Cambridge - McKinsey Risk Prize Bio-sketch and Photo Page

Student name: Tudor Suciu

Email contact: ts809@cam.ac.uk

Date of submission: 2 April 2024

Title of submission: Modelling Future Risk of Coastal Flooding in the UK: Risk Breakdown and Estimating Future Risk of Extreme Weather

I am a candidate for the degree: PhD Artificial Intelligence for Environmental Risks

Department: Computer Science

Linkedin profile link: https://www.linkedin.com/in/tudor-suciu/

Biosketch (approximately 150 words)

Tudor Suciu is a final year PhD student in the Artificial Intelligence for Environmental Risks (AI4ER) Centre for Doctoral Training, in the Computer Science Department, University of Cambridge.

His research explores methodologies that enable AI models to be applied in an explainable manner to generate reliable information for policy-makers. Tudor's PhD research focuses on utilising environmental sciences and machine learning to design a methodology that estimates future risks from coastal floods in the upcoming decades. This work touches on many topics, including time-series modelling, machine learning and statistics.

Tudor's research has been published and presented at leading science conferences in Europe and the US, as well as published in the Climate Resilience and Sustainability RMetS journal.

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Declaration Form

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Number of words of submission: 5,597

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Academic Institution/Department: Computer Science, University of Cambridge

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Modelling Future Risk of Coastal Flooding in the UK

Risk Breakdown and Estimating Future Risk of Extreme Weather

Cambridge - McKinsey Risk Prize Submission

Tudor Suciu

Executive Summary

As humanity faces the challenge of global warming and anthropogenic-driven climate change, understanding the risk posed by extreme weather events becomes paramount. Despite the focus in the public discourse on the global temperature rise, one of the most misunderstood consequences of global warming is its effect on extreme events, which pose the risk of significant disruption and damage to society, infrastructure, and human lives.

Disaster risk reduction strategies are hard to implement due to the uncontrollable nature of extreme weather. Thus, mitigation and adaptation strategies become crucial for building resilience against future disasters. Of particular importance is coastal flooding, being among the most damaging extreme events which poses a significant threat worldwide.

Understanding coastal flooding hazards requires a comprehensive assessment of contributing factors, such as weather patterns, tides, natural coastal features, and anthropogenic defences.

This essay explores risk modelling, presenting a novel data-driven approach to improve future predictions of coastal flooding intensity and likelihood.

Using Logistic Regression, we found that under a 'business-as-usual' emission scenario, the likelihood of storm-associated weather patterns (crucial for coastal flooding hazards) is expected to increase by 2.36 times from 2016 to 2059.

With this work, we aim to provide a perspective on the future risk of coastal flooding and potentially empower decision-makers in building resilience against the growing threat of coastal flooding in a changing climate.

1. Introduction

Global warming and anthropogenic-driven climate change are and probably will be the greatest challenges that humanity is facing in this century. Everyone is focused on the discussion about the global average temperature increase and where should humankind stop to not irreversibly damage the Earth's system. But, in our changing climate, the most misunderstood effect of global warming is the effect on extreme weather events. These phenomena are what create the most disruption and damage towards society, in all forms: financial, infrastructural, and operational, but especially damage towards people, leading to distress, health issues, casualties or even fatalities.

Munich Re estimates show that in the period 2013-2022, the global losses from natural disasters are in the trillions of dollars, with their approximation reaching 2.25 trillion $. Out of this, approximately only a third (35.2%) of those losses were insured for a sum of 793.5 billion $. Similarly, the UK's government estimates, in the National Risk Register 2023 edition (UK Cabinet Office, 2023), that extreme weather events[1] affected by climate change have an occurrence likelihood of 3-4 on a 5-point scale, and may be responsible for 100s of millions to billions of pounds worth of economic costs and 100s of fatalities, only in the British Isles. These numbers point out that the impacts of recent extreme weather events show a lack of preparedness for the current climate variability for countries at all levels of development (Suciu & Gunn, 2023).

Disaster risk reduction (DRR) strategies are extremely hard if not impossible to implement in this case. DRR is focused on reducing the chance of the hazard occurring, but as know, we can't control the weather and especially we can't stop extreme weather. Thus, we need to rely on mitigation and adaptation strategies for dealing with the aftermaths of those disasters - carefully building resilience for future extreme events requires a deep understanding of the event's likelihood and intensity (Pörtner et al., 1970).

Coastal flooding is usually regarded as the most damaging type of extreme weather event, yearly disrupting thousands of human lives and causing damages in the tens to hundreds of millions of dollars worldwide. The

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[1] - droughts, storms, surface water/fluvial/coastal flooding, extreme low and high temperatures and heatwaves.

Intergovernmental Panel on Climate Change (IPCC), the international body that collates all research on global warming and its effects, is confident is that storms and flooding induced damage in coastal areas has been increased by the effects of climate change, in all regions around the world.

