under RCP8.5
Carvalho *et al.*, 2021	SSP5-8.5	Yes	Decrease	• Europe: decrease in practically all of Europe (- 10-20%) • Northern Norway, Poland and western Ukraine: decrease - 25–30%
Martinez & Iglesias, 2021	SSP5-8.5	No	Increase and decrease	• Northern continental Europe/Central Mediterranean: significant reduction (up to 35%) • West Finland: increase
Qian & Zhang, 2021	SSP5-8.5	Yes	Increase and decrease	• Northwest Passage - North of 72°N: increase up to 30% • South of 70°N: decrease (about 20%)

3.2.2 Extreme conditions

Wind speeds are projected to shift towards more frequent occurrences below thresholds lowering the wind power production (Weber *et al.*, 2018) by the end of 21st century for RCP8.5 scenarios in EURO-CORDEX models. The probability of being below the cut-in velocity (< 3 m/s) increases and there is a general shift from higher to lower wind velocities in many parts of Europe. A contrary effect arises over the Baltic Sea, the Aegean Sea and the Strait of Gibraltar: there is a shift to higher wind velocities. Moreover, the probability and the persistence time of being in constant power output regime increase for these regions. The changes in seasonal wind variation are not robust for the Baltic Sea which implies positive effects for offshore wind power over there.

Wind stagnation events (low speed wind) may become more frequent in future climate scenarios in some areas of Europe in the second half of the 21st century (Horton *et al.*, 2014; Vautard *et al.*, 2018), with potential consequences on air quality for RCP8.5 scenarios.

In Northern Europe, 50-year return-period wind speeds increase beyond the historical envelope of variability only by the end of the 21st century. Despite relatively high uncertainty, there is some evidence that wind gust intensity will increase, up to +10%, over parts of northern Europe by the end of the 21st century (Pryor *et al.*, 2012).

Larsén *et al.* in 2024 shows an overall increase (<3%) in the extreme winds in the North Sea and the southern Baltic Sea, but a decrease (<5%) over the Scandinavian Peninsula and most of the Baltic Sea. They used extreme wind parameters, including the 50-year wind and the 95 %-percentile of the wind speed, and the change in turbine class at 50 m, 100 m and 200 m, between a near future period (2020–2049) and the historic period (1980–2009) from 18 models of CMIP6 and the high-emission SSP5-8.5 scenario.

Increased occurrences of non-useable wind speeds (lower than 3 m/s or higher than 25 m/s) are found for practically all of Europe including France, particularly using SSP5-8.5 scenario. SSP2-4.5 scenario projects some areas where these occurrences are expected to decrease (Turkey, eastern Ukraine and some areas in the vicinity of the North Sea) (Carvalho *et al.*, 2021). They mentioned that the areas where WPD is projected to increase (decrease) coincide with the areas where it is expected that the occurrence of wind speeds outside the cut-in and cut-off speeds will decrease (increase), but with considerable uncertainty associated to these changes due to the relatively high MME spreads.

A slightly increased frequency and amplitude of extratropical cyclones (winter storms), strong winds and extra-tropical storms is projected for Northern, Central and Western Europe by the middle of the century and beyond and for global warming levels of 2°C or more (medium confidence) for RCP8.5 scenario (Outten & Esau, 2013; Feser *et al.*, 2015; Forzieri *et al.*, 2016; Mölter *et al.*, 2016; Ruosteenoja *et al.*, 2019; Vautard *et al.*, 2019). The IPCC AR6 (IPCC, 2021) stated that the frequency of storms, including Medicanes (a class of severe cyclones in the Mediterranean), is projected to decrease in Mediterranean regions, and their intensities are projected to increase, by the middle of the century and beyond for RCP8.5 (medium confidence) (Nissen *et al.*, 2014; Feser *et al.*, 2015; Forzieri *et al.*, 2016; Mölter *et al.*, 2016; Tous *et al.*, 2016; Romera *et al.*, 2017; González-Alemán *et al.*, 2019; MedECC, 2020). Proxies of intense convection indicate that the large-scale conditions conducive to severe convection will tend to increase in the future climate (low confidence).

3.3 Physical processes

As stated above, mean surface wind speeds have decreased in Europe as in many other areas of the Northern Hemisphere over the past four decades (medium confidence) (IPCC, 2013), often referred to as stilling, with a reversal to an increasing trend in the last decade (low confidence). Several factors have been attributed to these trends, including forest growth, urbanization, local changes in wind measurement exposure and aerosols (Bichet *et al.*, 2012), as well as natural variability (Zeng *et al.*, 2019).

Vautard *et al.* in 2010 attributed the stilling to both changes in atmospheric circulation and an increase in surface roughness due to an overall increase in vegetation cover.

Rapella *et al.* in 2023 explained that the low winds events (below cut-in wind speed) are related to blocking patterns with the high-pressure zone centered over the affected area. In contrast, high winds (above cut-off) for British Islands, North Sea and Bay of Biscay were related to the same weather regime, namely the NAO+ phase.

Wu *et al.* in 2018 reported a decrease in historical terrestrial near-surface wind speed over Europe and most of the World using a large number of published studies (Tab. 5). They associated the physics due to changes in driving forces and drag forces. The changes in the driving forces are caused by changes in atmospheric circulation, and the changes in the drag forces are caused by changes in the external and internal friction in the atmosphere. Changes in surface friction are mainly caused by changes in the surface roughness due to land use and cover change (LUCC), including urbanization, and changes in internal friction are mainly induced by changes in the boundary layer characteristics.

The current best knowledge suggests that there are so many interacting and competing processes that it is "unknown whether anthropogenic warming will result in stilling (decreases in wind speed) or increased windiness" (Pryor *et al.*, 2020). In addition to the competing effects of land use change and greenhouse gas emissions examined here, Bichet *et al.* in 2012 find that aerosol emissions play a significant role in some places. Gonzalez in 2019 reported that projected 21st century wind speed changes from CMIP5 ensemble under RCP8.5 scenario over Western Europe are the result of two distinct processes: the first one is associated with changes in the large-scale atmospheric circulation, while the second one is likely to be more local in its connection to the near-surface boundary layer.

During 1980–2010, the Southern Hemisphere (SH) trade winds and sub-Antarctic westerly winds experienced intensified trends, which was caused by the enhanced Hadley cell over the SH (Deng *et al.*, 2021). The enhancement of the SH Hadley cell is primarily caused by the increased GHG forcing and the negative phases of the PDO (Pacific Decadal Oscillation). During 2010–2019, however, the SWS trends in the two hemispheres were reversed, which is suggested to be linked to the phase changes in the PDO and associated changes in large-scale atmospheric circulation (Fig. 6).

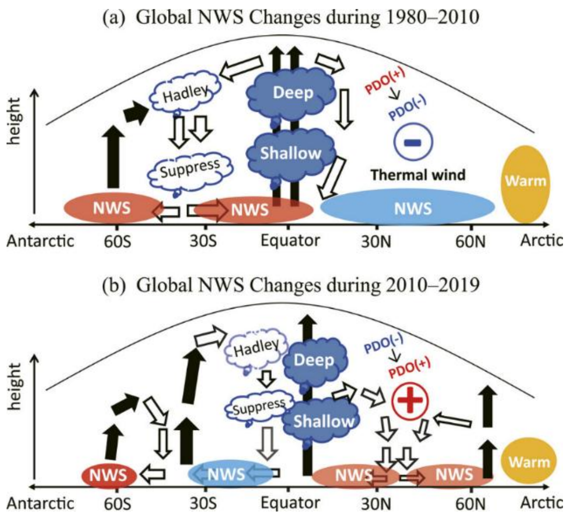

Fig. 6. Schematic diagrams of possible causes of global WS changes during (a) 1980–2010 and (b) 2010–19. (from Deng et al., 2021)

Tab. 5. The main causes of the changes in the terrestrial SWS across the globe (from Wu et al., 2018)

Region	Influence factor	Relationship	Study period	Original paper
Northern Hemisphere	Atmospheric Circulation	Explain 10-50% of slowdown (-)	1979-2008	Vautard *et al.*, 2010
Northern Hemisphere	Land Use and Cover Change	Explain 25-60% of slowdown (-)	1979-2008	Vautard *et al.*, 2010
Northern Hemisphere	Anthropogenic Aerosols	-0.03 (-)	1975-2005	Bichet *et al.*, 2012
All Europe	Land Use and Cover Change	Explain 25-60% of variability (0.05 level)	1962-2009	Wever, 2012
All Europe	Anthropogenic Aerosols	-0.05 $m.s^{-1}$ (-) (0.20 level)	1975-2005	Bichet *et al.*, 2012
Mediterranean and Adriatic	Air Temperature	Positive correlation (-/-)	1951-1996	Pirrazoli & Tomasin, 2003
Northwest	Arctic Oscillation/ North Atlantic Oscillation	Positive correlation (-/-)	1958-1998	Yan *et al.*, 2002
England	North Atlantic Oscillation	Positive correlation (-/-)	1980-2010	Earl *et al.*, 2013
Iberian Peninsula	North Atlantic Oscillation	Explain 10-15% of variability (0.10 level)	1959-2007	Jerez *et al.*, 2013
Spain/ Portugal	North Atlantic Oscillation	Negative correlation (-0.55/-0.52/0.05 level)	1961-2011	Blunder & Arndt, 2019
Turkey	Air Temperature	Negative correlation (-0.15/non.)	1975-2006	Dadaser-Celik & Cengiz, 2014

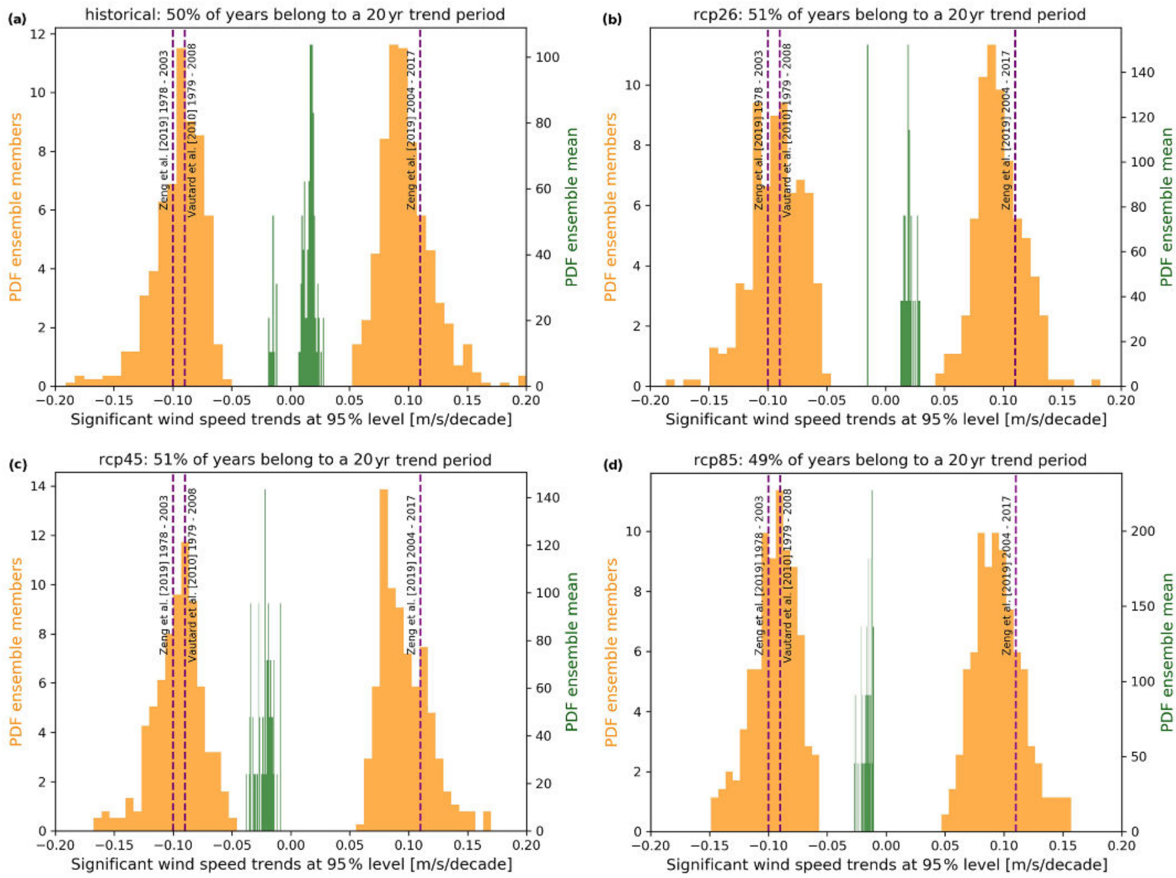

Fig. 7. Twenty-year trends in European annual mean wind speed in MPI-GE under historic and future climate conditions. Trends are computed for each ensemble member after subtraction of ensemble mean (yellow – representing internal variability) and for the ensemble mean (green – representing forced changes). Different subplots show different experiments. Trends are only shown if they are different from zero at a 95 % significance level (from Wohland et al., 2021)

