Department for Environment Food & Rural Affairs

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delivering benefits through evidence

Rapid evidence assessment of non-stationarity in sources of UK flooding

FRS18087/REA/R1

Flood and Coastal Erosion Risk Management Research and Development Programme

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Published by:
Environment Agency, Horizon House, Deanery Road,
Bristol, BS1 5AH

http://www.gov.uk/government/organisations/environment-agency

ISBN: 978-1-84911-470-7

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Dissemination status:
Publicly available

Keywords:
Stationarity, non-stationarity, rapid evidence assessment, fluvial, coastal, pluvial

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FRS18087

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This report is the result of research commissioned and funded by the Joint Flood and Coastal Erosion Risk Management Research and Development Programme. The Joint Programme is jointly overseen by Defra, the Environment Agency, Natural Resources Wales and the Welsh Government on behalf of all Risk Management Authorities in England and Wales:
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Professor Doug Wilson
Director, Research, Analysis and Evaluation

Executive summary

There is a perception that floods are becoming more frequent or more severe in parts of the UK. This has led to questions about the suitability of current approaches that are relied on for the planning and design of flood protection.

Methods used to estimate the probability and magnitude of floods tend to assume that measurements of floods from years ago have the same statistical properties as current measurements. In other words, all floods recorded at a particular location belong to the same statistical distribution as each other. Extrapolations are made based on this assumption of stationarity. Current estimates of extreme rainfalls, river flows, waves and storm surges all rely on this assumption. The only variable that is not routinely assumed to be stationary in UK practice is the mean sea-level component of total sea level.

If the assumption of stationarity is incorrect, estimates of flood and rainfall extremes may be biased, raising questions as to whether flood defences are being designed appropriately to protect communities against present and future risks and whether investment is being allocated appropriately.

For this project we synthesised current knowledge on stationarity or non-stationarity in sources of fluvial, coastal and pluvial flooding in the UK using a systematic approach. We followed the rapid evidence assessment (REA) process, which has been developed by the Department for Environment, Food and Rural Affairs (Defra) to provide a rigorous, transparent and exhaustive synthesis of evidence from scientific literature. An REA follows a similar process to a systematic review, but introduces some restrictions so that it does not take as long or cost as much.

The process involves definition of research questions, development of a protocol, a systematic search for evidence, screening of the evidence, extraction of evidence into a systematic map, critical appraisal of the evidence, synthesis and finally drawing of conclusions.

The primary question that we addressed in this project is:

- What is the evidence for stationarity or non-stationarity in sources of UK flooding?

We also addressed three secondary questions, at a lower level of detail:

- What can cause non-stationarity in the sources of UK flooding?
- What techniques are used to detect and account for non-stationarity in the sources of UK flooding?
- To what extent does an assumption of stationarity or non-stationarity alter the outcome of flood risk analysis?

The questions deal with the sources of flooding, such as rainfall, tides or river flows, rather than impacts such as the effect of floods on people or property.

Findings

Our initial search identified 9,749 articles from the literature that were potentially relevant to the questions. After screening, we reduced this to a more manageable set of 379. Of these articles, we found that 334 were accessible to us. We read all of them to extract evidence to populate the systematic map. Our critical appraisal led to a final set of 144 articles that we judged were sufficiently relevant and robust. Our findings are synthesised from these 144 studies.

The studies showed a general, but not universal, consensus that both precipitation and flood flows on rivers are increasing. Most of these studies analysed series of measured data, but about a third of the papers included an investigation of future changes, generally using modelling techniques. Most of these used climate change scenarios to represent potential future rainfall conditions, and some then applied rainfall-runoff models to compare the impact of present and future climatic conditions on river flows. Most of these modelling studies concluded that increases in extreme rainfall and peak river flows are expected. These findings have led to climate change allowances that are currently applied by practitioners. Other studies used models to investigate the effects of land use change on fluvial flooding.

Studies that found no change, or a decrease, in flood flows, were mostly focused on a small number of locations. However, some of them were broader studies that included historical data spanning several centuries. This provides an important longer-term perspective. It can be difficult to reliably diagnose non-stationarity in relatively short data series characterised by large variability, particularly given the tendency for clusters of flood-poor and flood-rich years. One consequence may be that even if changes in the climate or land use are having an impact on the sources of pluvial and fluvial flooding in the UK, we may not be able to detect this impact in some locations for many decades into the future.

These findings of non-stationarity in sources of inland flooding contrast with the current common practice of not allowing for non-stationarity when carrying out frequency analysis of rainfall and peak flow data.

The literature we reviewed in this study supports current practice for calculating coastal extremes based on historical data when sufficiently long time series exist, that being: assuming winds, waves, storm surge and astronomical tides are stationary and a linear increase in mean sea level. Studies find evidence that the future distributions of all coastal flood sources are non-stationary under climate change. However, for storm surge the consensus is that over century timescales, the distribution can be assumed to be stationary. These results mirror the latest climate change guidance (UK Climate Projections 2018 [UKCP18]), but not current practice used for future flood risk assessments, where the astronomical tide is assumed to be stationary. Studies agree tidal distributions are changing with sea-level rise: the larger the sea-level rise, the more inappropriate the assumption of stationarity becomes. Therefore, assuming observed astronomical tides come from a stationary distribution seems reasonable, as observed sea-level rise is small. However, assuming the astronomical tide distribution is stationary when assessing future epochs, with larger predicted sea-level rises, is not supported by the literature.

We found climate change and teleconnections to be the most frequently identified causes of non-stationarity in all sources of flooding. However, a large proportion of the studies which found non-stationarity either provided no information on its cause or could not attribute it to one specific cause.

We found little evidence to answer the question on the extent to which an assumption of stationarity or non-stationarity alters the outcome of flood risk analysis.

Acknowledgements

We are grateful to the Project Steering Group of technical experts who provided substantial input in shaping the project, including Sean Longfield, Peter Spencer, Sue Manson and Tim Hunt (Environment Agency), Glenda Tudor-Ward (Natural Resources Wales), Becky Wilson (Scottish Environment Protection Agency), Nick Reynard and Jamie Hannaford (Centre for Ecology and Hydrology), Ye Liu (HR Wallingford), Ivan Haigh (University of Southampton) and Thomas Kjeldsen (University of Bath). We are also grateful to Henry Moss of Lancaster University for advice and code for implementing topic models.

Ilaria Prosdocimi, Assistant Professor in Statistics at the Ca' Foscari University of Venice, provided a peer review of the draft report. We are grateful for her input and encouragement.

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1 Introduction

Our aim was to synthesise current knowledge on stationarity or non-stationarity in sources of fluvial, coastal and pluvial flooding in the UK using a systematic approach. This report is organised as follows: the introduction begins by defining the key terms used in the report and then details the assumptions made regarding stationarity in current flood risk assessments; Section 2 details the methodology used for the evidence review; Section 3 details the results of the review; and Section 4 summarises the key findings

1.1 Motivation

Multiple occurrences of widespread flooding in recent years have led to questions about the suitability of current approaches for flood estimation. Current flood frequency statistics assume, for all variables except the mean sea-level component of total sea level, that observed flood events at a single location belong to the same distribution, and extrapolations are made based on this assumption. If the assumption of stationarity is incorrect, flood and rainfall extremes may be incorrect, raising questions as to whether flood defences are being designed appropriately to protect local communities against future risks and whether investment in flood protection is being allocated appropriately.

The Environment Agency intends to use the findings from this evidence assessment to help guide the approach taken by emerging initiatives, such as the Hydrology Roadmap, NaFRA2 (the National Flood Risk Assessment) and a recently started project, Development of Interim National Guidance on Non-Stationary Fluvial Flood Frequency Estimation.

1.2 Rapid evidence assessments

The Department for Environment, Food and Rural Affairs (Defra) has worked with partners to develop methods for conducting evidence reviews that are designed to make the most of existing research investment. One of these methods is a rapid evidence assessment (REA), which follows a systematic review approach but is less resource intensive, while maintaining rigour and transparency. Detailed REA guidance is provided in Collins and others (2015).

Typically, REAs consist of a series of steps common to the systematic review process, but the aims and objectives of the study are defined so that it can be completed on a relatively short timescale. While an REA should be as rigorous and exhaustive as possible, restrictions can be applied to reduce the time and expense of delivery. This flexibility means that although the conclusions can be translated into practice in a reasonable timeframe, they are not as robust as results of a systematic review.

For this study we have broadly followed the methodology of Collins and others (2015), which describes in clear terms the necessary steps of a REA, along with the roles and responsibilities of all parties involved. The main parties are the review team, who undertake the review, and the steering group, a group of technical experts who guide and assist the review team where necessary to ensure the outputs of the REA meet the needs of end users.

Following this methodology, the main tasks of the REA review team are:

- to agree the research questions to be addressed in the study
- to develop a protocol outlining their approach to the study and agree it with the steering group
- to complete a search for relevant evidence
- to screen the evidence, retaining only evidence relevant to the research questions
- to systematically extract evidence relating to the research questions into a systematic map
- to critically appraise the evidence, evaluating it in terms of relevance to the research questions and robustness of the methodology applied
- to synthesise the evidence to produce summary information describing the volume and characteristics of the evidence base
- to draw conclusions from the results of the evidence review
- to communicate the evidence review findings

The steering group signs off the project.

We have followed this systematic approach to ensure the conclusions of our review are as robust as possible. We describe our methodology in Section 2.

1.3 Definition of stationarity

There are multiple definitions of stationarity, as discussed in Section 2.1.2. For this review we adopted the functional definition of stationarity defined in US Army Corps of Engineers (2018): a stationary time series is one that fluctuates within an unchanging envelope of variability.

1.4 Source–pathway–receptor model

The source–pathway–receptor model is a useful tool for understanding flood risk and flooding mechanisms and is used widely in the Environment Agency. It is a conceptual model for representing systems and processes that lead to a particular consequence. For a flood risk to arise there must be hazard that consists of a ‘source’ (for example high rainfall); a ‘receptor’ (for example flood plain properties); and a pathway between the source and the receptor (that is flood routes including defences). Changes in flood risk can arise from changes in pathways (for example new flood defences) and receptors (coastal populations). Here we focus on (non-)stationarity in the source component.

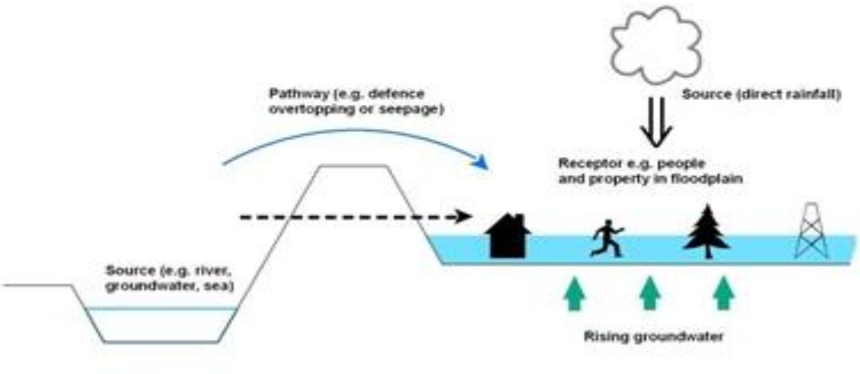

Figure 1.1 Example of source–pathway–receptor model, Environment Agency Fluvial Design Guide[1]

1.5 Sources of flooding considered

We focused on sources of flooding only and not impacts arising from them. We investigated stationarity or non-stationarity of the following sources of flooding:

- still sea levels (the sum of mean sea level, astronomical tide and storm surge)
- local wind climate (which affects waves; see below)
- offshore wave conditions
- precipitation
- extreme fluvial flows

The glossary provides definitions of the technical terms we have used.

One reason for including precipitation is that not all inland flooding is fluvial in origin. Intense precipitation (generally rainfall, but also potentially snowfall if it melts quickly) can also lead to flooding from surface runoff, also known as pluvial flooding. Because there are virtually no measurements of runoff before it enters watercourses, any information on expected changes in pluvial flooding is likely to be found in studies that investigate the stationarity or non-stationarity of precipitation.

The knowledge gained in this study will inform the Environment Agency's assessment of the suitability of current approaches for flood estimation. For coastal flood risk assessments, statistical analysis is performed on offshore wave conditions and therefore we did not consider changes in nearshore wave conditions. Similarly, beach erosion and accretion will dramatically change flood impacts at coastal locations, along with changes to flood defences; however, we did not consider these changes in our study as our focus is on offshore sources of coastal flooding.

We included local wind climate as well as waves because coastal flood risk assessments calculate nearshore wave conditions by propagating offshore waves inshore and by calculating locally generated wind waves. In sheltered locations, for

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[1] http://evidence.environment-agency.gov.uk/FCERM/en/FluvialDesignGuide.aspx

example inside estuaries or harbours, the waves at the coastline may be entirely locally generated. Local wind climate is described by the wind speed and wind direction, and also by cyclone frequency and intensity.

1.6 Current common practice

In current flood risk studies undertaken for the Environment Agency, non-stationarity is assumed for historic (Environment Agency, forthcoming) and future mean sea level (UKCP09 and UKCP18). All other historic time series of flood risk drivers are usually assumed to be stationary over the period of analysis.

This assumption of stationarity is usually dropped when considering future conditions. Future wind speeds, wave heights, rainfall intensities and flood flows are assumed to differ from present-day values as a result of climate change. However, for some applications, such as design of flood alleviation schemes, change factors are applied as a sensitivity test and then a managed adaptive approach is implemented, with defence heights being set for current conditions, with an option of raising defences in the future if necessary.

The following sections give more details on current common practice and supporting references.

1.6.1 Observed data

The current best estimates of extreme sea levels around the UK are provided by the Coastal Flood Boundary dataset (2019)[2]. This dataset assumes:

- non-stationarity of mean sea level
- stationarity of astronomical tides over an 18.6-year cycle
- stationarity of the skew surge distribution

It is assumed that mean sea level has increased and that a linear trend is appropriate. To account for the non-stationarity of mean sea level, sea-level time series are de-trended by removing a linear sea-level rise trend before extreme value analysis is undertaken.

All other flood-related variables are usually assumed to be stationary when analysing observed data. For example, the Flood Estimation Handbook methods and their updates (Institute of Hydrology, 1999; Kjeldsen and others, 2008; Stewart and others, 2013) assume stationarity of extreme rainfall and peak river flows. More recently some projects carried out for the Environment Agency have started to fit non-stationary frequency distributions to peak river flow data, for example as part of the planning of flood alleviation schemes in Cumbria.

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[2] https://www.gov.uk/government/publications/coastal-flood-boundary-conditions-for-uk-mainland-and-islands-design-sea-levels. [Accessed 1 August 2019].

1.6.2 Future conditions

Due to climate change, the future distributions of some flood risk variables are not assumed to be stationary. Existing flood risk studies use the Environment Agency's guidance (Environment Agency, 2016)[3] and the National Planning Policy Framework (NPPF) guidance (Ministry of Housing, Communities and Local Government, 2019) on which variables to treat as non-stationary and how these distributions might change. Table 1.1 details the variables that are assumed to be non-stationary; all other variables are assumed to be stationary.

Table 1.1 Variables considered as non-stationary in future epochs in existing flood risk assessments

Variable	Future change
Mean sea level	Increasing with spatially varying values around the coastline
Offshore wind speed	5% increase up to 2055 then a 10% increase
Extreme offshore wave height	5% increase up to 2055 then a 10% increase
Rainfall intensity	10–20% increase for the 2050s
Fluvial flows	Range of increases in peak flow depending on geographical location (river basin district) and epoch, with a range of percentiles to allow for uncertainty

UK climate change guidance has recently been updated (November 2018) and future studies will use UKCP18. The UKCP18 Marine Report (Palmer and others, 2018) investigated the stationarity of coastal flood risk drivers. The key findings are:

- UK coastal flood risk is expected to increase over the 21st century under all representative concentration pathway (RCP) climate change scenarios, predominately due to increases in mean sea level
- projections of mean sea-level rise vary according to geographic location and future emissions
- UK tide gauge records show year-to-year changes in coastal sea levels (typically several centimetres) – the report recommends that coastal decision makers account for this variability in risk assessments, particularly for shorter-term planning horizons
- based on storm surge modelling, the best estimate is that extreme sea levels will not significantly increase in future due to changes in storm surge – in ensemble surge simulations, the largest trend was 0.10 metres per century for the 1-year extreme sea level
- 21st century projections of average wave height suggest changes of the order of 10–20% and a general tendency towards lower wave heights. Changes in wave heights vary around the UK – in some locations there are increases and in some locations decreases (see fig 3.14). Changes in

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[3] based on UKCP09

extreme waves are also of the order of 10–20%, but there is no agreement among the model projections as to whether the waves are increasing or decreasing in height

- idealised tidal simulations suggest that mean sea-level increases above 1 metre could have a substantial (> 10%) impact on tidal amplitude around the UK, with large spatial variations

UKCP18 provides improved projections of the impact of climate change on extreme rainfall (Murphy and others, 2018). However, the results from the finest-resolution model simulations (2.2 kilometres) have not yet been released, and these will be key for understanding potential changes in convective rainfall.

Impacts of climate change on fluvial and pluvial flood risk depend not only on changes in rainfall, but also on the effects of temperature and other climatic variables on evapotranspiration and hence soil moisture and groundwater conditions. The Environment Agency has commissioned research to model these impacts, due to be completed in 2020.

2 Methodology

2.1 Research questions and scope

2.1.1 Primary question

The original scope specified a question asking if there was evidence of non-stationarity in flood (fluvial and coastal) and rainfall extremes in the UK. However, we altered this question as part of an iterative process following concerns about its wording. First, the original wording implicitly assumed that stationarity is the baseline position in flood studies, when this is not necessarily the case. It was also unclear whether the phrase ‘flood extremes’ is more suited to impact studies than an analysis with a focus on the source of flooding. Non-stationarity of flood impacts is expected to occur even if there is no change in meteorological, hydrological or marine processes due to interventions such as development on floodplains and construction of defences. The question was also posed such that the outcome would be binary and easily answered if one study was to provide evidence of non-stationarity.

After several iterations, the primary research question was finalised as:

What is the evidence for stationarity or non-stationarity in sources of UK flooding?

The question asks for the evidence rather than a binary outcome, and also ensures that the review starts from a position of not assuming either stationarity or non-stationarity as the baseline. We also reworded the question to specify sources of flooding as the focus of the study, as opposed to flood impacts.

One remaining issue was the definition of a non-stationary process, for which there appears to be little consensus in the statistical and hydrology literature.

2.1.2 What is non-stationarity?

A standard statistical definition of a non-stationary process is one whose joint probability distribution changes over time (Shumway and Stoffer, 2017). This can arise as a result of changes in the mean or variance in a time series over the period of record, perhaps manifesting as a trend or step change. A time series is considered strictly stationary if the joint distribution of a sequence of observations is the same no matter what interval of the time series is being analysed. A weaker definition commonly applied is one of second-order stationarity, that the mean, variance and autocovariance (covariance between lagged terms) remains constant over the period of record. In using this definition for flood risk management, difficulties arise due to the timescale of change not being specified.

River floods and extreme sea levels are subject to seasonal and/or astronomical cycles, resulting in the probability of observing a particular value changing over time. Dixon and Tawn (1999) refer to the astronomical cycle as one non-stationary component of sea level. However, because these cycles are well known, they are sometimes not regarded as non-stationary in a practical sense for flood risk management activities. There are also longer-term cycles, for example as seen in the alternation between flood-rich and flood-poor periods. Over the duration of a typical river flow record, these cycles may appear as a statistically significant trend, and therefore the observed time series may be classed as non-stationary, but it is unclear if the entire process can be classed as non-stationary given the short record length.

An alternative definition, adopted by the World Meteorological Organisation (WMO) and derived from studies such as Koutsoyiannis (2011), states that a non-stationary process has statistical properties that are deterministic functions of time. Under this definition, a stationary process can exhibit fluctuations, trends and excursions that can persist for decades. To identify non-stationarity under this definition it is therefore necessary to attribute trends to a physical cause that represents a known function. For example, non-stationarity would be identified where increases in flood flows can be confidently explained by urban development in the catchment. Attribution is key to this definition of non-stationarity.

Ideally, flood risk managers need knowledge of how sources of flooding will change into the future. In the absence of this, we could consider a third definition: a process is stationary if the distributional properties of measurements are constant over the observed period and expected to remain constant over the period of future predictions. The issue with this definition is typically the expectation of constancy into the future is inferred from past and present observations.

We consider each of these definitions of non-stationarity for this review. It may be the case that the technical definition of non-stationarity is distracting from the main question relevant to practitioners: is the probability of flooding changing over a time scale that is relevant to people who are affected?

Floods and non-stationarity: a review – US Army Corps of Engineers

US Army Corps of Engineers (2018) presents a helpful way forward in the debate over the definition of non-stationarity. The document provides a comprehensive review of approaches to handling non-stationarity as part of a hydrological flood frequency analysis. The authors emphasise that care must be taken not to dispense with the assumption of stationarity quickly, and that any observed non-stationarity may be a short- or long-term fluctuation of the climate system. Distinguishing between stationary and non-stationary processes is therefore difficult as such persistent excursions can occur within a stationary process. The authors use the term ‘functional non-stationarity’ to describe change in the behaviour of a dataset (rather than a physical process), which can be associated with the statistical population from which the dataset is drawn.

If the population is stationary but the dataset features a long excursion due to climate dynamics, the authors recommend the use of paleo-flood information to constrain and/or interpret flood frequency estimates. Otherwise non-stationarity should be explicitly modelled and the authors propose a range of methods to accomplish this. The authors also review a range of risk measures appropriate for non-stationary processes.

We adopt the functional definition of non-stationarity for this review due to its ease of use and the substantial evidence base on the subject. Where possible, we make links with the WMO definition through identification and attribution of change to physical drivers.

2.1.3 Secondary questions

REAs allow for a review of secondary research questions to supplement the findings of the primary question. We addressed the following three additional research questions:

1. What can cause non-stationarity in the sources of UK flooding?
2. What techniques are used to detect and account for non-stationarity in the sources of UK flooding?
3. To what extent does an assumption of stationarity or non-stationarity alter the outcome of flood risk analysis?

2.1.4 Scope

The scope of the review describes its geographical, language and date constraints, as determined by resourcing and time available and informed by the wording of the research questions. Note that we made changes to the initial scope based on the number of results obtained during the evidence search. We discuss this in further detail in Section 2.2.

Geography: the primary question refers to the evidence relating to non-stationarity in the UK. The initial scope aimed to include evidence from other countries with similar climates and processes to the UK. For example, we initially included all countries with coastlines on the European Continental Shelf for review as these countries experience offshore conditions similar to the UK. However, as the evidence base expanded beyond the limits of the project, we decided to constrain the scope. For this reason, we restricted the literature search to analysis of sources of coastal, fluvial or pluvial (surface water) flooding in the UK.

Language: the evidence search was limited to the English language as it was expected that the vast majority of sources would be written in English.

Date: we initially decided to extract evidence relating to the primary question by focusing on the literature in the period 1998–present, which contains most studies of trends in UK flooding. Due to the unmanageable number of articles uncovered during the evidence search, we restricted this period to 2009–present, that is the last 10 years. We deemed this appropriate as more recent studies include more data than older studies and use better climate predictions, and thus generally supersede earlier work.