This essay addresses risk modelling with both the industry and academia in mind. Further, we provide a novel way of improving the future predictions of coastal flooding intensity and likelihood, using a data-driven approach developed at the University of Cambridge. Following the update on modelling the coastal hazards, we provide a perspective on the future estimate of coastal flood and its estimated damages. Finally, we engage in a discussion on the uncertainty of the modelling practises, both the in-house method presented in here and across the industry, and we also provide an overlook on how this uncertainty can be further reduced.

2. Contextualising Coastal Flooding

In this section we will explore how the case study of coastal flooding in the UK is aligned to the risk industry's standard terminology. The definitions for each term used here are based on the Sendai Framework for Disaster Risk Reduction 2015 - 2030 (UNISDR, 2017).

Hazard	Coastal flooding is perceived as the primary hazard. It is characterised by the inundation of low-lying areas along the coast due to storm surges, high tides, or extreme weather events, directly threatening human life, property, and the environment.	**Disaster**	When coastal flooding exceeds the ability of a community or society to cope using its own resources, it transforms into a disaster. This can result in loss of life, significant damage to property, disruption of economic activities, and environmental degradation.
Exposure	Exposure in this context includes the populations, properties, infrastructure, and ecosystems located in coastal zones that are susceptible to flooding. The exposure could range from residential areas to critical infrastructure such as power plants, roads, and water treatment facilities situated near the coastline.	**Disaster Risk Management**	Encompasses the processes and measures to prepare for, respond to, and recover from coastal flooding disasters. It involves steps such as hazard identification, risk assessment, mitigation, preparedness, response, and recovery efforts aimed at minimising the impact of coastal flooding.
Vulnerability	Vulnerability to coastal flooding is influenced by factors such as the level of coastal defence (e.g., sea walls and flood barriers), the resilience of buildings and infrastructure, emergency preparedness, and the socio-economic resilience of individuals and communities to flood events.	**Disaster Risk Reduction**	Actions and strategies aimed at preventing new and reducing existing disaster risk related to coastal flooding. Measures involve enhancing coastal defences, implementing land-use planning to avoid building in high-risk areas, and improving early warning systems and evacuation plans.
Capacity	This refers to the resources, strategies, and abilities that communities, organisations, and governments have to manage and reduce the risk of coastal flooding. Capacity includes factors such as physical infrastructure, technological solutions, knowledge and information, legal frameworks, and social networks.	**Mitigation**	Mitigation efforts focus on reducing the severity of coastal flooding and its potential impacts. This may involve constructing flood defences, restoring natural barriers such as mangroves and wetlands, and implementing policies to reduce greenhouse gas emissions that contribute to sea-level rise.
Disaster Risk	The risk of disaster arises from the interaction between the coastal flooding hazard, the exposure of coastal communities and assets, and their vulnerability. It encompasses the potential for significant adverse effects on the population, economy, and environment.	**Resilience**	The capacity of coastal communities, systems, and infrastructures to anticipate, absorb, adapt to, and recover from the effects of coastal flooding in a timely and efficient manner. This includes maintaining essential functions and structures during and after a flood event and the ability to adapt to future risks.

Table 1: Aligning the case study of coastal flooding to the risk industry's standard terminology. Author: Tudor Suciu

3. What creates a Coastal Flooding Hazard?

In order to assess the disaster risk of coastal flooding, we need to understand precisely what are all of the contributors to such a hazard. It is only through breaking down the contributors into manageable metrics for each individual factor when we are able to constrain and estimate coastal flooding.

a. Weather - Storms;

Just like any extreme weather event, coastal flooding hazards and risks are associated everywhere around the globe with extreme weather phenomena. Particularly, in this case, the extreme weather phenomena responsible are storms. Whether tropical, subtropical or extratropical cyclones, these are all types of storms and weather systems that can lead to floods. The taxonomy differentiates them slightly in terms of either the global regions where they can occur or in terms of some small variations in the atmospheric conditions, such as maximum wind speeds. Yet, among those 3 types of storms, the most damaging and impactful are the tropical cyclones, also called hurricanes or typhoons. In

2023, the estimates show that the financial loss from all the storms around the planet adds up to more than $92 billion, with fatalities passing 6,500. The UK cannot be directly affected by the tropical cyclones, only through cross-basin aftermaths, it can impacted by their ‘smaller brothers’.