Wohland *et al.* in 2021 focus on the relative importance of land use change and altered CO2 concentrations in explaining forced wind speed change and report that land use change plays a pivotal role in explaining periods of exceptionally high (historical 1950–2000) and low (RCP4.5 2050–2100) wind speeds. Also, forced changes become relevant in the long run and can arise from land use change. They argue that stilling-like periods will continue to occur under future climate conditions (RCP2.6, RCP4.5, RCP8.5) in approximately 50% of all years independent of the applied greenhouse gas and land use forcing (Fig. 7). Land use changes are as important as greenhouse gas emission scenarios for onshore winds. Given that different land use scenarios can share the same level of greenhouse gas emissions (and vice versa), it follows that changes in wind speeds and wind power generation cannot be directly linked to a certain level of greenhouse gas emissions. Instead, many combinations are theoretically possible, and some of them can lead to even greater wind speed changes. Planning of future renewable energy systems must account for forced long-term trends in wind speeds, as well as multidecadal wind power fluctuation from internal climate variability. The multidecadal fluctuations have implications for wind power since the timescale of these fluctuations is of the same order as the timescale of wind power projects.

In terms of extreme conditions, there is low confidence (IPCC, 2021) in past-century trends in the number and intensity of the strongest extratropical cyclones over the Northern Hemisphere due to the large interannual-to-decadal variability and temporal and spatial heterogeneities in the volume and type of assimilated data in atmospheric reanalyses, particularly before the satellite era. Over the Southern Hemisphere, it is likely that the number of extratropical cyclones with low central pressures (<980 hPa) has increased since 1979. The frequency of intense extratropical cyclones is projected to decrease (medium confidence). Projected changes in the intensity depend on the resolution of climate models (medium confidence). There is medium confidence that wind speeds associated with extratropical cyclones will change following changes in the storm tracks.

Winds are directly linked to atmospheric circulation, jets and storm tracks. IPCC AR6 reported that there is also overall low confidence in projected regional changes in the NH low-level westerlies, particularly for the North Atlantic basin in boreal winter. CMIP6 models show overall low agreement on changes in Extra-tropical cyclone (ETC) density in the North Atlantic in boreal winter. There is only medium confidence in the projected decrease in the frequency of intense NH ETCs. And there is medium confidence that the frequency of atmospheric blocking events over Greenland and the North Pacific will decrease in boreal winter in the SSP3-7.0 and SSP5-8.5 scenarios (IPCC, 2021). There is low confidence in projected poleward shifts of the Northern Hemisphere mid-latitude jet and storm tracks due to large internal variability and structural uncertainty in model simulations. There is high confidence that Southern Hemisphere storm tracks and associated precipitation have migrated poleward over recent decades, especially in the austral summer and autumn, associated with a trend towards more positive phases of the Southern Annular Mode (SAM) and the strengthening and southward shift of the Southern Hemisphere extratropical jet in austral summer. It is likely that wind speeds associated with extratropical cyclones will strengthen in the Southern Hemisphere storm track for SSP5-8.5. There is low confidence in the potential role of Arctic warming and sea ice loss on historical or projected mid-latitude atmospheric variability.

The IPCC report (IPCC, 2021) also concludes that observed mean surface wind speed trends are present in many areas (Section 12.4 in Working Group I), but the emergence of these trends from the interannual natural variability and their attribution to human-induced climate change remains of low confidence due to various factors such as changes in the type and exposure of recording instruments, and their relation to climate change is not established. For future conditions, there is limited evidence of the emergence of trends in mean wind speeds due to the lack of studies quantifying wind speed changes and their interannual variability. The same limitation also holds for extremes wind (severe storms, tropical cyclones, sand and dust storms).

3.4 Summary about the impacts of climate change on wind

Wind	Mean conditions	Extreme conditions
Historical	Northern hemisphere Decrease (0.08-0.1 m s^{-1}decade^{-1}) for NH Land (**observation**) Southern hemisphere Increase (0.1 m s^{-1} decade^{-1}) for SH Ocean (**altimeter and reanalysis**)	Europe • Decrease: -0.2 m s^{-1} decade^{-1} (1979-2016) of p90 wind speed for Europe. (Tian *et al.*, 2019) (**observation**) • Decrease in strong wind frequency (SWS > 5.0 m s^{-1}) (Zhao *et al.*, 2023) (1981-2010) (**observation**) • Increase for high winds: British Islands, North Sea and Bay of Biscay (Rapella *et al.*, 2023) (1950-2020, **ERA5**) • Increase / Decrease of low wind events: Central Mediterranean and Balkan Peninsula/ British Islands, North Sea and Bay of Biscay (Rapella *et al.*, 2023) (1950-2020, **ERA5**)
Future	Europe • Significant decrease for Northern continental Europe/Central Mediterranean (up to 35%) and increase for West Finland (Carvalho *et al.*, 2021 for **SSP5-8.5**) • Decrease in major part of Europe (up to -40% in the Mediterranean) but increase for Baltic Sea and surrounding areas (Carvalho *et al.*, 2017 for **RCP8.5**)	Europe • Increased occurrences of non-useable wind speeds (< 3 m/s & > 25 m/s) are found for all of Europe (Carvalho *et al.*, 2021, **SSP5-8.5**) • More frequent occurrence of 100 m wind speeds below the cut-in velocity (3 m/s) for all of Europe, except the Baltic Sea (Moemken *et al.*, 2018, **RCP8.5**) • Increase of low wind events: All Europe except Baltic Sea, the Aegean Sea and the Strait of Gibraltar (Weber *et al.*, 2018, **RCP8.5**) • Increase in the extreme winds (95th percentile) in the North Sea for 2020–2049 (Larsén *et al.*, 2024, **SSP5-8.5**)

4 Impacts of climate change on waves and sea level

In the context of climate change, waves and water levels can evolve. These two metocean parameters are important to study when talking about offshore wind, because they can size the different structures that make up the farm and are also important for operations and maintenance.

Waves can be classified in two broad categories: wind seas (locally generated), composed of irregular, short period waves formed by local winds, and swell (generated in distant areas), composed of more regular, long-period waves that may travel long distances. The sea state is defined as the wave conditions at a given location and time, which may be composed of both wind seas and swell. Sea states (or the wave conditions) can be characterized by their significant wave height Hs, mean period Tm and/or peak period Tp (wave period of the sea state containing the maximum energy), mean or peak direction, wavelength, and phase velocity.

Sea level is composed of three main components: the mean sea level, the tidal level (due to tides) and the residual component, also called surge level. The mean sea level is a very slowly evolving phenomenon which is mainly linked to sea temperature and the melting of glaciers. Tides are a periodic process mainly due to gravitational forces exerted by the Moon and the Sun on the Earth. The surge level can be positive or negative and mainly results from wind stress and local atmospheric pressure.

There are many challenges to cope with when studying the evolution of waves and sea level over a long period of time. One of them is the shifting seasonality of our climate in the context of climate change. A recent study by Breton *et al.* in 2022 indicates that for waves, the duration of winter conditions decreases over 1979–2100 than over 1979–2017 (starting later in the year and ending earlier), while the duration of summer conditions increases (starting earlier in the year and ending later). This new seasonality observed in the North Atlantic is validated by other studies (Cassou & Cattiaux, 2016; Ruosteenoja *et al.*, 2020) and will be interesting to investigate through the research work planned in 2C NOW. Finally, the evolution of sea states around France has a strong seasonal component, with difficult sea conditions in winter and weaker ones in summer (Laugel *et al.*, 2014), that must be considered to precisely quantify the evolution of sea states.

4.1 Historical period

4.1.1 Mean conditions

Sea level

Global sea levels are currently rising by an average of 3.7 mm per year, according to the IPCC (IPCC, 2023), and this observation of a rise in mean sea level has also been made by numerous other studies (Marcos & Woodworth, 2017; Calafat *et al.*, 2022). A recent study estimates the rise in global mean sea level as 15 mm between June 2014 and May 2016 (Llovel *et al.*, 2023), which is 8 mm higher than the global trend of 4 mm/year estimated in the 2006-2017 period from satellite gravimetry data and in situ measurements. From 1880 to 2009, Church & White in 2006 found a global increase of 210 mm around the world estimated from satellite altimeter data and coastal measurements. The corresponding linear trend is + 1.7 mm/year from 1900 to 2009 and + 1.9 mm/year since 1961. Church & White in 2006 also announced that there was a significant acceleration in the last 10 years of sea level rise. From tide gauge stations in France, Dodet *et al.* in 2019 agree with this last result showing an increase of 1.2 mm/year in the 20th century versus 2.4 mm/year in the last two decades from 1998 to 2018. They also found that local variability is important, presenting different magnitudes such as an increase of 1.23 mm/year in Roscoff compared to 4.25 mm/year in Nice (Ta. 6). Local trends show great variability over small areas such as in the English Channel, where sea levels are increasing on average between 0.8 to 2.3 mm/year (Haigh & Griffiths, 2009). Finally, more locally in Brest, using the oldest tide gauge station in France, Reinert *et al*. in 2021 estimate an average sea level rise of 12.5 cm per century (1.25 mm/year) between 1840 and 2020.

Waves

Using two measurement stations in the North Atlantic and the North Sea (Seven Stones Light Vessel (1962-1986) and Ocean Weather Station Lima (1975-1988), a historical trend in the mean wave Hs was identified: in the North Atlantic, Hs has increased by 2% per year since 1950, and in the North Sea, it has increased since 1960, with a peak in 1980, then a decrease since 1984, followed by an increase in recent years (Bacon & Carter, 1991). Bertin *et al.* in 2013 confirmed an increase of Hs in the North Atlantic Ocean during the last decade. Also, the buoy at Belle-Île-en-Mer indicates a change in the mean wave direction of 20° clockwise changing from W-SW to W-NW (Morim *et al.*, 2019), and other buoys in the North Atlantic Ocean tend towards the West direction.

