delivering benefits through evidence


# Recommendations for future research and practice on non-stationarity in UK flooding

FRS18087/REA/R2

Flood and Coastal Erosion Risk Management Research and Development Programme

We are the Environment Agency. We protect and improve the environment.

Acting to reduce the impacts of a changing climate on people and wildlife is at the heart of everything we do.

We reduce the risks to people, properties and businesses from flooding and coastal erosion.

We protect and improve the quality of water, making sure there is enough for people, businesses, agriculture and the environment. Our work helps to ensure people can enjoy the water environment through angling and navigation.

We look after land quality, promote sustainable land management and help protect and enhance wildlife habitats. And we work closely with businesses to help them comply with environmental regulations.

We can't do this alone. We work with government, local councils, businesses, civil society groups and communities to make our environment a better place for people and wildlife.

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

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

**ISBN:** 978-1-84911-471-4



Email: fcerm.evidence@environment-agency.gov.uk

Further copies of this report are available from our publications catalogue:
http://www.gov.uk/government/publications

or our National Customer Contact Centre:
T: 03708 506506

Email: enquiries@environment-agency.gov.uk

**Author(s):**
Fay Luxford and Duncan Faulkner

**Dissemination status:**
Publicly available

**Keywords:**
Non-stationarity, stationarity, fluvial, costal, pluvial, rainfall.

**Research contractor:**
JBA Consulting
1 Broughton Park, Old Lane North, Broughton, Skipton, North Yorkshire, BD23 3FD
www.jbaconsulting.com

**Environment Agency's Project Manager:**
Dr Sean Longfield
Lead Scientist

**Theme Manager:**
Dr Susan Manson
Incident Management and Modelling Theme Manager

**Collaborator(s):**
Kevin Horsburgh, Angela Hibbert, Lucy Bricheno, Francisco Calafat, all from the National Oceanographic Centre

**Project number:**
FRS18087

# Evidence at the Environment Agency

Scientific research and analysis underpins everything the Environment Agency does. It helps us to understand and manage the environment effectively. Our own experts work with leading scientific organisations, universities and other parts of the Defra group to bring the best knowledge to bear on the environmental problems that we face now and in the future. Our scientific work is published as summaries and reports, freely available to all.

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:
http://evidence.environment-agency.gov.uk/FCERM/en/Default/FCRM.aspx

You can find out more about our current science programmes at:
https://www.gov.uk/government/organisations/environment-agency/about/research

If you have any comments or questions about this report or the Environment Agency's other scientific work, please contact research@environment-agency.gov.uk

Professor Doug Wilson
**Director, Research, Analysis and Evaluation**

# Executive summary

In 2019 JBA Consulting carried out a rapid evidence assessment (REA) on behalf of the Environment Agency to synthesise current knowledge on stationarity or non-stationarity in sources of fluvial, coastal and pluvial flooding in the UK. The results of that study are reported in 'Rapid Evidence Assessment of Non-Stationarity in Sources of UK Flooding', June 2019.

This report describes a follow-on phase of work that investigated how the Environment Agency, along with equivalent bodies in other UK countries, might deal with the issues that were identified in the REA. It includes a review of international practice in the USA, Canada, Australia, Netherlands, Germany and Switzerland, covering official guidance from flood risk management authorities and approaches used by practitioners. It also identifies other UK initiatives on non-stationarity at research institutes, UK universities and in the insurance sector.

Based on these findings the following recommendations for future research and practice are made:

- Take a more holistic approach to non-stationary fluvial flood frequency that looks beyond annual maximum peak flows to consider aspects such as the magnitude and frequency of all floods, their tendency to cluster, their duration, and hydrograph shapes and volumes.

- Develop a practical method of non-stationary flood frequency estimation that can be applied on ungauged catchments and reduces the uncertainty associated with single-site frequency analysis.

- Integrate the modelling of past and future non-stationarity in flood flows. This will include work to attribute observed trends.

- Commission a scoping study that looks at trends in extreme rainfall, options for incorporating non-stationarity in UK rainfall frequency analysis, and the need to merge modelling of past trends and future expected climate change.

- As part of the sensitivity testing in flood risk mapping, test the impact of increasing/decreasing the future tidal range by +/- 10% of the mean sea level rise being applied.

- Further analysis of regional tidal models and their response to sea level rise, to reduce uncertainty around the local sign and magnitude of tidal changes.

- Analyse the changes to future tidal curves from existing studies investigating the impact of sea level rise on astronomical tides.

- Improve quantification of the natural variability of storm surges.

- Reassess tide gauge records for accelerating sea level rise when next updating either the Coastal Flood Boundary or State of the Nation data sets.

- Test the sensitivity of inshore wave direction to changes in offshore wave direction.

- Maintain the current networks of tide, river and rain gauges.
- Acquire high quality, multi-decadal wave observations in suitable locations.
- Research methods to correct/blend hindcast and observed data to improve wave hindcasts.
- Run a high-resolution UK scale long wave hindcast based on ERA-5 winds (1950 to 2020).

# Acknowledgements

We are grateful to all of the following for responding to our requests for information:

Rory Nathan, Associate Professor in Hydrology & Water Resources, University of Melbourne, Australia

Donald H Burn, Professor Emeritus, Civil & Environmental Engineering, University of Waterloo, Canada

Gabriele Villarini, Director, IIHR—Hydroscience & Engineering; Associate Professor, Civil & Environmental Engineering, University of Iowa, USA

John Chester, Amod Dhakal and Alexis Dufour, San Francisco Public Utilities Commission, USA

Dr Ferdinand Diermanse, Delft Hydraulics/Deltares, Netherlands

Prof Steffen Bold, Rottenburg University of Applied Sciences, Germany

Dr Michael Stölzle, Freiburg University, Germany

Dr Uwe Ehret, Karlsruhe Institute of Technology, Germany

Peter Mittag and Frank Wolters, Administrative District Office, Tübingen, Germany

Andreas Stegmaier, Regional Authority Tübingen, Germany

Sven Berendsen, Newcastle University, previously Aquantec Karlsruhe, Germany

Dr Thomas Wöhling, Dresden University of Technology, Germany

Bernd Mehlig, State Agency for Nature, Environment and Consumer Protection North Rhine-Westphalia, Germany

Dr Manuel Antonetti, Zurich University of Applied Sciences, Switzerland

Caroline Kan, Bundesamt für Umwelt (BAFU), Switzerland

Dr Louise J. Slater, Associate Professor, University of Oxford; Chair, Oxford Water Network

Dr Emma Eastoe, Lancaster University

Professor Jonathan Tawn, Lancaster University

Dr Thomas Kjeldsen, University of Bath

Dr Stephen Blenkinsop, Newcastle University

Dr Elizabeth Lewis, Newcastle University

Dr Simon Brown, Lead Scientist and Climate Extremes Research Manager, Met Office

Dr Mark McCarthy, Manager National Climate Information Centre, Met Office

Lisa Stewart, UK Centre for Ecology and Hydrology

Dr Kathleen McInnes of CSIRO, Australia.