Assessing from a physical perspective how a storm is linked to a coastal flooding hazard, three mechanisms stand out, all linked to particular features of the atmosphere during the event. First of all, the storm is characterised by a low atmospheric pressure system, especially in the ‘eye’ (centre) of the cyclone. This directly causes the sea to surge, consequently raising the water level above the regular rest measurement. The second cyclonic feature is the presence of high wind speeds, which determines the two other mechanisms that increase the risk of a flood. Constant high winds can push water towards the exposed coastal communities, compounding with and increasing the amount of water height gained through the surge. High-speed wind gusts also contribute to unsettling the water surface of the sea, driving and causing higher and more energetic waves to hit the barriers and increasing the chances of both flooding through wave overtopping and via defence breaching.

b. Tides;

Tides are the natural oscillations in sea water level that occur due to the small gravitational forces of the Moon and the Sun, plus other small effects of the orbits. The main tidal cycle occurs once every ~12 hours and 25.2 minutes. This means that in that interval one can observe a full oscillation from high tide, to low and back to high tide. This makes the interval between high and low tide occur every 6 hours and 12.6 minutes, which affects all activities in coastal areas around the world.

This semi-diurnal cycle can swing the water level by more than 12m every about 6 hours, in the case of spring tides (the Sun and the Moon are aligned, creating a bigger effect; also called King tides, they are unrelated to the season). This range is affected by the shape of the coastline and the bathymetry (topography of the sea/ocean floor). Particularly, around the UK, we can encounter mean spring tide ranges in the lower levels of 1.9m, in Lowestoft (Suffolk, East of the UK), or up to 12.3m in the Bristol Channel (West of the UK), which is the 3rd biggest such range around the globe (NTSLF, 2024).

The tidal system is extremely influential in coastal flooding hazards and has a significant contribution. High tides bring the water level closer to where the defence systems reach their capacity. Hence, tidal (or nuisance) flooding occurs when the tide height is exceptionally high and can easily affect the draining systems in cities. For example, this can be seen around manholes in London while walking on the Thames banks, during a particular high tide.

One significant issue can arise when pairing a particularly high tide with a moderate storm. An average surge, from a storm with a 1-in-5 years return period, paired with the spring tide, can increase the intensity and severity of a coastal flooding hazard, compared to large storm systems (Haigh et al., 2017). The worst case scenario is having extremely large storms crossing the country when the astronomical tide is near its spring tide levels.

c. Natural Factors - Coastal and Geographical Specificities;

Other contributors to coastal flooding hazards, such as coastal features, coastal erosion, coast orientation, the bathymetry of the sea floor and topography of the land around the coast are grouped in the category of Natural Factors.

Coastal features could refer to naturally occurring barriers and defences that could stop the storm surge or wave overtopping, such as mangrove forests, or to the fact that the coastline is constantly changing. Linked to this, high levels of coastal erosion can exacerbate the exposure to coastal flooding hazards. It was found that in storms occurring sequentially (here, within 15 days), the vulnerability associated with the second cyclone is increased by the previous one, due to mechanisms related to weakening coastal infrastructures (Xi et al, 2023).

The orientation of the coast plays an important role in increasing or decreasing the risk of flood, when the wind direction of the storm is considered. In an interview with an RNLI Lifeboats volunteer, working in the surroundings of Cromer (Norfolk, East of England), we learn that turbulent waters are happening when winds blow from North, East and North-East directions, while the sea surface is steadier and calmer with southerly and westerly winds.

The bathymetry of the sea floor impacts directly how waves are created close to the coast and how high they can get. Finally, here, the topography of the coastal cities, settlements and surroundings changes where the direct surge flood can reach and which areas or buildings will be affected.

d. Anthropogenic Factors - Defences, Barriers and Infrastructure built for protection;

As part of the adaptation and mitigation strategies, we count the societal changes mainly in the form of building infrastructure to protect against flooding hazards. The efficiency of those is not towards mitigating the hazard itself but towards reducing the risk via decreasing the exposure and vulnerabilities of coastal communities. Those features, even though non-natural, have a direct impact on the intensity of a coastal flood that is felt by the exposed cities.

Those infrastructure projects can take shape in many different forms. Sea walls protect against direct flooding, surges and waves, helping to prevent water build-up on land and, indirectly, helping reduce coastal erosion. Moreover, rock or timber revetments or breakwaters using large concrete blocks are protections that dissipate the energy of the incoming waves, breaking them before they reach other defences during storms. Dikes and levees are mostly used to protect against river floods but can act as part of the flood water management where estuaries exist. Flood gates (or sluices, if smaller) are used to control the flow of water within the flood barriers, reservoirs, rivers or levee systems and to keep water from reaching the exposed areas - one such example is the Thames Barrier, built after the North Sea Flood of 1953, the biggest coastal flooding event that hit the British Isles in the past 100 years.