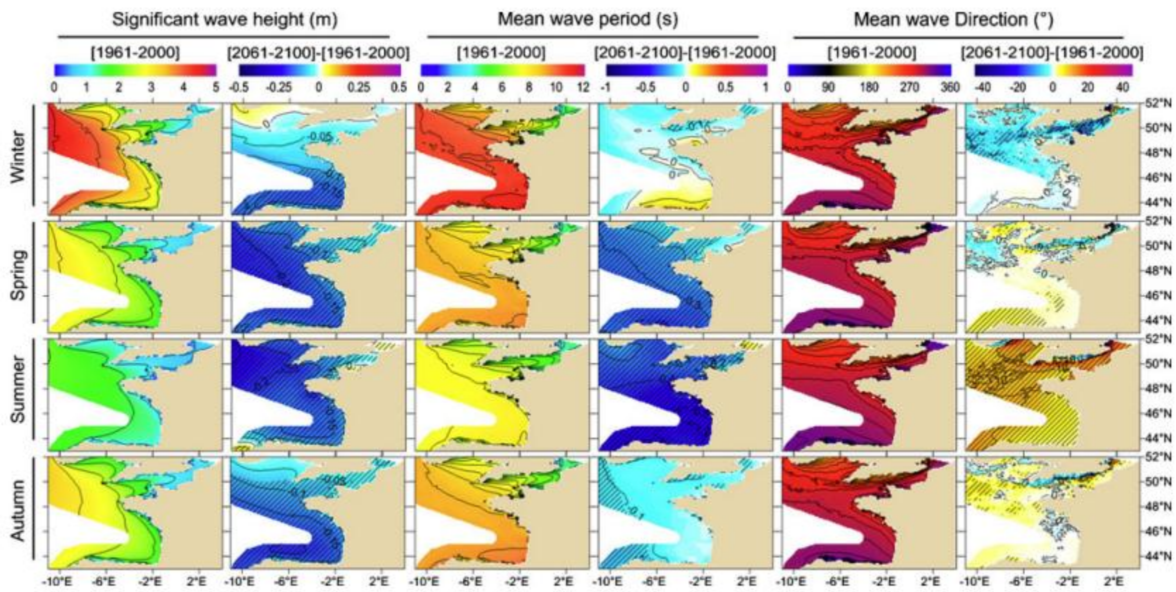

Fig. 8. Maps of significant wave height, mean wave period and mean wave direction for the present scenario REF (1961-2000) and differences between the future scenario A2 (2061-2100) (from Charles et al., 2012)

Tab. 6. Differences of magnitudes of sea level rise around France (from Dodet et al., 2019)

Station	Hs (m)			Tidal range (m)			Max. storm surge (m)	Relative sea level trends (mm/y)			Vertical land movement (mm/y)
	Year	Sum.	Wint.	Min.	Mean.	Max.		[1900-1990]	[1970-2018]	[1993-2018]	
Dunkerque	0.79	0.65	0.93	2.19	4.52	6.65	2.31	N/A	1.75 ± 0.27	2.01 ± 0.85	- 0.18 ± 0.71
Calais	0.85	0.69	1.01	2.41	5.22	7.84	1.66	N/A	1.18 ± 0.30	3.33 ± 0.82	N/A
Boulogne-sur-Mer	0.94	0.75	1.13	2.55	6.20	9.47	1.59	N/A	N/A	N/A	N/A
Dieppe	1.02	0.81	1.25	2.56	6.54	10.20	1.41	N/A	N/A	N/A	- 0.60 ± 0.47
Le Havre	0.86	0.67	1.06	2.10	5.28	8.28	1.55	N/A	2.39 ± 0.26	2.34 ± 0.65	N/A
Ouistreham	0.70	0.54	0.87	2.01	5.13	8.09	1.29	N/A	N/A	N/A	N/A
Cherbourg	0.74	0.56	0.93	1.08	3.92	6.71	1.10	N/A	1.44 ± 0.29	1.82 ± 0.65	- 0.30 ± 0.34
Dielette	1.18	0.91	1.48	1.53	6.16	10.50	1.25	N/A	N/A	N/A	N/A
Saint-Malo	1.13	0.86	1.42	2.09	7.77	13.35	1.20	N/A	N/A	2.04 ± 0.68	- 0.63 ± 0.55
Roscoff	0.84	0.59	1.10	1.63	5.60	9.48	1.00	N/A	1.80 ± 0.26	1.23 ± 0.60	- 1.28 ± 0.43
English Channel	**0.91**	**0.70**	**1.12**	**2.02**	**5.63**	**9.06**	**1.44**	**N/A**	**1.71 ± 0.41**	**2.13 ± 0.63**	**- 0.60 ± 0.50**
Le Conquet	1.48	1.02	1.96	1.26	4.25	7.29	0.97	N/A	2.86 ± 0.83	2.36 ± 0.62	- 0.53 ± 0.34
Brest	1.21	0.83	1.60	1.26	4.33	7.51	1.05	1.26 ± 0.10	2.69 ± 0.23	2.05 ± 0.61	0.01 ± 0.30
Concarneau	1.30	0.87	1.72	0.94	3.10	5.38	0.93	N/A	N/A	1.86 ± 0.95	- 0.46 ± 0.42
Port-Tudy	0.87	0.63	1.12	0.96	3.12	5.39	0.85	N/A	2.37 ± 0.27	1.51 ± 0.62	- 0.10 ± 0.43
Le Crouesty	0.86	0.58	1.12	1.05	3.39	5.84	0.99	N/A	N/A	N/A	N/A
Saint-Nazaire	1.75	1.24	2.29	1.13	3.70	6.37	1.41	N/A	2.03 ± 0.26	2.04 ± 0.68	N/A
Montoir-de-Bretagne	0.86	0.58	1.12	1.20	3.88	6.70	1.40	N/A	N/A	N/A	N/A
Saint-Gildas	1.75	1.24	2.29	1.08	3.55	6.09	1.26	N/A	1.78 ± 0.26	2.19 ± 0.75	N/A
Herbaudière	1.75	1.24	2.29	1.09	3.52	6.04	0.79	N/A	N/A	N/A	N/A
Les Sables d'Olonne	1.52	1.11	1.95	1.01	3.28	5.71	1.37	N/A	N/A	2.46 ± 0.59	- 0.05 ± 0.37
La Rochelle La Pallice	1.60	1.19	2.03	1.11	3.76	6.53	1.57	N/A	N/A	2.80 ± 0.73	- 0.11 ± 0.32
Île d'Aix	1.60	1.19	2.03	1.15	3.83	6.66	1.15	N/A	N/A	N/A	N/A
Port-Bloc	1.69	1.24	2.17	1.12	3.18	5.30	1.34	N/A	N/A	N/A	N/A
Arcachon Ayrac	1.65	1.24	2.08	0.94	2.94	4.93	1.72	N/A	N/A	N/A	- 1,30 ± 0.43
Bayonne Boucau	1.63	1.20	2.06	0.78	2.53	4.32	1.00	N/A	1.94 ± 0.29	3.15 ± 0.68	- 0.82 ± 0.43
Saint-Jean-de-Luz Socoa	1.56	1.14	2.00	0.88	2.75	4.78	0.61	N/A	1.63 ± 0.23	N/A	N/A
Atlantic Ocean	**1.44**	**1.03**	**1.86**	**1.06**	**3.44**	**5.93**	**1.15**	**1.26 ± 0.10**	**2.19 ± 0.43**	**2.27 ± 0.47**	**- 0.42 ± 0.38**
Port-Vendre	0.43	0.25	0.56	0.03	0.15	0.30	0.64	N/A	N/A	N/A	- 0.39 ± 0.60
Port-La-Nouvelle	0.52	0.33	0.65	0.03	0.15	0.31	0.75	N/A	N/A	N/A	N/A
Sète	0.49	0.31	0.61	0.03	0.16	0.31	0.73	N/A	N/A	N/A	- 0.87 ± 0.27
Fos-sur-Mer	0.61	0.44	0.72	0.03	0.16	0.32	0.59	N/A	N/A	N/A	N/A
Marseille	0.55	0.41	0.64	0.03	0.16	0.33	0.93	1.13 ± 0.08	1.78 ± 0.19	N/A	- 0.24 ± 0.18
Toulon	0.42	0.26	0.51	0.03	0.17	0.33	0.52	N/A	N/A	3.09 ± 0.62	N/A
Port-Ferreol	0.53	0.29	0.71	0.04	0.17	0.30	0.47	N/A	N/A	N/A	N/A
La Figueirette	0.29	0.17	0.37	0.04	0.18	0.32	0.67	N/A	N/A	N/A	- 0.68 ± 0.25
Nice	0.18	0.08	0.26	0.04	0.18	0.34	0.49	N/A	N/A	4.25 ± 0.82	- 0.06 ± 0.34
Monaco Fontvieille	0.18	0.08	0.26	0.04	0.18	0.35	0.51	N/A	N/A	1.99 ± 0.80	- 0.48 ± 0.79
Mediterranean Sea	**0.42**	**0.26**	**0.53**	**0.03**	**0.17**	**0.32**	**0.63**	**1.13 ± 0.08**	**1.78 ± 0.19**	**3.11 ± 0.92**	**- 0.45 ± 0.41**

An intensification of waves is visible according to the dynamic downscaling method used in the following two studies in the Bay of Biscay. Off the Bay of Biscay from 1953 to 2009, Hs is higher on average per year in winter by 0.19 cm and in summer by 0.16cm. Wave directions also change, moving further south by 0.0581° in winter and 0.0018° in summer (Dodet *et al.*, 2010). Similar results are found by Charles *et al.*, in 2012 with data from a buoy placed in the Bay of Biscay. The increase in Tm per year is 0.018 s in winter from 1963 to 2001 and 0.009 s in summer from 1966 to 2001, while Tm decreases in fall by -0.03 s from 1978 to 2001 (Fig. 8). And a maximum increase in Hs was found at the buoy in summer of 0.54 cm/year from 1970 to 2001. These two studies exposed well the strong seasonality of waves along French coasts with higher waves during the winter than the summer. Also, results are often well visible for winter/summer seasons whereas there are more blurred for spring/fall seasons.

4.1.2 Extreme conditions

Sea level

Extreme sea levels are increasing with mean sea levels and at a similar rate, which is interesting to note (Marcos & Woodworth, 2017; Calafat *et al.*, 2022). In Brest, according to the tide gauge station, the increase in extreme sea level calculated using the 99 percentile is 11.5 cm per century (1.15 mm/year) from 1840 to 2020 (Reinert *et al.*, 2021). Using this measurement and a model from 1980 to 2010 extending from Brest to the Portugal coast, an increase of 1.27 mm/year in extreme sea levels that are associated with local effects such as surge is observed (Fortunato *et al.*, 2016) (Fig. 9). As for the centennial water levels, local increases in sheltered areas are important: around 20-30 cm from the mouth to the head in funnel-shaped rias in the North of Spain (Fortunato *et al.*, 2016). Other studies indicate no significant changes of extremes with minor trends difficult to separate from natural variability, for example in the Baltic or North Sea (Weisse & Weidemann, 2017).

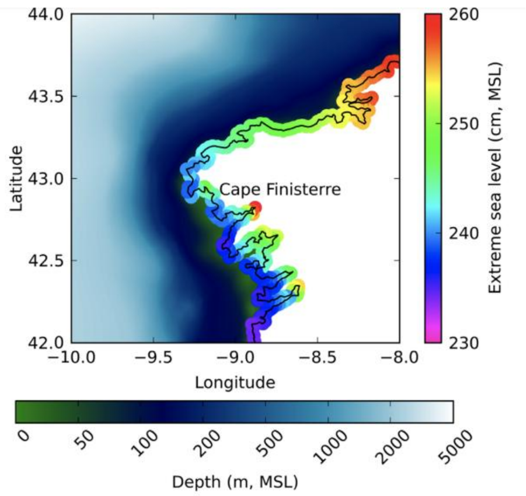

Fig. 9. Extreme sea levels in the north-western Iberian Atlantic coast for a return period of 100 years (from Fortunato et al., 2016)

Waves

Based on annual maxima in the North Atlantic, extreme Hs have been increasing by 5 cm per year with observed data from 1958 to 1997 (Wang *et al.*, 2014). Using a statistical downscaling method along the French coast, Wang *et al.* in 2012 shows a visible intensification, with an increase in Hs of 1.5 to 2 cm per year from 1958 to 2001 and 1 to 1.5 cm from 1871 to 2010. This increase of Hs agrees with Zieger in 2021, who reports an increase of 4 to 5 cm per year from 1985 to 2008 using the 99th percentile.

In the Bay of Biscay, a seasonal analysis shows an increase in extreme waves, as indicated by Charles *et al.* in 2012, with an increase in Hs extremes calculated with the 95th percentile of 1 to 2 cm/year from 1970 to 2001 in Summer. A clockwise shift of winter swell directions is also observed explained by the intensification of strong wind in the North Atlantic Ocean and its north-eastward shift. As for mean conditions, a strong seasonality in extreme waves is spotted.