Dr Arne Arns, University of Rostock, Germany

Dr Sönke Dangendorf, University of Siegen, Germany

Dr Robert Vos, Rijkwaterstaat, Netherlands

Dr Kathleen White, US Army Corps of Engineers, United States

Prof. Thomas Wahl, University of Central Florida, United States

Dr Judith Wolf, National Oceanographic Centre, UK

Enda Murphy, National Research Council Canada, Canada

# Contents


| | | |
|---|---|---|
| **1** | **Background** | **7** |
| 1.1 | Wave conditions | 8 |
| **2** | **Purpose of this report** | **9** |
| **3** | **Approach to investigation** | **10** |
| **4** | **International practice for handling non-stationarity in flood risk management** | **11** |
| 4.1 | USA | 11 |
| 4.2 | Canada | 14 |
| 4.3 | Australia | 16 |
| 4.4 | Europe - general | 17 |
| 4.5 | Netherlands | 18 |
| 4.6 | Germany | 19 |
| 4.7 | Switzerland | 21 |
| 4.8 | Summary of international practice | 23 |
| **5** | **Practice for handling non-stationarity in the insurance sector** | **24** |
| **6** | **Related initiatives** | **26** |
| 6.1 | University research programmes | 26 |
| 6.2 | Met Office | 28 |
| 6.3 | UK Centre for Ecology and Hydrology (UKCEH) | 29 |
| 6.4 | National Oceanography Centre | 29 |
| 6.5 | Marine Climate Change Impacts Partnership | 30 |
| 6.6 | Wave climate projections | 31 |
| **7** | **Recommendations for future research and practice** | **34** |
| 7.1 | Rivers | 34 |
| 7.2 | Rainfall and run-off | 37 |
| 7.3 | Estuaries | 39 |
| 7.4 | Non-stationarity of astronomical tides | 39 |
| 7.5 | Storm surges | 40 |
| 7.6 | Sea level rise acceleration | 40 |
| 7.7 | Waves | 41 |
| 7.8 | Data | 42 |
| 7.9 | Summary of recommendations | 43 |
| **References** | | **45** |
| **List of abbreviations** | | **50** |
| **Appendix A: Summary of coastal flood risk and flood management guidance in the UK, USA, Australia, Germany, and the Netherlands** | | **52** |

# 1 Background

In 2019 JBA Consulting carried out a rapid evidence assessment (REA) on behalf of the Environment Agency to synthesise current knowledge on stationarity or non-stationarity in sources of fluvial, coastal and pluvial flooding in the UK.

The primary question was:

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

Three secondary questions were also addressed:

- 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 assessment extracted evidence from 334 published articles, selected from an initial list of nearly 10,000 identified by a literature search. A critical appraisal led to a final set of 144 articles that were judged to be sufficiently relevant and robust.

A final report, ‘Rapid Evidence Assessment of Non-Stationarity in Sources of UK Flooding’, was submitted in June 2019. The report summarised the findings of the articles in relation to the presence or absence of non-stationarity, the aspects of flood hazard that are thought to be non-stationary, the direction of change, the way in which change was detected and the causes of non-stationarity.

The evidence showed a general, but not universal, consensus that both precipitation and flood flows on rivers are increasing. 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.

On coastal extremes, the evidence agreed with current practice for present day extremes analysis but disagreed for assessments of future climates. The evidence indicated a discrepancy with current practice regarding the assumption of stationarity of the astronomical tide distribution (once the rise in mean sea level is accounted for). Studies found evidence that the future distributions of all coastal flood sources are non-stationary under climate change.

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.

A separate project, also commissioned by the Environment Agency and led by JBA, has developed interim guidance and tools for practitioners to apply non-stationary frequency analysis of fluvial flooding. The project report, completed in March 2020, includes several recommendations for further research and development.

## 1.1 Wave conditions

There is a special focus on wave conditions in this background section, not given to any other variables because the wave conditions used in extreme value assessments do not go directly into flood risk mapping unlike extreme sea levels and fluvial flows.

Near the coast wave conditions are strongly depth dependent and, for this reason, the nearshore wave climate is highly non-stationary under rising mean sea level. Statistical assessments used for flood risk studies in England are based on offshore waves which do not show this same behaviour. All references to waves in this study refer to the offshore wave conditions used in statistical assessments.

For context, the following explains the link between these offshore wave conditions and the resulting flood maps used by the Environment Agency for the two methods currently used. In both methods, extreme sea levels applied to produce the return period flood maps are based on tide gauge data, dynamically interpolated around the coast using a hydrodynamic model (Coastal Flood Boundary Dataset).

Much coastal flood modelling carried out over the last 15 years has been based on the FD2308 joint probability guidance, which follows this methodology:

- Calculate extreme sea level and wave height return period events based on nearshore sea levels and offshore wave heights.
- Use wave transformation modelling or a simplified approach to transform offshore waves to the inshore.
- Calculate the wave overtopping based on these inshore waves and water level conditions.
- Produce return period flood maps from a hydrodynamic model using return period wave overtopping inflows and a return period sea level boundary.