Other solutions can be less intrusive and resemble natural solutions more, such as beach, sand dune replenishment or beach drainage, consolidating against coastal erosion through groundwater management, enlarging wetlands and replenishing mangrove forests. Other anthropogenic factors that should be considered are population increase/decrease and the evolution of the coastal cities.

e. Interference with other type floods;

The potential damage of a coastal flooding hazard can be amplified by other flooding hazards happening at the same time, in the same location. Pluvial (or surface water) flooding is caused by massive quantities of rainfall exceeding the capacity of the drainage systems or of the ground absorbing it. This can often happen concomitantly with surges, as storms usually bring large amounts of precipitation as well as the high wind and the low pressure systems necessary for the coastal impacts. Pluvial flooding inference with coastal flooding is twofold: it increases the groundwater level, making the ground less absorbent to the surge water and making it more dangerous, but also it creates another layer of stress to the coastal community and its systems, such as passing the capacity of the drainage infrastructure.

Fluvial (or river) flooding is caused by sustained and large amounts of rainfall over the river catchment, making the water of said river to rise. Common occurrences can also happen seasonally, due to ice and snow from the mountains melting, increasing the flux of water in a basin in spring. Fluvial floods can negatively interfere with coastal floods in cities and communities that have an estuary (river reaching the sea), such as London, Bristol, Cardiff, Aberdeen, etc. High water from rivers and from the storm surge together create extensive pressure over the disaster risk reduction systems, more than the infrastructure may be designed to handle in the case of only one flood.

For example, in an interview with an employee of the Environmental Agency, we learn that the worst-case scenario for London is to have extensive rainfall over the Thames' catchment that rises Thames' water level, paired with a storm that creates more rainfall and a surge, during a particularly high tide. In certain unfortunate combinations of this scenario, the Thames Barrier might not be able to handle the extreme high water levels, thus allowing for extensive damage to occur throughout London.

f. Flooding mechanisms - Direct (Surge), Overtopping or Breaching;

Briefly mentioning the terms before, the flooding mechanism can also affect the coastal hazard and losses from it. Floods can be direct floods, caused by the sea water level rising during a storm surge; floods can be caused by wave overtopping, when high waves break over the defences and bring water past the barriers; or, floods can be caused by breaching the barriers, where vulnerable defences can fail during a storm under the surge and wave pressure, and partially or completely fail. Multiple flooding mechanisms can occur during the same event, increasing the intensity of the hazard.

g. Sea level rise.

The final contributor presented here is the sea water level, particularly its change: sea water level is an outcome of climate change and global warming, increasing the height of the planetary waters by a small amount each year, due to polar ice caps and glaciers melting or due to heat-driven ocean water expansion. When taking this effect into account, sea-level rise dominates future coastal risk in the upcoming decades, while being dependant on the future emission scenarios (Perks et al., 2023).

It is worth noting that the disaster risk for coastal floods is highly localised, as many contributors can differ wildly, even in two adjacent coastal cities. For example, from one year to the next, there could be defence breaches in Cardiff and none in Bristol, which will make the next storm impact both of those cities differently. As well, the disaster risk varies with respect to time, over long periods, purely from the climatic factors. We already know that sea level rise is creating a large problem in the future decades, but research shows that storms and the weather necessary for a coastal flooding hazard is likely to change, with those events potentially becoming more frequent and more intense.

All those factors mentioned above contribute to determine the extent of the damage that a coastal flooding hazard or disaster can have over an exposed community. To understand future risk, it is necessary to constrain and predict information regarding all factors and understand how the effects are compounding together, for each coastal community. The insurance industry, policy makers and academia have to work together in order to share information and estimate those future risks as accurately as possible, in order to drive change in the disaster risk management and in building resilience in the vulnerable communities.

3.1 Discussion about Coastal Flooding Risk Breakdown

The contributors to coastal flooding risks presented in the previous section have different timelines in which they change. Similarly, we possess different levels of knowledge associated with them. In this section we will describe the sources uncertainty associated with each of the coastal flooding risk contributors, starting with the ones we have most knowledge of and moving towards the more uncertain ones.