4.2 Future period

4.2.1 Mean conditions

Sea level

The overall sea level is tending towards an increase by 2100 (IPCC, 2023). According to the AR6 IPCC SSP5-8.5 scenario, sea levels will rise by more than a meter by 2100 compared with 1995-2014 (Fox-Kemper *et al.*, 2019). Vousdoukas *et al.* in 2017 announce an increase of 21 cm (RCP4.5) and 24 cm (RCP8.5) for 2050 of the mean sea level around European coasts and an increase of 53 cm (RCP4.5) and 77 cm (RCP8.5) for 2100. The Baltic Sea shows the smallest increase in relative sea level (compare to land as opposed to absolute sea level) rise caused by local post glacial rebound (Johansson *et al.*, 2014).

The annual rate of sea level rise increase is 7.89, 6.41 and 5.70 mm/year in the near term (2021-2040), medium term (2041-2060) and the long term (2081-2100) respectively, compared to the reference period from 1995 to2014 in the Baltic Sea and is similar with scenarios SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5 (IPCC, 2023). These last results mean that this increase slows down over time. Other parts of the world may experience even larger sea level rise such as Taiwan with an increase of 165 mm with RCP4.5 and 236 mm with RCP8.5 in the period 2022-2057 with respect to 1986-2005 (IPCC, 2023) but other studies indicate smaller changes with an increase of 2.8 mm/year between 2000 and 2039 (Hsu *et al.*, 2017).

Waves

In contrast to rising sea levels, future wave projections point to a decrease in mean wave heights along the French coast (Lemos *et al.*, 2021; Lobeto *et al.*, 2021). A decrease of 6% (RCP 4.5) and 10% (RCP 8.5) in wave height is expected over the central Northeast Atlantic at the end of the century relative to the period 1971-2000 (Aarnes *et al.*, 2017), which is contradictory with the historical part showing an increase. This decrease agrees with the study by Dobrynin *et al.* in 2015, which predicts an even lower Hs with RCP 8.5. It is interesting to note that the wave height decrease is more pronounced in the North Atlantic than in the English Channel or the Mediterranean Sea (Bricheno & Wolf, 2018). Along European coasts, following the RCP 4.5 and 8.5 scenarios, a 0.2 m decrease in Hs is predicted by 2100, with more significant changes occurring in the second half of the century (Bricheno & Wolf, 2018).

Overall, the projections made with CMIP5 predict a decrease in Hs by the end of the 21st century, which is more notable following the RCP 8.5 scenario (Wang *et al.*, 2014; Dobryin *et al.*, 2015; Aarnes *et al.*, 2017; Casas-Prat *et al.*, 2018; Morim *et al.*, 2018, 2019). This decrease in Hs is visible on average in both annual and seasonal studies (Semedo *et al.*, 2012; Morim *et al.*, 2018, 2019; Lemos *et al.*, 2019, 2021). The Tp also shows a decrease of 5 to 15% for the RCP 8.5 scenario and a change in mean wave direction of 5 to 15° (Morim *et al.*, 2019). However, Ibarra-Berrastegui *et al.* in 2023 estimate that changes in the wave climate around France from 2015 to 2100 remain small, even more with the SSP5-8.5 scenario.

In contrast, another study by Laugel *et al.* in 2014 using a dynamical downscaling method on the ARPEGE CLIMAT model over the North Sea, Atlantic Ocean and the English Channel from 2061 to 2100 shows an increase in Hs and Tp in the North Sea. Around European coasts, from 1970 to 2100 with SSP5-8.5 we can observe a decrease of mean Hs and Tp in the Atlantic Ocean and the Mediterranean Sea in accordance with Melet *et al.* in 2020 and Chaigneau *et al*. in 2023. The decrease of Hs is more important in the northwestern part including the English Channel and the North Sea with 10% less equivalent to 30 cm and the decreases of Tp is more important in the southeastern including the Bay of Biscay and the Mediterranean Sea part with 6% less equivalent to 0.5 s (Chaigneau *et al.*, 2023). In other regions of the world, Hs decreases for example in Madagascar as well, whereas it increases in southern Australia for the RCP 4.5 and 8.5 scenarios from 1979 to 2100 based on 7 GCM models and CMIP6's FIO-ESM v2.0 model (Ewans & Jonathan, 2023). An increase in the wave energy flux in the Baltic Sea is noticed with RCP8.5 of 20% by the end of the century or at least superior to 10%.

In a study of the global ocean, using CMIP6 from 1961 in a GCM with WW3 and SSP1-2.6 and SSP5-8.5, the North Atlantic stands out as a region that will undergo the most important changes in waves over the next century, along with the North Pacific, the Southern Ocean, and the Arctic (Meucci *et al.*, 2023). Overall, Hs is predicted to decrease in the northern hemisphere and increase in the southern hemisphere by 2100 linked to the intensification of the poleward movement of the westerlies (Goyal *et al.*, 2021).

4.2.2 Extreme conditions

Sea level

Tebaldi *et al*. in 2021 estimate that well before 2100 more than half of the World's coasts will have experienced the present 100-year return period of extreme sea levels even for the scenario with only a 1.5°C increase in the global mean temperature. An increase of the order of 0.1 m in the 1-to-10-year storm surge levels is projected when the median sea levels of 1951-1980 are compared with those of 2021-2050 in global projections (Muis *et al*., 2023). In addition, projections of extreme sea levels in 2100 are estimated to increase by 57 cm (RCP4.5) and 81 cm (RCP8.5) around European coasts (Vousdoukas *et al*., 2017). The North Sea shows the greatest increase (up to 1 m), followed by the Atlantic coasts, then the Norwegian, Baltic and Mediterranean Seas (Vousdoukas *et al*., 2017).

Waves

In contrast to average waves, extreme waves are predicted to increase, particularly in the Atlantic, more than in the English Channel and the Mediterranean Sea, with an annual maximum of +0.5 to 1 m Hs in 2100 relative to 2006. However, there are large uncertainties associated with future changes in extreme waves that cannot be separated from the natural variability.

This suggests an increased intensity of wave events associated with less frequent but more intense storms in the future (Bricheno & Wolf, 2018, RCP8.5). The direction of sea states is also impacted with the strongest sea states moving more northward over the last 30 years of the next century while weak sea states are moving southward (Laugel *et al*., 2014).

However, not all studies agree with each other. Aarnes *et al*. in 2017 indicates a consensus between different models towards a decrease in Hs for extreme waves before the end of the 21st century for high percentiles (p90, 95 and 99), but not for annual maxima. In the Bay of Biscay, the extremes detected by the 95th and 99th percentiles are even stronger in the northern part, in contradiction to Laugel *et al*. in 2014, who states that in the North Sea the extremes are less strong than in the Bay of Biscay. The 10- and 20-year return levels studied with the RCP 4.5 scenario are projected to increase over the North Atlantic and the British Isles (Aarnes *et al*., 2017). Around the globe, extreme Hs calculated with the 99th percentile will increase by 1% each year in all oceanic basins of mid-latitudes (Young *et al*., 2011).

Some studies question the future changes of extreme waves as extremes are difficult to predict because we do not know yet well their variability, like in the Baltic Sea (Rutgersson *et al*., 2022). However, many state an increase, even in the Baltic Sea, with an increase of Hs of 5% during summer in the future (2075-2100) compared to historical values (1980-2005) under RCP8.5 scenario. In the North Sea along the East Coast, an increase of the intensity of waves is predicted to be 5-8% by the end of 21st century for the 99th percentile wave height. Whereas for the Dutch coast of the North Sea no increase in annual maximum conditions or reduction in return periods for extreme wave events is predicted (De Winter *et al*., 2012).

In conclusion, studies on the prediction of future extreme waves do not converge towards the same trend and different trends may exist along the three French metropolitan coasts.

4.3 Physical processes

Multiple parameters, astronomical, atmospheric, oceanic, and terrestrial, play a role in the rise of sea levels, starting with global warming. Llovel *et al*. in 2023 estimate that, between 2014 and 2016, 80% of the global rise of sea levels was caused by an increase of the ocean mass correlated to a decrease of the terrestrial water storage, with only 20% attributable to global warming. Sea level related to surges can be correlated to NAO index for better predictions (Reinert *et al*., 2021; Roustan *et al*., 2022). Wind and waves also play a role in determining sea level. Wind impacts sea level directly via wind stress and surges (Mastenbroek *et al*., 1993; Pineau-Guillou *et al*., 2018), or indirectly via wave generation and the morphodynamics evolution of the coastline (Coco *et al*., 2014; Masselink *et al*., 2016). The so-called “steric sea level” refers to the change of the sea level caused by the variation of the water density, which is a function of the salinity and the temperature of the water. This effect is important in deep waters but must also be analysed in coastal environments (Meyssignac *et al*., 2017; Calafat *et al*., 2018). Turki *et al*. in 2020 estimate that, in the North Atlantic Ocean French coasts, the main parameters influencing sea level are the sea surface temperature (SST), the sea level pressure (SLP), the zonal wind and the NAO index. Some parts of the world are also influenced by the presence of extratropical cyclones (e.g. typhoons in Taiwan) with strong winds and a low atmospheric pressure center that may generate large storm surge, resulting in damage to nearby coastal areas. The phenomenon of seiche is particularly important near ports and may enhance extremes sea levels. Because extreme wind events are predicted to be reinforced in the future, stronger seiche events may entail larger amplitudes of sea level extremes (Nesteckyte *et al.*, 2023). On the contrary, tides do not seem to affect sea level rise at regional scales (Vousdoukas *et al.*, 2017).

The rise of sea level has important impacts on coastal erosion, flood events and saline intrusions (van de Wal *et al.*, 2024). These impacts will continue to increase with the rise of sea level in mean and extreme conditions with climate change (Bednar-Friedl *et al.*, 2022; Glavovic *et al.*, 2022; Le Cozannet *et al.*, 2022). And locally, impacts of climate change can be reinforced by human activity (Carbognin & Tosi, 2002).

Waves and sea levels are linked to wind, and these two parameters need to be studied in parallel to assess future changes (Bacon and Carter, 1991; Mori *et al.*, 2010). Indeed, wind creates waves, but waves also modify flows at the air-sea interface (Semedo *et al.*, 2012). Wind-wave climate results from weather changes of surface wind fields over the ocean (Young & Ribal, 2019) but also from morphological changes on the coast caused by sea level changes, tides, and beach sediment dynamics (Bertin *et al.*, 2013). Wave climate is influenced by a large combination of factors such as prevailing wind patterns, storm tracks, local variations in bathymetry or topography (Neill, 2024), strong tidal currents (Hashemi *et al.*, 2015) and large tidal ranges (Lewis *et al.*, 2019) leading to complex temporal and spatial variability. Sea level can have an important effect on waves especially in macrotidal regions (Chaigneau *et al.*, 2023). Then, even at small local scales such as an offshore wind farm, sea states need to be studied locally and non-locally, to successfully consider all variability, particularly in the case of storm surges. For example, there may be a decrease in Hs predicted locally and an increase in Hs predicted non-locally (Lemos *et al.*, 2021). A recent study proposed that the decrease of the mean Hs around Europe is directly connected to the decrease of wind speeds using SSP5-8.5 from CMIP6 (Carvalho *et al.*, 2021). A study on all oceans announced that wind is the main driver for waves except in the Arctic (Meucci *et al.*, 2023).

The three French coasts stand out in terms of sea states influences: the English Channel is a mixed area with the western part of the Channel particularly influenced by the North-East Atlantic Ocean, while the eastern part corresponds to a superposition of sea states originating from the North Sea and those that have crossed the Channel (Laugel *et al.*, 2014); the Atlantic is dominated by ocean swells created non-locally by storms that can cross the Atlantic, called extratropical storms (Perez *et al.*, 2015); and the Mediterranean Sea, dominated by younger waves generated by wind in a closed sea. In the Bay of Biscay, spatial variations in Hs are similar according to the season, with strong values coming from the North-East Atlantic and then gradually decreasing as the coast approaches, as do the period and energy flow. Waves can be divided by a latitudinal limit of 50°N, with sea states above them propagating eastwards, and sea states below them propagating south-eastwards to reach the British or Aquitaine-Iberian coasts respectively. This latitudinal variability is weaker in the South than in the North.