2.2 Literature search

2.2.1 Data sources

Based on the definition of the primary question, we compiled a list of keywords and then converted them into search strings that were used to search academic databases and in search engines. We selected the Web of Science and Scopus online databases as the primary sources of peer-reviewed literature. Both are among the most comprehensive sources of peer-reviewed articles online and offer practical means of inputting complex search strings, meaning that only one search was required. Both also offer ways of constraining the evidence search so that it avoids searching articles that are too old, or irrelevant, for example in a radiotherapy journal. Web of Science and Scopus also provide practical means of exporting search results into an appropriate format for sharing and editing, such as a Microsoft Excel spreadsheet.

It is important to consider the value of grey literature as part of this study. Grey literature refers to research produced by organisations outside the typical academic environment. This type of evidence is typically harder to acquire. Google Scholar is commonly used to source grey literature, and indeed there have been studies as to its effectiveness in doing so (Haddaway and others, 2015). In addition to using Google Scholar, we also acquired grey literature from connections within the review team as well as the steering group, drawing upon our previous experience and expertise on the topic of non-stationarity.

Through the review team's prior knowledge of the field, we compiled a small list of additional unpublished and published academic studies and added them to the database of articles subject to screening.

2.2.2 Search strings

We developed an initial list of keywords based on the review team's prior knowledge of non-stationarity and expanded it after reading a small number of well-known articles in the field. This list provided the basis for constructing search strings for use in Web of Science, Scopus and Google Scholar. We refined the list iteratively to balance the breadth of the evidence search with an acceptable number of sources that could be reviewed within the agreed timeframe. We used keywords that were each relevant to a category of relevance to answering the primary question. No attempt was made to restrict the search to certain types of driver of change, such as climatic changes as opposed to land use changes for fluvial flooding.

To construct the search string, we combined the keywords from each category in Table 2.1 using Boolean operators, for example AND, OR, and used truncation wildcards so that words with the same root term would be picked up by the search string. For example, the term 'hydrolog*' will detect occurrences of 'hydrology', 'hydrological' and 'hydrologic'. We defined the final search string for use in Web of Science and Scopus, in terms of the code notation in Table 2.1:

IND AND STAT AND ((SOU-FLU AND LOC-UK) OR (SOU-PLU AND LOC-UK) OR (SOU-MET AND LOC-UK) OR (SOU-COA AND LOC-EUR))

While Web of Science and Scopus can handle complex search strings easily, Google Scholar has a 256-character limit and cannot handle truncation wildcards. In addition, Google Scholar does not provide practical means of exporting results, with previous studies resorting to purpose-built software for extracting information from the search engine. However, it appears that since these studies were published, efforts were taken to prevent automatic extraction of information from the search engine. Attempts to use this software and custom-written programs for web scraping were unsuccessful. We revised the list of keywords and created a total of 80 search strings, writing a program to extract the first 20 results from the HTML files from each search. The list of keywords is shown in Table 2.2.

Table 2.1 Keywords, sorted by category, used in the academic database search

Category (code)	String[4]
Indicator of stationarity/non-stationarity (IND)	non-stationar* OR stationar* OR trend* OR chang* OR increas* OR decreas* OR homogene* OR heterogene*
Statistical quantity (STAT)	extreme* OR “time* series” OR statistic* OR “return* level*” OR “flood* frequency” OR “design* flood” OR “return period*” OR frequency OR severity OR rare OR quantile OR “design* life” OR “exceedance probability” OR covariate* OR magnitude* OR maximum OR maxima OR “peaks* over* threshold” OR “variability”
Source – fluvial (SOU-FLU)	river* OR flow* OR fluvial OR flood* OR catchment* OR discharge* OR hydrolog* OR runoff
Source – pluvial (SOU-PLU)	rain* OR “surface* water” OR precipitation OR snow* OR pluvial
Source – coastal (SOU-COA)	“wave height*” OR “sea* level*” OR (surge* NOT "surgery") OR tide* OR “sea* state*”
Source – meteorological (SOU-MET)	storm* OR “wind speed*” OR “North Atlantic Oscillation” OR “East Atlantic Pattern” OR “storm duration*” OR “storm track*” OR “jet stream” OR “climate variability” OR “climate index” OR "climate indices" OR “global warming” OR anthropogenic OR “greenhouse warming”
Location – UK (LOC-UK)	“United Kingdom” OR UK OR Britain OR England OR Scotland OR Wales OR “Northern Ireland” OR British
Location – Western Europe (LOC-EUR)	“United Kingdom” OR UK OR Britain OR England OR Scotland OR Wales OR “Northern Ireland” OR British OR Europe OR Ireland OR Portugal OR Spain OR France OR Belgium OR Netherlands OR Germany OR Denmark OR Norway OR Sweden OR “North Sea” OR “Irish Sea” OR “Celtic Sea” OR “English Channel” OR “Bay of Biscay”

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[4] In general, quotation marks are needed when search terms have more than one word. There appear to be one or two exceptions such as “variability” where the quote marks could be removed if desired for consistency.

Table 2.2 Keywords, sorted by category, used in the Google Scholar literature search

Category	String
Indicator of stationarity/non-stationarity	non-stationarity OR trend OR change OR stationary
Source - fluvial	river OR flow OR flood OR discharge
Source - pluvial	rain OR surface water OR precipitation
Source – meteorological	storm OR climate variability OR North Atlantic Oscillation OR wind speed
Source – coastal	Wave height OR sea level OR surge
Location	United Kingdom OR UK OR Britain OR England OR Scotland OR Wales OR Northern Ireland

Web of Science and Scopus have the capability to include or exclude articles from particular disciplines or journals. Before the screening phase took place, we used this feature to limit the search results further to a manageable number. We selected the disciplines and journals to include/exclude as part of an iterative process, ensuring that any excluded articles were not relevant to the primary question. More information about this pre-screening phase is detailed in Appendix A.

During the synthesis stage, we identified that we had found no papers on changes in future astronomical tides in our search. As we were aware of such research having taken place, we investigated further by comparing our search results with the UKCP18 Marine Report references. We found that a significant number of the UKCP18 references were not included in our search because they did not include any location keywords, for example ‘Trends and acceleration in global and regional sea levels since 1807’. If our search had not included location keywords, it is likely that the number of results would have been unmanageable for an REA. The UKCP18 Marine Report references three papers studying changes in astronomical tides; none were found in our search because we used the keyword ‘Europe’ and the papers use ‘European’. We subsequently added these three papers to the search results to provide a sample of literature on this important topic.

You can find the full list of search results in the file called ‘FRS18087 Search results.csv’ published alongside this report (see Table 2.6 for a description).

2.3 Literature screening

The literature search led to a list of 9,749 articles on flooding (after duplicates were removed), drawing articles from varied disciplines including climatology, hydrology, oceanography, engineering and statistics. While these articles were selected on the basis of the constructed search strings, many were irrelevant to the primary question. Because the total number of articles was so large, a manual screening of the entire database would require resources beyond the scope and timescale of this project. Therefore we firstly conducted preliminary automated screening, in which articles were excluded from the database if their title contained a pre-specified warning word. We created a list of warning words following visual inspection of articles with no clear links to flooding. These are listed in Appendix A. You can find the search results remaining after this screening and removal of duplicate sources in the file called ‘FRS18087 Search results removing duplicates and warning words.csv’ published alongside this report (see Table 2.6 for a description).

We manually screened the remaining articles using a set of inclusion/exclusion criteria that determined whether each article was relevant to the primary question:

- article is relevant to sources of coastal, fluvial or pluvial flooding
- article focused on sources of UK flooding
- article was written in the period 2009–present
- article investigates changes in sources of flooding

In the original protocol, we included articles in the period 1998–present along with coastal studies affecting anywhere on the European Continental Shelf. However, the number of articles remaining following the screening phase was too large for the scope of an REA, so we refined these criteria to include only the most relevant and up-to-date articles.

We discarded papers focusing on linear trends in historic mean sea level or future mean sea-level rise since existing flood risk assessments already account for a historical linear change in mean sea level and future increases due to greenhouse gas emissions. We kept papers that investigated whether a linear trend in historic sea levels is appropriate or alternatively sea-level rise is accelerating. We also reviewed papers looking at periodic changes in mean sea level, for example due to natural variability.

The manual screening was a two-phase process. The first phase involved a judgement of the title of the article and marking it as clearly relevant, clearly irrelevant or uncertain. Evidence marked as clearly irrelevant was removed at this stage. Some evidence was easier to exclude than others, for example all evidence sourced from journals related to veterinary medicine. The second phase of the screening involved reading the abstract or first paragraph of the remaining articles to identify those that met the inclusion criteria, which we retained for full-text review, evidence extraction, critical appraisal and synthesis.

Three reviewers carried out this manual screening in parallel. Beforehand, we set aside 100 articles for screening by all three reviewers and cross-checked the results for consistency. We found 90% agreement between the three reviewers during this exercise, and differences with the remaining 10% were resolved before the full screening got underway.

The results of the literature search and screening process are detailed in Table 2.3. A total of 379 articles remained after the screening stage, determined by title and abstract screening of the articles remaining after removal of articles with the warning words, and application of the refined screening criteria. We carried these articles forward for full-text review and critical appraisal. Of these, the review team could not access 45 articles, which were thus discarded. Many of these were short papers found in conference proceedings, for which interpretation and appraisal of results is more difficult given the restricted page limit. You can find more details in the file called ‘FRS18087 Screening.xlsx’ published alongside this report.

Table 2.3 Breakdown of number of papers at the end of each stage of the review

Stage	Number of papers
Web of Science search	5,732
Scopus search	5,547
Google Scholar search	885
Other sources	118
Combined search, removing duplicates	9,749
Warning word screening	6,659
Manual screening	379
Reviewed	334 (45 inaccessible)

The title and abstract screening provided some interesting insights that, while beyond the scope of the research question, may prove useful for the flood risk management community. You can read more about these in part A3 of Appendix A.

2.4 Evidence extraction

We now took the articles remaining after the screening phase, assessed the full text and extracted information relevant to the primary question. For this we used a set of pre-specified qualitative fields aimed at summarising the information of interest. The database of extracted information is referred to as a systematic map of the evidence (Collins and others, 2015). We did not extract information from articles now deemed to be irrelevant after reading the full text. In some cases, the full text was not available, in which case we discarded the article. Some pieces of evidence report studies relating to multiple sources of flooding, in which case each study was recorded separately. The systematic map is published alongside this report in a file called ‘FRS18087 Systematic Map.xlsx’.

The qualitative fields extract information relevant to the type of flooding source and the region of the study, as well as information relating to non-stationarity, including the methods of detection, and attribution and direction of long-term change. While this approach cannot capture the subtle complexities of individual studies, these fields help to detect any consensus among the evidence. Data analysis can be used to quantify this consensus and produce insights into the changing patterns of flood risk relevant to different flood sources and regions, as well as identify gaps in the evidence with regard to detection and attribution of non-stationarity in environmental data.

The information we extracted from relevant articles includes:

- context of flooding – whether the object of the study is inland or coastal flooding, or related to a flood source not constrained to either, for example storminess
- flooding source type – the flooding source being investigated, for example river flow, wave height
- region – the location or locations the study relevant to (summarised by country or sea)

- historical data or future – whether the study bases its conclusions on patterns in historical data or on future projections
- model or observational data – whether the study is based on collected data or outputs from a computational model
- season – whether the results are relevant to a particular time of year
- type of non-stationarity investigated – for example trends, step changes, inter-annual changes
- direction of long-term change – whether the analysis suggests that the magnitude of flood source is increasing or decreasing
- timescale of change – the timescale in which significant change occurs, for example inter-annual, decadal
- attribution – whether the study investigates the drivers of non-stationarity
- drivers –the identified drivers of non-stationarity
- methods of detection – the approaches used to identify stationarity or non-stationarity
- methods of attribution – if attribution is explored, how the authors deal with attribution of non-stationary behaviour

The full systematic map, featuring the entire list of fields is published alongside this report in a file called ‘FRS18087 Systematic Map.xlsx’. The synthesis of these results features a restricted set of fields, and aggregation was performed where possible.

2.5 Critical appraisal

After the extraction stage, we evaluated each study for its relevance to the research questions posed by the REA and the robustness of the methodology utilised. We combined assessment of the evidence’s relevance and robustness to give an overall score for each article. We used a set of criteria to judge relevance and robustness giving scores for each and combining.

Four reviewers from different disciplines carried out the critical appraisal stage, ensuring that we used expert knowledge effectively to inform the article’s overall score. We carried out cross-checks to ensure the appraisals were fair and consistent across reviewers. Inevitably there is a degree of subjectivity with regard to this scoring system, but the reviewers completed their evaluation using identical criteria (Table 2.4 and Table 2.5).

Table 2.4 Criteria used to score articles for relevance to the primary question

0	1	2	3
Not relevant to sources of flooding, changing patterns of flood sources or not relevant to the UK.	Little emphasis on investigating stationarity or non-stationarity. For example, focus may be more on methodology development.	Clear investigation of stationarity or non-stationarity.	Clear investigation of stationarity or non-stationarity.
	Relevant to the UK but location of the study not UK-based, or large-scale global/ continental study with little analysis of UK-specific results, or only one UK location.	Based on analysis of a smaller number of UK locations.	Based on a large collection of UK locations.
	No attempt to quantify cause and/or effect of stationarity/non-stationarity on the flooding source. For example, focus may be on mean flows or mean rainfall rather than flooding.	Some acknowledgement of exploring cause and/or effect of stationarity/non-stationarity on the source of flooding.	Explicit characterisation of cause and/or effect of stationarity/non-stationarity on the source of flooding.

Table 2.5 Criteria used to score articles for robustness

1	2	3
Under-reporting and invalid conclusions based on omitted results. Methods wrongly applied or interpreted. Hypotheses not tested.	Use of slightly outdated methods, conclusions still backed up by results.	Use of up-to-date methods and valid conclusions supported by these methods.
Use of old datasets or extremely short data records.	Use of slightly outdated datasets. Limited amount of data used.	Use of best-available data and analysis based on appropriate record length.
No acknowledgement of limitations of the study.	Little reference to other works in the field and limitations of the study.	Acknowledgement of strengths and weaknesses of the study.
Model unable to reproduce phenomena to high enough accuracy to support results.	Model shows some accuracy at representing process.	Model used accurately represents process.

As shown in Table 2.4 and Table 2.5, an overall score of 1, 2 or 3 was given based on how well the evidence satisfies the criteria, that is which column of the table best represents the article. Scores for relevance and robustness were combined multiplicatively to give an overall score of quality, for example a relevance score of 2 and a robustness score of 3 would give an overall score of 6.

We used the scoring system to further exclude evidence from going forward to the synthesis stage. After careful consideration, we decided to exclude all evidence with a score of less than 4 at this stage. Using this criterion and scoring system, only evidence that was both relevant and robust (scoring > 1 in both) passed through to the synthesis stage. In total, 144 papers progressed to the synthesis stage. They are listed in Appendix B.

2.6 Synthesis

We carried forward the evidence judged to be sufficiently relevant and robust and used it to generate summary findings to answer the primary and secondary questions. We derived these findings from exploratory data analysis of the results of the systematic map, which identified, for example, particular sources of flooding for which there is greater consensus of increased risk. We also used this information to identify gaps in the research community and possible future directions for flood risk management activities.

We also used machine learning approaches to evaluate the contents of the systematic map to cross-check our interpretation of the results and potentially provide extra information. Non-negative matrix factorisation (Lee and Seung, 2001) was used to group evidence into clusters, or topics. Given a user-specified number of topics, this algorithm finds the optimal set of topics and membership weights for each abstract.

Results of the synthesis stage are presented in Section 3.

2.7 Outputs

A full list of digital project outputs to accompany this report is given in Table 2.6.

Table 2.6 Project outputs

Filename	Description	Number of papers
FRS18087 Search results.csv	Full list of searched literature from academic database search and literature sourced internally.	12,282
FRS18087 Search results removing duplicates and warning words.csv	Full list of searched literature after removing results duplicated between sources and screened using a list of warning words	6,659
FRS18087 Screening.xlsx	Full list of literature remaining after manual screening phase, including the list of inaccessible sources and reviewers of each source.	553, 379 of them from last 10 years
FRS18087 Systematic Map.xlsx	Full list of literature reviewed, including extracted evidence related to primary and secondary questions and critical appraisal scores. Some papers have multiple entries if they cover more than one source of flooding. Includes papers with critical appraisal scores below the threshold, which were not used for the synthesis.	334 papers, 428 entries in total

3 Primary question results

This section provides further analysis of the evidence that passed the critical appraisal stage of the review. We considered this evidence the most relevant and robust for the purpose of addressing the primary question. The section features exploratory data analysis of the various characteristics of the evidence base, both in broad terms and segmented by flood sources. It highlights notable articles with particularly high appraisal scores. Finally, it uses a natural language processing approach to cross-check against the general findings of our review, with the potential for identifying additional conclusions.

3.1 Overview

The appraised evidence comprised 144 sufficiently relevant and robust articles, containing studies relevant to stationarity or lack thereof in sources of UK flooding. This section provides summary statistics on the collection of studies.

Figure 3.1 shows the distribution of studies across various sources of flooding, with strong representation in precipitation, river flow and wave height studies. In Figure 3.2 to Figure 3.4 the data have been split into fluvial, coastal and meteorological, with meteorological representing wind and precipitation only. The wind is included directly in coastal flood risk offshore statistics, but studies also investigated changes in the spatial occurrence of storms, which affect all types of flooding.

In interpreting the results, you should bear in mind that some articles present results for more than one source of flooding. We created one entry in the systematic map for each source of flooding per study, giving 206 entries in total that passed through the critical appraisal. This is why, for instance, the total number of studies in Figure 3.1 appears to be more than 144.

It is important to reiterate that the well-researched topic of mean sea-level increase was not included in this review unless the studies assessed accelerating trends in historic data.

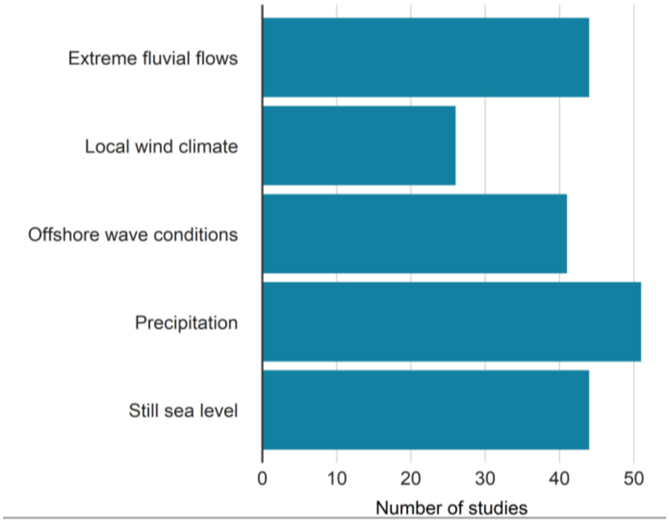


Figure 3.1 Number of studies relevant to each source of flooding

Figure 3.2 shows that there is a similar number of studies using model (41%) or observational (47%) data for the basis of their analysis, with 12% of studies using a combination of the two.

Figure 3.3 shows that the majority of studies (68%) base their conclusions regarding future flood sources on analysis of historical data, with a small percentage (11%) basing their findings on future projections. Around a fifth (21%) of studies use some combination of historical and future data, with consideration of both more likely in the meteorological literature, where perhaps greater availability and use of climate model data makes this possible.

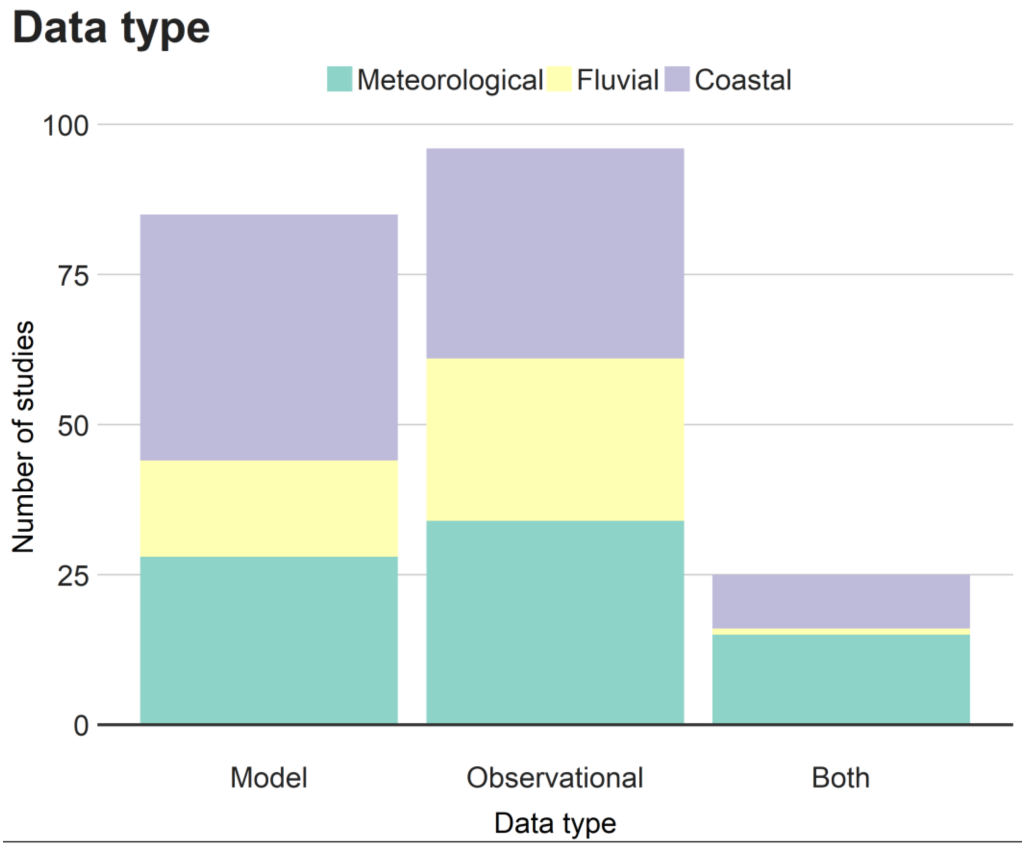


Figure 3.2 Number of studies using model or observational data, or a combination of both, segmented by coastal, fluvial and meteorological flood sources

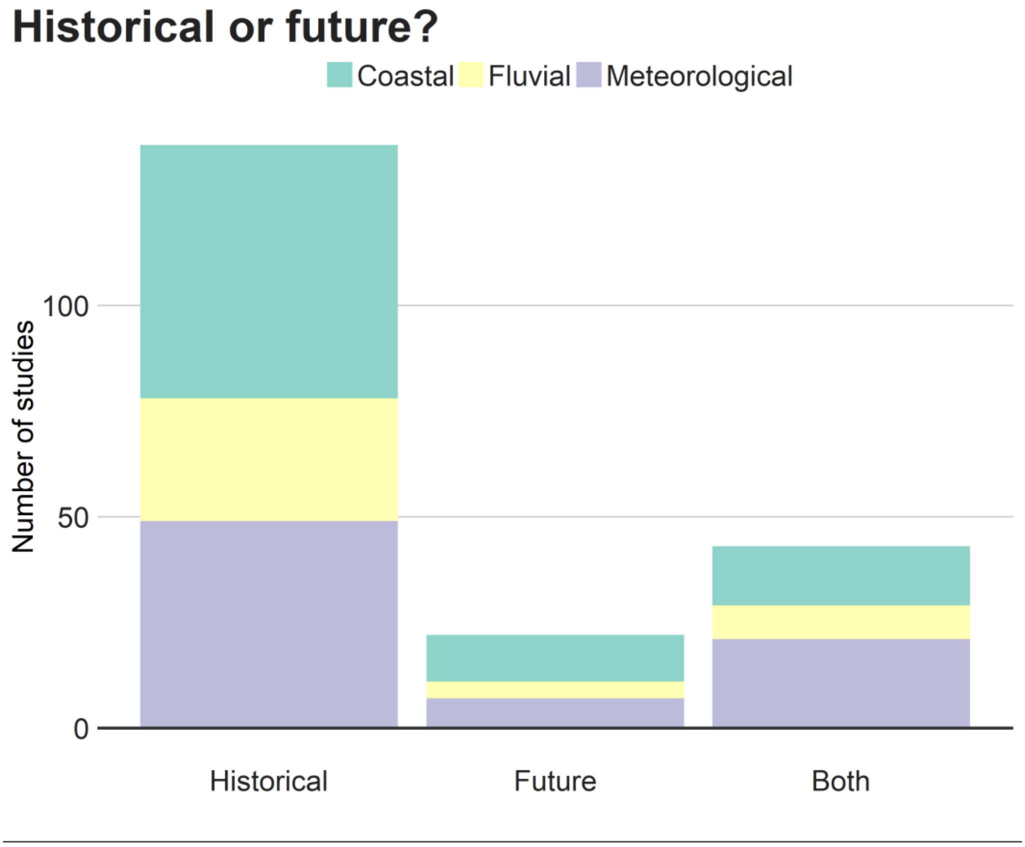


Figure 3.3 Number of studies using historical data or future projections, or a combination of both, segmented by coastal, fluvial and meteorological flood sources

3.1.1 Short-term variability

Waves, mean sea level, storm surge, precipitation, winds and fluvial flows were found to be variable at inter-annual time scales, driven by large-scale modes of variation such as the North Atlantic Oscillation. Short-term variations are less likely to lead to wrongful conclusions of non-stationarity seen by studies mistaking long-term decadal cycles for trends.