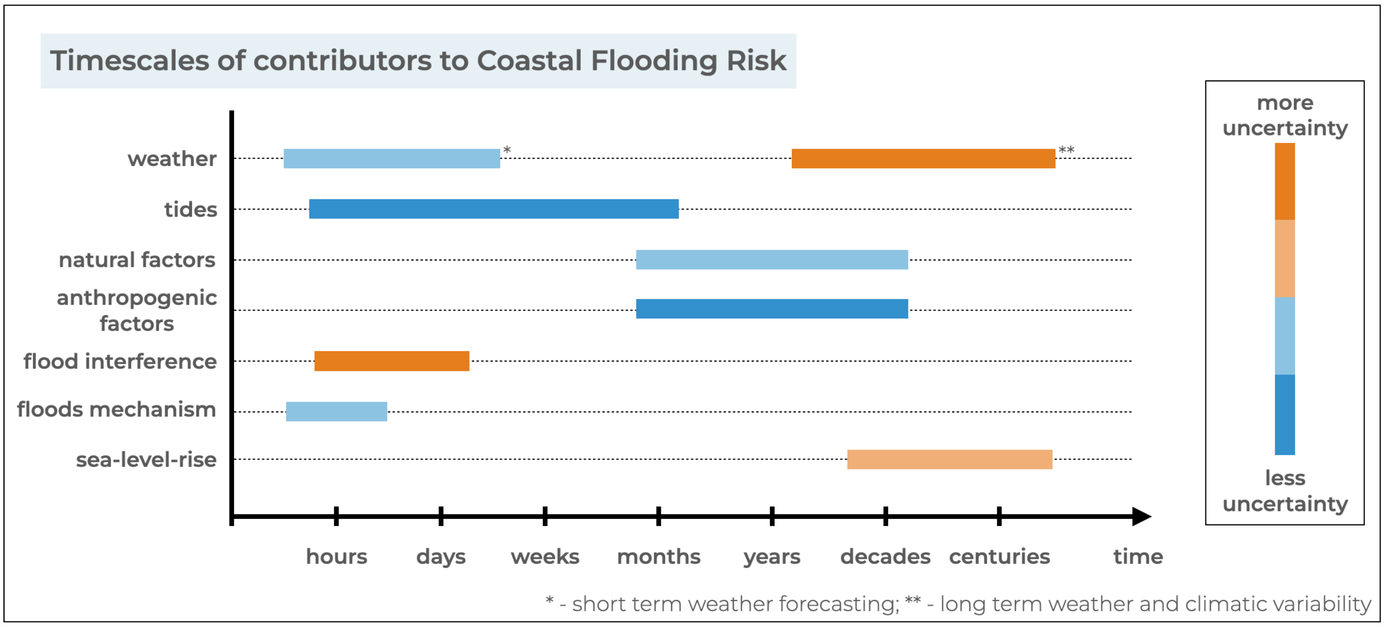

Figure 1: Timescale of contributors to Coastal Flooding Risk. Illustration by Tudor Suciu.

Tides can be very accurately constrained in the future due to the knowledge we have about the positions of the Earth, Moon, Sun and our ability to calculate the tidal influence on the sea water level, with many of its physical constituents.

We also estimate that **anthropogenic factors** have a higher degree of knowledge surrounding them, as in the UK (at least) the government and the Environmental Agency have data on the quality of the barriers, defences and human-made infrastructure destined to retain coastal floods. Similarly, we assume that all future infrastructure projects are known and approved years to decades in advance.

Short term weather forecast is very well constrained due to the efforts of national agencies, such as the MetOffice, or international ones, such as the European Centre for Mid-range Weather Forecast (ECMWF), which has the most accurate physics-based models to simulate the atmospheric conditions. The ECMWF forecast is shared within all European countries and usually forms the basis of what we see in the media forecasts. Recently, large data-driven and Artificial Intelligence initiatives have been able to surpass the accuracy of the ECMWF forecast, with the agency recognising the efforts of Google DeepMind and Huawei and incorporating some of those models on their online platform. Operationally, the Environmental Agency, in collaboration with the MetOffice, uses a nowcasting alerting system, which allows the citizens of the exposed areas to learn days in advance about an imminent storm and the likelihood of a flood affecting their area.

Moreover, the aforementioned agencies and risk industry have developed over the years storm surge models, like NEMO, SLOSH, the RMS® North Atlantic Hurricane Models (from Moody's RMS) or the AIR Storm Surge Module (from Verisk). Those models aim to estimate numerically how far water will spread during storms, which can improve the operational alerts and understand much better which areas and buildings are at risk

When it comes to **Natural Factors**, even though they are more uncertain than human-made defences, they are less susceptible to change, remaining the same for multiple years to decades. Changes in the coastline's shape or coastal erosion can be inferred long before it has happened and societal decisions can work together with those natural effects to counteract the increasing risk.

Flood mechanisms are very location-dependent and act in conjunction with natural and anthropogenic factors. Looking at two different examples: 1) wave overtopping might be the principal flood mechanism around a coastal town with a sea floor bathymetry that encourages high waves, while 2) direct flooding will happen predominantly in regions with very low lands, such as the East of England or the Netherlands. We assume that each coastal community or industry and governmental stakeholder is aware of which flood mechanisms have a higher chance of occurring from past experiences and careful surveying of the areas around.

We previously said that **sea-level rise (SLR)** will become extremely important in the future decades, as it will create a constant threat of high sea water levels. The uncertainty associated with SLR is still high and future SLR estimation is mostly a function of how the global efforts actively mitigate climate change via reducing and storing greenhouse gases emissions. However, the trajectories are easier to constrain compared to the next 2 factors, especially the upper and lower ends of them. There is also, more research on SLR evolution in the next decades, thus we don't consider it in the most extreme level.