The decrease in mean waves and the increase in extreme waves are linked to climate change. The poleward shift and weakening of the storm track in the North Atlantic will bring more storms to mid-latitude regions, i.e. an increase in surface winds (Hemer *et al*., 2007; Aarnes *et al*., 2017; Haarsma, 2021), even though these cyclones do not show a clear evolution for the past 25 years (Mori *et al*., 2010). A study of 5 reanalyses reports that in the North Atlantic, the number of cyclones with a weak center of pressure increased from 1979 to 1990 and then decreased until 2010 (Tilinina *et al*., 2013). A recent literature review by Feser *et al*. in 2015 on storms in the North Atlantic indicates that studies over a few years show a trend towards an increase in the number of storms, whereas longer-term studies over 100-150 years show no trend, as strong decadal variability is present. However, the intensity of extratropical cyclones is underestimated even with CMIP5 and CMIP6, as the resolution of these global climate models remains coarse and not all processes are resolved, so we are likely to experience even more significant changes than those predicted (Priestley & Catto, 2022). These changes in storm tracks may lead to major changes in weather and ocean conditions in certain regions (Morim *et al*., 2019; Pristley and Catto, 2022; IPCC, 2021), and the increase in extratropical cyclones (IPCC, 2021) by 2100 will lead to the increase in extreme waves (Charles *et al*., 2012; Hochet *et al*., 2021). A 17% increase in the frequency of future extratropical cyclones in the Atlantic is predicted (Seiler & Zwiers, 2016). Through ice melt and storm change, Hs decreases on average in the Northeast Atlantic, while it increases in the North through the increase in the northernmost westerly swell (Thomson & Rogers, 2014; Khon *et al*., 2014; Lobeto *et al*., 2021).

The increase in the frequency of "atmospheric blocking regimes" also plays a role in the decrease in mean swells in line with the decrease in the negative phase of the North Atlantic Oscillation, the NAO index and weather patterns dominated by storm tracks at low latitudes in the North Atlantic (Lemos *et al*., 2021). In fact, the negative phase of NAO in our regions indicate cold winters with few storms. In the North Atlantic, weather patterns such as the NAO can be correlated with the evolution of Hs (Bacon & Carter, 1991; Wang *et al*. 2012), and with wave direction and period (Dodet *et al*., 2010). A correlation can also be found with the East Atlantic Pattern (EAP) and the seasonality of sea states in the area (Vautard *et al*., 2010). The EAP brings a lot of precipitation and storms to the north-eastern Atlantic region. In the Irish sea, the wave power is correlated to the NAO index from September to March (Woolf *et al*., 2002). The wave height and its strong seasonality, simulated over the period 2012-2021 with the SWAN model forced by ERA5 winds, is also correlated to the NAO index (Neill, 2024). A recent, more regional index, called WEPA for West Europe Pressure Anomaly was introduced by Castelle *et al*. in 2018 because it shows a correlation with the variability of storms (e.g. Hs in winter) along northern European coasts. Finally, the geometry of the North Atlantic sub-basin, given the shift of storm tracks to higher latitudes and the presence of sheltering land masses such as Greenland and Iceland, are also important elements to consider (Semedo *et al.*, 2012). The more pronounced results in the RCP 8.5 scenario are consistent with greater Arctic warming (Overland *et al.*, 2014) than in the RCP 4.5 scenario, for example (Aarnes *et al.*, 2017). Indeed, if the temperature gradient between the Arctic and extratropical regions is increased, then baroclinic instabilities and cyclogenesis will increase (Seiler & Zwiers, 2016). In addition, some studies estimate that anthropogenic activity is not yet impacting sea states, but that this will change as early as 2050 (Hochet *et al.*, 2023).

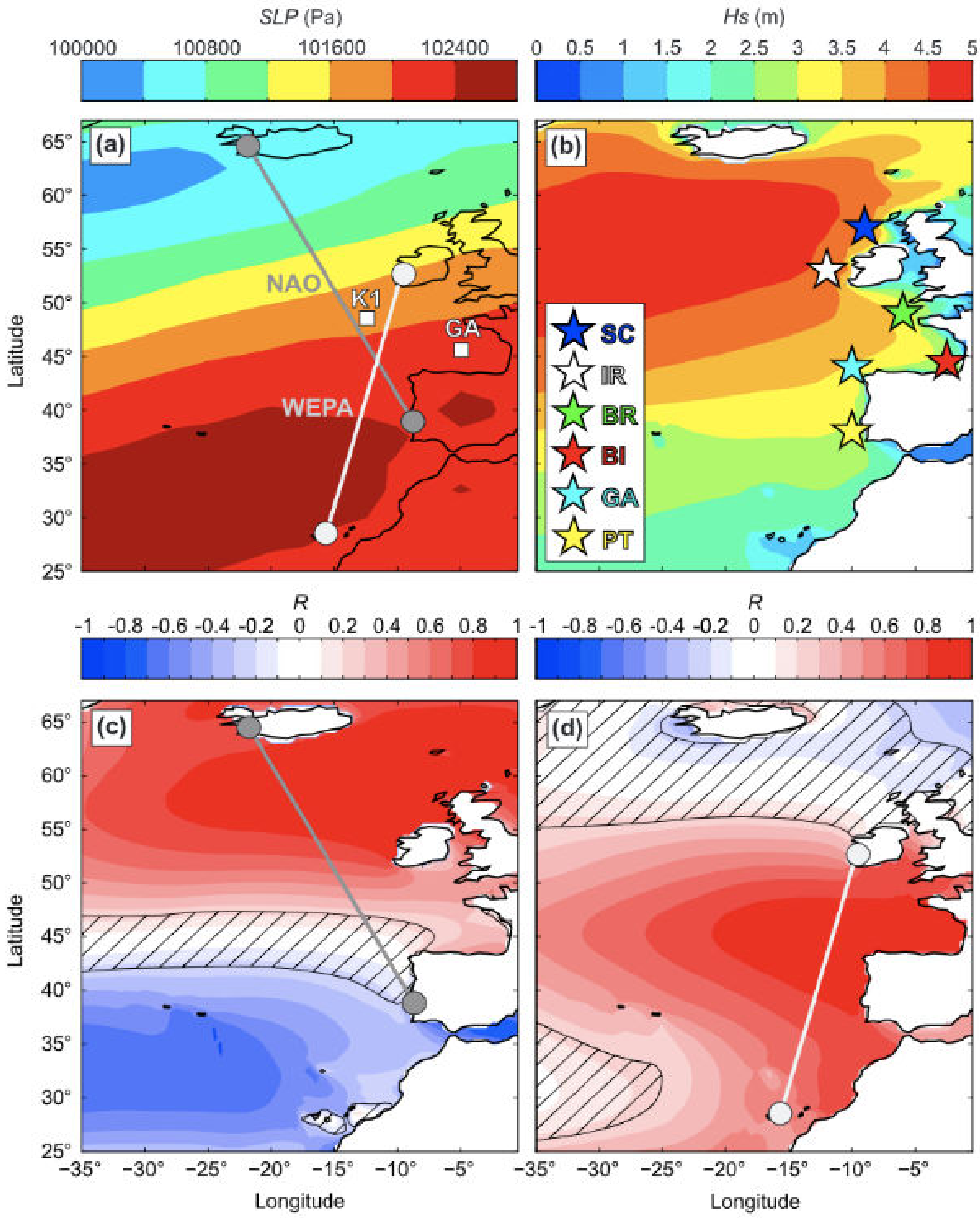

Fig. 10. Winter mean (a) sea level pressure (b) Hs (c) correlation between Hs and NAO and (d) correlation between Hs and WEPA (from Castelle et al., 2018)

4.4 Summary on the impacts of climate change on sea level and waves

Sea Level	Mean conditions	Extreme conditions
Historical	Global: Increase + 3.7 mm/y (IPCC, 2023) France: Increase + 1.25 mm/y (Reinert *et al.*, 2021) • Strong local differences: + 1.23 mm/y Roscoff VS + 4.25 mm/y Nice • Intensity increases stronger in the last 2 decades (+ 2.4 mm/y)	Global: Increase similar to MSL (Marcos & Woodworth, 2017; Calafat *et al.*, 2022) Baltic and North Sea: No significant trend (Weisse & Weidemann, 2017) France: Increase + 1.5 mm/y (Reinert *et al.*, 2021)
Future	Europe: Increase 2050 => + 21 cm (RCP4.5) + 24 cm (RCP8.5) 2100 => + 53 cm (RCP4.5) + 77 cm (RCP8.5) (Vousdoukas *et al.*, 2017)	Europe: Increase 2100 => + 57 cm (RCP4.5) + 81 cm (RCP8.5) • Up to 100 cm in the North Sea (Vousdoukas *et al.*, 2017) • Increase slowing down over time (IPCC, 2023)

Waves	Mean conditions	Extreme conditions
Historical	North Atlantic: Increase by 2% since 1950 (Bacon & Carter, 1991 - confirmed by Bertin *et al.*, 2013) France: Increase in the Bay of Biscay: 0.19 cm in winter and 0.16 cm in summer (Dodet *et al.*, 2010 - similar results found by Charles *et al.*, 2012) • Changes of wave direction (Morim *et al.*, 2019) • Strong seasonality of waves along French coasts (Dodet *et al.*, 2010; Charles *et al.*, 2012)	North Atlantic: Increase + 4 to 5 cm/y (Wang & Swail, 2002) France: Increase + 1 to 2 cm/y (Wang *et al.*, 2012)
Future	Global: Decrease in North hemisphere and increase in South hemisphere (Goyal *et al.*, 2021) North Atlantic: Decrease 2100 => - 6% (RCP4.5) - 10% (RCP8.5) (Aarnes *et al.*, 2017) Europe: Decrease 2100 => - 0.2m (RCP4.5 & 8.5) (Bricheno & Wolf, 2018) North Sea & Baltic Sea: Increase + 10% (RCP8.5) (Hemer *et al.*, 2013) Atlantic and Mediterranean: Decrease (Chaigneau *et al.*, 2023) Bay of Biscay: General decrease for all seasons (Charles *et al.*, 2012)	Global (oceanic basins of mid latitudes): Increase +1 %/y (Young *et al.*, 2011) Europe and France: no clear signal Increase: Baltic and North Sea + 5-8% (Bricheno & Wolf, 2018) Decrease (Aarnes *et al.*, 2017)

5 Impacts of climate change on offshore wind farms

As explained in Section 4, climate change may impact wind speed depending on regions and emission scenario. More specifically, impacts of climate change on the wind resource can be characterized in terms of changes on long-term wind speed distribution, strong and extreme wind speeds and finally daily or seasonal distributions. Section 4.1 gives some insights on this aspect. Besides, climate change may also have an influence on other climate variables (such as sea level, waves, ice, salinity, temperature, etc.) which are important for the design of offshore wind assets. Section 4.2 provides information on how climate change could impact the design of offshore wind farms.

5.1 Resource

The wind energy resource can be estimated in terms of wind power density (WPD, equations (1) and (5)). The changes in surface wind speed will affect the wind power density and then significantly affect the development of offshore wind farms. The WPD metric only considers the wind resource available on-site and is relevant to compare different locations or select the most wind energetic regions. The wind power density varies with the wind speed cubed, small changes in the wind speed leading to significant changes in the wind resource. In addition, two characteristics intrinsic to each turbine model play an important role: turbine radius, which determines the rotor area (A), and the rotor power coefficient (Cp), defined as a ratio of power extracted by the wind turbine to the energy available in the wind stream, which accounts for the efficiency of the wind turbine. Betz's law (Betz, 1966) states that no turbine can produce more than 16/27 (59.26%) of the kinetic energy in wind; this value is called Betz's coefficient. This is a theoretical maximum, but in practice, the efficiency is lower due to frictional losses, blade surface roughness, and mechanical imperfections. Modern wind turbines operate with efficiency coefficients around 40%.