However, knowledge of the drivers of short-term variations can benefit a statistical analysis, giving improved risk estimates and perhaps decreasing uncertainty. Of the 206 entries in the systematic map that passed the critical appraisal, 49 explore short-term variations (< 10 years).

Unknown drivers

Many studies tend to account for non-stationarity by incorporating known covariates into statistical models. This essentially amounts to regressing the parameters of an extreme value distribution.

Eastoe (2019) considers a scenario where these drivers are unknown, or unavailable. Random effects models are used to account for the variability from year to year, which improve risk estimates and allow for identification of physical drivers.

3.1.2 Long-term change

Of the 206 entries in the systematic map that passed the critical appraisal, 157 explore some aspect of long-term change on decadal, multi-decadal or century timescales.

The majority of studies draw a conclusion as to whether flood sources are changing, and Figure 3.4 shows how this varies. Overall, 38% of studies found an increasing trend in the flood source (note, for most studies this refers to increasing magnitude [e.g. higher river flows, higher sea levels, more intense storms] but some may have focused on frequency of floods, and a few on their duration), but a significant number of studies (24%) also report no change; 11% of studies report increases and decreases in the flood source, which typically arises from spatial variation in trends. Conclusions tend to vary across the different sources of flooding: 54% of fluvial studies report an increase in sources of flooding, compared to 14% that report no change. In contrast, 33% of coastal studies report an increase compared with 26% reporting no change. Sources of coastal flood risk vary around the UK and it is important to note that reports of increasing and decreasing trends – and indeed no trend – can all be consistent results if the studies are based on different locations. For example, if extreme westerly winds were to become more frequent and extreme, this would lead to increases in extreme waves on the west coast, but would decrease wave energy on the east coast.

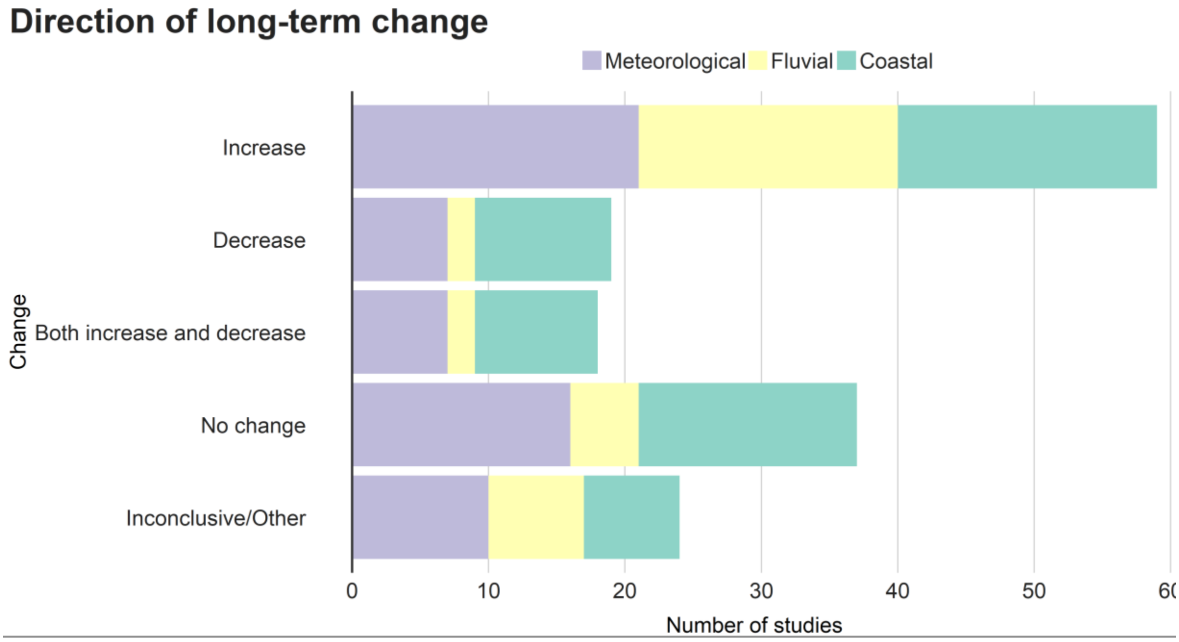


Figure 3.4 Number of studies reporting different types of long-term change.

Notes: Studies analysing short-term variability have been excluded. The Inconclusive/Other category includes studies where no conclusions on the direction of change were made, and also studies where increases and decreases in hazards are not relevant, for example wind direction, storm track location.

Direction of long-term change means a change in the severity of floods, whether this is measured by magnitude, frequency, duration or any other metric.

3.2 Meteorological sources of flooding

This review covers the following meteorological sources of flooding: wind speed, wind direction, cyclone frequency, cyclone intensity, atmospheric rivers and precipitation.

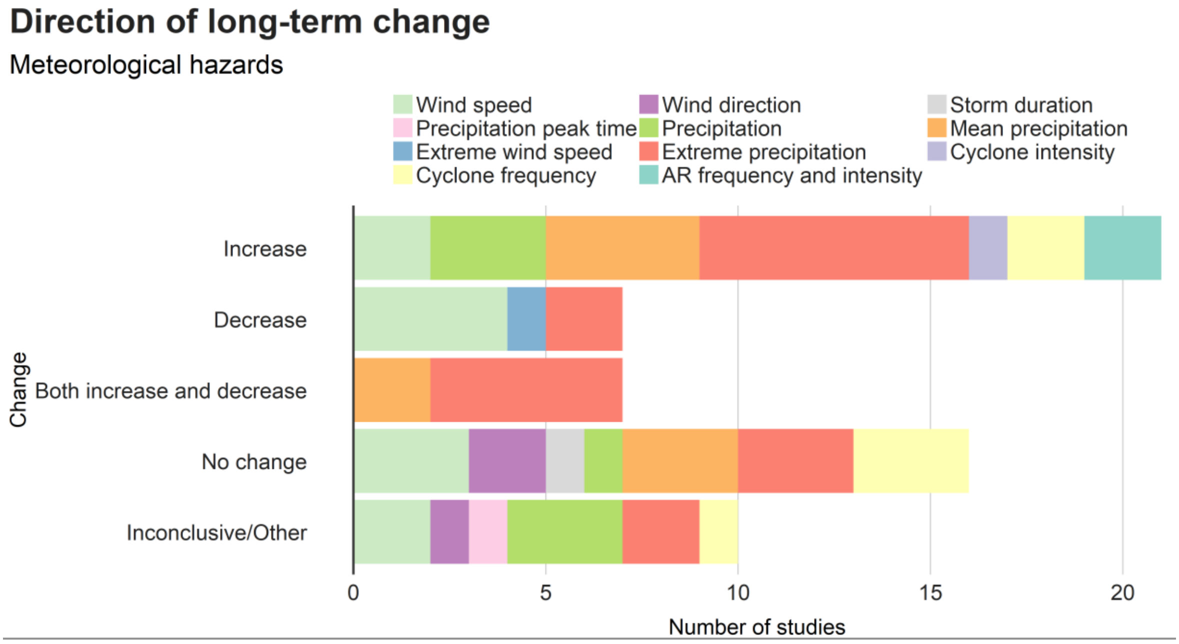


Figure 3.5 Summary of changes in meteorological forcing

Note: AR = atmospheric river.

Figure 3.5 summarises the results on the (non-) stationarity of meteorological forcing, which offer different conclusions for meteorological sources of flooding. Of extreme precipitation studies, 37% report an increase (intensity, magnitude or frequency of extreme precipitation); this conclusion is mostly derived using historical observational data (see Figure 3.6 and Figure 3.7). There is no consensus on a change in the wind climate and differing conclusions on changes in mean precipitation.

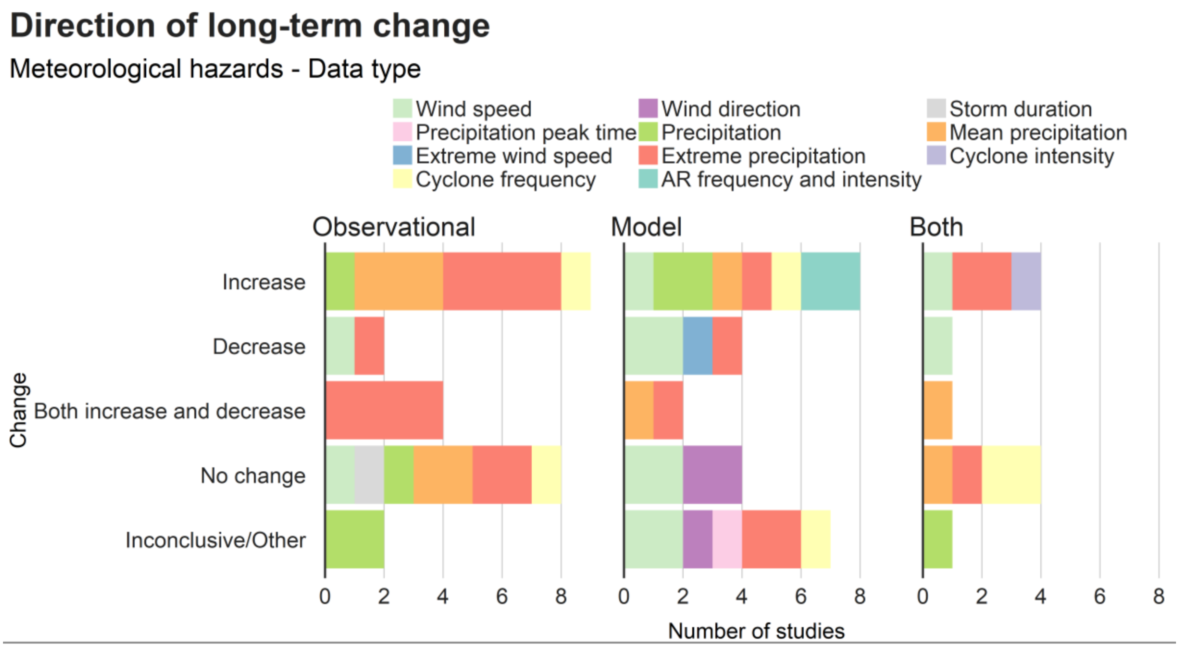


Figure 3.6 Summary of changes in meteorological forcing, segmented by studies that use observational or model data, or a combination of both

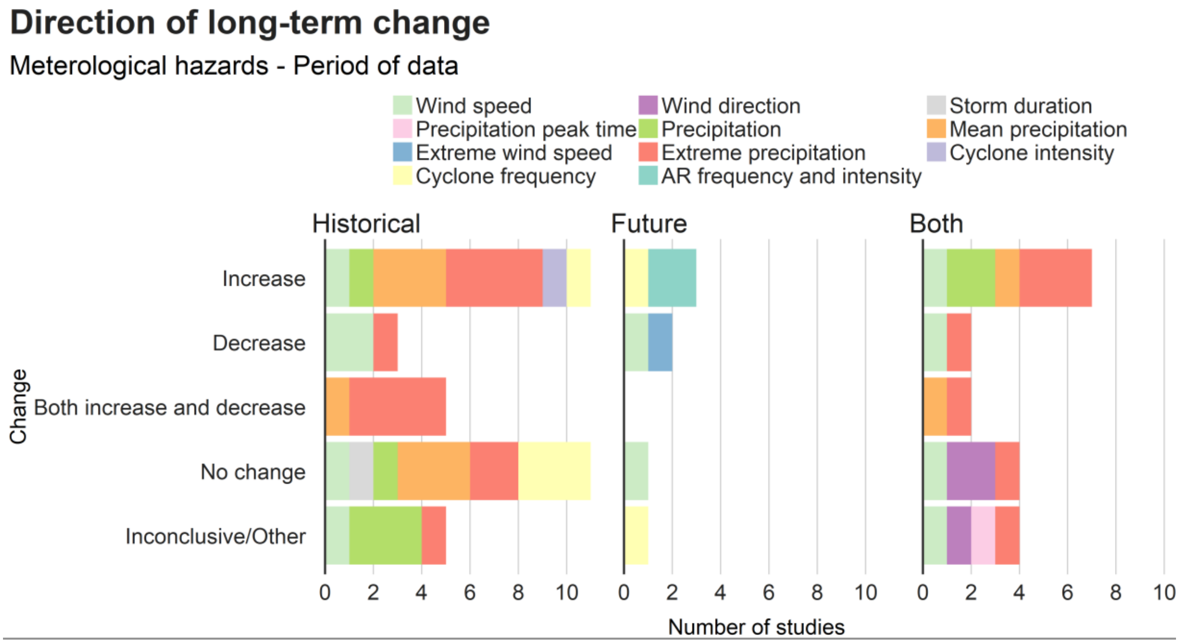


Figure 3.7 Summary of changes in meteorological forcing, segmented by studies that use historical or future data, or a combination of both

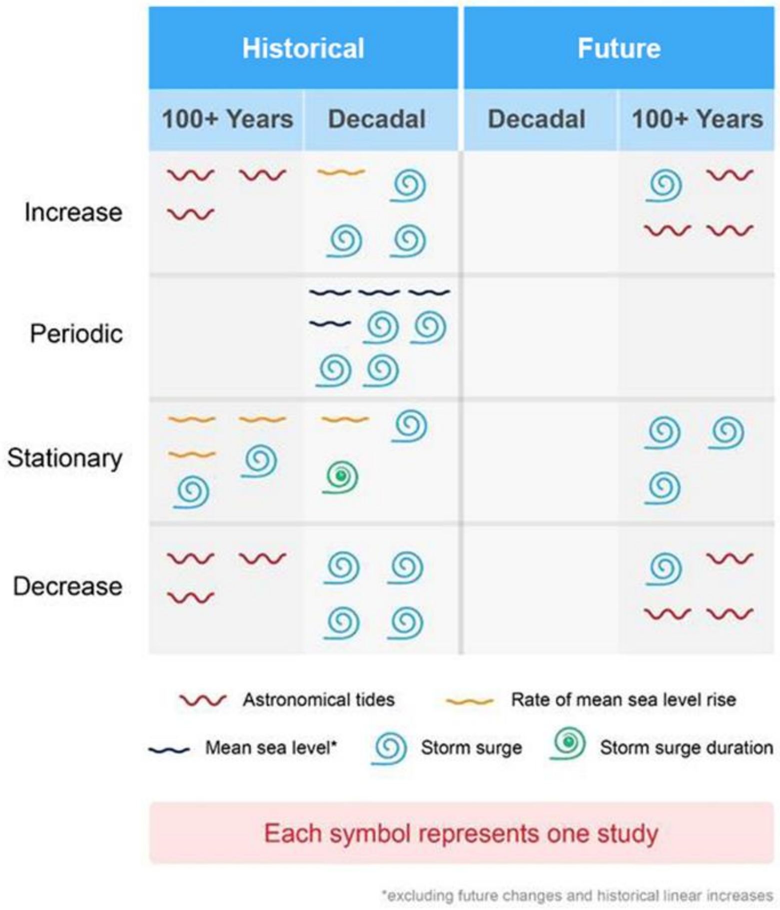
3.2.1 Local wind climate

The local wind climate is described not only by the wind speed and wind direction, but also cyclone frequency and intensity. The evidence base contains 22 studies on changes in local wind climate. After the critical appraisal, we identified only one paper investigating changes in storm duration based on meteorological conditions.

Figure 3.5 shows that there is little consensus regarding future changes in the local wind climate. Half of wind speed studies report a future decrease in wind speed, and this conclusion is mostly derived from model data. Few studies look at changes in cyclone intensity or frequency, storm duration or wind direction, which represents a key gap in the evidence for future changes in sources of UK flooding.

The variability of these flooding sources is summarised in Table 3.1. The table divides the studies into those which found the distribution of the source variables to be stationary and those that found it to be non-stationary (increase, decrease and periodic). For the studies that found the source distributions to be non-stationary, the table further distinguishes between studies finding an increasing trend in the variable; a decreasing trend or those that found ‘periodic’ variations. When there are periodic variations in a flooding source, the distribution could be considered stationary if data are available over a long enough period; however, if the distribution is described from samples taken from different shorter time slices, it can appear non-stationary. An example of this is shown in Figure 3.15 for extreme sea levels.

Table 3.1 Variability in local wind climate



Each symbol represents one study

*excluding future changes and historical linear increases

Ten studies provided information on wind speed with nine reaching a conclusion. The evidence concludes that wind speeds are either decreasing or stationary over the long term. The one study on extreme wind speeds also finds a decreasing trend in future, over the long term. There is no clear picture regarding changes at decadal timescales.

There are only four studies on cyclone frequency; they find no trend in historical data, but decadal variability and a small increase in future frequency. There is only one study on cyclone intensity, which found an increasing intensity trend in the historical data.

In the UK wind speed and direction and cyclone frequency and intensity are predominately controlled by the North Atlantic jet stream. When analysing results based on models, it is important to consider how well the model represents the current conditions; this is especially true of the North Atlantic storm tracks. Model skill at representing features such as jet stream position and tilt varies between models; we factored this into the robustness scoring in the critical appraisal stage.

3.2.2 Precipitation

The majority of precipitation studies tend to focus on extreme precipitation, generally over short durations, of the type that may lead to river or surface-water flooding. These studies generally tend to suggest an increase in extreme precipitation over the UK, whereas for mean and general precipitation, the pattern is not clear. Several studies refer to an increase in winter rainfall depths in the northern part of the UK, or in upland areas.

Figure 3.5 shows that 40% of studies report an increase in extreme precipitation and Figure 3.6 and Figure 3.7 show that this conclusion was mostly found from analysis of historical observations, with only three studies basing their findings on future projections. One study investigated a change in the timing of extreme precipitation, but the results were not conclusive.

Other studies focus more on longer-term or seasonal precipitation totals. While changes in storm intensity might be expected to have a fairly direct impact on flooding, the impact of changes in longer-duration rainfall could be more subtle. There is the potential for any increases in soil moisture due to greater seasonal rainfall accumulations to be balanced out by, or even reversed by, increases in evaporative demands due to rising temperatures. The combined effects of changes in precipitation and evaporation are considered in some of the studies of fluvial flood sources (Section 3.3).

The main arguments behind changes in precipitation generally revolve around the ability of a warming atmosphere to retain more moisture (thermodynamic changes), along with changes in circulation (dynamic changes) (Schaller and others, 2016). These effects may result in an increased intensity of convective precipitation, along with the rain that arises from the passage of extratropical storms in the North Atlantic.

Two studies report an increase in atmospheric river activity. Atmospheric rivers are flowing columns of condensed water vapour in the atmosphere responsible for producing significant levels of rain and snow. These systems are often associated with flood events in the western United States and have been linked with major events in the UK, such as the Welsh floods of October 2018.

We identified a small number of key papers for further comment.

Trend or natural variability?

Statistically significant trends are often interpreted as evidence of climate change without considering the impact of variations in the climate system. **Brown (2018)** explores a number of atmospheric indices, including the North Atlantic Oscillation (NAO), to examine whether the variability in UK precipitation data can be explained by these patterns.

The NAO was found to have the largest effect, with positive NAO reducing the likelihood of extreme rainfall from spring to autumn but increasing its likelihood in winter. Inclusion of these indices in statistical models reduced the magnitude and significance of time trends in winter months. This demonstrates the importance of attribution where change occurs in flood source data. In addition, it raises the further question of what is driving the changes in the NAO: purely natural variability or a man-made component?

Fine-resolution model projections

Projections can give valuable insights into possible future precipitation patterns, but are of course dependent on the parameters and resolution of the climate model used. **Chan and others (2018)** compare future mean and extreme precipitation intensities using a 1.5 kilometre simulation from a climate model capable of picking up convective processes.

Results for the northern UK predict a mean precipitation increase in winter and a large decrease in summer. Extreme precipitation is expected to intensify in summer, but the projected change is expected to be more intense for the southern UK.

3.3 Sources of fluvial flooding

Of studies that address fluvial flooding, 61% found that sources of flooding (that is extremes of river flow) are changing in the long term. In the vast majority of this subset (78%), the change was an increase in sources of flooding. Most of those that do not report an unequivocal increase in sources of fluvial flooding do not reach an opposite conclusion; for example, some do not discuss this aspect of the results; others do not carry out statistical tests; others show a mixture of increases at some sites and decreases elsewhere. Figure 3.8 shows that the vast majority of studies investigate changes in peak flow.