Flood interference makes up a big portion of the uncertainty associated to coastal flooding risk, as it is extremely hard to constrain timely and acts on very short time-scales. Even if paired with an accurate short term weather forecasting system, the reaction of the system entire to the forecasted weather is close to impossible to calculate. It would require models with extremely precise information on everything: how much water reaches a river's catchment and how much snow and ice is melting in the catchment, how much rainfall will be expected, what is the current flow of the human-made rain water drainage systems in cities, likelihood of failing for every subunit in those systems and how the other subunits are influenced, groundwater level, etc. Shortly said, it would require and extremely precise digital-twin of the natural and urban environment, plus accurately modelling the randomness of the human population. While positive work is done in this direction, flood interference still remains a large part of the uncertainty associated with the risk, but, luckily, on very short time-scales.

The biggest uncertainty comes, in our opinion, from the **long term weather and climatic variability**. Weather cannot be accurately predicted more than 2 weeks in advance, so how can we draw information on how many flooding-inducing storms should we expect in the next 10 years? IPCC estimates that storms, cyclones and, more generally, weather patterns will change in the future, with extreme weather changing the most. The change in the frequency and intensity of future extreme weather is where the biggest amount of uncertainty in estimating future coastal flooding risk lies, and, this is also an underdeveloped area of study in the climate sciences domains, especially compared to other extreme events or SLR estimations.

In order to protect against coastal flooding hazards and build resilience for them, timely action is necessary more than ever. The uncertainty of the information on this contributor of the hazard creates extensive problems with planning the disaster risk reduction strategies for the upcoming years and decades. To name a few issues, without accurate information:

- not enough defence systems might be built in areas where an unexpected increase in number of storms will happen, creating more vulnerability;
- planned defences are built with a smaller expectation of storms, which might result in infrastructural design decisions that might not last as long as planned, with potential of barriers to fails earlier than expected;
- misunderstandings in future intensity of extreme weather might affect building defences not strong enough for one storm, or not big enough, to contain more intense storms and surges.

Our work in the past years was focused on creating a data-driven methodology that assess how the weather conditions necessary for coastal flooding hazards is changing in the future. Using climatic projections under different emission scenarios, we were able to constrain how many such weather conditions we expect in the future decades, compared to the past ones.

4. Improving Future Risk Estimates of Coastal Flooding Hazards with Data-Driven Methods

4.1 Goal

Starting with the aim of this project, our goal was to develop a data-driven methodology to :

- use past records of coastal floods around the UK and weather observations;
- find the best understandable and interpretable model, to approximate the likelihood of a coastal flood to occur, based on atmospheric data around a particular coastal community;
- for each location, use the best model to obtain the future expectation of weather conditions necessary for storms and/or coastal floods to occur;
- compare the future expectation with past observations, under different emission scenarios, to obtain actionable information on how the frequency of future coastal floods and storms will change.

4.2 Data

The data is used in this study to find the best model for each location, to train those models and to generate the predictions afterwards. For locations around the UK coast, we used 33 locations from the British Oceanographic Data Centre (BODC) tide surge network. Data on coastal flooding records comes from the SurgeWatch 2.0 project (Haigh et al., 2016), which collated many different sources of information together to create a dataset that contains all coastal flooding events around the chosen locations in the period 1916-2015. Past weather data, such as pressure, temperature, wind speed, cumulative precipitation or vertical vorticity of the wind, is gathered from the ERA5 reanalysis data (Hersbach et al., 2020) in the period 1960 - 2015. The ERA5 dataset is the closest to real observations of the atmosphere and is a gold standard in climate science for this.

Future simulations of atmospheric variables come from 8 models in the CMIP6 (CMIP6) ensemble of Global Circulation Models (GCMs). The timeframe chosen for the assessment is 2016-2059; as the models are old but still state-of-the-art, 2016 is the initial year in the simulation, so we choose to use it as such. The GCM data is bias corrected before it is used in the simulations, which is a standard procedure. The emission scenario chosen here for the study is the SSP 5-8.5, which stands for the Shared Socio-economic Pathways 5-8.5, in which is the global economy continues the fossil-fueled development (Canada GOV, 2019). This is colloquially known as the 'business-as-usual' emission scenario.

4.3 Methodology

Finding the best model for approximating whether there is a a high likelihood of a flood or not, at any given time point can become fairly technical, but for the purpose of this report, we will keep the content light. Initial tests on different Artificial Intelligence algorithm showed improvement with increasing their complexity, reaching the stage in which we started delving into Deep Learning territory.

A change of paradigm was motivated by policy-makers and by the risk industry. Using very large deep learning models, that are hard to understand and interpret, is not desirable for the purposes of obtaining a KPI that might be part of an investment strategy. While there exist techniques of disentangling the black-box deep learning models, those methods are still recent and can lack the trustworthy-ness of simpler data-driven models that have inherent understandability to them.