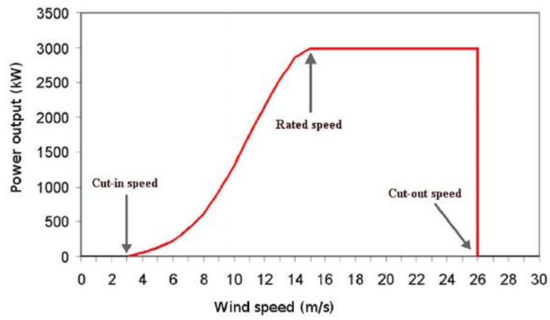

Fig. 11. Power curve of the wind turbine model Vestas V90 3MW (from de Castro et al., 2019)

Hence, the power output (usually expressed in kilowatts) generated by a turbine can be calculated as:

$$P_{out} = WPD.AC_p \qquad (5)$$

Therefore, wind power production strongly depends on the wind speed. The power curve (Fig. 11) shows how large the power output will be at different wind speeds. It varies depending on each turbine model. Note that a minimum velocity, called the cut-in velocity (usually around 3 m s–1), is necessary to start turbine rotation. Moreover, to avoid rotor damage, the wind turbine stops when it reaches a cut-out velocity (usually around 26 m s–1). Each turbine model also has a rated wind speed, which represents the minimum wind speed at which the maximum power output is reached. The cut-in and cut-out wind speeds refer to the wind speed at the hub height of the wind turbine.

The mean wind speed is not always a good predictor of the wind power resource. By far, the most widely used method to characterize wind speed involves the Weibull distribution (Hennessey, 1977; Monahan, 2006; Morgan *et al*., 2011) which represents the frequency distribution of each wind speed range. To estimate the annual energy output (kWh y–1) from a turbine, the Weibull distribution and the power curve must be combined.

$$P_{mean} = \sum P_T(v)\, f(v)$$

where ƒ(v) is the probability of the wind speed interval v and PT is the value of the power curve for that wind speed interval. The energy output of a turbine is usually expressed as a capacity factor (CF). It is a ratio of the energy generated over a period (usually a year) to a theoretical maximum that the turbine could generate, or in other words, the amount of energy produced if the turbine had been generating at rated power all the time.

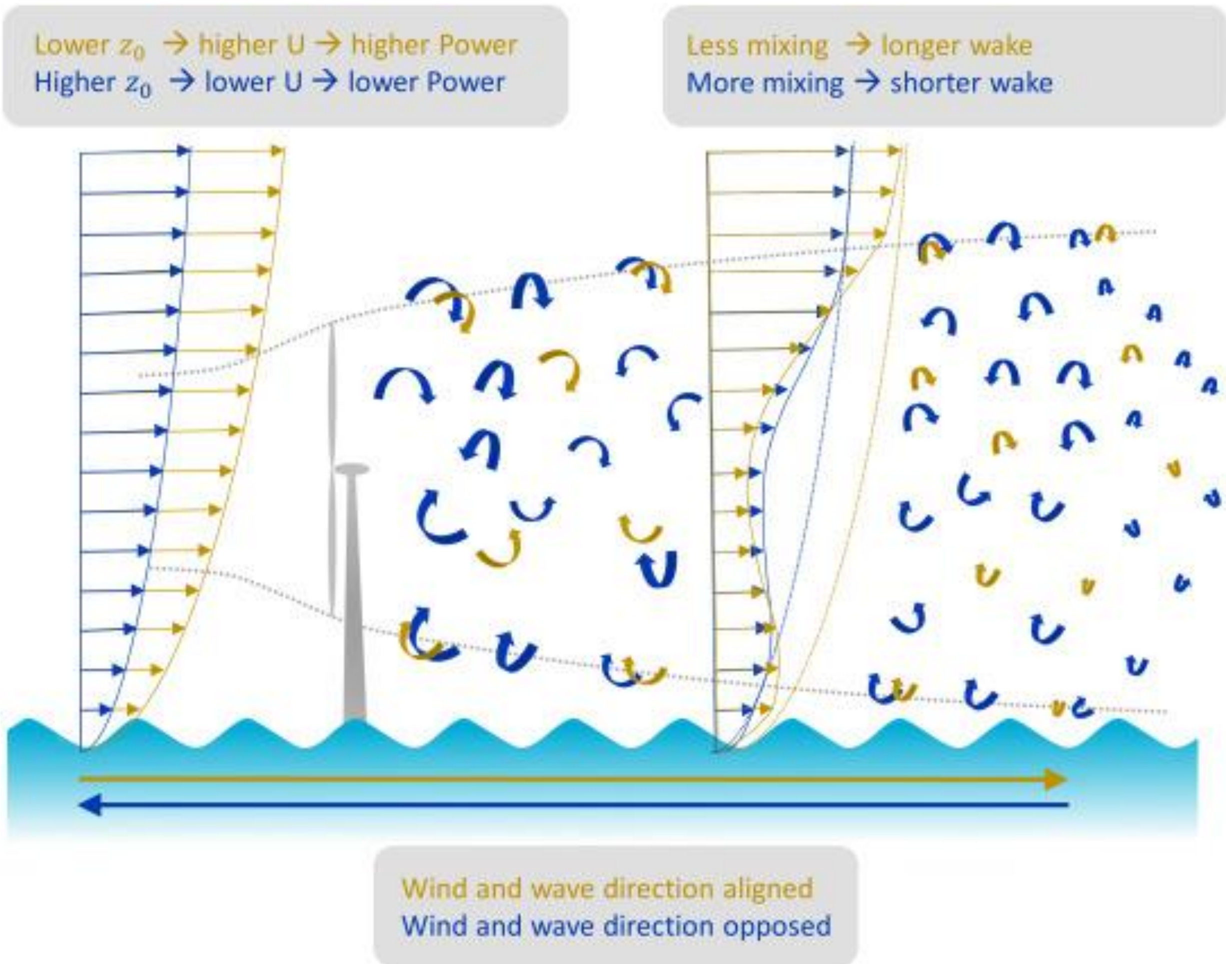

Fig. 12. Influence of wind-wave alignment on a single offshore wind turbine (from Porchetta et al., 2021)

In Section 4 of this document, we saw that the trend in terms of wind resources is downward for average conditions, whether for the historical period or future periods (projections). For the extreme conditions, there is no obvious consensus, but the trend is nevertheless towards an increase in low wind and strong wind events, respectively below the cut-in and above the cut-out velocities, i.e. out of the range of wind turbine generator (WTG) operability, if we look at climate projections (Carvalho *et al.*, 2021). Everything is therefore moving in the direction of a decrease in the WPD, which will nevertheless have to be quantified for each location in France and associated with uncertainty.

For wind resource assessment, the spatial inter-annual variabilities and annual cycles/seasonal variability of SWS are important along with mean value. Day-to-day variability can also cause challenges relating to the balancing of the grid and daily load demand. Seasonal variability (e.g. increased power availability in winter, reduced power in summer) can affect the profitability of the OWF's energy output, even if annual output is unaffected, as fluctuating energy prices throughout the year can lead to losses. Inter-annual variability can be detrimental to finance management and the ability to reimburse debt as it can result in unpredictable cash flow. Several studies have highlighted the increase in daily, seasonal and interannual variability of the wind resource due to climate change effects. Particularly, the wind power density is expected to increase during winter periods while significant decrease (sometimes reaching 30%) are expected for summer periods (Carvalho *et al*, 2017; Barkanov *et al*, 2024; Innosea, 2023; Costoya *et al*, 2022).

The study of direction and intensity of waves in the areas of offshore wind farms is also an important parameter because it can have a direct impact on the wind power production. Waves and wind traveling in the same (opposite) direction are estimated by models to generate a larger (smaller) power production for wind farms at sea (Porchetta *et al*., 2021) (Fig. 12). Yang *et al*. in 2014 found an increase of 13.6% (considering a moderate wind speed of 10 m/s) of average energy harvesting of an offshore wind turbine when aligned with swell waves in agreement also with Al Sam *et al*. in 2015.

Wave and wind resources are calculated over annual energy, and this is often coming from a specific direction with a specific intensity for most of the amount of energy considered for a farm as it is the case for Fuerteventura Island in the Atlantic Ocean (Veigas *et al*., 2014).

5.2 Design

5.2.1 Introduction

Offshore wind farms are now planned and designed for very long lifetime of about 30 years. Lifetime extension is also considered in the design of future and currently operating wind farms. Offshore wind assets are designed to reach this fatigue life corresponding to the lifetime, and to resist extreme metocean events. This design is based on the design load basis which is generally built on long historical site measurements assumed to be representative of the site-specific environmental conditions.

However, as explained in the previous sections 4 and 5, climate change may impact future environmental site conditions. The design of wind farms for longer lifetime implies sufficient accuracy of the site conditions design basis. However, basing the design on historical measurements only may not be sufficient and representative enough of the real environmental conditions during operation as those ones are prone to evolution due to climate change and may be influenced by climate variability. Fig. 13 below illustrates a typical temporal coverage for a wind farm, from the measurement for the design basis to the decommissioning stage.

In this context, it is important to investigate the impact that climate change could have on the design of wind farm components. Focusing on foundations, WTGs and subsea cables is particularly relevant given their dynamic interactions with the environment.

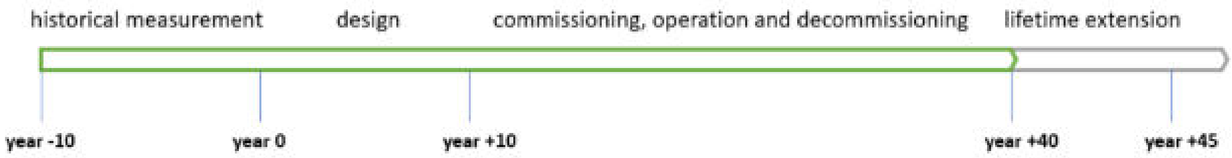

Fig. 13. Typical wind farm temporal coverage

5.2.2 Wind turbine generator foundations

Design of foundations for bottom-fixed Wind Turbine Generator (WTG) typically rely on the following norms for ultimate and fatigue assessment (non-exhaustive list as many different norms exist and equivalence can be found between them):

- **DNV-ST-0126**: Support structures for wind turbines (2021)
- **DNV-RP-C202**: Buckling strength of shells (2021)
- **DNV-RP-C203**: Fatigue design of offshore structures (2021)
- **Eurocode 3 EN-1993-1-6**: Strength and stability of shell structures (2021)
- **Eurocode 3 EN-1993-1-9**: Fatigue (2005)
- **IEC 61400-3-1**: Design requirements for fixed offshore wind turbines (2019).

The foundations design lifetime is inherent to the design fatigue and thus the design load basis. The design load basis relies on climate variables describing the sea states and wind resource. For example, as specified by DNV-ST-0126 (2021), the design load basis for offshore wind turbine support structures shall describe: wind climate, air density, temperature, snow and ice, water level, seabed level, wave climate, current, marine growth, and salinity for the design of cathodic protection systems.

The target lifetime is defined at early development stage. The design lifetime covers the full life cycle of offshore wind assets: installation and commissioning (typically 2 years), operational lifetime (typically 25 years, if set equal to the "WTG certified design life", see hereafter) and decommissioning (typically 1 year). Typical design lifetime seen on the industry currently is thus 28 years.

These operational site conditions may vary from the design load basis because of the effect of climate change on those parameters. Moreover, climate change may impact maintenance phases which are highly required in the later years of the wind farm and for lifetime extension (vessels access, harbour access, etc.).

Hence, climate change may impact the design of the wind turbine generator foundations:

- Changes in **wind speed**, leading to change of loads.
- Number and intensity of **extreme wind speed and gust** may increase/decrease (impacts on wind shear and turbulence which are main drivers for foundation fatigue), specially impact the wind-wave directional on-site.
- Changes in **sea level rise** which affect foundations design:
  - Corrosion mitigation measures may be extended/reduced on a part of the foundation.
  - Hydrodynamic loads may increase/decrease compared to the design load basis.
- Changes in **temperature** may drive ice melting and drifting sea ice likely to damage foundations.
- Changes of **wave conditions** may increase/decrease loads (impacting fatigue and extreme loads) and affect access conditions for wind turbine generator maintenance.
- Changes in **drifting sea ice**:
  - Drifting ice can collide with the foundations, creating an additional static (ice load) and dynamic load (drifting sea ice) which is often considered at design stage.
  - This load can destabilize foundation or cause fatigue. Measures such as ice-breaking cones can be attached to the structure at the water level as mentioned by James *et al.* in 2023
  - Significant reduction in sea ice thickness, ice days and sea ice extend due to climate change in areas such as the Baltic Sea leads to the reduction in ice loads in the near future (being an opportunity for the design) (James *et al*., 2023).
- Changes in **marine growth**:
  - Korpinen *et al*. in 2007, Nakano & Strayer in 2014, Sawall *et al*. in 2012 and Ahola *et al.*, 2021 show that close sea such as the Baltic Sea are particularly threatened by eutrophication changing the type of marine growth and density.
  - It may have an important impact on the drag loads (for the design) and regular cleaning and measurement are recommended (during operation) to check the integrity of the assets and evolution of the marine growth.