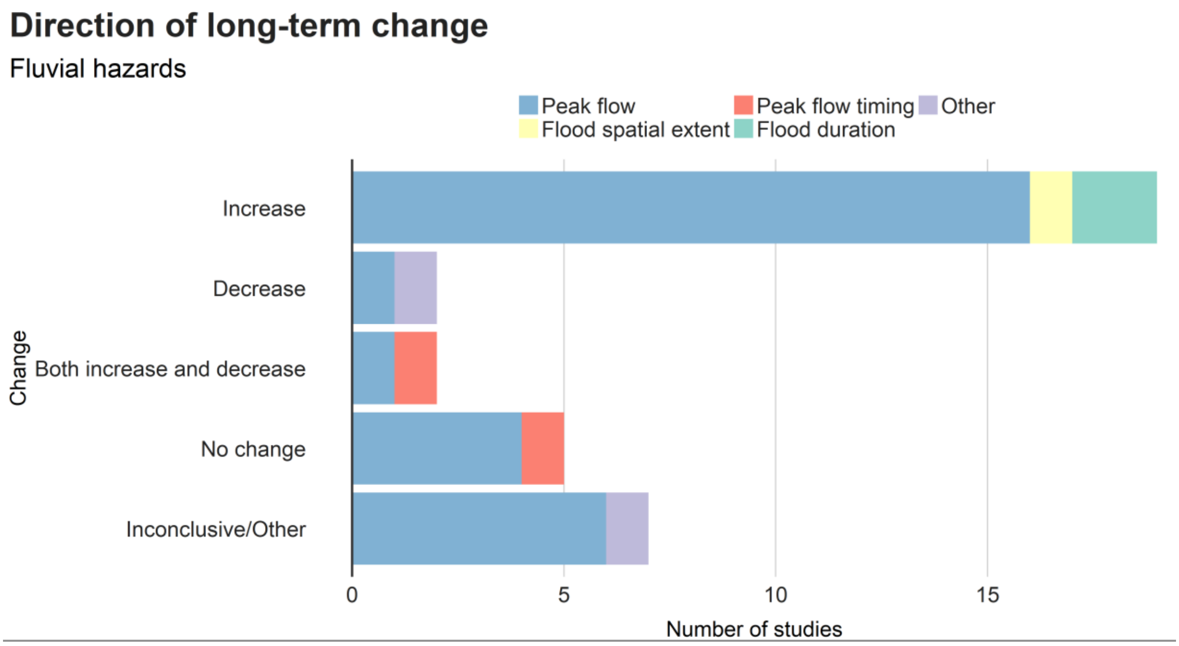


Figure 3.8 Summary of changes in fluvial variables.

Note: Studies focusing on short-term variability were discarded.

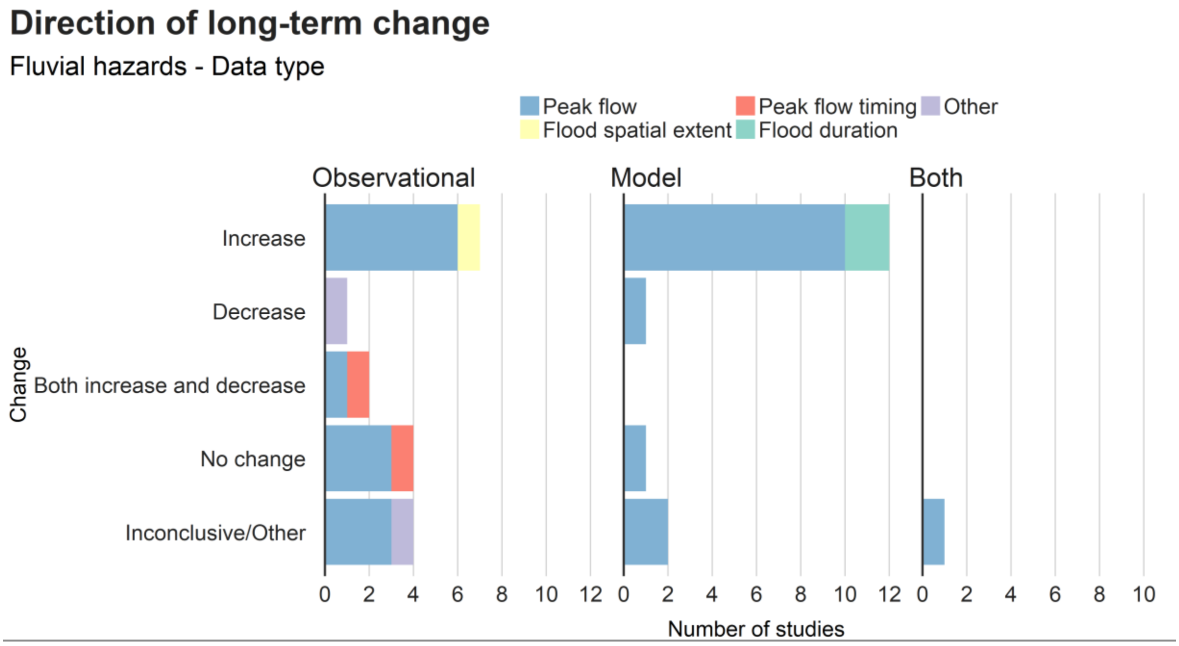


Figure 3.9 Summary of changes in fluvial sources of flooding, segmented by studies that use observational or model data, or a combination of both

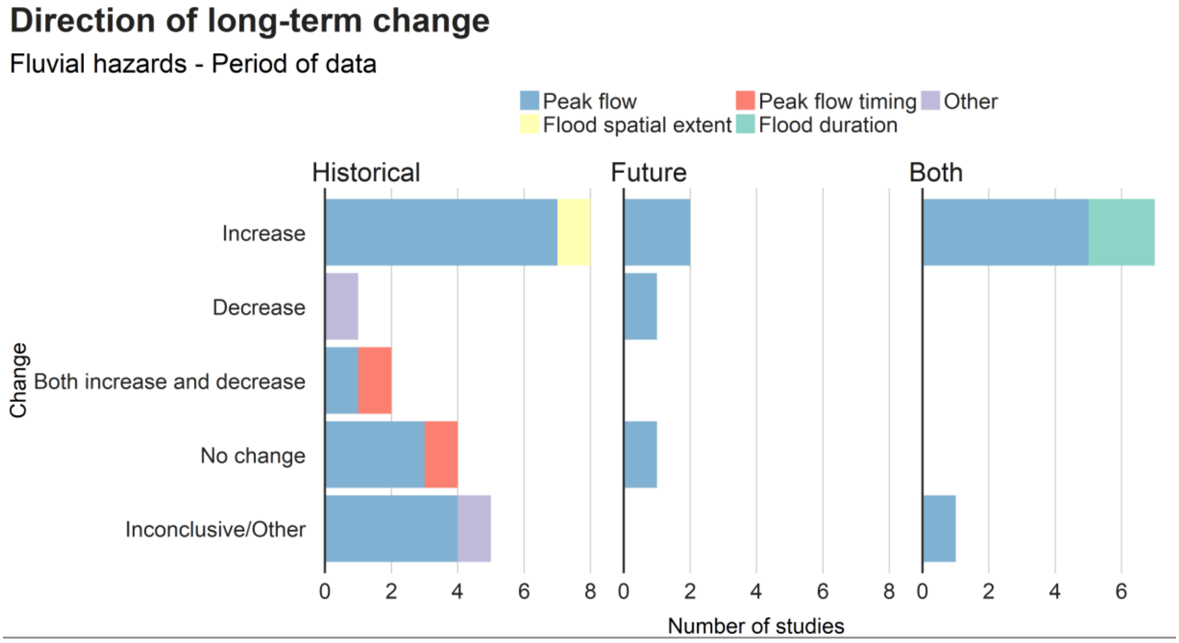


Figure 3.10 Summary of changes in fluvial sources of flooding, segmented by studies that use historical or future data, or a combination of both

The studies that report an increase in sources of fluvial flooding are fairly evenly split between those that analyse observed data and those that base their findings on modelling (see Figure 3.9). Models were applied both to simulate past conditions and to predict future conditions. Overall, the majority of studies base their conclusions on analysis of changes seen over the past (whether observed or modelled, see Figure 3.10), with only a small number relying on future projections.

Of the observational studies, 15 report clear conclusions about the direction of trend in peak flows or flood frequency. Of these, 7 report an increase, one a decrease (in the frequency of flash floods), three report no trend and the others have findings that varied with location in the UK.

Nearly all studies of sources of fluvial flooding look at changes in the magnitude of flood flows. A much smaller number investigate other aspects, such as the duration of flooding, its seasonality, the speed of rise of floods or their spatial extent (see Figure 3.8).

Where models were used to assess changes in sources of fluvial flooding, these are generally either climate models or rainfall-runoff models. Most such studies involve running rainfall-runoff models with inputs representing baseline and possible future climates, the latter based on outputs from climate models. Such modelling exercises consider the impact not just of changes in short-term precipitation, but also changes in soil moisture and, in some cases, groundwater conditions.

The boxes below summarise selected key papers from the review of sources of fluvial flooding. All scored either 6 or 9 in the critical appraisal – the highest two scores possible. We have chosen them from among high-scoring papers because of their widespread coverage of the UK and the way they illustrate a variety of techniques and issues.

Trend testing

Many studies test river flow records for the presence of statistically significant trends. Terms like ‘trend’ or ‘change’ are used more commonly then ‘non-stationarity’ in these articles. A recent UK-wide study of trend in river flow is by **Harrigan and others (2018).** The authors tested for trend in a range of flow statistics across 146 near-natural catchments. Most flow records started in the 1960s or 70s.

The highest flow statistic tested was Q5, the 5th percentile on the flow duration curve. This is the daily mean flow that is exceeded 5% of the time, so a high flow but not likely to be one that causes flooding. Published comprehensive studies of trend in UK peak flows are less up-to-date, although see the box below on Prosdocimi and others (2014).

A significant upward trend in Q5 was found for 28% of the catchments, mostly located in the west of Great Britain. None of the catchments showed a significant downward trend in Q5.

A longer-term perspective

Some sources examine non-stationarity over a much longer time scale. **MacDonald and Sangster (2014)** analysed detailed historical records, merged with systematic river flow measurements, spanning the period 1750–2014. The study covers 12 catchments across England, Wales and Scotland. The authors conclude that the recent flood-rich period is not unprecedented. They suggest, from a subjective assessment, that their results show no shift in long-term flood frequency.

They found historical patterns of flooding to be linked to drivers including the NAO, the Atlantic Meridional Oscillation (AMO) and solar activity.

Non-stationarity in UK rainfall and flood flows

Prosdocimi and others (2014) is one of the few references found that uses the term non-stationarity in an analysis of changes in rainfall and flood flows at a national scale.

The authors fitted both stationary and non-stationary frequency distributions to annual and seasonal maximum daily rainfalls and peak river flows for 446 catchments. They tested two null hypotheses, one being that peak flows are increasing at a rate that would see an increase of more than 20% by the year 2085 (assuming observed change continues at the same rate), and the other being that any increase would be less than 20% by 2085.

They found that, for over 80% of gauging stations in the UK, neither null hypothesis could be rejected. In other words, on the basis of trends observed up to 2009, they could not determine whether or not a 20% uplift in peak flows is adequate to account for the expected change in flows by 2085. Indeterminate results like this draw attention to the difficulty of making inferences from relatively short records with high variability. The authors found that sample sizes of hundreds of years would be needed before their null hypotheses could be confirmed or negated with confidence.

Spatially consistent trend detection

Indeterminate findings like those of Prosdocimi and others (2014) can potentially be avoided if the power of statistical trend tests is increased. **Brady and others (2019)** did this by exploiting spatial information. The idea was to pool the trend signals among gauges, rather like the way that regional frequency analysis pools information.

Analysing 660 gauging stations in Great Britain with at least 20 years of record, the authors found clear evidence of a Britain-wide increasing trend in peak flow. They found evidence of a stronger trend signal in north-west England and parts of southern Scotland. The period of record analysed included data up to water year 2015/16.

The authors point out that, in the light of the expected impacts of climate change, conventional trend tests that take a null hypothesis of no trend might be effectively investigating a straw man null hypothesis, which is deemed to be false even before the statistical modelling begins. They therefore test other null hypotheses, along the lines of Prosdocimi and others (2014).

3.4 Sources of coastal flooding

Studies on the long-term (non-)stationarity of six coastal variables were included following the critical appraisal: mean sea level (excluding future changes and historical linear increases), astronomical tide, storm surge, storm surge duration, wave height and wave period. There were no studies on wave setup or wave direction. Figure 3.11 summarises the long-term trends found for each variable. For wave height we needed to distinguish between the mean of the distribution and the extremes, as opposing trends were found in the literature. The studies we reviewed did not split wave conditions into swell and wind waves.

Study conclusions vary depending on the source of coastal flooding. Figure 3.11 shows that 60% of mean wave height studies report a future decrease in mean wave heights, all of which are derived from modelling studies (see Figure 3.12). Of storm surge studies, 42% report no change, relatively evenly spread between studies of observational and model data, and historical data and future projections. There is also some evidence for an increase in wave height, with mixed results for astronomical tides.

This section provides summaries of three papers that all scored highly in the review. The reviewers selected them for their figures, which help to illustrate the review findings.

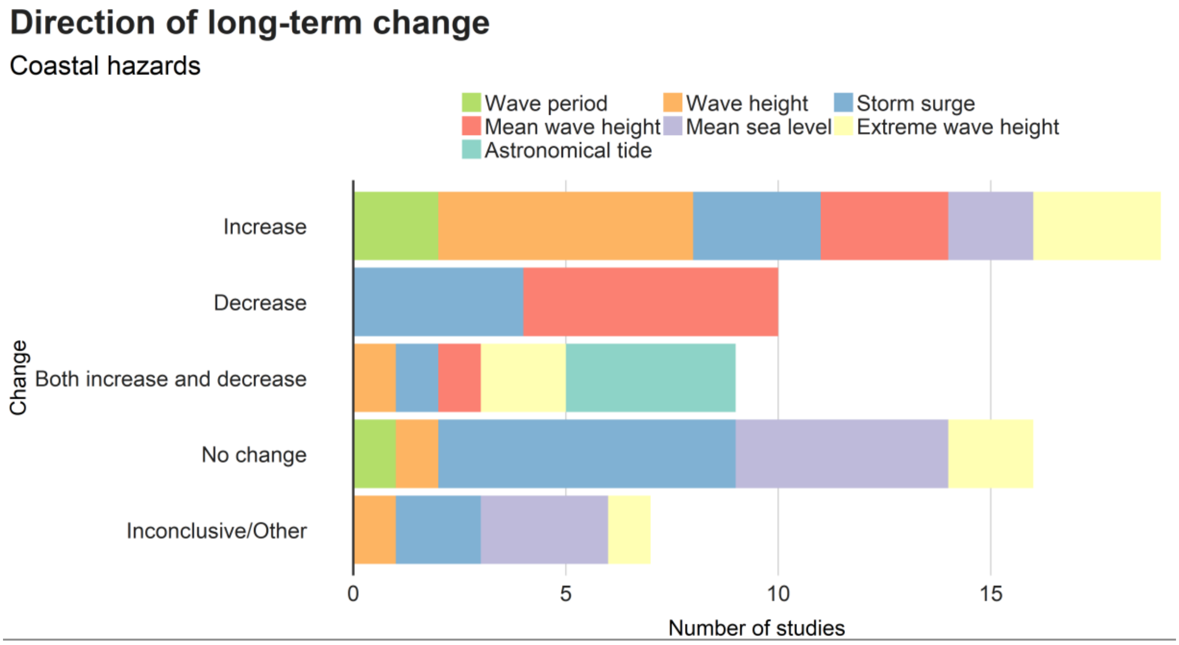


Figure 3.11 Summary of changes in coastal variables

Note: Mean sea level excludes future changes and historical linear increases.

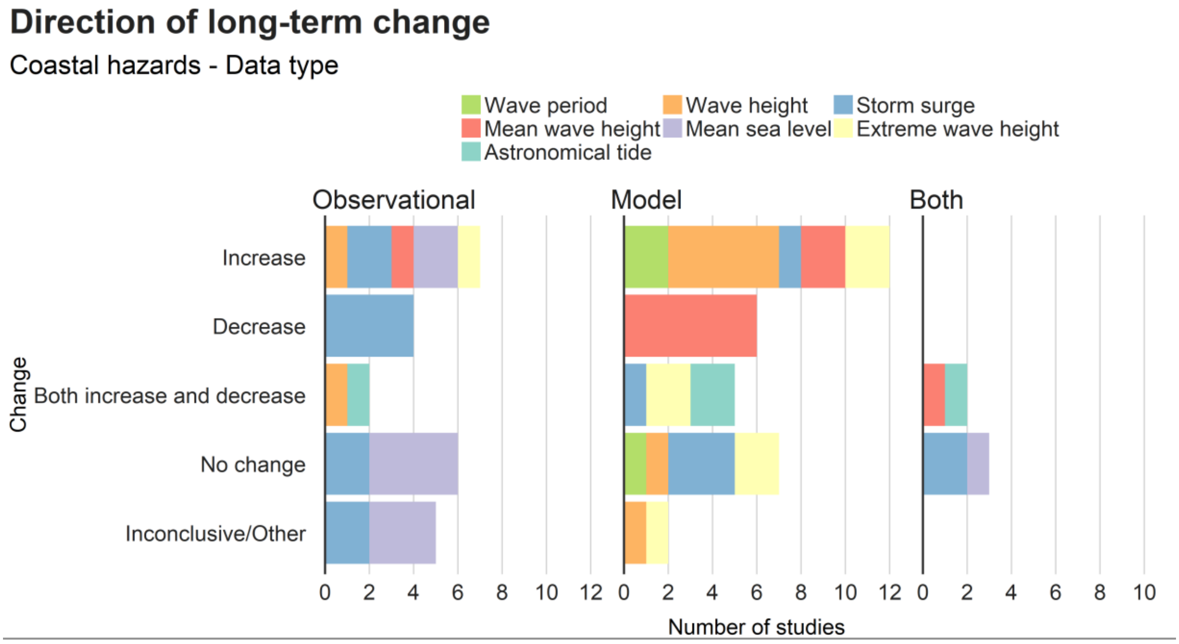


Figure 3.12 Summary of changes in coastal variables, segmented by studies that use observational or model data, or a combination of both. Mean sea level excludes future changes and historical linear increases

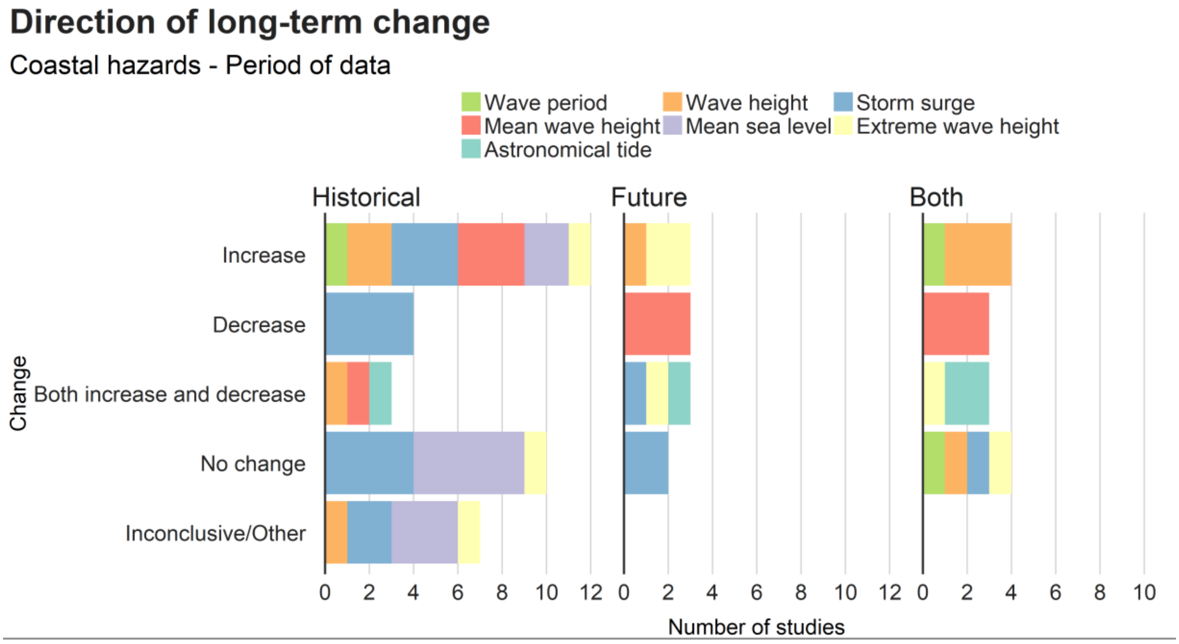


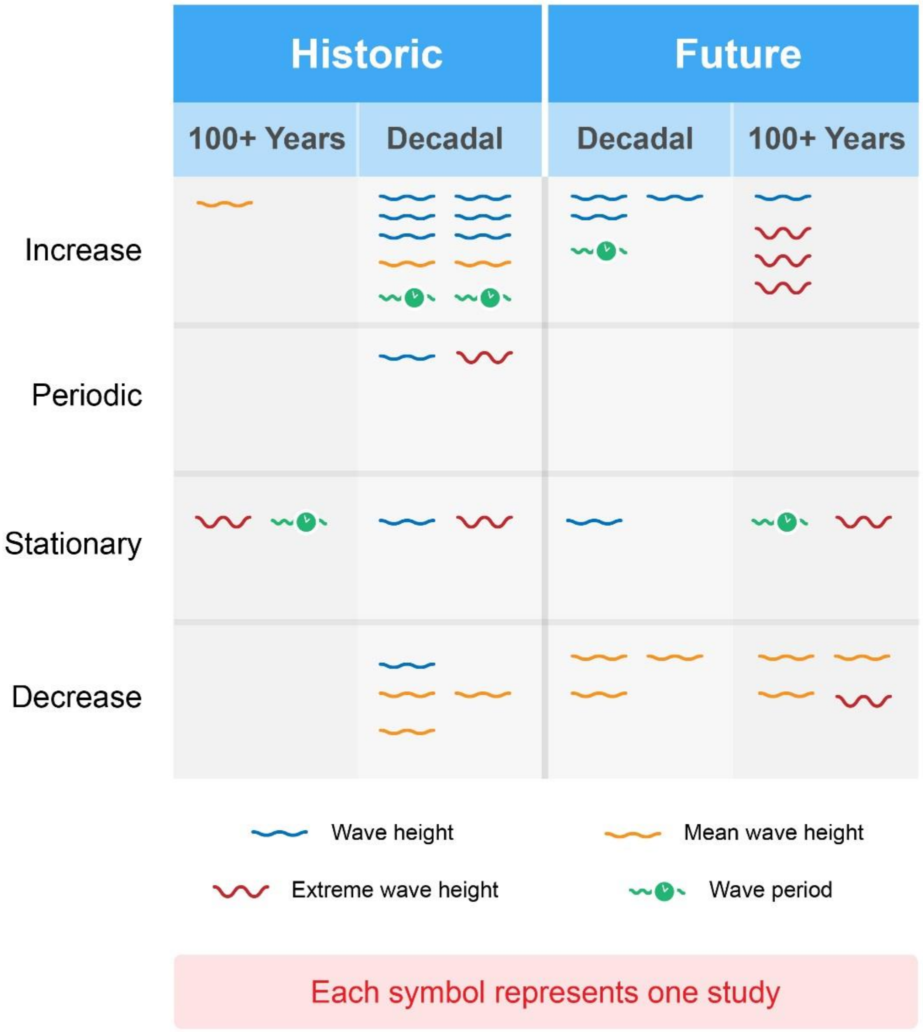
Figure 3.13 Summary of changes in coastal variables, segmented by studies that use historical or future data, or a combination of both. Mean sea level excludes future changes and historical linear increases

3.4.1 Waves

Studies analysing potential changes in wind speed and direction distributions were discussed in Section 3.1.1. Changes in wave distributions are strongly reflective of these driving wind conditions, but with the additional influence of fetch limitations. We found that 30 studies assess the stationarity of wave distributions at decadal to century timescales:

Table 3.2 summarises the findings. The table divides the studies into those that found the distribution of the source variables to be stationary and those that found it to be non-stationary. For the studies that found the source distributions to be non-stationary, the table further distinguishes between studies finding an increasing trend in the variable, a decreasing trend, or ‘periodic’ variations. With periodic variations in a flooding source, the distribution could be considered stationary if data are available over a long enough period; however, if the distribution is described from samples taken from different shorter time slices, it can appear non-stationary. An example of this is shown in Figure 3.15 for extreme sea levels.