We now have the more advanced State of the Nation methodology which considers more parameters in the joint probability and assesses the return period based on the wave overtopping rate as opposed to the likelihood of the offshore conditions. This method is as follows:

- Extreme storm conditions (coincident wave, wind and sea level) conditions are assessed based on offshore winds and waves and tide gauge sea levels.
- Local wave transformation modelling and emulation is carried out to transform offshore storms (wave, wind, sea level) to inshore wave and water level conditions.
- Wave overtopping is calculated based on these inshore wave and water level conditions. Wave overtopping is ranked to obtain return period flows.
- Return period flood maps are produced from a hydrodynamic model using return period wave overtopping inflows and a return period sea level boundary.

Therefore, Environment Agency flood maps already account for the non-stationarity between present day and future nearshore wave conditions and wave overtopping due to mean sea level rise.

# 2 Purpose of this report

The rapid evidence assessment (REA) process does not necessarily translate straightforwardly into a plan of action. Its aim is to answer questions rather than develop recommendations. The REA report did identify some gaps in knowledge and some potential ways forward, but more targeted work was needed to identify areas for future research and practice. Another requirement was to set the future direction within an international context since the REA was focused on non-stationarity in the UK, and did not specifically focus on literature about methods for non-stationary frequency estimation, which do not tend to be location-specific.

A particular reason for studying the international context is to address the perception that some countries are more advanced than the UK in the way that they deal with non-stationarity in flood risk management. The USA and the Netherlands have been cited as examples and so this investigation has focused on them, along with a number of other developed countries.

This note describes a follow-on phase of work that investigates how the Environment Agency, along with equivalent bodies in other UK countries, might deal with the issues that were identified in the REA. Its aims are to:

- carry out an international review of current practice in allowing for non-stationarity in rainfall frequency, pluvial, fluvial and coastal flooding, covering both official guidance from flood risk management authorities and approaches used by practitioners
- identify any other UK initiatives on non-stationarity, for example at the Met Office or in UK universities and the insurance sector
- in light of the findings from the REA and tasks 1 and 2, formulate recommendations for a programme of future work on non-stationarity in:
    - rainfall
    - pluvial flooding
    - fluvial flooding (looking beyond the interim guidance project mentioned above)
    - coastal flooding

The above aims are covered in sections 4 to 7 of this report, following a brief description of how the information on current practice and related initiatives was sought.

# 3 Approach to investigation

This investigation covers a broader scope than the REA, which focused largely on academic literature. It does not claim to be a comprehensive and systematic investigation. Rather, it has been targeted at countries, universities, research institutes and other bodies that are more likely to be applying or developing methods of non-stationary flood frequency estimation and from which information could more easily be obtained. The information search was restricted to material written in English, German or Dutch.

Information was sought both from official sources such as policy and guidance documents and unofficial sources such as individual researchers, flood managers and practitioners. A large number of people were consulted, either via email, phone conversations or face to face. The project team is grateful to all who responded. They are listed in the acknowledgements.

The focus of the investigation of international practice was on approaches that allow for non-stationarity within the practice of flood risk management, as distinct from research into the topic and detection of trends without allowing for them in frequency analysis.

For fluvial/pluvial flooding, the study did not focus on adjusting stationary flood estimates to allow for the potential future impact of climate change as this practice is now long-established, including in the UK. Instead, the focus was on non-stationary analysis, which generally represents gradual changes over time. This is the aspect for which the REA identified a gap between research findings and current UK practice.

The REA results supported the methodology currently used for present day extremes assessments for coastal flood risk. With respect to coastal flood risk, the discrepancy between current practice and the REA findings regarded future extremes. Therefore, for coastal aspects this investigation of international practice focused on adjusting present day estimates to allow for potential future impacts of climate change.

# 4 International practice for handling non-stationarity in flood risk management

A summary of the coastal flood risk and flood management guidance used to inform this section is summarised in Appendix A. This summary includes the scientific basis at the time of writing; if the guidance is statutory and the climatological assumption for tides, waves and storm surges. For comparison, the summary includes the guidance for England, Scotland and Wales.

## 4.1 USA

Water management in the USA can be considered at the federal (national), state and city (and/or county) level. All levels of government have the authority to issue flood policy or technical guidance. Individual states and cities/counties are responsible for local flood policies and management and their guidance may vary from federal guidance. Information on non-stationarity from those three levels is summarised below.

### 4.1.1 Fluvial/pluvial

At a federal level, the United States Geological Survey (USGS) published guidance on flood frequency estimation is Bulletin 17C (England and others, 2019). This document is used nationally for flood frequency estimation, as per the Flood Estimation Handbook (FEH) in the UK. Bulletin 17C recognises non-stationarity but does not provide guidance on how to incorporate it practically within flood estimates:

"The Work Group did not evaluate methods to account for nonrandomness and (or) multidecadal trends in flood frequency. Additional work in this area is warranted, as it is a seriously unresolved problem. If multidecadal trends of this sort are identified through appropriate statistical tests and data analysis, it is recommended that the underlying physical mechanisms be investigated to gain hydrological understanding. How to adjust such a record for flood frequency is an unresolved problem".

Indeed, Bulletin 17C suggests addressing non-stationarity in a future study. Academically, modifying the earlier Bulletin 17B methods to allow for non-stationarity has been considered, but these do not appear to have been applied operationally (Griffis and Stedinger, 2010; Luke and others, 2017; Over, 2016).

The US Army Corps of Engineers (USACE) has developed a web tool for identifying non-stationarity in historical time series (USACE, 2018a) and guidance for using it (USACE, 2018b), but has not yet provided any guidance on how to allow for non-stationarity in carrying out hydrological estimates. An author of the guidance has told the JBA project team that he expects the next step will be to move from detection towards attribution, and to then incorporate that information in future designs.

Similarly, the US Environmental Protection Agency (USEPA) has carried out research advocating the need to allow for adaptation (Yang, 2010) and also provides monitoring of climate indicators (USEPA[a] and USEPA[b], undated). However, no guidance on how to directly account for non-stationarity appears to be currently available from the EPA.

There is a similar picture at a state level. For example, the State of California Energy Commission carried out research on changes to depth duration frequency curves under climate change (AghaKouchak and others, 2018) recognising non-stationarity, but it is unclear if this research has been applied operationally. On the east coast, the South Florida Water Management District has also studied non-stationarity (Obeysekera and others, 2011), but it does not appear to be practically applied in water management other than indirectly through adaptation measures.