We settled on the Logistic Regression algorithm for this analysis, a class of model that provides automatically ways to understand how the inputs affect the output. Thus, the task at hand was to find the best model that takes all the inputs from the atmospheric variable, the tides and NAO, and predicts the probability of a flood to occur at a given time, at a given location. This procedure involved statistical and machine learning concepts that reduce the overfitting[2] of the model, such as cross-validation, hyper-parameter search and regularisation, improving the accuracy of the outputs and solving the problem of extreme class imbalance. For each location we found the best model, taking into account all of those details in the procedure.

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[2] overfitting a model specialises that model in the training data, which will affect performance on new datasets; here, this is prevented to not bias the predictions

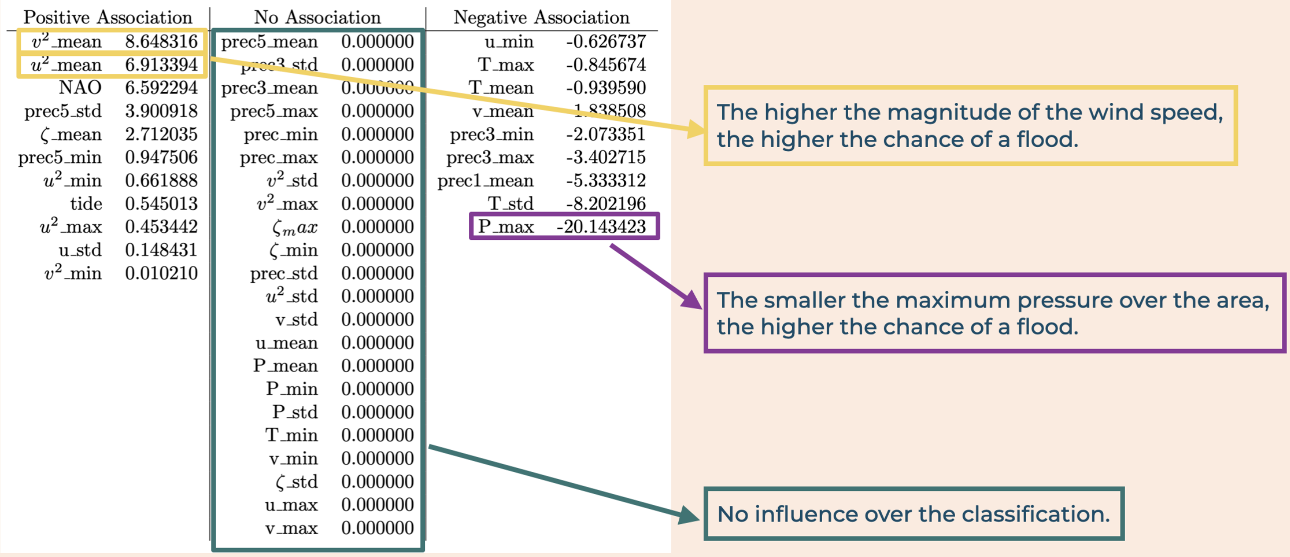
Case Study - best model for Aberdeen

Currently, the most improved for Aberdeen model contains, in the form of the average, minimum, maximum and the standard deviation over an area of 420x680 Km (or 6.25°x6.25° latitude-longitude) around Aberdeen, the following variables:

- pressure, P
- temperature, T
- zonal wind speed and its square, u and u^2
- meridional wind speed and its square, v and v^2
- cumulative precipitation over last 1/3/5 days
- vertical vorticity of the wind, ζ_k

The NAO and the tides in Aberdeen are also added, as a single time-series.

Looking inside at the weight, we can understand what feature the model uses to predict the probability of a flood.



Positive Association		No Association		Negative Association	
v^2_mean	8.648316	prec5_mean	0.000000	u_min	-0.626737
u^2_mean	6.913394	prec3_std	0.000000	T_max	-0.845674
NAO	6.592294	prec3_mean	0.000000	T_mean	-0.939590
prec5_std	3.900918	prec5_max	0.000000	v_mean	-1.838508
ζ_mean	2.712035	prec_min	0.000000	prec3_min	-2.073351
prec5_min	0.947506	prec_max	0.000000	prec3_max	-3.402715
u^2_min	0.661888	v^2_std	0.000000	prec1_mean	-5.333312
tide	0.545013	v^2_max	0.000000	T_std	-8.202196
u^2_max	0.453442	ζ_max	0.000000	P_max	-20.143423
u_std	0.148431	ζ_min	0.000000		
v^2_min	0.010210	prec_std	0.000000		
		u^2_std	0.000000		
		v_std	0.000000		
		u_mean	0.000000		
		P_mean	0.000000		
		P_min	0.000000		
		P_std	0.000000		
		T_min	0.000000		
		v_min	0.000000		
		ζ_std	0.000000		
		u_max	0.000000		
		v_max	0.000000		

The higher the magnitude of the wind speed, the higher the chance of a flood.