Table 3.2 Variability in wave distributions



Only five studies address wave period, but they show values to be either stationary or increasing. There are no studies on variability of wave direction at decadal or longer timescales. The wave height results show a split depending on which part of the distribution is considered. When considering studies of mean wave height only, 75% show a decrease. When considering studies of extreme wave height, or when the whole distribution is considered, 59% of studies show an increase. This division is not supported by all studies and it is important to recognise the spatial non-homogeneity of changes in the wave climate; an example of this is shown in Figure 3.14. The box below summarises a key paper analysing future wave conditions around Europe.

Bricheno LM and Wolf J. ‘Future wave conditions of Europe, in response to high-end climate change scenarios’

Journal of Geophysical Research: Oceans 2018: volume123, pages 8762–91.

This recent paper uses the best available data and methodologies to assess changes in Europe’s future wave climate.

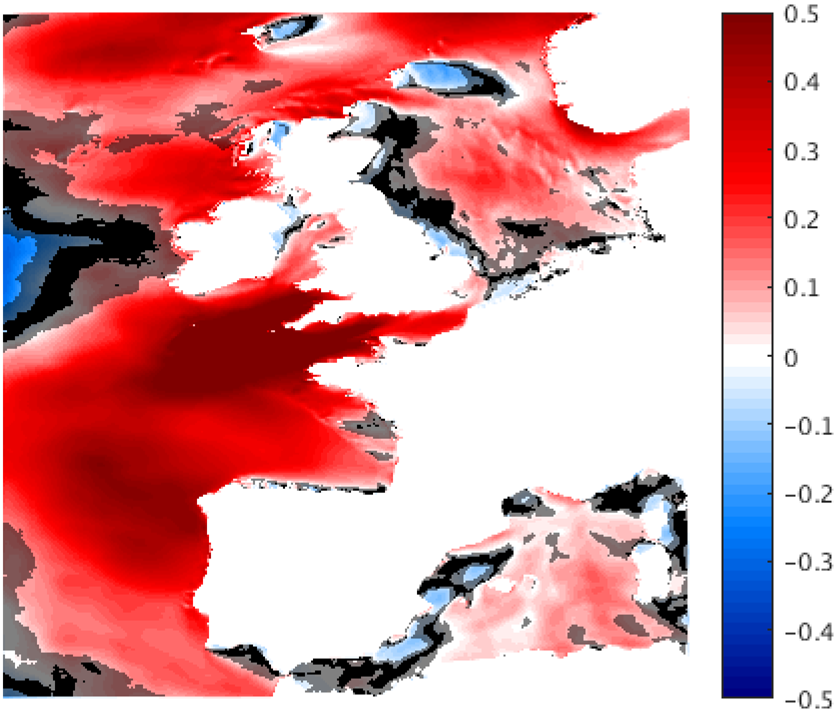


Figure 3.14 Example of the modelled change in annual maximum wave height (metres) for RCP 8.5, mid-century minus historic

Notes: Areas masked in black (grey) have a confidence interval below 50% (75%); RCP = representative concentration pathway.
Source: Figure reproduced from Bricheno and Wolf (2018).

The study found a decrease in mean significant wave height of the order of 0.2 metres across most of the European coast, increases in the annual maximum and 99th percentile wave height as large as 0.5–1.0 metres in some areas but with a more complex spatial pattern (see Figure 3.14), and an increase in waves to the north of Scotland mainly caused by a reduction in sea ice. The reduction in mean wave height was statistically robust, but there are wider confidence intervals for the changes in extremes waves.

3.4.2 Sea level

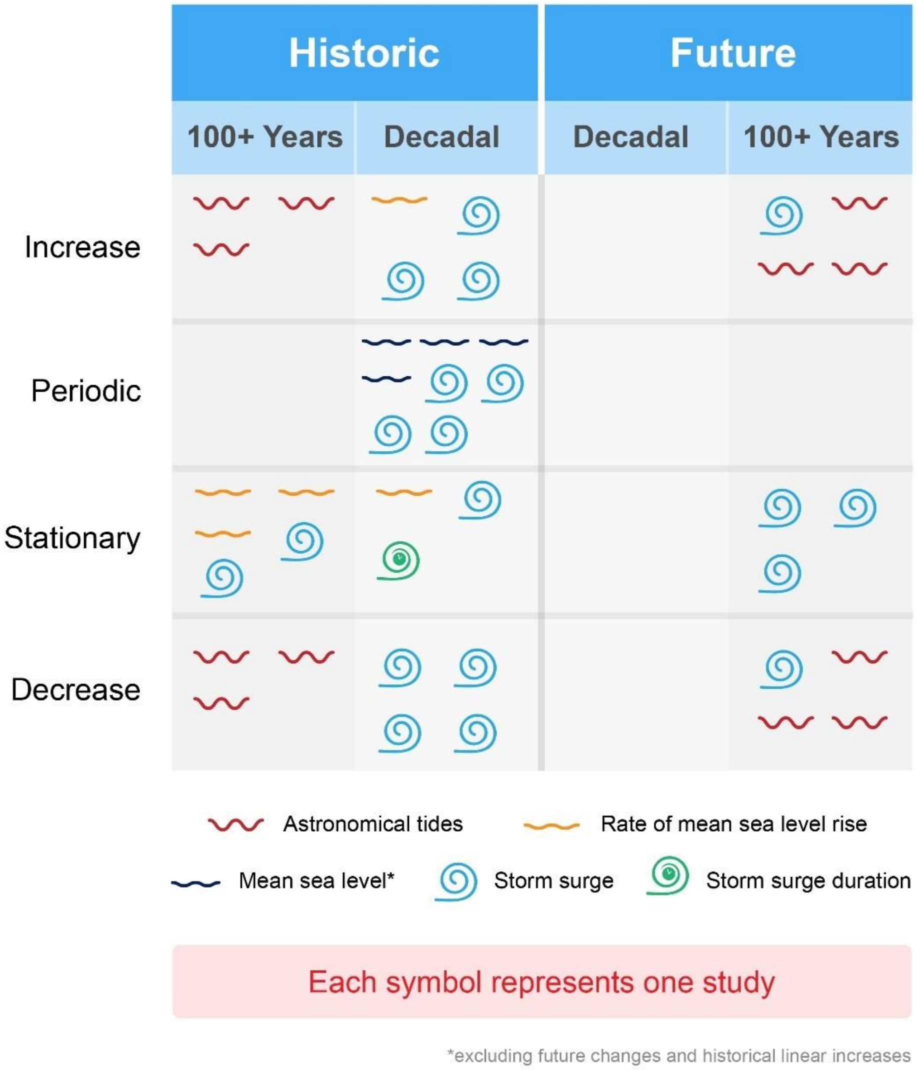
Extreme sea levels, as measured at tide gauges, are the combination of several components:

- astronomical tides
- mean sea level
- storm surge
- wave setup

No studies on wave setup were included following the critical appraisal. Mean sea level is already considered non-stationary due to climate change induced mean sea-level rise and post-glacial rebound (IPCC, 2013; Palmer, 2018); we did not consider studies focusing on the aspects already accounted for in flood risk studies in this review, as detailed in Section 2.3. We did, however, include studies addressing periodic mean sea-level variations (for example due to changes in seawater density and ocean circulation) and accelerating trends in historical mean sea level (due to climate change). Table 3.3 summarises the findings. It divides the studies into those that found the distribution of the source variables to be stationary and those that found it to be non-stationary (increase, decrease and periodic).

For the studies that found the source distributions to be non-stationary, the table further distinguishes between studies finding an increasing trend in the variable, a decreasing trend, or those that found ‘periodic’ variations. With periodic variations in a flooding source, the distribution could be considered stationary if data are available over a long enough period; however, if the distribution is described from samples taken from different shorter time slices, it can appear non-stationary. An example of this is shown in Figure 3.15 for extreme sea levels.

Table 3.3 Variability in sea-level component distributions



	Historic		Future	
	100+ Years	Decadal	Decadal	100+ Years
Increase	〰 〰 〰	≈ 🌀 🌀 🌀		🌀 〰 〰 〰
Periodic		∼ ∼ ∼ ∼ 🌀 🌀 🌀 🌀		
Stationary	≈ ≈ ≈ 🌀 🌀	≈ 🌀 ◎		🌀 🌀 🌀
Decrease	〰 〰 〰	🌀 🌀 🌀 🌀		🌀 〰 〰 〰

〰 Astronomical tides ≈ Rate of mean sea level rise

∼ Mean sea level* 🌀 Storm surge ◎ Storm surge duration

Each symbol represents one study

*excluding future changes and historical linear increases

Four studies examine changes in astronomical tides over century timescales: all found changes in the tidal pattern with increasing sea levels. As the pattern is changing, the tidal range increases in some locations and decreases in others, as exemplified in Figure 3 16. The magnitude of the change in astronomical tides is generally proportional to the amount of sea-level rise (for sea-level rise below 2 metres). It is a robust finding that the pattern changes with rising mean sea level; however, the actual changes vary between studies and are likely subject to the accuracy of the model used. Studies show that the response of tides to sea-level rise also depends on future coastal defences, that is, whether we allow areas to flood or not. The phase of the tides changes as well as the magnitude; Pickering and others (2012) found in some locations that this phase change altered the length of double high waters, which would affect inundation durations.

Climate models predict acceleration of the rate of mean sea-level rise, but four of five studies found no acceleration in the historical rate of sea-level rise. One study found evidence over decadal time scales. Periodic variations in mean sea level are also captured in decadal scales, as found in four studies.

The studies on storm surges found the historical distribution to be stationary over long time periods; however, again, given the periodic variations over decadal time scales, increasing and decreasing trends were found. Most studies predict the future storm surge distribution to be stationary, but one study showed both increases and decreases depending on location: storm surge changes were less than 0.1 metres for the 50-year return period. Only one study on storm surge duration found no trend in the historical data reviewed when inter-decadal variability due to the NAO was accounted for.

Multiple studies show evidence of the decadal variability in mean sea-level and storm surge distributions. Some studies also found trends in the storm surge distribution over these time scales. Decadal variability could lead to the findings of spurious trends when analysing time series over decadal timescales. Figure 3.15 demonstrates this decadal variability.

The boxes below summarise selected key papers.

Wadey MP and others. 'A century of sea level data and the UK's 2013/14 storm surges: an assessment of extremes and clustering using the Newlyn tide gauge record'

Ocean Science 2014: volume 10, issue 6, pages 1031–45

This study analysed the UK's longest and most complete sea level record from Newlyn, which spans a century. The authors extracted high water levels from the gauge record and assigned return periods based on comparison with the 2008 Coastal Flood Boundary dataset. They calculated return periods using joint probability analysis of the skew surge and astronomical tide distributions, and detrended both datasets to remove linear sea level rise.

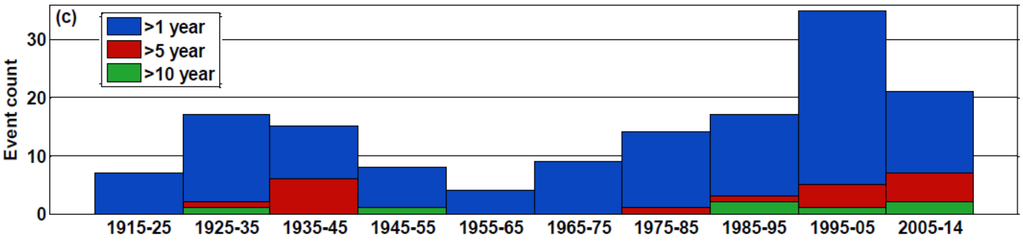


Figure 3.15 Frequency of extreme sea levels at Newlyn

Source: Figure reproduced from Wadey and others (2014).

Figure 3.15 shows the variation in the occurrence of extreme sea levels between decades. The authors made a qualitative comparison of annual high water counts with different components of sea level and the NAO index. They found periods of low counts of extreme high waters (and skew surges) coinciding with periods when the average variability in NAO was smaller; generally they found the clustering of extreme sea levels to be a combination of multiple sea level components.

Idier D and others. ‘Sea level rise impacts on the tides of the European Shelf’

Continental Shelf Research 2017: volume 137, pages 56–71

This study models changes in the tides across the European Shelf for sea level rises from -0.25 metres to +10 metres above present-day sea levels.

The authors tested uniform sea level rise across the shelf and non-uniform rise based on RCP 4.5 predictions. Figure 3.16 shows changes in the annual maximum tide (based on 2009 boundary forcing) in 2100 under RCP 4.5, using non-uniform sea level rise (global mean sea-level rise is 0.5 metres for this scenario). This demonstrates the spatial variation in tidal changes. Other scenarios gave similar spatial patterns for sea level rise up to 2 metres, but with different magnitudes of change. Generally, these changes were proportional to the sea level rise. The results in Figure 3.16 assume all present day coastlines are defended; results are different if coastal areas are allowed to flood.

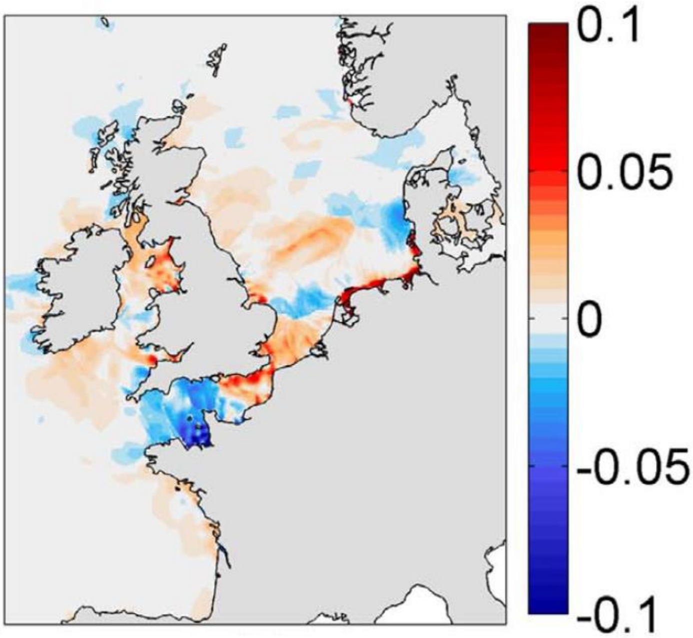


Figure 3.16 Predicted change in the annual maximum tide level (metres)

Note: predicted change under global mean sea level rise of 0.5 metres in 2100 and the RCP 4.5 climate change scenario. Source: Figure reproduced from Idier and others (2017).

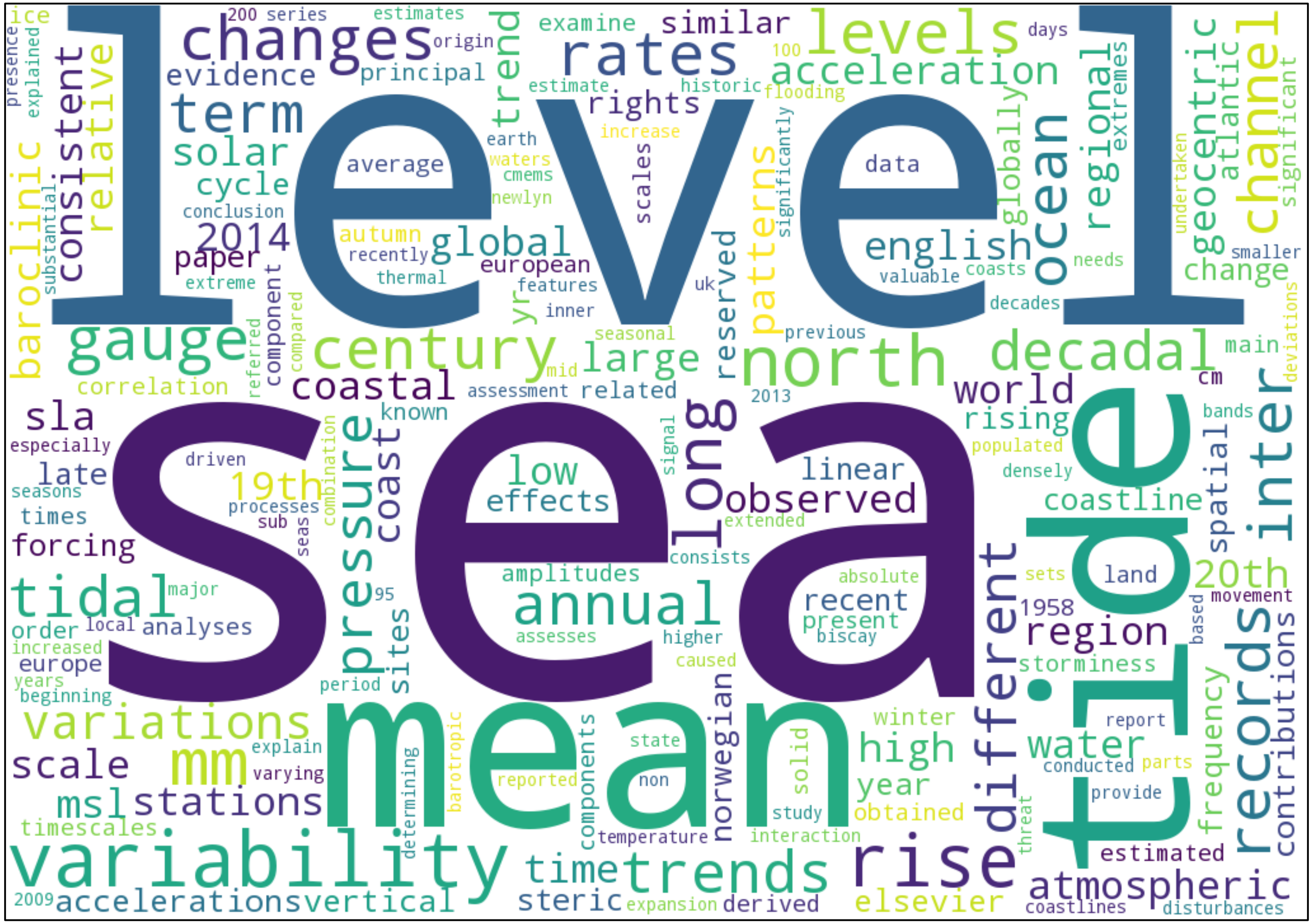
3.5 Topic modelling

Methods from natural language processing provide ways of automatically scanning through and analysing documents to provide insights into what topics they deal with and the frequency with which these topics occur. This so-called topic modelling offers the opportunity of an alternative to the analysis described above, which relies on the judgement of experts, who are subject to human biases.

These methods operate by clustering words that are more likely to appear together within the same document. This can help to assign papers to topics that are associated with each cluster. The approach applied here is non-negative matrix factorisation. You can find more details of this method in Lee and Seung (2001).

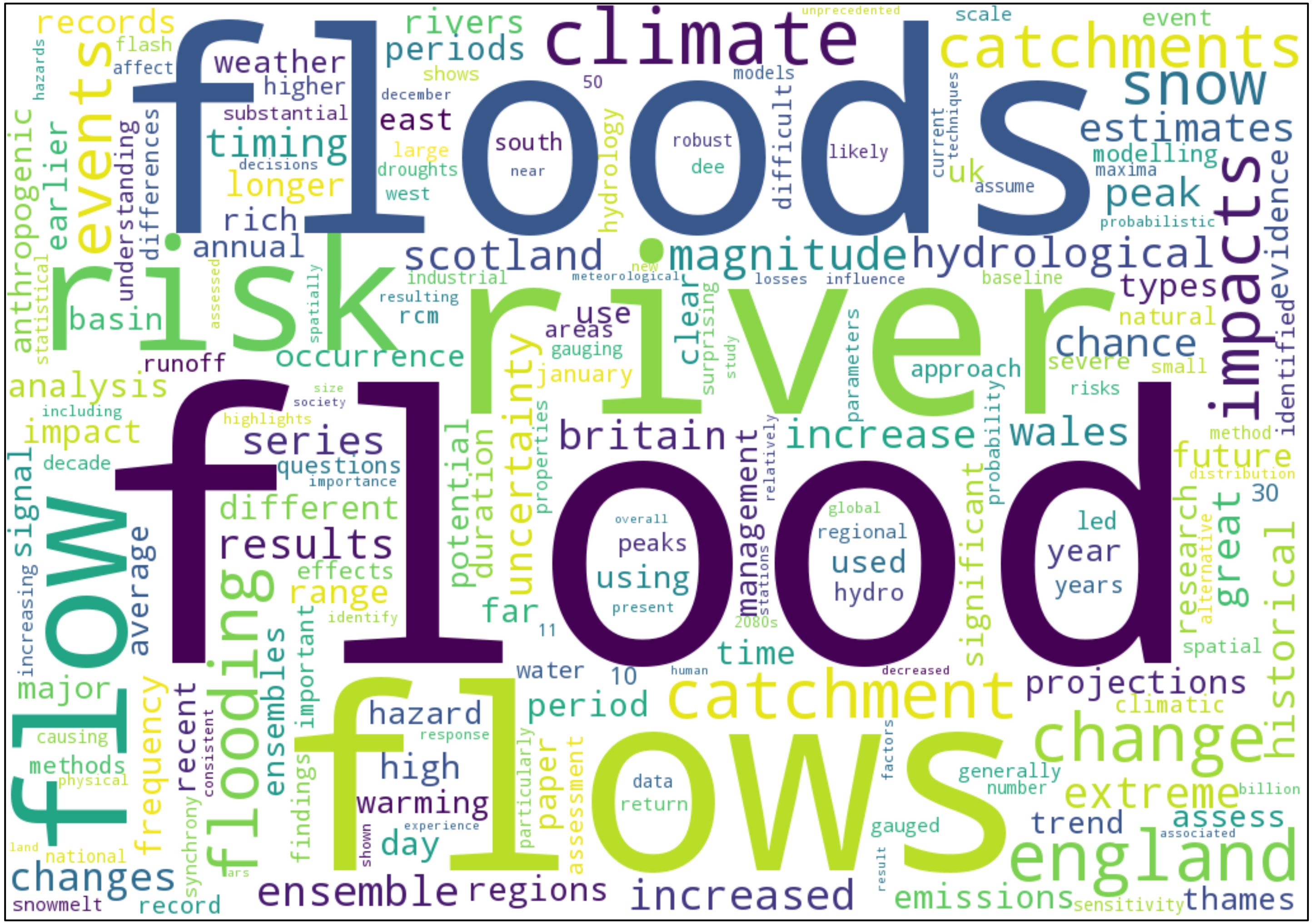
We applied this approach to the set of abstracts corresponding to studies passing the critical appraisal phase. The number of topics needs to be specified in advance, but through an iterative process we obtained a final solution of nine coherent topics. Word clouds showing the 200 most frequent words in each topic are presented below, with the size of each word representing its relative importance within each topic.