At a local level (for example, city or county level), many water utilities have identified non-stationarity as an issue. For example, a manager at the San Francisco Public Utilities Commission (SFPUC), restated the "Stationarity is dead" quotation when interviewed (Carpe Diem West, 2011). The SFPUC, together with 11 other local water utilities, including New York City Department of Environmental Protection (DEP) and Seattle Public Utilities, is part of the Water Utility Climate Alliance (WUCA) which is seeking to manage climate change at a local level. WUCA provides climate change adaptation case studies (WUCA, undated [a]) ranging from water quality in Seattle to dam safety in Colorado. However, none of the adaptation studies provided directly account for non-stationarity.

Similarly, studies on depth duration frequency curves (Storm Water Solutions, 2019) carried out on behalf of the New York DEP describe the issue of non-stationarity and the need for climate resilience (Rosenweig and Solecki, 2015; WUCA, undated [b]) but do not appear to provide practical application of accounting for non-stationarity. Information from Seattle Public Utilities (Fleming, 2012) also paints a similar picture.

### 4.1.2 Coastal

At the national level, there are 4 primary agencies issuing infrastructure or building policy and guidance: the US Army Corps of Engineers, the Department of Defense (DoD), the Federal Emergency Management Agency (FEMA), and the Federal Highway Administration (FHWA). The USACE provides extensive guidance around sea level changes and coastal erosion, as do other US agencies, including the US Geological Survey and National Atmospheric and Oceanic Administration (NOAA). The USACE policy and guidance related to changing sea level is encapsulated in Engineer Regulation 1100-2-8162 (USACE, 2019a) which applies to all USACE elements having civil works responsibilities and applies to all USACE civil works activities. The guidance is that all planning studies and engineering designs over the project life cycle, for both existing and proposed projects, must consider alternatives that are evaluated for ‘low’, ‘intermediate’, and ‘high’ sea level changes, corrected for local rates of vertical land movement. The low, intermediate and high scenarios at NOAA tide gauges can be obtained through the USACE online sea level calculator (USACE, undated). The USACE guidance makes no future allowances for storm surges, tides or waves, basing its approach on a consensus that changes to tropical cyclone frequency and intensity cannot identify any climate change signal from within the natural variability (Knutson and others, 2010).

More detailed guidance and worked examples are provided in the USACE Engineer Pamphlet 1100-2-1 (USACE, 2019b). This pamphlet acknowledges the importance of potential non-stationarity in assessing future sea level conditions, making the statement: “USACE SLC adaptation addresses the potential for non-stationary conditions through the use of a multiple scenario approach, which includes a range of future potential sea level change rates.” However, it makes no further comment regarding non-stationarity in tide, wave or storm surge conditions.

The Department of Defense (DoD) policies and guidance (DoD, 2018a; 2018b) also make explicit reference to climate change allowances. These two guidance documents are currently being revised to incorporate a spatially varying approach to sea level change in the same way as UK Climate Projections 2018[1] (UKCP18). The sea level scenarios will follow the advice given in Hall and others (2016), which provides a global scenario database for regionalised sea level and extreme water level scenarios for 3 future time horizons (2035, 2065, and 2100) for 1,774 DoD sites worldwide. The extreme still water level estimates are provided for different annual chance events whose probabilities depend on the underlying scenario assumptions. The extreme water levels include the effects of tides and storm surge, occurring on top of rising seas as specified in the 5 sea level rise scenarios. However, they do not include the effects of waves. Neither do they account for potential non-stationarity in future storminess.

There is large diversity in the quality of guidance and approaches taken at the state and city level (and the scope and duration of this project did not permit a thorough comparison and analysis of all US locations). New York, New Jersey, Maryland and California all have well described policy for coastal development, supported by good technical guidance. Here, we summarise the approach of the more forward-looking New Jersey state-level response to climate change. New Jersey has made it compulsory to consider sea level changes through Executive Order 100 (27 January 2020). This states that [authorities must] “within two years of the date of this Order and consistent with applicable law, adopt Protecting Against Climate Threats (PACT) regulations”; and that these regulations shall, “integrate climate change considerations, such as sea level rise, into its regulatory and permitting programs, including but not limited to, land use permitting, water supply, stormwater and wastewater permitting and planning, air quality, and solid waste and site remediation permitting.” The State of New Jersey Department of Environmental Protection tasked a team led by Rutgers University to produce a guidance document (Kopp and others, 2019) based on the most current science on sea-level rise projections and changing coastal storms, considering the implications for the practices and policies of local and regional stakeholders, and providing practical options for stakeholders to incorporate science into risk-based decision processes. That report (Kopp and others, 2019) provides future sea level guidance in a manner very similar to UK Climate Projections 2018 (UKCP18), (and arguably uses more scientific language and detail than UKCP18). However, the guidance does not consider any changes to the future climatology of storm surges, stating that there is no clear basis for planning guidance for New Jersey to deviate from the most recent examinations of the issues by the New York City Panel on Climate Change (Orton and others, 21019). Nor does it assume any changes to future tidal characteristics or wave climate.

### 4.1.3 USA summary

While non-stationarity is recognised as an issue in fluvial/pluvial assessments in the USA, it is not being directly addressed in the way that flood frequency estimation is carried out. The problem of future changes to flood risk is being addressed via adaptation measures such as allowances for climate change. For coastal flood risk assessments of future conditions, these allowances for climate change account for rising mean sea level but assume tides, storm surge and waves are stationary. The Department of Defense policies and guidance is currently being updated and they do plan for future extreme sea levels to include the effects of tides and storm surge, occurring on top of rising seas, but will still not account for potential changes in waves or storminess.

[1] https://www.metoffice.gov.uk/research/approach/collaboration/ukcp/index [accessed 16 July 2020]. [Accessed 21 July 2020]

## 4.2 Canada

### 4.2.1 General

The federal government has recently standardised approaches through its Federal Floodplain Mapping Guidelines Series. The Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation 2019 (Natural Resources Canada, 2019) provide technical guidance on hydraulic and hydrological procedures for preparing flood hazard maps in Canada, including incorporating non-stationary processes such as climate change. This guidance recommends careful trend analyses before carrying out extreme value analyses.