Currently, the only climate change stimuli considered in the design of wind turbine generator foundations (as per the norms mentioned above) is the sea level rise. Sometimes, the sea level rise values used in the design for hydrodynamic calculations are based on climate projections from the CMIP5 simulations (or before) which are not the last up-to-date projections and making any calculations that use this value less conservative, such as wave height definition, hydrodynamic loads, minimum splash zone, and so on. It is important to keep the values up to date, by using the latest report of IPCC (currently AR6) or their interactive atlas (IPCC, 2023; Meier *et al.*, 2022).

Detailed design is an expensive computer-based challenge which requires running many different simulations using these design loads. Wilkie & Galasso in 2020 developed a surrogate model to replace this method and assess various offshore wind structure performance metrics. This model allows running structural simulations with a small training sample of wind and wave conditions to predict failure due to fatigue. Specifically, this model allows estimating fatigue damage, fatigue reliability and financial losses due to structural failure using different environmental conditions projected by climate models for example. This method could be applied to assess the possible impacts of climate change on the foundations by using various design load basis which would include changes/variations (induced by climate change) compared to the original design load basis, without requiring heavy calculations, at design or later stage during operation.

As expected, Wilkie & Galasso in 2020 found in their case study (using a 5 MW open-source wind turbine generator model) that fatigue damage and structural safety are sensitive to changes in the site environmental conditions. However, the financial losses due to structural failure were found to be less sensitive to the considered climate change conditions as they also depend on non-structural components which are characterized by much higher failure rates. Bisoi & Haldar in 2016 and 2017 studied the climate change effects on the dynamic behaviour of monopiles foundations for wind turbine generators on the west coast of India. Similarly, they found that fatigue damages are sensitive to the evolution of climate conditions. Using CMIP5 simulations and a 5 MW wind turbine generator model they found that safety margin considering serviceability and fatigue life decreases and thus requires modification in the design.

Paul *et al*. in 2014 has developed an empirical model to predict the corrosion rate and hence life of the structure which can be used if changes in temperature or salinity are observed.

5.2.3 Wind turbine generators

Considerations for the wind turbine generators foundations are largely applicable to the wind turbine generators (tower + rotor nacelle assembly, or rotor-nacelle assembly) itself. Detrimental evolutions of wind and wave conditions induced by climate change may complicate offshore operations, leading to a less efficient maintenance of wind turbine generators, threatening the good operability of wind turbine generators and reducing the possibility of lifetime extension. In the case of floating wind, the risks and uncertainties are larger than in the case of bottom-fixed because of the lack of knowledge/experience concerning major maintenance operations such as:

- Offshore large component exchange, from a floating vessel (as opposite to a jack-up) to a floating wind turbine generator.
- Disconnection and tow-to-port of floating wind turbine generator.

In addition, the integrity of the rotor nacelle assembly may be affected by other climate change stimuli:

- **Blades** (especially in carbon fibre) and the **electronic control system** are the most sensitive parts of the wind turbine to lightning as highlighted by Zhang *et al*. in 2019.

- **Lightning strikes** create corrosion initiation (Cruz & Krausmann, 2013) which can influence preventive maintenance planning and potentially the frequency of maintenance operations.
- The damage due to **raindrops** has an erosive and a fatigue contribution on blades due to the impact force (Fiore *et al*., 2015; Bech *et al*, 2018). Damage can then propagate further through resins and fibres. Hence changes in precipitation pattern may affect the blades aerodynamics and so the power production. Adapting pitch and blade speed through controller may be a solution to ensure blades integrity and avoid leading edge erosion.
- Light **accumulation of ice** can affect blade aerodynamics and so reduce energy production, particularly in arctic latitudes (James *et al*. 2024). As reported, some studies in different regions of the world reported that the average number of icing events could decrease in the future due to climate change. A study (Pryor & Barthelmie, 2013) found that integrating a heating system within the blades at design stage could result in a net benefit of 19% increase in total electricity production with a 2% decrease in yield under normal operation, for sites (within Europe) most severely impacted by icing. This system needs to be integrated in detail in the design stage and will also increase the cost of the wind energy systems by approximatively 5%.
- A **rise in temperature** above certain limits of the wind turbine generator would result in a reduced energy yield as turbines limit energy output if certain temperature thresholds are met.

5.2.4 Tower

The tower primary steel is ultimately a “structural extension” of the foundation. As such, the insights and norms for wind turbine generator foundations are generally applicable to the wind turbine generator tower, accounting for some specificities:

- Some original equipment manufacturers have specific, non-public SN-curves (defining the number of cycles N to failure for a given stress S) for fatigue assessment of the tower. In this case, contribution of the original equipment manufacturers to the lifetime assessment is required. As mentioned above, Wilkie & Galasso developed in 2020 a model allowing to estimate fatigue damage in an efficient manner, and this method would be more accurate using the specific SN-curves for the tower.
- The fatigue life re-assessment must encompass the connection of key tower internals (such as the ladder and lift) to the inside of the tower primary steel.

5.2.5 Rotor nacelle assembly

The design of wind turbine generators typically rely on the following norms (non-exhaustive list as many different norms exist and equivalence can be found between them):

- **DNV-ST-0437**: Loads and site conditions for wind turbines (2021)
- **DNV-SE-0190**: Project certification of wind power plants (2023)
- **IEC 61400-3-1**: Design requirements for fixed offshore wind turbines (2019)
- **IEC 61400-3-2**: Design requirements for floating offshore wind turbines (2019).

As the rotor nacelle assembly is unlikely to be fully replaced, it should generally reach the targeted lifetime or extended lifetime (though repair or replacement of a few components such as blades can be considered, but not at the wind farm scale). The feasibility of rotor nacelle assembly lifetime extension can be assessed by checking the rotor nacelle assembly loads, typically: loads at blade bearings, loads at yaw bearing, drivetrain loads, and nacelle acceleration.

Climate change may impact these rotor nacelle assembly loads and a comparison with the type certificate loads, as detailed below, can also help to conclude on the feasibility for the rotor nacelle assembly to reach its design lifetime or not.

Unlike the wind turbine generator foundation and wind turbine generator tower, the rotor nacelle assembly of offshore wind turbines is not specifically designed for a wind farm. Instead:

- **The rotor nacelle assembly is designed for generic site conditions selected by the original equipment manufacturer.** These generic site conditions do not constitute a reference themselves.
- **The rotor nacelle assembly loads are assessed by the original equipment manufacturer for these generic site conditions.** The rotor nacelle assembly design is certified on this basis, leading to “type certificate loads”, that constitute a reference.
- **During the design of an offshore wind farm, site-specific loads are assessed by the wind turbine generator supplier.** These loads are compared to type certificate loads:
    - o If the site-specific loads are lower than the type certificate loads, then the rotor nacelle assembly is considered suitable for the specific wind farm.
    - o The fact that the rotor nacelle assembly suitability is assessed on rotor nacelle assembly loads (rather than on stresses of rotor nacelle assembly components, such as blades, gearbox, drivetrain) means that the original equipment manufacturer shares no information with the developer about the structural design and fatigue checks of these components.

A process to assess how climate change affects wind turbine generator lifetime could be based on a comparison of type certificate loads with the loads that are estimated using climate projections. This process is usually done when lifetime extension is assessed by comparing type certificate loads with real-life loads obtained by measurement or modelling. If the type certificate loads are more severe than the loads projected by climate models, there is a likely conservatism regarding changes induced by climate change, and thus possibly lifetime headroom. Along the same lines as the wind turbine generator foundations, the methods for modelling loads need to be in line with the state-of-the-art approaches (see norms mentioned above). Note however that, unlike for wind turbine generator foundations, the approach for rotor nacelle assembly is limited to loads, since the relationship between loads and fatigue life of rotor nacelle assembly components is unknown as well as the safety margin embedded into this relationship.

As such, if the type certificate loads are less severe than the loads projected by climate models, it will be difficult to conclude, given that the relationship between loads and fatigue life of rotor nacelle assembly components may, or may not, include a safety margin. In such case, the options to conclude on the impacts of climate change on the rotor nacelle assembly are the following:

- **Conclude that selecting this wind turbine generator is inappropriate** due to an under conservative type certificate loads turbine, based on loads comparison only.
- **Ask the original equipment manufacturers to conduct detailed fatigue analyses** on rotor nacelle assembly components based on the projected loads, to check if safety margins in the design can be challenged to conclude on the conservatisms and targeted lifetime of the rotor nacelle assembly. It is however unlikely that the original equipment manufacturers would engage significant engineering efforts in this task (the original equipment manufacturers' engineering teams being generally overloaded with the design of new wind turbine generator models and the assessment of site-specific loads for new wind farm project), although performing this assessment would be very relevant in an industrial context of long lifetime target and lifetime extension.
- **Conduct an independent assessment of the fatigue life** of rotor nacelle assembly components with specialized consultancies. Though it can be useful, this approach is likely to be more qualitative than quantitative, for the following reasons:
    - o Several specialized consultancies will have to be consulted depending on the rotor nacelle assembly component (for blades, the drivetrain, gearbox, etc.). This will make it more difficult to have a holistic understanding of the rotor nacelle assembly suitability.
    - o The consultancies will not have access to the detailed design of rotor nacelle assembly components. Their analyses will likely be based on generic, representative components. This will be useful to derive tendencies, but not accurate enough to provide a quantitative assessment.

5.2.6 Subsea cables

Climate change will likely lead to changes in water levels, wave conditions, precipitation patterns (inducing changes in flows at estuaries) and coastal erosion. Consequently, hydro-sedimentary regimes (especially in or near estuaries) may be modified, affecting the risk of scouring around foundations and cables. As such, the effect of climate change should be accounted for in cable routing and burial risk assessment engineering.

The design of subsea cables typically relies on the following norms for mechanical requirements (non-exhaustive list as many different norms exist and equivalence can be found between them):

- **DNV-RP-0360**: Subsea power cables in shallow water (2021) (cable routing)
- **IEC 60502-2**: Construction, dimensions and testing requirements for power cables for fixed installations such as distribution grids (2005)
- **DNV-ST-0119**: Floating wind turbine structures (2021)
- **DNV-OS-E301**: Position mooring (2021).

The term climate change is never specified in these norms. However, as highlighted by figure 14 hereafter and detailed in DNV-RP-

0360 (2021) many climate stimuli impact the design and construction of subsea cables, such as:

- **Strong winds** can restrict construction (vessel and cranes operational weather windows) or induce cable drifting.
- **Waves** can restrict vessel operations, induce cyclic loading (fatigue), erode beaches and impact subsea operations in some areas.
- **Tides, storm surge and low water levels** in general can impact navigation, cable laying and burial activities.
- **Currents** cause scour, vibrations (cyclic loading inducing fatigue) and may affect stability of cables lying unprotected on the seabed.
- **Precipitation** may particularly impact onshore activities and cable landing by opening trenches.
- **Sea ice** can exert mechanical loads on offshore units and connected cables. Icebergs can impact the seabed as well.
- **Salinity and marine growth** are also important parameters for cable design.