3.5.1 Mean sea level and tidal



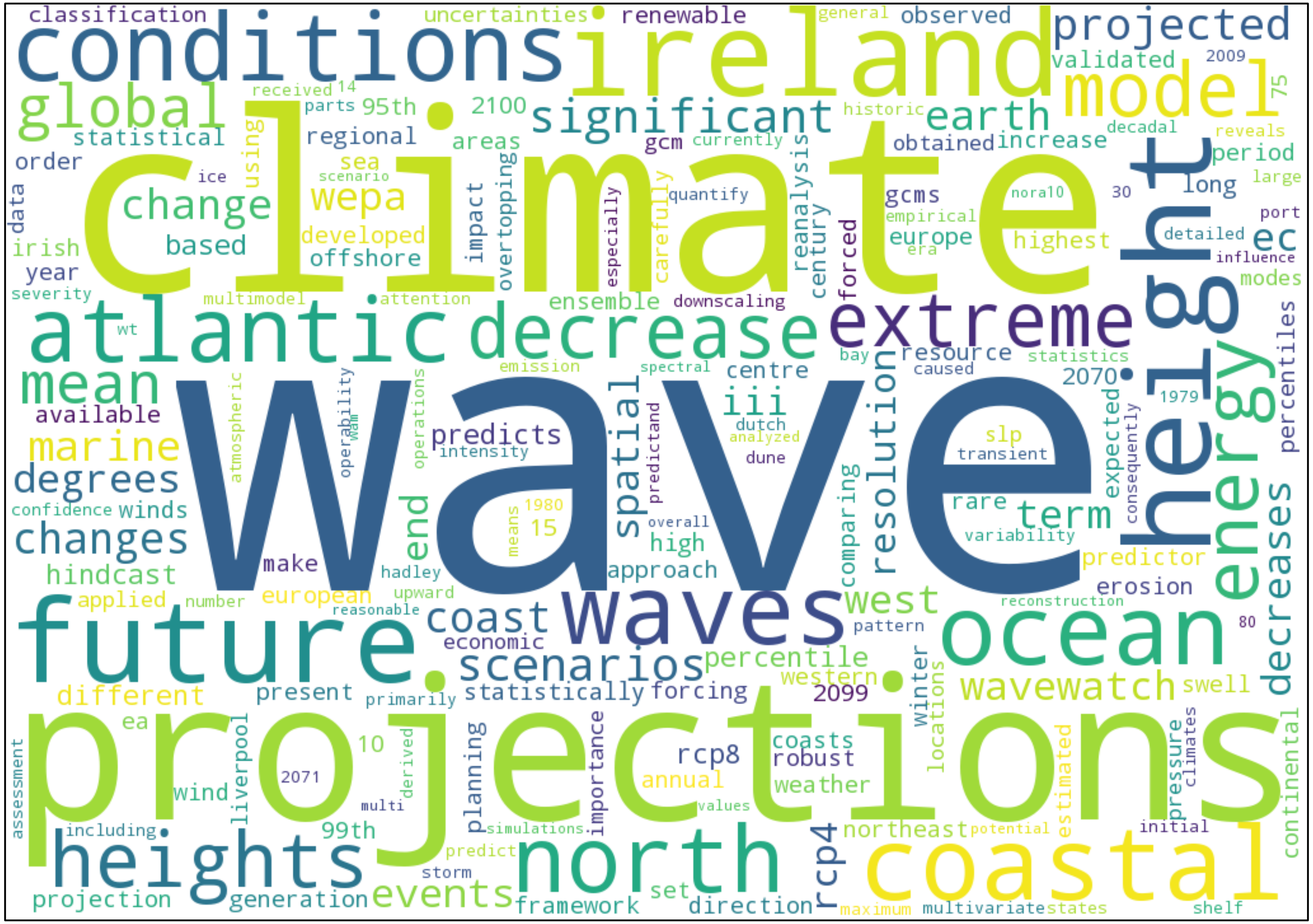
This topic shows a clear focus on sea-level and tidal studies, featuring analyses of changes in mean sea level and whether the rate of change is increasing. The word cloud alludes to some coverage of variability on long time scales and attribution of this variation to atmospheric drivers.

3.5.2 Fluvial



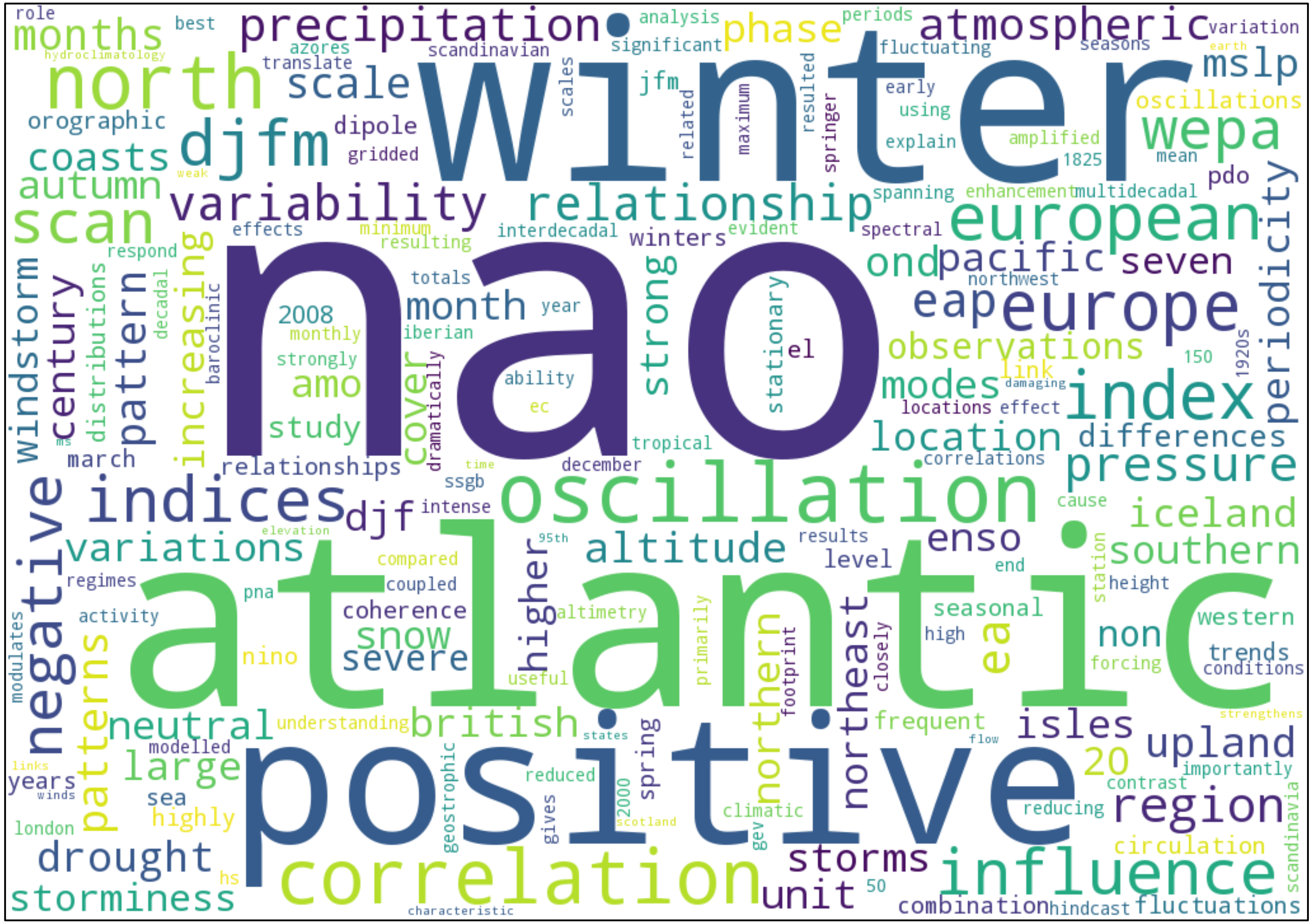
This topic shows an emphasis on flooding arising from peak river flows, which appear to be more linked to impact (flooding, risk, etc). Notable links to these studies include climate, catchment characteristics and snow melt.

3.5.3 Waves



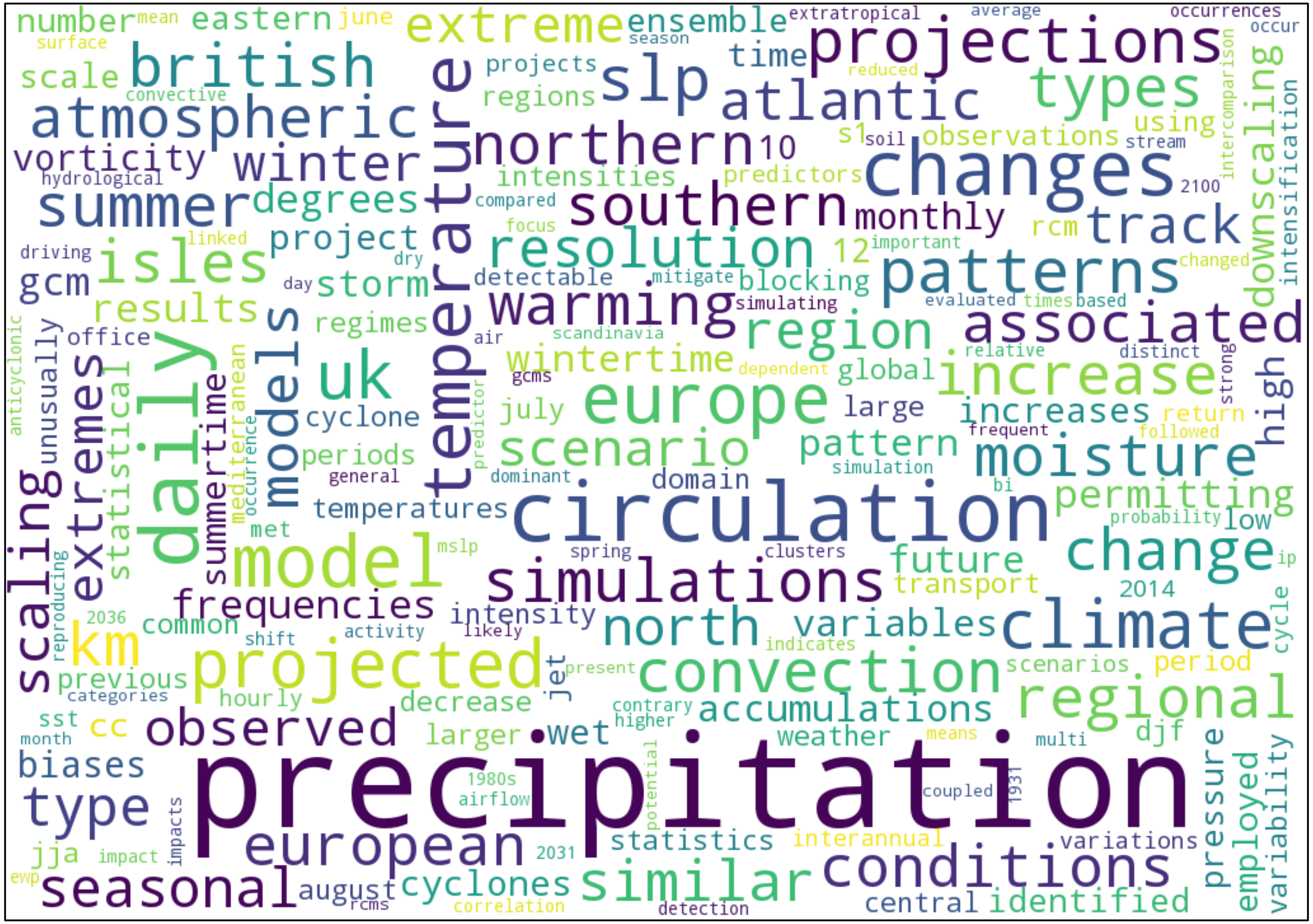
This topic sees a focus on extreme waves, with particular emphasis on modelling studies; conclusions may be largely derived from climate projections and future scenarios. Studies are based in the Atlantic Ocean and North Sea and tend to suggest possible decreases in wave heights in the future.

3.5.4 Climate variability



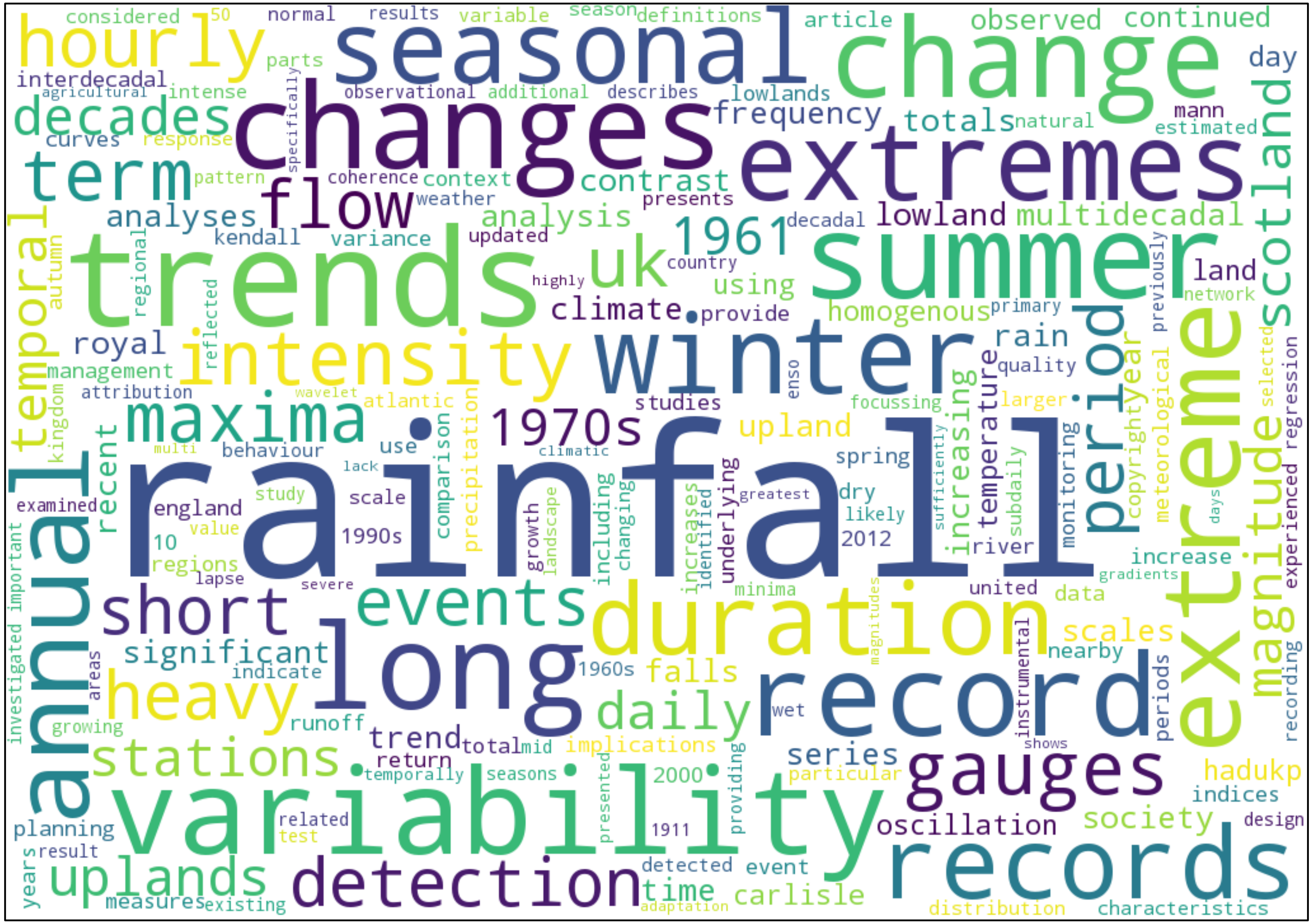
This topic covers atmospheric indices and time-averaged drivers of variability. It shows some emphasis on meteorological sources of flooding, but the topic is dominated by the NAO index and other pressure indices. This topic is particularly interesting as climate variability featured relatively rarely in our search strings, but comes out as an important topic. This emphasises the importance of atmospheric drivers in consideration of non-stationary processes.

3.5.5 Precipitation (modelling)



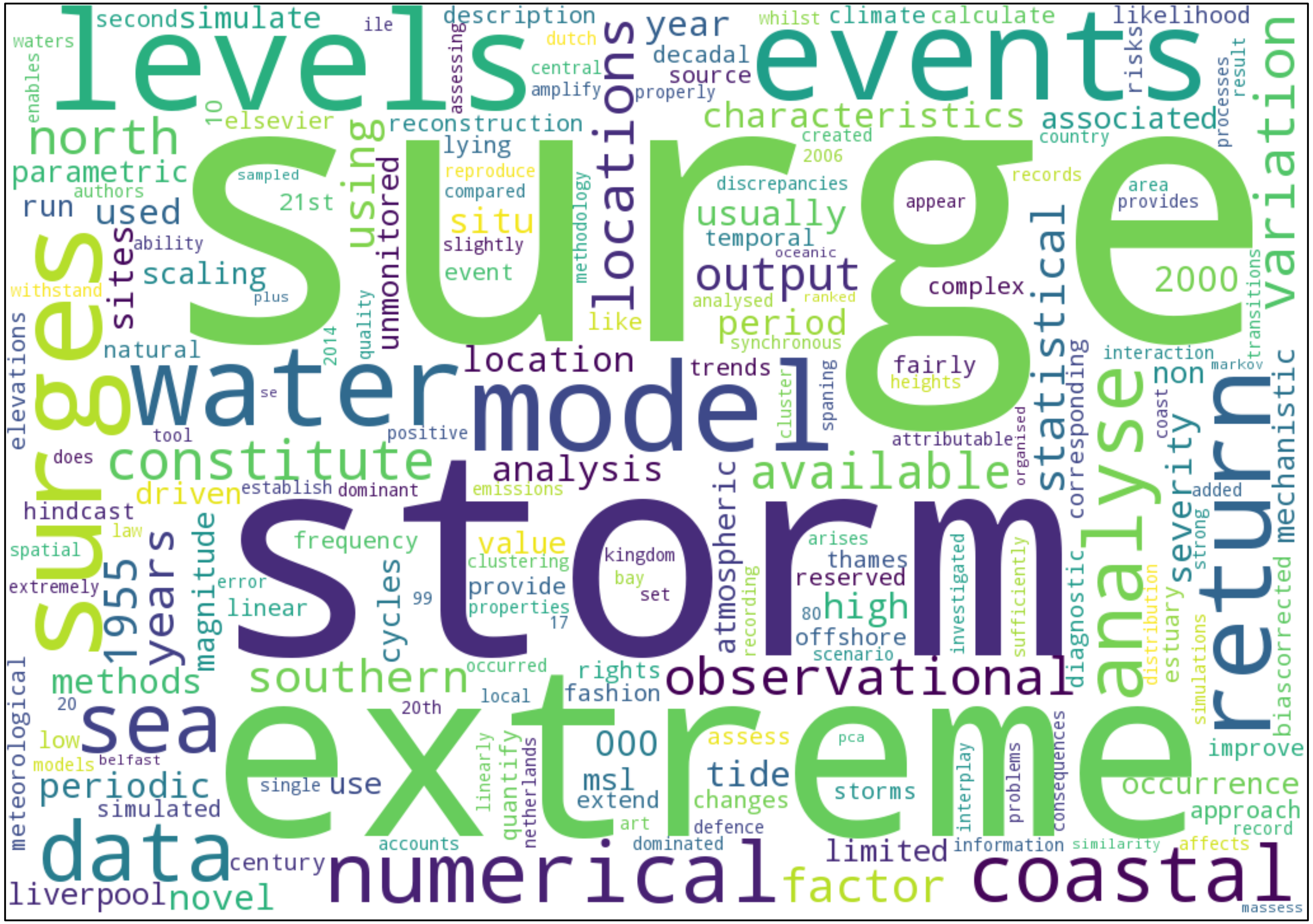
This topic comprises precipitation studies and associated links to atmospheric circulation, moisture and temperature. There appears to be a specific emphasis on modelling studies, with results coming from model projections and climate change scenarios.

3.5.6 Precipitation (observational)



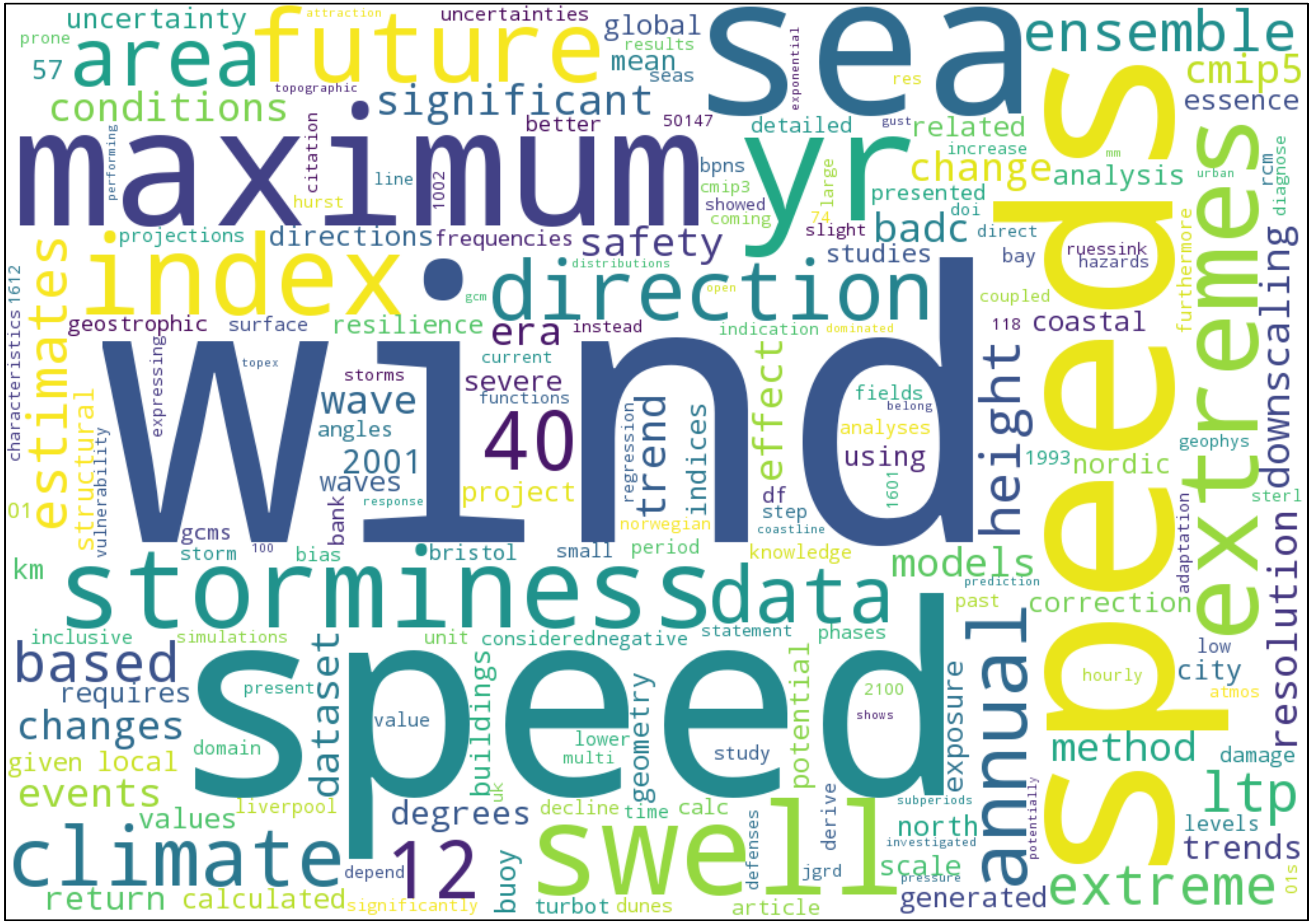
This topic has a similar focus on precipitation, but is clearly more related to observational studies, with mention of gauge records and weather stations. These studies are concerned with changes in extremes, whether these be long-term trends or due to natural variability.