The smaller the maximum pressure over the area, the higher the chance of a flood.

No influence over the classification.

These features are aligned with the information we have from domain science, on what are the signatures of storms. During a storm, we have high winds (in yellow) and we have a low-pressure system (in purple). Other features complement those features, adding more information, or are removed from the model (features that show a weight of 0), to reduce the overfitting effect.

5. Results

Using the best models for each of the 33 location chosen in the study, in the 'Business-as-usual' (SSP 5-8.5) scenario, we expect an increase of 2.36 ± 0.52 times in the likelihood of occurrence of weather patterns that are necessary for storms and coastal flooding hazards.

location	future frequency	standard deviation	location	future frequency	standard deviation	location	future frequency	standard deviation
Aberdeen	**1.41**	0.55	Holyhead	**4.57**	1.03	Port Ellen	**2.37**	0.68
Avonmouth	**2.05**	0.40	Ilfracombe	**2.13**	0.62	Port Patrick	**1.61**	0.49
Barmouth	**2.30**	0.40	Immingham	**4.43**	0.79	Portsmouth	**1.71**	0.50
Bournemouth	**4.08**	0.57	Kinlochbervi	**1.37**	0.32	Sheerness	**1.44**	0.38
Cromer	**0.62**	0.15	Leith	**1.25**	0.16	Stornoway	**1.72**	0.40
Devonport	**3.00**	0.85	Llandudno	**2.34**	0.30	Tobermory	**2.89**	1.43
Dover	**2.56**	0.34	Lowestoft	**2.06**	0.23	Weymouth	**3.27**	0.43
Fishguard	**5.23**	1.04	Millport	**1.34**	0.22	Whitby	**0.85**	0.37
Harwich	**0.88**	0.15	Mumbles	**3.58**	0.46	Wick	**1.41**	0.39
Heysham	**4.41**	0.92	Newlyn	**2.00**	0.38	Workington	**3.20**	0.78
Hinkleypoint	**1.86**	0.23	Newport	**3.08**	0.58			

Table 2: Results of estimating the future frequency of weather patterns necessary for storms and coastal floods in the 'business-as-usual' scenario. Author: Tudor Suciu.

Breaking this down into each location, we have most location expecting an increase in the storm-associated weather patterns, but we do have some cases in which the expected frequency is smaller in the period 2016-2059 compared to 2008-2015.

6. Conclusion

Tropical, subtropical and extratropical cyclones are the worst extreme weather events that can impact coastal communities around the globe. In the UK, only the extratropical and subtropical (less often) can create havoc and cause financial loss, casualties and even fatalities. Those storms are one of the biggest contributors towards the risk of coastal flooding hazard.

Coastal floods risk can be described as a function of weather, tides, natural factors, anthropogenic factors, interference with other types floods, the mechanism of the flooding event and by the sea-lever rise. We presented a breakdown of all the risks associated to coastal flooding events and created a taxonomy of ranking them from the least to the most uncertain. The second most uncertain contributor to coastal floods are the interferences with other floods, while the biggest level of uncertainty is drawn from the long term variability in the weather conditions necessary of creating such storms and floods.

We presented a methodology of estimating how the frequency of the future weather patterns that are necessary for storms and coastal flooding hazards, using a data-driven approach. Our modelling stage is based on the paradigm that, for decisions that are involving large scale infrastructural developments and large financial costs, it is better to use something inherently understandable, reliable and trustworthy. The logistic regression models where chosen for this study, with the potential of expanding the modelling repertoire with other explainable machine learning methods. Inside the models, the automated feature selection and the weights of those show that the models learn to predict the probability of occurrence of hazard-inducing weather by using features that are the signature of a surge-causing storm (i.e. low pressure system and high wind speed magnitudes).

Our simulations show that, over the entire UK, in the period 2016-2059, there is an expected increase in the frequency of the future weather patterns that are necessary for storms and coastal flooding hazards of 2.36 ± 0.72 times, in the ‘business-as-usual’ emissions scenario and when compared to the period 2008-2015. The uncertainty in this estimation comes from using multiple (8) global climate models. The biggest increase is observed in Fishguard, of 5.23 ± 1.04 times, while the smallest change is estimated in Cromer, of 0.62 ± 0.15.

The models and the procedure can be further improved and more future scenarios can be used to see how each specific pathway is affecting the future risk. This work presented an overview of what can be done to address the future risk of coastal flooding, from a data-driven perspective, by choosing to tackle the problem with the biggest uncertainty.

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