The risk of coastal flooding is not only determined by mean sea level but from the combined impact of precipitation, sea level rise, storm surge, wave setup, wave run-up, and flooding (Tinker *et al.*, 2016). When designing the landing zone of an offshore wind farm, it is necessary to have a certain stability in the thickness of sediments which cover these cables. The burial depth is directly linked to the protection of the cables, a significant depth being equal to significant protection, but also to the overheating of these cables and to the cost (significant depth = significant cost). Furthermore, it can be one of the highest risks to maintain operability of a wind farm (Porter & Philipps, 2020). The complicated design of the cable pathway, including cable length, required installation drilling distance, and position as well as potentially even a certain number of shoreline landfalls for multiple farms (e.g. Buljan, 2022) in a localized area, has caused site selection to become an increasingly studied topic. The target is to minimize the impacts on coastal environment and to optimize the Levelized Cost of Energy (LCOE) improving the overall business case.

In a recent study using satellite images, it was estimated that approximately 24% of the planet's sandy coasts are currently eroding at a rate of more than 0.5 m/year (Luijendijk *et al.*, 2018), and the impacts of climate change could accentuate this situation with changes in water level, local wave regimes, particularly extreme ones, and different sediment inputs (Toimil, 2019). The IPCC report (IPCC, 2022) indicates that coastal areas at elevations near sea level have high risks of future erosion, but studies of predicted changes are often limited to simple models considering only a single physical process (e.g. sea level rise), with high uncertainties, or site-specific studies (Magnan *et al.*, 2022).

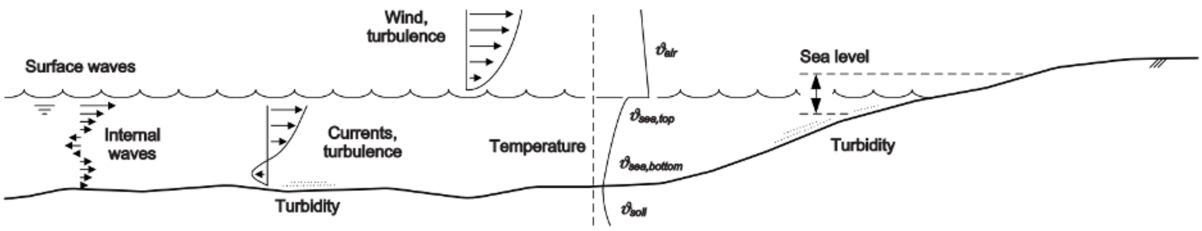

Fig. 14. Marine and terrestrial conditions along a cable route

Coastal evolution depends on many physical processes, ranging from hydrodynamic forcings (winds, waves, currents, and water levels) to local geological and morphological context, showing great spatial variability, requiring coastal evolution models on a local scale. Current models of projected shoreline changes most often rely on the extrapolation of historical trends, the application of simple empirical laws focusing on single processes (e.g. Bruun's rule in response to sea level rise (Bruun, 1962) or "expert" evaluations (Le Cozannet *et al.*, 2014). Current research (e.g. Montaño *et al*., 2020) focuses on using a wide range of different models with reduced complexity to make robust predictions of future shoreline changes, requiring probabilistic approaches and the integration of uncertainty estimates (Thiéblemont *et al*., 2021). When making projections of future shoreline changes, deterministic approaches predicting a single result should be replaced by probabilistic approaches, such as ensemble averages, allowing to make estimates of the associated uncertainties (Montaño *et al*., 2020). These uncertainties can be classified (Kroon *et al*., 2020) as: intrinsic (irreducible spatial and temporal uncertainties) or epistemic related to reducible model (e.g. formulation, numerical implementation, calibration parameters) and observational uncertainties (e.g. forcing conditions, model inputs).

5.2.7 Supporting assets

Damages to structures, movable assets and critical equipment as well as disruption to operations due to climate change can also be critical for offshore wind farms. Particularly, flood and inundation events can entail high risk:

- Sea level rise combined with surge events can lead to coastal flood events.
- Increasing annual and extreme precipitation, mean wind speeds, coastal erosion and extreme wave heights can also be responsible for floods and inundation.

Flood risk is generally assessed at design stage with specific flooding analysis, particularly for O&M base and onshore substation. Assets presenting high risks of floods can be relocated or elevated to mitigate the consequences of flood events.

Electrical infrastructure such as electricity distribution system can be vulnerable to failures, particularly aerial lines, due to storms, extreme wind speed events, ice or floods.

5.2.8 Applicability to floating wind

Although floating offshore wind turbines represents a minor part of the currently installed offshore wind turbines, the ambitious goals of development of offshore wind require a progressive shift towards deeper seas and so floating wind. Very few studies on the impacts of climate change on floating structures and floating wind exist so far:

- James *et al*. released in January 2024 a study about the impact of climate change on the design of spar floating wind turbines.
- Zou *et al*. in June 2014 studied the impact of climate change on fatigue assessment specifically for floating structures, but this work is not made public available.

Foundations

Foundations for floating wind encompass the floating structure, the mooring lines, and the anchors. Though the dynamic is not the same as that for fixed turbines, the floating foundation lifetime is assessed with the same process. Floating wind structures may be designed according to specific norms such as DNV-ST-0119 (2021) but their requirements are generally covered by the norms listed in Section 4.2.2. The content of this section is thus generally applicable to floating wind turbines, with some adaptations:

- **Marine growth** may be easier to inspect and less important to monitor comparing to bottom-fixed foundations:
    - o Only some models of floaters can be concerned with marine growth issues e.g., floaters including braces of small diameter.
    - o Additional drag induced by marine growth is not a major driver for fatigue on the mooring lines and anchors compared to WTG loads or corrosion.
- **Corrosion mitigation strategies** may be different:
    - o Impact of the corrosion on the floater fatigue is similar to bottom-fixed foundations.
    - o Corrosion is a major driver for the mooring lines fatigue. It is likely that monitoring and inspection would be required for this component.
- **Installation cases**: Towing of the floater may be more complex due to climate change if the weather windows are shorter and/or less frequent.

James *et al*. in 2024 used a climate model with the SSP2-4.5 scenario to analyse the effects of climate change on the floating structure:

- **Normal and extreme conditions** were assessed for two locations:
    - o One in the North Sea, at the Hywind Tampen floating wind farm location
    - o One off the west coast of India in the Arabic Sea
- **Bending moment, mooring tension and von Mises stress evolutions** were assessed using an Abaqus model. More severe extreme conditions leading to increases in bending moments, mooring tension and von Mises stresses, are expected. They suggest increasing the safety factors for regions with more frequent extreme wind and wave events to make the structure more robust.
- **Conservatism** has increased for the North Sea whereas it is decreased for the west coast of India due to the strengthening of extreme events. The variation was found to be minimal in normal operation but significant in extreme loading conditions. Therefore, the effects of climate change are found to be more pronounced in shutdown than in normal operation for both regions.

Wind turbine generator

Challenges for a floating wind turbine generator should remain almost the same as for a fixed wind turbine generator though including full consideration of the floating structure, which has a more dynamical behaviour. Therefore, the insights from Section 4.2.3 are applicable to floating wind as well.

It is worth mentioning that the study performed by James *et al*. in 2024 (mentioned above) also analysed some wind turbine generator design parameters such as the tower deflection or nacelle acceleration under future climate conditions. They found a decrease in the wind speed and wave height in normal operations for two locations, one in the North Sea and one off the west coast of India, leading to a reduction of tower deflection by 3-8% and a decrease of tower rotation and acceleration by 4%.

Subsea cables

Behaviour of dynamic umbilical is well understood for oil and gas applications; however, a significant learning curve is required for adapting technologies for the scales of offshore wind farms.

Dynamic subsea cables are designed considering the mechanical fatigue of the cable induced by the motions of the floating wind turbine generator and the direct hydrodynamic loads (from waves and currents) on the cable. Floating wind turbine generator subsea cables have a large dynamic part compared to bottom-fixed wind turbine generator subsea cables and as such may be more impacted by the climate change stimuli listed in Section 4.2.4.

The fatigue curves of the cables are in general not provided by the cable suppliers. These curves quantify the number of cycling loading allowable on the cable, depending on the nature of the load (tension, bending, torsion) and the load amplitude. This means that the cable supplier should contribute if the impact of changing loads due to climate change is assessed.

The structural health monitoring of dynamic cables for the floating wind industry is less mature than for foundations. As of now, some confidential R&D projects are ongoing to monitor motions and loads of dynamic cables of floating wind turbines. It is advised to follow how the state of the art on this topic evolves in the coming years.

A specificity of dynamic subsea cable is that the potential lifetime extension is not only driven by the fatigue limit state, but also by ultimate limit state. The reason for this is related to marine growth, which may be impacted by climate change as mentioned in Section 4.2.4:

- **Marine growth accumulation** onto the dynamic cable modifies its weight in water over time.
- Because of this, the **cable configuration** (the shape of the cable trajectory between the floater and the seabed) is not the same at the start of the wind farm life (no marine growth) and at the end of life (maximum, “design” marine growth thickness).
- During the design stage, **Ultimate Limit State (ULS) analysis** that supports the design considers both the start-of-life and end-of-life conditions. However, these “conditions” do not consider climate change impacts on the marine growth as it is very difficult to assess.
- **In case of lifetime extension**, the extra time allowing marine growth development may lead to exceeding the initially considered end-of-life conditions, making the lifetime extension unfeasible.

To deal with this topic, it is recommended to monitor marine growth development over time and include margin in the end-of-life conditions for possible increase of marine growth due to climate change.

5.3 Summary about the impacts of climate change on offshore wind farms

Impact on resource	• Wind power density is projected to decrease by 0 to 10% in the Mediterranean and very South of North Sea and increase between 0 and 10% in the North of North Sea according to SSP2-4.5 and SSP5-8.5 scenarios. • Less usable wind speeds, i.e. out of the wind turbine generator's operability range, are projected for future scenarios. • Daily, seasonal and inter annual variability are affected by climate change. • Results are highly dependent on the region of interest. It is difficult to quantify the changes for a large and global region e.g. the North Sea.
Impact on design	• Only the sea level rise caused by climate change is currently considered in the norms and guidelines used for the design of offshore wind assets. • Many other climate stimuli defined in the design load basis and used for the design of offshore wind assets could be affected by climate change. Effects of climate change on these stimuli are not yet considered in the guidelines. • Uncertainties related to the impacts of climate change on the integrity of offshore wind assets may be solved using conservatism in the design. • Long-lifetime and lifetime extension scenarios can be particularly threatened by climate change.

6 Conclusion

The impacts of climate change on wind, water levels, and waves has been investigated through a literature review. This synthesis focuses on both average and extreme conditions for each parameter, distinguishing between historical periods and future climate projections. The geographical scope is primarily Europe, with a particular emphasis on France when relevant studies are available.

It is important to note that future projections referenced in the literature are based on different generations of climate models and IPCC scenarios. As a result, discrepancies may arise between studies using older models (e.g., CMIP3) and those using more recent ones (e.g., CMIP6). In such cases, greater confidence should be placed in the most recent studies.

Table 7 summarizes the main trends identified in the scientific literature. Readers are referred to the relevant sections of this report for further details. The table highlights that consensus is not always achieved, particularly regarding extreme wind and wave conditions.

Moreover, this review shows that even when certain trends appear to be well established, results remain sensitive to temporal variability, geographic location, and the type of data used (observations or models). This is especially true for future projections, which depend on the selected scenarios. It is therefore appropriate to refine these conclusions for each of France's maritime regions, using long-term observational datasets, reanalyses, and state-of-the-art climate models wherever possible, in order to better estimate associated uncertainties.

Table 7. Main European trends for wind, sea level and waves. Please note that this table is there to help the reader and that it is difficult to summarize the historical and future periods of the exercises of the different papers reviewed. "Historical" means time periods generally cover several decades before 2020, with respect to 1970 or 1980; "Future" means the time horizons covered by the climate projections; generally, 2050 and 2100, with respect to periods before 2020. Please refer to the sections indicated for further details.

		Mean conditions	Extreme conditions	Section
Wind (in Europe)	Historical	Decrease	Decrease / Increase	4.1
	Future	Decrease	Increase (of low and high wind events)	4.2
Sea Level (in Europe)	Historical	Increase	Increase	5.1
	Future	Increase	Increase	5.2
Waves (in Europe)	Historical	Increase	Increase	5.1
	Future	Decrease	Decrease / Increase	5.2

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