### 4.2.2 Fluvial/pluvial

The federal procedures mentioned above state that most projects assume stationarity when assessing fluvial flood frequency. One paragraph provides two references to research that has applied non-stationary techniques, and recommends that the practitioner considers whether the additional complexity is warranted. It concludes, "For example, it may be more cost-effective to account for climate change by applying a reasonable but conservative factor to the results of a stationary FFA."

The ongoing FloodNet research initiative is a concerted effort that aims to enhance flood forecasting and management capacity in Canada. Funded by the Natural Environment and Engineering Research Council of Canada, it is expected to lead to practitioners applying manuals, guidelines, design methods and software tools, including a Canadian equivalent of the UK's Flood Estimation Handbook.

FloodNet has produced numerous papers that mention non-stationary methods, for both rainfall and river flood frequency. One of the outputs from the research programme will be a set of procedures for flood estimation applicable throughout Canada, for the first time. At this stage, the team is not planning for this to include non-stationary flood frequency analysis procedures. It does not consider that the methodologies it has explored are mature enough to be included (which is an interesting comment from Professor Don Burn who has published works on non-stationary flood frequency for many years). Practitioners in Canada are starting to incorporate non-stationary techniques or consider non-stationarity in rainfall frequency analysis. For this reason, the FloodNet team is planning to provide some guidance on non-stationarity for rainfall frequency analysis.

### 4.2.3 Coastal

There is currently no standard approach for including non-stationarity in coastal flood risk assessments in Canada. Land use planning and zoning is typically governed at the provincial or municipal level and, as such, approaches to flood risk assessment have varied widely across the country. Based on our correspondence with the National Research Council Canada who recently reviewed current guidance and practice for the federal government, the most common approach to non-stationarity in Canada is to incorporate regional relative sea-level rise projections to the end of the 21$^{st}$ century, detrend historical water level records, and assume all other variables are stationary. It is rare to see studies including (even notional) changes in winds, waves or storm surges.

As an example of current guidance, the province of British Columbia has had guidelines for Flood Hazard Area Land Use in place since about 2010 (draft amendment in 2013, adopted in 2018). These guidelines include a recommended sea level rise curve (Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2018a, section 3.5.3). But overall, they are pretty crude in how they account for non-stationarity. Consequently, a provincial professional association (Engineers & Geoscientists British Columbia) developed its own professional practice guidelines (Ministry of Forests, Lands, Natural Resource Operations and Rural Development, 2018b). However, these are more informational/educational and not prescriptive: “Hydro-climatological modelling is an expert activity; the responsibility of the QP is to be familiar with current model-based projections, including the specified precision of those projections. Professional judgment must be exercised to extract the most appropriate design parameters for particular projects from currently available climatic projections. Results should be compared with the historical record to determine whether they are plausible for the project site.” Other coastal provinces, such as New Brunswick, are really only just beginning to look at policies for land use planning/regulation that consider coastal flood risk, and are only considering mean sea level rise not changes in storm surge, waves or tides.

The Procedures for Flood Hazard Delineation (Natural Resources Canada, 2019), provide guidance on sea level rise. In the case of historical sea level rise, the practitioner can choose to detrend the time series of historical peaks and correct it to present-day water levels before calculating present-day return values. Future sea level rise must then be accounted for in projecting future extreme water levels. The impact of future sea level rise on wave heights must also be examined, but only the influence of sea level rise on wave run-up and overtopping, not non-stationarity in the offshore wave climate.

Canada’s Changing Climate Report 2019 (Bush and Lemmen, 2019) states that relative sea level rise and declining sea ice conditions are the major risk factors for coastal flood risk, and that less is known about changes in the frequency and intensity of storm surges and waves. The National Research Council and academic partners are presently carrying out research focused on downscaling regional climate model data to provide projections of future changes in storm surges, extreme waves and ice conditions in some coastal regions of Canada. However, these have large uncertainty bands and this type of approach is not common practice.

New national guidelines on coastal and flood risk assessment for building and infrastructure design applications is currently being developed. This focuses heavily on non-stationarity and the dynamic nature of risk but is not prescriptive and, as such, is not expected to lead to immediate significant changes in how non-stationarity is addressed.

## 4.3 Australia

### 4.3.1 Fluvial/pluvial

Australian Rainfall and Runoff (ARR)[2] is an equivalent publication to the FEH, published by Geoscience Australia, a government agency. Comprehensively updated in 2019, ARR acknowledges the availability of non-stationary methods, and suggests considering them in some cases, but the focus is still very much on assuming stationarity. One of the main authors, expects few, if any, practitioners are likely to be pushed into applying non-stationary flood frequency procedures by the ARR guidance.

However, it would be expected that practitioners would investigate any gross changes in catchment land-use when interpreting possible shifts in the behaviour of annual maximum flows. Most practitioners would resolve any such shifts by censoring or making some adjustment to the annual maxima, rather than by fitting a non-stationary probability model. While there is good evidence that flood behaviour in Australia is influenced by inter-annual climate drivers such as the Interdecadal Pacific Oscillation and El Nino, their variability is assumed to be stationary, at least over the historical record.

The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Bureau of Meteorology (BoM) make reference to non-stationarity in climate for both rainfall and temperature (and resulting derived quantities) in many of their climate statements and research project summaries. They do not, however, appear to provide guidance on how trends might be accounted for.

### 4.3.2 Coastal

In Australia, sea level rise planning guidelines are the responsibility of state governments rather than the federal government; coastal planning and management decisions are made by local governments within the jurisdiction of a state/territory. Accordingly, local governments require clear policy direction from state/territory governments, financial assistance to implement coastal adaptation initiatives, and access to locally specific scientific information about the coastal impacts of climate change. The scope of state government responses to rising sea levels is varied at the local government level in Australia, and, as with the US, the nature and quality of the guidelines (and the degree to which they are statutory) differs among states.