3.5.7 Storm surges



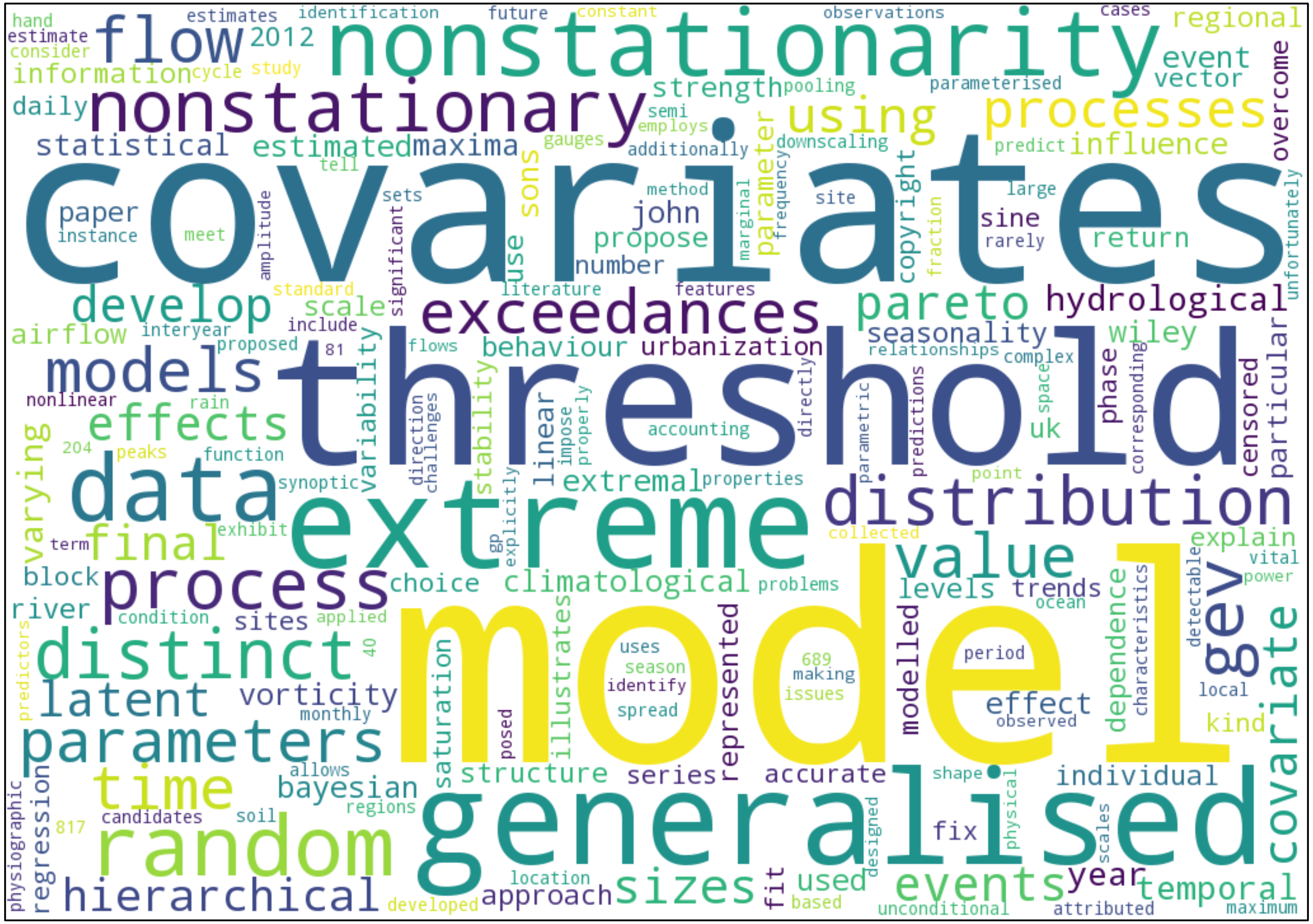
There is another focus here on sea-level extremes, but the topic is more concentrated on the contribution of storm surge. It demonstrates some emphasis on the statistical models used to generate sea-level return levels.

3.5.8 Extreme winds and storminess



This topic focuses on the effects of storminess, including wind speeds. It shows some emphasis on modelling studies.

3.5.9 Statistical concepts



Finally, this topic focuses on statistical studies investigating non-stationarity in environmental datasets. Most common methods appear to be extreme value models linked to annual maxima and peaks-over-threshold. It has a major emphasis on the need for covariates in order to inform and guide modelling of non-stationarity.

This approach can also reveal information as to the depth of the literature base for each topic. Figure 3.17 shows that, as in Figure 3.1, the most common topics cover sources of fluvial flooding and precipitation, although the waves topic is not as prominent here compared to Figure 3.1. This suggests that wave studies are more likely to be assigned to another topic, for example wave heights are associated with winds and storminess, and are useful datasets for statistical studies.

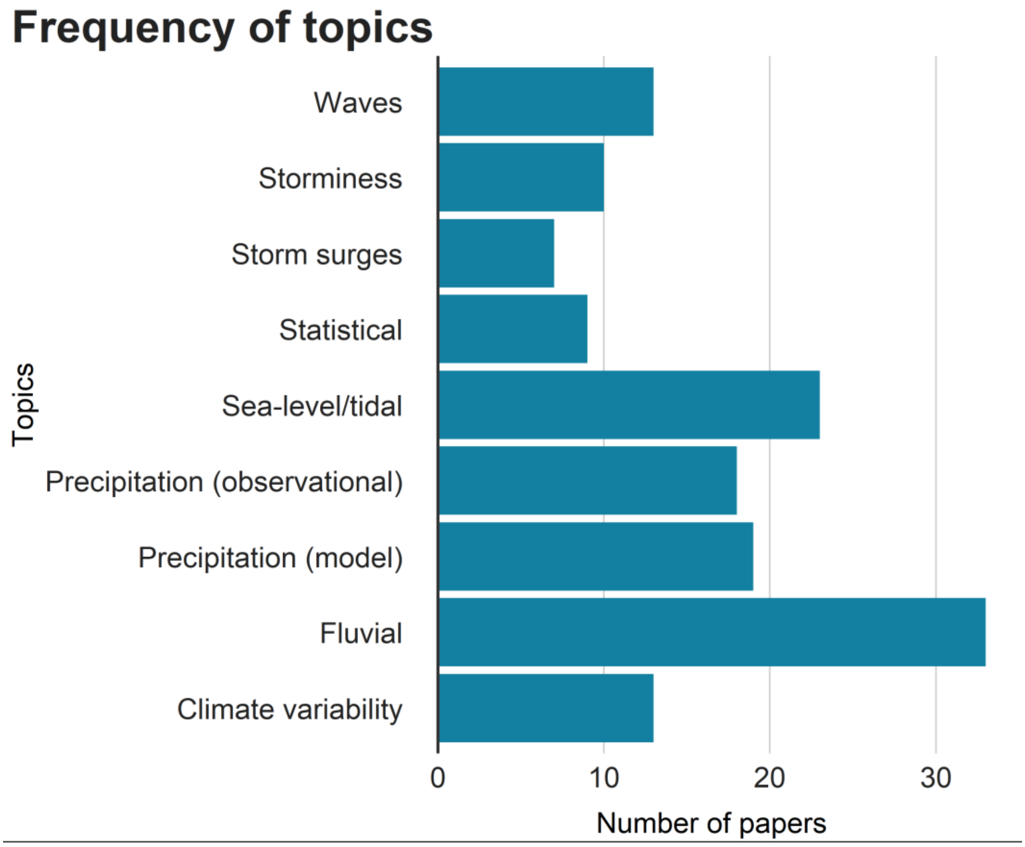


Figure 3.17 Number of studies corresponding to each topic

4 Secondary question results

The three secondary questions are addressed in Sections 4.1, 4.2 and 4.3 respectively.

4.1 What can cause non-stationarity in the sources of UK flooding?

Results of this summary analysis should be interpreted with care. Not all of the studies approached attribution from the point of view of first detecting a trend in observed data and then attempting to explain it. Some focused solely on investigating the effect of a particular driver, often climate change, on flooding. So the findings should not be taken as indicating, for example, that 29% of observed trends can be attributed to climate change.

We have summarised in Figure 4.1 the causes of non-stationarity identified in the literature we appraised. Climate change (29%) and teleconnections (27%) are the most frequently identified causes of non-stationarity; however, a large proportion (31%) of the studies that found non-stationarity either provided no information on the cause of non-stationarity, or could not attribute it to one specific cause. The teleconnections group includes large-scale patterns of mean sea-level pressure anomalies, such as the dominant mode of climate variability in the Atlantic and the NAO, and associated patterns including the East Atlantic/Western Russia mode. Also included in this group is the global teleconnection pattern, El Niño – Southern Oscillation (ENSO).

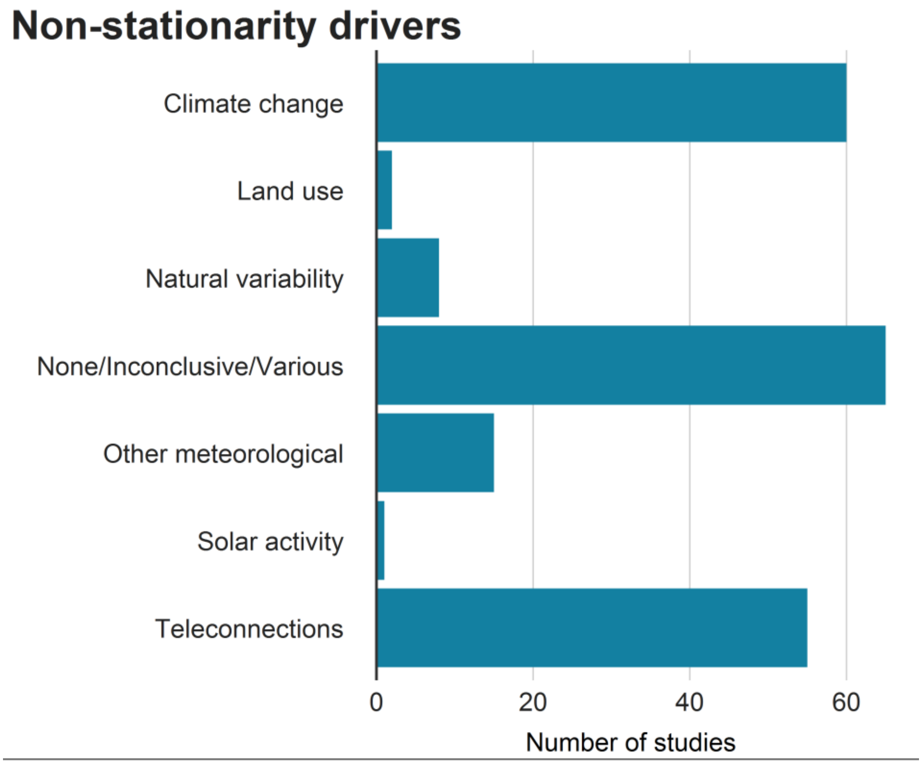


Figure 4.1 Number of studies corresponding to the drivers of non-stationarity

Drivers varied to some extent between the various types of flooding, but the most common drivers, that is, climate change and teleconnections, were identified in a substantial number of studies as covering both inland flooding and coastal flooding.

4.2 What techniques are used to detect and account for non-stationarity in the sources of UK flooding?

We have split this secondary question into two parts: firstly, Section 4.2.1 reviews the techniques used to detect non-stationarity; and then Section 4.2.2 reviews the methods used to account for non-stationarity in sources of UK flooding.

4.2.1 What techniques are used to detect non-stationarity in the sources of UK flooding?

During the evidence extraction stage of the review, we extracted evidence on techniques used to detect and attribute non-stationarity. This secondary question only asks about detection techniques; however, we considered information on methods used to attribute the non-stationarity to be complementary and hence included it. Figure 4.2 summarises methods used in the appraised literature for detecting and attributing non-stationarity.

Note that there is a contrast in the order of detection and attribution between observational and model studies. Observational studies usually attempt first to detect non-stationarity and then if detected, attempt to attribute it. Conversely, modelling studies often start with a postulated driver of change, for example modelling tides under two different mean sea-level scenarios, and then attempt to detect a difference between the results, implying non-stationarity or not.

The most commonly used method for both detecting the presence of non-stationarity and attributing it to a specific cause is the comparison of different periods of observed or modelled data (comparing time slices). Most studies following this approach use climate change scenarios to represent potential future climatic conditions. Some then apply rainfall-runoff models to compare the impact of present and future climatic conditions on river flows. Three of the papers have a different focus, aiming to estimate the extent to which recent inland floods (in 2000 and 2013–14) were exacerbated by climate change. In those studies, the comparison is between present-day conditions and a modelled pre-industrial climate.

The second most commonly used method for detecting the presence of non-stationarity is trend analysis of time series. Trend analysis for detection and attribution of non-stationarity includes (a) extreme-value statistical models, where time-varying climate variables are included as covariates and hence influence parameters used to characterise the extreme-value distribution, and (b) linear statistical models, where typically a linear regression model is employed with time-varying climate variables as covariates. Statistical methods employed to investigate the cause of non-stationarity include the comparison of correlation coefficients based on climate-variable indices.

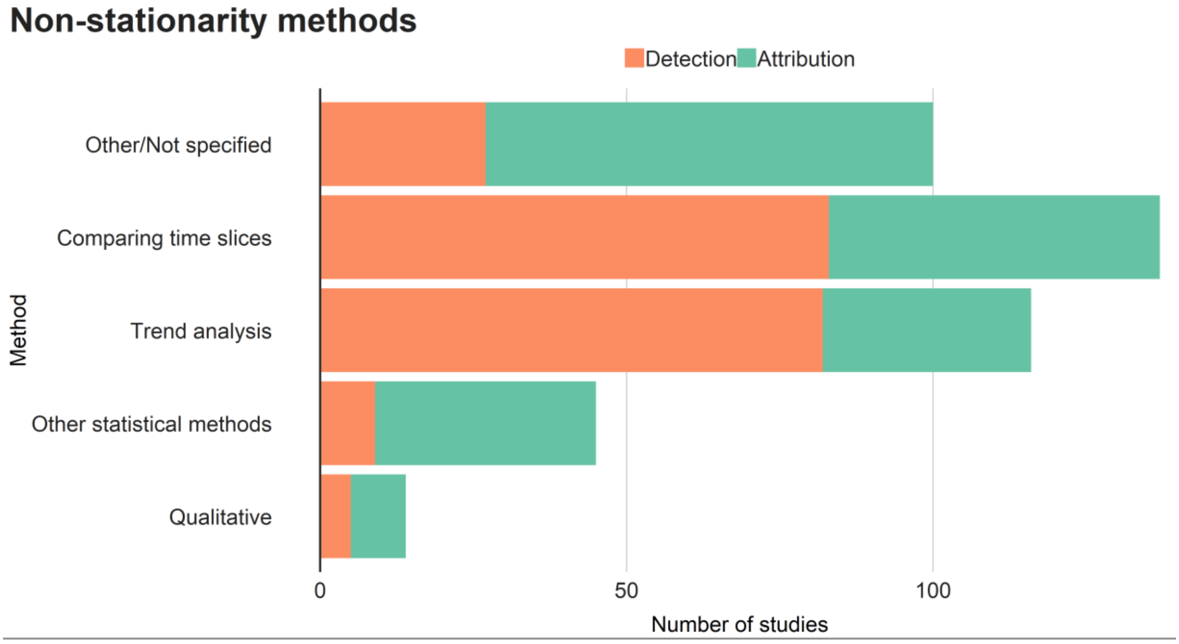


Figure 4.2 Number of studies corresponding to the methods for detecting and attributing non-stationarity

Note: The “Other/Not specified” category for attribution includes 34 studies that did not investigate attribution of non-stationarity.

Merz and others (2010) propose a distinction between ‘hard’ and ‘soft’ attribution of changes in flood characteristics. To qualify as hard attribution, studies need to show:

- evidence that the detected change is consistent with the proposed drivers of change
- evidence that the detected change is inconsistent with changes due to alternative possible drivers
- a quantified level of confidence showing that the attribution statement is reliable

Within the scope of this project we have not been able to classify the attribution studies in accordance with this framework.

4.2.2 What techniques are used to account for non-stationarity in the sources of UK flooding?

Some of the studies in the literature move on from detection of non-stationarity to carry out a frequency analysis that accounts for non-stationarity. Methods employed include de-trending prior to frequency analysis (typically used for sea-level data) and fitting of distributions whose parameters can vary over time or with physically based covariates. While there are many articles in general on methodologies for accounting for non-stationarity, we discovered relatively few through the literature search due to its geographical focus on the UK. An example is highlighted below.

Accounting for non-stationarity

Prosdocimi and others (2015) account for the effect of urbanisation on flood frequency on the River Lostock in Lancashire, along with a neighbouring rural catchment as a control. They fitted statistical models to both annual maximum and peak-over-threshold floods, relating the location parameter of each model to three candidate covariates: time, urban extent and extreme daily rainfall. The threshold exceedances were represented using a point process model, which had the benefit of allowing the covariates to influence both the frequency and magnitude of floods.

The authors fitted each model using maximum likelihood estimation, which allowed the estimation of confidence intervals.

An advantage of including rainfall as a covariate was that it removed much of the year-to-year variability, making the effect of the urbanisation on flood frequency more apparent.

4.3 To what extent does an assumption of stationarity or non-stationarity alter the outcome of flood risk analysis?

A flood risk analysis includes multiple steps. It starts with a statistical assessment of the sources of flooding and usually finishes with return period flood inundation maps, sometimes with associated economic costs. Transforming the source to the impact requires numerical modelling of the pathways and receptors. It takes significant effort to reach the outcome of a flood risk study, which may explain why, based on screening paper titles and abstracts, there are no published studies that performed a full flood risk assessment under both the assumption of stationarity and compared the results with a flood risk assessment under the assumption of non-stationarity. We are aware of a study of this nature that was not found in our literature search as its title does not contain any locational words (see the box below).

Implications of non-stationarity for flood risk management

Rehan and Hall (2016) explore the implications of non-stationary analysis for economic decision-making in flood risk management. They conclude that a move to non-stationary analysis makes little difference to the economic performance of decisions and suggest that an assumption of stationarity is preferable for practical application of flood risk management. However, they do not recommend dismissal of non-stationary methods. One reason they quote for at least considering non-stationary models alongside stationary analysis is that the former can lead to a higher variance in estimates of optimal flood protection. The study was based on flow data from the Thames at Kingston, perturbed to introduce an artificial trend in the location parameter of a range of magnitudes. This is an unusually long dataset in a UK context, dating back to 1883, and so the conclusions are not necessarily applicable to locations with more typical record lengths or to non-stationary analysis carried out using different methods.

5 Concluding remarks

5.1 Conclusions

5.1.1 Overview

In this review we have assessed a wide range of evidence across a number of disciplines with the aim of exploring stationarity or non-stationarity in sources of UK flooding. We have explored evidence of functional non-stationarity, that is, whether a change occurs in the observed behaviour of a source of flooding. To consider the WMO definition, one must consider the drivers of change, which we have included as a secondary question.

We have observed a variety of conclusions referring to different sources of flooding and locations as to whether indeed non-stationarity is an important consideration in flood risk management.

Causes of non-stationarity are frequently cited as being climate change or teleconnections; however, several studies included in the review focused solely on investigating the effect of a postulated driver on flooding rather than considering a number of possible reasons for an observed trend.

The topic modelling approach that we applied to the set of abstracts supported the findings of the review, providing additional information about the spread of topics in the literature base. This procedure also highlighted the importance of time-averaged indices of atmospheric variability in sources of flooding as key aspects to explore when considering non-stationarity. Given their lack of use in current flood frequency estimation practice, it is worth considering the benefits of incorporating this information to explore attribution of trends and improve risk estimates.

5.1.2 Inland flooding

Out of the studies that passed the data screening and critical appraisal stages, the largest number (48) investigate non-stationarity in precipitation over the UK. Most of these focus on extreme precipitation, for which there was a general consensus of an increase, mainly found from analysis of historical observations. Methods currently used by practitioners to estimate design rainfalls for flood studies and drainage design assume stationarity. In light of the research findings, this assumption may need to be revisited.

Based on 36 studies that passed the critical appraisal, the literature base suggests a broad consensus on increasing flood flows in UK rivers, although a small number of studies observed no change or decreases. These exceptional studies are mostly focused on a small number of locations. However, some of them focus on the longer term, including historical data spanning several centuries. This provides a broader perspective in comparison with gauged records, many of which start during the 1960s or 70s, a relatively flood-poor period.

Inevitably, national-scale studies of trends in river flow find a mixture of results, with no significant trend seen at many locations. There were many more instances of increasing trends than of decreasing ones. Again, this finding contrasts with the current common practice of not allowing for non-stationarity when carrying out frequency analysis of recorded peak-flow data.

Several studies refer to the difficulty of identifying trends in relatively short data series characterised by large variability. Even if changes in the climate are already having an impact on the sources of pluvial and fluvial flooding in the UK, this impact may not be detectable in some locations for many decades into the future.

Nearly a third of the papers on inland flooding that passed the critical appraisal include an investigation of future changes, generally using modelling techniques. Most of these use climate change scenarios to represent potential future rainfall conditions, and some then apply rainfall-runoff models to compare the impact of present and future climatic conditions on river flows. Most of these modelling studies found that increases in extreme rainfall and peak river flows were expected, and these results have led to the change allowances that are currently applied by practitioners.

Three of the papers have a different focus, aiming to estimate the extent to which recent floods (in 2000 and 2013–14) were exacerbated by climate change. Although all conclude that greenhouse gas emissions were likely to have had a contribution to these events, the results were highly uncertain, with the range of possibilities including no exacerbation.

5.1.3 Coastal flooding

The literature we reviewed in this study identified the most important discrepancy with current practice to be the assumption of stationarity of the astronomical tide distribution. Studies agree tidal distributions are changing with sea-level rise: the larger the sea-level rise, the more inappropriate the assumption of stationarity becomes. Therefore, assuming observed astronomical tides come from a stationary distribution seems reasonable as observed sea-level rise is small (over the 20th century, tide gauge observations show that the global sea level on average rose by about 0.17 metres [Bindoff and others, 2007]). However, assuming the astronomical tidal distribution is stationary when assessing future epochs with larger predicted sea-level rises is not supported by the literature.

The review supports current best practice for calculating coastal extremes based on historical data when sufficiently long time series exist, that being: to assume winds, waves, storm surge and astronomical tides are stationary and a linear increase in mean sea level. Studies highlight the decadal variability in storm surges and mean sea level; accounting for this in statistical analyses of long time series would reduce uncertainty. If datasets of mean sea level and storm surges only cover a few decades, then they may appear non-stationary due to these decadal variations.

Studies find evidence that the future distributions of all coastal flood sources are non-stationary under climate change. However, for storm surge the consensus is that over century timescales, the distribution can be assumed to be stationary. These results mirror the latest climate change guidance (UKCP18), but not current practice used for future flood risk assessments, where the astronomical tide is assumed to be stationary.