The most up to date scientific advice is provided for each local government area in the 'Sea Level Rise and you' section of the CoastAdapt dataset[3]. This climate services portal was developed by the National Climate Change and Adaptation Research Facility (NCCARF). For each future climate scenario (RCP) this tool gives (a) the mean sea level rise along with uncertainties and (b) the 'allowances' needed to maintain the same standard of protection as today. For any date epoch, allowances do not necessarily equate to the median projected sea level rise due to the shape of the return period extreme sea level curve. In this data set, stationarity is assumed for tides, storm surges and waves. While individual states could, and arguably should, use the advice given in CoastAdapt, they are not obliged to do so by law. State legislation also only requires non-stationarity of future mean sea level to be considered.

[2] http://arr.ga.gov.au/ [accessed 15 July 2020] [Accessed 21 July 2020]
[3] https://coastadapt.com.au/sea-level-rise-information-all-australian-coastal-councils [accessed 15 July 2020] [Accessed 21 July 2020]

## 4.4 Europe - general

### 4.4.1 Fluvial/pluvial

Madsen and others (2013) provide a review of applied methods in Europe for flood-frequency analysis in a changing environment. Quotations include:

"Concerning the potential effects of environmental change on the frequency and magnitude of design floods, Norway, the UK, two river basin authorities in Belgium, and two federal states in Germany were identified as having developed guidelines for directly adjusting design flood estimates derived from models assuming stationarity". This is referring to adjustments to allow for future changes in climate or land use.

"For most countries flood frequency estimation is currently being undertaken using models based on a fundamental assumption of a stationary historical record, be it flood flows or rainfall".

"The move beyond a sensitivity-type approach and towards a new non-stationary framework based on the use of non-stationary frequency models has been identified as an important aspiration within the European hydrological science community".

Luke and others (2017) refer to this review, stating that two non-stationary methods of flood frequency analysis are described: (1) the use of precipitation projections from future climate scenarios in rainfall-run-off models and (2) the use of a safety margin to adjust the design flood estimates derived from stationary extreme value analysis. Neither of these approaches is truly non-stationary.

The findings from Madsen and others (2013), indicating that non-stationary methods are not generally applied in practice in Europe, have been borne out by information received from practitioners and others in the Netherlands, Germany and Switzerland as reported below.

## 4.5 Netherlands

In the Netherlands, the general governmental policy for sea level rise, lake-level allowances and peak river flows is written down in the 'National Water Plan'. The latest version is for the period 2016 to 2021 (available in Dutch). The guidelines are quite general and apply to national programmes that deal with flood protection by levees, storm surge barriers, sluices, and dunes.

### 4.5.1 Fluvial/pluvial

Deltares has informed the project team that non-stationary methods of flood frequency estimation are not currently included within formalised procedures in the Netherlands. Rijkswaterstaat, part of the Ministry of Infrastructure and Water Management, was not able to provide any information on the application of non-stationary methods in the Netherlands. The project team has found no references to operational use of non-stationary flood frequency estimation in the Netherlands.

### 4.5.2 Coastal

The largest national programme for flood protection is Hoog Water Beschermings Programma (HWBP). The design of levees, storm surge barriers and sluices in this programme takes account of future sea level rise, but assumes wind, tides and storm surges are stationary. Changes to nearshore wave properties (due to increases in mean sea level) result from the wave models used SWAN (simulating waves near shore) despite no prescribed changes to the wind forcing. This project fits with our understanding of the general Dutch approach, which is: assume the same wind scenarios for 2100 as present, and force local wave models with adjusted sea levels but the same winds to account for changes to depth limiting.

Understanding flood risk management concepts from Rijkswaterstaat has been reviewed to understand the general guidance on how coastal flood risk drivers are changing. For the assessment of present day risk, the report states that mean sea level rise (MSLR) off the Dutch coast has been approximately 0.20 m but sea level acceleration is not visible in the North Sea (possibly due to the large variations from year to year associated with variations in wind). Therefore, it is assumed that when assessing present day extremes, sea levels data is detrended to remove a linear trend in sea level rise (SLR). Note, in the Netherlands, land subsidence is also a major issue and therefore the analysis of recorded sea levels also has to take account of this. For the assessment of future extremes, the report states that although wind speeds will probably get higher, it probably won't apply to winds from the northwest. Storm surges along the Dutch coast are mainly caused by winds from the northwest and therefore no significant change in storm surge this century is expected. Therefore, we deduce that future assessments of coastal flood risk assume the surge risk in the future is the same as today. The report does not consider tides in its section on developments with effect on the water safety.

Deltares has applied non-stationary methods to wave statistics, but that was a research project.

## 4.6 Germany

In Germany, the different states are responsible for flood protection, which means that there are different approaches to flood risk in each federal state.

### 4.6.1 Fluvial/pluvial

Information from academic staff at Rottenburg University of Applied Sciences and Freiburg University indicates that, while non-stationarity is becoming increasingly important in research, most engineering consultancies and their clients do not consider it, although this may start to change.

Implementing non-stationary methods in practice within Germany (and anywhere else) is complicated by the fact that all models/processes have to estimate the influence of climate change on historical data, and it is difficult to be confident in these estimates. It is also felt that the priority is to improve stationary methods first, for example reconsidering the choice of distribution for the regionalisation of rainfall frequency, for which the German Meteorological Service currently assumes the Gumbel distribution.

Non-stationarity is thought to be particularly important with regards to snowmelt in alpine regions and intense rainfall.

#### *Baden-Württemberg, Bavaria and Rhineland-Palatinate*

Information from several members of staff at regional authorities and consultants indicated that non-stationary methods of flood frequency estimation are not applied. In some cases, trends are extrapolated, and assumed to be linear. When designing flood defences, climate change factors are added.

#### *Saxony*

Practitioners apply methods based on assuming stationarity. Non-stationarity is a topic of interest in research, for instance at the Dresden University of Technology.

#### *North Rhine-Westphalia*

The State Agency for Nature, Environment and Consumer Protection, North Rhine-Westphalia, provided a useful perspective, saying:

"Non-stationary statistics are not being applied in water management as there are still no methods that have proven to be practicable, let alone decisive, with regard to application in practice. R&D projects currently show that climate change-related trends in precipitation time series are not clear, and that changes in measurement technology or meteorological cyclical changes can also cause change points, which may overlay the trend caused by climate change. So far, non-stationary statistics have not provided any clear or generally accepted solutions that are relevant in practice. Currently the workaround is to calculate additional scenarios, to check the sensitivity of the system and to include the result in the design of the system."

### 4.6.2 Coastal

In Germany, the federal government adopted the German Strategy for Adaptation to Climate Change in 2008 (DAS), which provides a framework for all climate adaptation actions in Germany. The DAS is supported by a second policy document called the

Adaptation Action Plan (APA), which was adopted by the federal government in 2011 (updated in 2015) and constitutes the central reference element of the German climate adaptation policy. In simple terms, the APA specifies the options and possible activities to implement the actions suggested in the DAS.

Regarding coastal protection specifically, beyond any differences in approaches across German states, stationarity is generally assumed for all sources of coastal flooding except mean sea level for which a constant rate of sea-level rise (no acceleration in sea level) is considered. The mean sea level rate used differs between regions. Hazard mitigation plans incorporate safety margins, which discount uncertainty in current estimates of future sea-level rise as well as, at least partly, non-stationarity in other sources of flooding such as storm surges, waves and tides.

## 4.7 Switzerland

### 4.7.1 Fluvial/pluvial

The Federal Office for the Environment (BAFU) published a guide for flood assessment in 2003 in which statistical methods are described that are commonly used in practice. All of these methods are based on the assumption of stationarity.

However, the BAFU also publishes reports on flood statistics[4] for all gauges in Switzerland with a catchment area larger than 100 km$^2$ that summarise results of calculations based on a variety of methods, some of which are non-stationary. A guide to the reports is also provided, released in 2017 (BAFU, 2017). The reports are used to identify non-stationarity in data, and to assess the differences between the results from different methods.

The methods applied are:

- annual maximum flow analysis
    - stationary
    - non-stationary: linear time trend in location parameter
    - non-stationary: quadratic time trend in location parameter
    - non-stationary: linear time trend in scale parameter
    - non-stationary: linear time trends in location and scale parameters
    - discontinuous variant of a linear model, with a change point in the location parameter, to represent abrupt structural changes such as construction of a dam
- peaks over threshold (POT) flow analysis
    - stationary
    - non-stationary: linear time trend in location parameter for flood magnitude
    - discontinuous variant of a linear model, with a change point in the location parameter

(note that non-stationarity in the flood occurrence rate is not considered)

The (untranslated) table below from the guidance shows the formulae for the parameters in each model variant, with t representing the year.

[4] An example report: https://www.hydrodaten.admin.ch/lhg/sdi/hq_studien/hq_statistics/2602_hq_Bericht.pdf [accessed 15 July 2020]. [Accessed 21 July 2020]

**Tabelle 1:** Verwendete Modellvarianten des BLOCK-Ansatzes. $\mu$ Lageparameter (mu), $\sigma$ Skalenparameter (sigma), $\kappa$ Formparameter (kappa)

| **Modellvarianten BLOCK** | | | |
|---|---|---|---|
| **Name** | **Beschreibung** | **Parameter (t: Jahr)** | **Anzahl Parameter** |
| stat | Stationäre Variante | $\mu, \sigma, \kappa$ | 3 |
| mul | Linearer Trend von $\mu$ | $\mu = a_1 + a_2 * t,\ \sigma, \kappa$ | 4 |
| muq | Quadratischer Trend von $\mu$ | $\mu = a_1 + a_2 * t + a_3 * t^2,\ \sigma, \kappa$ | 5 |
| sigl | Linearer Trend von $\sigma$ | $\mu, \sigma = b_1 + b_2 * t,\ \kappa$ | 4 |
| musigl | Linearer Trend von $\mu$ und $\sigma$ | $\mu = a_1 + a_2 * t,\ \sigma = b_1 + b_2 * t,\ \kappa$ | 5 |
| mujump | Nicht-kontinuierliche Veränderung von $\mu$ zum Zeitpunkt $t_0$ | $\mu = a_1 + a_2 * i,\ \sigma,\ \kappa,$ $i = 0$ für $t < t_0$, $i = 1$ für $t \geq t_0$ | 4 |

**Tabelle 2:** Verwendete Modellvarianten des POT-Ansatzes. $\sigma$ Lageparameter (sigma), $\kappa$ Formparameter (kappa)

| **Modellvarianten POT** | | | |
|---|---|---|---|
| **Name** | **Beschreibung** | **Parameter (t: Jahr)** | **Anzahl Parameter** |
| stat | Stationäre Variante | $\sigma, \kappa$ | 2 |
| sigl | Linearer Trend von $\sigma$ | $\sigma = b_1 + b_2 * t,\ \kappa$ | 3 |
| sigjump | Nicht-kontinuierliche Veränderung von $\sigma$ zum Zeitpunkt $t_0$ | $\sigma = b_1 + b_2 * i,\ \kappa,$ $i = 0$ für $t < t_0$, $i = 1$ für $t \geq t_0$ | 3 |

*Table 4-1 Example of non-stationary parameters in BAFU (2017)*

It is up to the reader to decide which set of results will be selected, and a flow chart is provided to help with this decision. The main factors to consider when deciding which model to select are:

- a statistical comparison of the model fit using likelihood ratios, where this is possible
- hydrological plausibility
- checks of model fit using diagnostic plots

The guidance makes it clear that even when methods are taking non-stationarity into account, they only approximate reality. Furthermore, it remains unclear whether a trend will continue in the future. Nevertheless, the site history may help draw conclusions about the causes of a change. If these are known, future developments may be estimated.

This is the only example outside the UK that the project team has found where non-stationary methods are applied in practice.

## 4.8 Summary of international practice

### 4.8.1 Present day extremes

Apart from sea level rise, non-stationary methods of flood frequency estimation are not mandated by flood management authorities or generally used by practitioners in the USA, Canada, Australia, the Netherlands or Germany. The only example that the project team found of them being used by practitioners is in Switzerland, where the Federal Office for the Environment has fitted a range of non-stationary models to peak flow data from many catchments and provided brief guidance on model selection.