There is high uncertainty in future changes to extreme winds and waves. Changes across the UK are spatially dependent on changes in the North Atlantic jet stream, which is not well represented in climate models. Studies agree on a reduction of mean wave heights; however, this review focuses on flood risk and we find no reliable consensus on the (non-)stationarity of future extreme winds and waves.

Most studies did not find evidence of sea-level rise acceleration in historical data and hence support removing a linear sea level rise trend from historical data to produce a stationary dataset. Climate change studies predict acceleration of mean sea level in future, but distinguishing an accelerating trend from natural variability is difficult until either the acceleration has been recorded for a significant amount of time, or the interannual variability is removed and accounted for. Therefore, we recommend that this finding should be reviewed regularly against the latest science.

A limitation of this study is that papers required a locational keyword to be included in the review. This was necessary to reduce the number of papers to a manageable number. However, this has led to relevant papers not being included. Most notably, at review we identified recent papers (Nerem and others, 2018; Dangendorf and others, 2017) finding statistically significant acceleration in sea-level rise when looking at global sea-level datasets.

5.2 Knowledge gaps

We identified the following points as not being well-represented in the literature base, and they may provide opportunities for further research or a differently focused literature review:

- only two papers on changes in flood duration passed the critical appraisal and only one paper on changes in storm duration was found to inform coastal flood risk studies
- only one study explores whether the spatial extent of widespread flood events is changing over time – the spatial extent of flooding is an important aspect for the insurance sector, and also for emergency planning
- no studies explore how the dependence between offshore coastal variables is changing over time, which may be useful for flood risk studies requiring use of joint probability methods
- a number of studies explore the relationship between sources of flooding and modes of natural climate variability, but it is still unclear how practitioners might effectively use this information to inform estimates of flood risk
- little evidence was found to answer the question on the extent to which an assumption of stationarity or non-stationarity alters the outcome of flood risk analysis
- only a few articles address methodologies for accounting for non-stationarity in flood risk estimation

To keep the task manageable, we focused the search for evidence on articles clearly dealing with UK conditions, or with Western Europe for coastal flooding. It may be that some of the gaps listed above can be filled by examining literature without such a specific geographical focus. For example, the scientific literature is replete with articles that present or review methodologies for accounting for non-stationarity, with papers on this topic published somewhere in the world at a frequency that seems almost daily. Because the evidence search was focused, properly, on the primary question, we included relatively few of these methodological articles in the evidence base. The Environment Agency is reviewing a wider range of literature on this topic as part of a separate project: ‘Developing interim national guidance on non-stationary: fluvial flood frequency estimation’.

5.3 Recommendations

The Environment Agency, along with equivalent bodies in other UK countries, will need to consider the implications of these findings for flood risk management activities. Potential ways forward include:

- consider whether to amend UK rainfall frequency statistics to allow for non-stationarity in rainfall records
- consider whether to amend practice in river flood frequency estimation to allow for non-stationarity; the project mentioned above is addressing this recommendation
- change practice to allow for non-stationarity of the astronomical tide distribution when estimating future tide levels
- review future research for evidence of an accelerating trend in sea-level rise

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List of abbreviations

AMO	Atlantic Meridional Oscillation
AR	atmospheric river
CMIP5	Coupled Model Inter-comparison Project Phase 5
Defra	Department for Environment, Food and Rural Affairs
ENSO	El Niño – Southern Oscillation
GCM	general circulation model
NaFRA2	National Flood Risk Assessment 2
NAO	North Atlantic Oscillation
NPPF	National Planning Policy Framework
RCP	representative concentration pathway
REA	rapid evidence assessment
UKCP09	UK Climate Projections 2009
UKCP18	UK Climate Projections 2018
WMO	World Meteorological Organisation

Glossary

Astronomical tide	The sea level that would result from gravitational effects, for example of the moon and sun, without any atmospheric influences.
Fetch	Horizontal length of sea over which the wind blows in an essentially constant direction, thus generating waves.
Mean sea level	The sea level halfway between the mean levels of high and low water.
Storm surge	The change in sea level as a result of wind and atmospheric pressure changes associated with a storm. This report does not distinguish between residual storm surge and skew surge.
Storm surge duration	The number of hours for which the storm surge is above a given threshold.
Teleconnections	Large scale pattern of atmospheric circulation
Tidal pattern	Spatial variations in astronomical tidal range.
Wave height	In this report wave height refers to significant wave height.
Wave period	In this report we have not distinguished between types of wave period. The reader is referred to the original paper (via the systematic map) for the wave period used in each study.
Wave setup	Wave setup is the additional elevation of the water level due to the effects of transferring momentum from breaking waves in the surf zone.

Appendix A: Additional screening

A1 Database inclusion/exclusion criteria

Web of Science and Scopus are equipped with the capability to automatically refine search results based on including or excluding articles from a particular discipline or journal. The Review Team applied the following inclusion/exclusion criteria to the complete set of articles before the results were exported.

Table A.1 Inclusion/exclusion criteria applied to Web of Science search results

Include/Exclude	Type	Items
Exclude	Category	Geology, Paleontology, Surgery, Biodiversity Conservation, Energy Fuels, Zoology, Medicine General Internal, Agronomy, Evolutionary Biology, Clinical Neurology, Engineering Electrical Electronic, Computer Science Interdisciplinary Applications, Agriculture Multidisciplinary, Dentistry Oral Surgery Medicine, Engineering Mechanical, Engineering Geological, Green Sustainable Science Technology, Astronomy Astrophysics, Biolog, Pediatrics, Veterinary Sciences, Economics, Health Care Sciences Services, Genetics Heredity, Infectious Diseases, Cardiac Cardiovascular Systems, Entomology, Neurosciences, Imaging Science Photographic Technology, Respiratory System, Toxicology, Chemistry Analytical, Microbiology, Urology Nephrology, Archaeology, Ornithology, Peripheral Vascular Disease, Psychiatry, Critical Care Medicine, Orthopedics, Obstetrics Gynecology, Biochemistry Molecular Biology, Oncology, Physiology, Mechanics, Mineralogy, Radiology Nuclear Medicine Medical Imaging, Emergency Medicine, Engineering Chemical, Pharmacology Pharmacy, Mycology, Biophysics, Anthropology, Urban Studies, Biotechnology Applied Microbiology, Horticulture, Management, Ophthalmology, Health Policy Services, Immunology, Otorhinolaryngology, Construction Building Technology, Engineering Petroleum, Telecommunications, Engineering Multidisciplinary, Gastroenterology Hepatology, Chemistry Multidisciplinary, Computer Science Information Systems, Endocrinology Metabolism, Rehabilitation, Agriculture Dairy Animal Science, Mining Mineral Processing, Social Sciences Interdisciplinary, Transportation Science Technology, Acoustics, Medicine Research Experimental, Thermodynamics, Geriatrics

		Gerontology, Hematology, Materials Science Multidisciplinary, Parasitology, Physics Fluids Plasmas, Chemistry Physical, Food Science Technology, Instruments Instrumentation, Nursing, Pathology, Primary Health Care, Sport Sciences, Anesthesiology, Reproductive Biology, Social Sciences Mathematical Methods, Agricultural Engineering, Business Finance, Computer Science Theory Methods, Engineering Aerospace, Automation Control Systems, Demography, Engineering Industrial, History, Mathematical Computational Biology, Transplantation, Information Science Library Science, Optics.
Include	Category	Geosciences Multidisciplinary, Environmental Sciences, Meteorology Atmospheric Sciences, Water Resources, Geography Physical, Oceanography, Engineering Civil, Limnology, Multidisciplinary Sciences, Engineering Environmental, Engineering Ocean, Geography, Environmental Studies, Statistics Probability, Engineering Marine, Mathematics Interdisciplinary Applications, Mathematics Applied
Exclude	Source	Geomorphology, Earth Surface Processes And Landforms, Marine Geology, Holocene, Marine Ecology Progress Series, Atmospheric Chemistry And Physics, Journal Of Paleolimnology, Marine And Petroleum Geology, Climate Of The Past, Aquatic Conservation Marine, Freshwater Ecosystems, Journal Of Biogeography, Biogeosciences, Journal Of The Geological Society, Geological Society Of America Bulletin, Environmental Pollution, Environmental Monitoring And Assessment, Journal Of Atmospheric And Solar Terrestrial Physics, Ecological Applications, Cryosphere, Journal Of Soils And Sediments, Journal Of Geophysical Research Biogeosciences, Geological Magazine, Ecological Engineering, Journal Of Environmental Radioactivity, Chemosphere, Environmental Science And Pollution Research, Environmental Science Policy, Global Biogeochemical Cycles, Journal Of Environmental Quality, Journal Of Glaciology, Fisheries Oceanography, Geological Journal, Environmental Geology, Global Environmental Change Human And Policy Dimensions, Land Use Policy, Wetlands, Wit Transactions On Ecology And The Environment, Quaternary Science Reviews Or Journal Of Quaternary Science, Quaternary International, Quaternary Research, Quaternary Geochronology.

Table A.2 Exclusion criteria applied to Scopus search results

Include/Exclude	Type	Items
Exclude	Category	Medicine, Agricultural and Biological Sciences, Social Sciences, Biochemistry, Genetics and Molecular Biology, Arts and Humanities, Pharmacology Toxicology and Pharmaceutics, Immunology and Microbiology, Computer Science, Neuroscience, Chemistry, Nursing, Health Professions, Materials Science, Dentistry, Business Management and Accounting, Chemical Engineering, Economics, Psychology, Veterinary
Exclude	Source	Journal of Applied Ecology, Geomorphology, Marine Geology, Sedimentary Geology, Atmospheric Chemistry and Physics, Geological Society Special Publication, Sedimentology, Global Change Biology, Quaternary International, Journal of Sedimentary Research, Journal of Turbulence, Wit Transactions on Ecology and Environment, Ecological Modelling, Water Air and Soil Pollution, Journal of Medical Engineering and Technology, Marine Micreopaleontology, Bulletin of the Geological Society of America, Ecological Engineering, Energy Policy, Geological Magazine, Hydrogeology Journal, Physics and Chemistry of the Earth, Geological Journal, International Journal of Ambient Energy, Journal of Atmospheric and Solar Terrestrial Physics, Journal of Contaminant Hydrology, Climate of the Past, Environmental Science and Pollution Research, Journal of the Geological Society, Biogeochemistry, Environmental Toxicology and Chemistry, Journal of Environmental Quality, Journal of Wind Engineering and Industrial Aerodynamics, Special Paper of the Geological Society of America, Advances in Space Research, Chemical Geology, Global Biogeochemical Cycles, Bulletin of the Seismological Society of America, Cave and Karst Science, Climate Policy, International Water Power and Dam Construction, Journal of Ecology, Proceedings of the Institution of Mechanical Engineers, Tectonophysics, Ecology and Society, Geobios, Holocene, International Journal of Greenhouse Gas Control, International Journal of Pavement Engineering, Journal of Petrology, Journal of Soils and Sediments, Paleoceanography, Petroleum Geology Conference Proceedings.

A2 Warning words

The literature search resulted in 9,746 articles. To make the article screening more efficient, the Review Team chose a subset of these articles to screen in a broad sense to identify any words or phrases common to titles of articles of no relevance to the primary question. The following words were used to reduce the number of articles to be manually screened down to 6,657:

> *"ecolog","ecosystem","quaternary","glac","pollution","chemistry","chemical","arctic","antarctic","wetland", "ice sheet", "sediment", "transport", "Australia", "British Columbia", "New South Wales", "biodiversity", "stratig", "habitat", "marsh", "nitrate", "fossil", "ecohydro", "biogeo", "carbon", "isotope", "particle", "electric", "nitrogen", "karst", "volcan", "canad", "tectonic", "hurricane", "acoustic", "geolog", "vegetation", "jurassic", "plankton", "landslide", "landfill", "phosph", "water quality", "air quality", "mineral", "fauna", "flora", "species", "organic", "ozone", "oxide", "rainforest", "radiat", "tsunami", "gravit", "monsoon", "iodine", "chlorophyll"*

A3 Additional insights

Despite discarding a large number of papers during the screening phase, the Review Team obtained the following additional insights into the literature base from reading the abstracts.

- a breadth of research investigates how well climate models can actually simulate extreme events
- several papers conclude there is high uncertainty in the regional downscaling of climate projections; in one, this uncertainty was larger than all other elements when looking at changes in the resulting rainfall distribution (including emissions scenarios), but in others uncertainty due to general circulation models (GCMs) was consistently larger than that of downscaling techniques
- some authors define non-stationarity as the dependence of one variable on a covariate, such as direction
- several papers discuss changes in what could be indirect drivers of flooding, for example sea surface temperatures, Gulf Stream position, but these have been excluded as no direct link to a source of flooding has been established
- numerous papers cover multivariate dependence of different parts of the wave climate; however, these abstracts do not refer to non-stationarity, and it seems that stationarity is an assumption worth making to get across the novelty of the paper's method or findings

Appendix B: Articles from which the findings were synthesised

Listed below are the 144 articles that successfully passed through the screening and so were used to synthesise the findings.

Authors	Title	Publication name	Date
Afzal, Muhammad; Gagnon, Alexandre S.; Mansell, Martin G.	Changes in the variability and periodicity of precipitation in Scotland	THEORETICAL AND APPLIED CLIMATOLOGY	2015
Allan, Rob; Tett, Simon; Alexander, Lisa	Fluctuations in autumn-winter severe storms over the British Isles: 1920 to present	INTERNATIONAL JOURNAL OF CLIMATOLOGY	2009
Archer, David R.; Parkin, Geoff; Fowler, Hayley J.	Assessing long term flash flooding frequency using historical information	HYDROLOGY RESEARCH	2017
Arns A., Jensen J., Wahl T.	A consistent return level assessment considering present day and future mean sea level conditions	KUSTE	2014
Atyeo, Jonathan; Walshaw, David	A region-based hierarchical model for extreme rainfall over the UK, incorporating spatial dependence and temporal trend	ENVIRONMETRICS	2012
Baggaley, N. J.; Langan, S. J.; Futter, M. N.; Potts, J. M.; Dunn, S. M.	Long-term trends in hydro-climatology of a major Scottish mountain river	SCIENCE OF THE TOTAL ENVIRONMENT	2009
Bakker, Alexander M. R.; van den Hurk, Bart J. J. M.	Estimation of persistence and trends in geostrophic wind speed for the assessment of wind energy yields in Northwest Europe	CLIMATE DYNAMICS	2012
Barcikowska, Monika J.; Weaver, Scott J.; Feser, Frauke; Russo, Simone; Schenk, Frederik; Stone, Daithi A.; Wehner, Michael F.; Zahn, Matthias	Euro-Atlantic winter storminess and precipitation extremes under 1.5 degrees C vs. 2 degrees C warming scenarios	EARTH SYSTEM DYNAMICS	2018
Belleflamme, Alexandre; Fettweis, Xavier; Erpicum, Michel	Do global warming-induced circulation pattern changes affect temperature and precipitation over Europe during summer?	INTERNATIONAL JOURNAL OF CLIMATOLOGY	2015
Berghuijs, W.R., Allen, S.T., Harrigan, S. and Kirchner, J.W.	Growing spatial scales of synchronous river flooding in Europe	GEOPHYSICAL RESEARCH LETTERS	2019
Biggs, Eloise M.; Atkinson, Peter M.	A characterisation of climate variability and trends in hydrological extremes in the Severn Uplands	INTERNATIONAL JOURNAL OF CLIMATOLOGY	2011
Blenkinsop, S.; Chan, S. C.; Kendon, E. J.; Roberts, N. M.; Fowler, H. J.	Temperature influences on intense UK hourly precipitation and dependency on large-scale circulation	ENVIRONMENTAL RESEARCH LETTERS	2015
Blenkinsop, S.; Zhao, Y.; Quinn, J.; Berryman, F.; Thornes, J.; Baker, C.; Fowler, H. J.	Downscaling future wind hazard for SE London using the UKCP09 regional climate model ensemble	CLIMATE RESEARCH	2012
Bloschl, G., Hall, J., Parajka, J.and many others	Changing climate shifts timing of European floods	SCIENCE MAGAZINE	2017
Bricheno, Lucy M and Wolf, Judith	Future Wave Conditions of Europe, in Response to High-End Climate Change Scenarios	JOURNAL OF GEOPHYSICAL RESEARCH: OCEANS	2018
Bromirski, Peter D.; Cayan, Daniel R.	Wave power variability and trends across the North Atlantic influenced by decadal climate patterns	JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS	2015
Brown, Jennifer M.; Wolf, Judith; Souza, Alejandro J.	Past to future extreme events in Liverpool Bay: model projections from 1960-2100	CLIMATIC CHANGE	2012

Authors	**Title**	**Publication name**	**Date**
Brown, Simon J.	The drivers of variability in UK extreme rainfall	INTERNATIONAL JOURNAL OF CLIMATOLOGY	2018
Burt, T. P.; Ferranti, E. J. S.	Changing patterns of heavy rainfall in upland areas: a case study from northern England	INTERNATIONAL JOURNAL OF CLIMATOLOGY	2012
Burt, T. P.; Holden, J.	Changing temperature and rainfall gradients in the British Uplands	CLIMATE RESEARCH	2010
Burt, T. P.; Howden, N. J. K.	North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain	WATER RESOURCES RESEARCH	2013
Burt, T. P.; Howden, N. J. K.; Worrall, F.	The changing water cycle: hydroclimatic extremes in the British Isles	WILEY INTERDISCIPLINARY REVIEWS-WATER	2016
Butler, Adam; Heffernan, Janet E.; Tawn, Jonathan A.; Flather, Roger A.	Trend estimation in extremes of synthetic North Sea surges	JOURNAL OF THE ROYAL STATISTICAL SOCIETY SERIES C-APPLIED STATISTICS	2007
Butler, Adam; Heffernan, Janet E.; Tawn, Jonathan A.; Flather, Roger A.; Horsburgh, Kevin J.	Extreme value analysis of decadal variations in storm surge elevations	JOURNAL OF MARINE SYSTEMS	2007
Caires, Sofia; Groeneweg, Jacco; Sterl, Andreas	Past and future changes in the north sea extreme waves	COASTAL ENGINEERING 2008, VOLS 1-5	2009
Camus, P.; Losada, I. J.; Izaguirre, C.; Espejo, A.; Menendez, M.; Perez, J.	Statistical wave climate projections for coastal impact assessments	EARTHS FUTURE	2017
Castelle, Bruno; Dodet, Guillaume; Masselink, Gerd; Scott, Tim	A new climate index controlling winter wave activity along the Atlantic coast of Europe: The West Europe Pressure Anomaly	GEOPHYSICAL RESEARCH LETTERS	2017
Castelle, Bruno; Dodet, Guillaume; Masselink, Gerhard; Scott, Tim	Increased Winter-Mean Wave Height, Variability, and Periodicity in the Northeast Atlantic Over 1949-2017	GEOPHYSICAL RESEARCH LETTERS	2018
Chafik, Leon; Nilsen, Jan Even Oie; Dangendorf, Soenke	Impact of North Atlantic Teleconnection Patterns on Northern European Sea Level	JOURNAL OF MARINE SCIENCE AND ENGINEERING	2017
Chan, S. C.; Kendon, E. J.; Fowler, H. J.; Blenkinsop, S.; Roberts, N. M.	Projected increases in summer and winter UK sub-daily precipitation extremes from high-resolution regional climate models	ENVIRONMENTAL RESEARCH LETTERS	2014
Chan, Steven C.; Kahana, Ron; Kendon, Elizabeth J.; Fowler, Hayley J.	Projected changes in extreme precipitation over Scotland and Northern England using a high-resolution regional climate model	CLIMATE DYNAMICS	2018
Chen, Xinping; Dangendorf, Soenke; Narayan, Nikesh; O'Driscoll, Kieran; Tsimplis, Michael N.; Su, Jian; Mayer, Bernhard; Pohlmann, Thomas	On sea level change in the North Sea influenced by the North Atlantic Oscillation: Local and remote steric effects	ESTUARINE COASTAL AND SHELF SCIENCE	2014
Chiverton, A.; Hannaford, J.; Holman, I. P.; Corstanje, R.; Prudhomme, C.; Hess, T. M.; Bloomfield, J. P.	Using variograms to detect and attribute hydrological change	HYDROLOGY AND EARTH SYSTEM SCIENCES	2015
Climent-Soler, D.; Holman, I. P.; Archer, D. R.	Application of flow variability analysis to identify impacts of agricultural land-use change on the River Axe, southwest England	HYDROLOGY RESEARCH	2009
Cloke, Hannah L.; Wetterhall, Fredrik; He, Yi; Freer, Jim E.; Pappenberger, Florian	Modelling climate impact on floods with ensemble climate projections	QUARTERLY JOURNAL OF THE ROYAL METEOROLOGICAL SOCIETY	2013
Collet, L.; Beevers, L.; Stewart, M. D.	Decision-Making and Flood Risk Uncertainty: Statistical Data Set Analysis for Flood Risk Assessment	WATER RESOURCES RESEARCH	2018
Collet, Lila; Beevers, Lindsay; Prudhomme, Christel	Assessing the Impact of Climate Change and Extreme Value Uncertainty to Extreme Flows across Great Britain	WATER	2017

Authors	Title	Publication name	Date
Collet, Lila; Harrigan, Shaun; Prudhomme, Christel; Formetta, Giuseppe; Beevers, Lindsay	Future hot-spots for hydro-hazards in Great Britain: a probabilistic assessment	HYDROLOGY AND EARTH SYSTEM SCIENCES	2018
D Maraun, HW Rust, TJ Osborn	Synoptic airflow and UK daily precipitation extremes	EXTREMES,	2010
Dawkins, Laura C.; Stephenson, David B.; Lockwood, Julia F.; Maisey, Paul E.	The 21st century decline in damaging European windstorms	NATURAL HAZARDS AND EARTH SYSTEM SCIENCES	2016
de Leeuw, Johannes; Methven, John; Blackburn, Mike	Variability and trends in England and Wales precipitation	INTERNATIONAL JOURNAL OF CLIMATOLOGY	2016
de Winter, R. C.; Sterl, A.; Ruessink, B. G.	Wind extremes in the North Sea Basin under climate change: An ensemble study of 12 CMIP5 GCMs	JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES	2013
de Winter, Renske C.; Sterl, Andreas; de Vries, Johannes W.; Weber, Susanne L.; Ruessink, Gerben	The effect of climate change on extreme waves in front of the Dutch coast	OCEAN DYNAMICS	2012
Déborah Idiera, François Parisa, Gonéri Le Cozanneta, Faiza Boulahyaa, Franck Dumasb	Sea-level rise impacts on the tides of the European Shelf	CONTINENTAL SHELF RESEARCH	2017
Dieppois, Bastien; Durand, Alain; Fournier, Matthieu; Massei, Nicolas	Links between multidecadal and interdecadal climatic oscillations in the North Atlantic and regional climate variability of northern France and England since the 17th century	JOURNAL OF GEOPHYSICAL RESEARCH-ATMOSPHERES	2013
Eastoe, E.	Non-stationarity in peaks-over-threshold river flows: a regional random effects model	ENVIRONMETRICS	2019
Faulkner, D., Warren, S., Spencer, P. and Sharkey, P.	Can we still predict the future from the past? Implementing non-stationary flood frequency analysis in the UK	SUBMITTED PAPER	2019
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