### 4.8.2 Future extremes

Sea level change accelerations are implicit in the UK allowances for future epochs since the recommendations derive from the dynamical models. At the time of writing, the UK is unique among the countries examined in both using the most up to date scientific advice (from UKCP18 and the CMIP5 climate models of IPCC AR5) and for making it compulsory to use that advice. Comparing the UK with other national approaches, only specific city authorities and states in the US, and a minority of states in Australia adopt the same rigorous approach.

In all the international reviews carried out as part of this report, all countries assume that the future climatology of storm surges, tides and waves is unchanged (that is, they assume stationarity). However, the potential for changes, particularly in waves, is recognised and accommodated through the recommendation of sensitivity tests for flood risk.

# 5 Practice for handling non-stationarity in the insurance sector

Flood modelling within the insurance industry is carried out by catastrophe (cat) modelling vendors whose modelling practice in relation to non-stationarity is considered here. Firstly, a quick summary of the core components of a cat model is provided for context.

Flood-based cat models are made up of 3 components: the hazard (hydrometeorology and the sea – 'hydrology'), the hazard mapping, and the vulnerability (resulting in financial loss estimates). For present-day rainfall and fluvial scenarios, statistical methods and hydrological models are applied assuming stationary data. Due to the clear rise in mean sea levels, the present-day sea level extremes are estimated after removing a linear trend.

The results of these rainfall, flow, and sea level and wave models are applied to mapping models (usually hydrodynamic) to provide the mapped extents of coastal, river and pluvial flooding and associated depths. The mapping boundary conditions are either point estimates, usually based on some form of regional frequency analysis (in the case of fluvial mapping), or directly from simulating correlated events. In the former case, simulated events are then attributed associated return period depths in the a priori flood maps. The catastrophe model assesses the severity of the physical risk (flood) at each location, using the extent and depth information from the hazard map and stochastic event set data. Vulnerability functions denote the depth-damage relationship for different property types, which helps determine the potential financial loss at a given location. Cat modelling vendors can sell products holistically or individually, as the mapping, the loss estimation or the simulated event sets. This is an important distinction because baseline flood maps, which are similar to those produced by the Environment Agency, can be updated to account for scenario projections in relatively simple ways, whereas updating the simulation of nationally (and internationally) spatially and temporally correlated events across flood perils is non-trivial.

The risk management and banking sectors increasingly need to take climate change into account, as regulatory authorities question organisations about their resilience measures and introduce requirements for them to meet. The Prudential Regulatory Authority (PRA) for example, recently requested that the potential impact of different projections on average annual loss (AAL) and the 100-year loss be considered for all relevant insurance contracts.

Given the 3 main components of the cat models, there are 3, or combinations of 3, ways in which a cat modelling vendor could account for projected changes in the rainfall and coastal levels (the hazard):

1. directly to the hazard
2. adjustment of the mapping
3. adjustment of the losses

All approaches require assumptions, but the assumptions become broader and less justifiable moving towards number three when the step before is not considered. Ideally, the projected changes would be applied to the hazard, and the associated changes to the mapping and losses would be dynamically linked. Furthermore, there would be projected changes in topography and land use, as well as projected changes to properties and associated financial losses as a function of flooding. However, cat vendors generally assume that the topography and the properties remain the same for any future scenario being considered when supplying projection-based and portfolio-wide products (where a portfolio is a set of insured properties attributed to a single insurer or re-insurer).

Currently cat vendors that offer spatially correlated flood risk products relating to projected rainfall, temperature, and/or coastal increases, do so as adjustments to baseline modelling as opposed to specifically remodelling, with the projections used to adjust the conditioning data. For example, JBA Risk Management, for its UK Climate Change Flood Model, has adjusted extreme value, scale (variability), parameters, based on the UK Climate Change Risk Assessment 2017, to re-attribute frequencies to the flow, rain, and coastal levels in their simulated events sets. These adjusted frequencies are then attributed the associated depths in the flood mapping. Other vendors in the market attribute the projected changes directly to the flood map (interpolating between the return period and depth relationship in the baseline maps), assuming that a change in input is linearly related to a change in flood depth. In some cases, this assumption has also been made directly on the financial losses. Here, a projected change in the rainfall is assumed to translate into the same proportional change in the losses.

JBA Risk Management is working on methods to incorporate non-stationarity in the present-day simulation of events and methods to quickly simulate events trained on, projection adjusted, data which then produce maps dynamically. Cat vendors are private enterprises and, as such, the methods and R&D plans are often unclear for anyone but clients. However, given the push from regulatory authorities and the market for future loss estimates based on projected scenarios, it is assumed that the majority of cat vendors are working towards methods to improve the way they model projected scenarios and account for hydrological non-stationarity in their present estimates.

# 6 Related initiatives

## 6.1 University research programmes

The project team has contacted several academic staff at UK universities who are involved in research on non-stationarity in flooding. The information below summarises current and potential future research initiatives.

### 6.1.1 University of Bath

Dr Thomas Kjeldsen, Senior Lecturer in the Department of Architecture and Civil Engineering at the University of Bath, has published work on non-stationary methods of flood frequency estimation, including several papers covered by the REA.

A recent element of research at Bath has been to merge statistical hydrology with meteorology, examining the storm tracks of UK annual maximum rainfalls using the HYSPLIT software developed by the National Oceanic and Atmospheric Administration's Air Resources Laboratory, which tracks the origin of parcels of moisture in the atmosphere.

The ultimate aim is to examine how these synoptic conditions might change in the future, using climate models, and therefore what the impacts would be on annual maximum rainfalls over the UK. The university would like to take this investigation much further but currently has little funding allocated to it.

A previous proposed initiative from the university, funded via a Natural Environment Research Council (NERC) Industrial fellowship, focused on modelling trends in peak over threshold flow data. The proposal included trend detection, attribution using drivers such as rainfall or climatic variability indices and proposal of new methods for flood frequency estimation at a national scale. This work has made only modest progress due to staff changes.

### 6.1.2 Oxford University

Louise Slater, Associate Professor at the School of Geography and the Environment, University of Oxford, leads the Water and Climate Extremes Research Group.

The group explores how and why the characteristics of extremes (magnitude, frequency, extent, duration) are changing in the past and future. The group is currently working on applying non-stationary methods of flood frequency estimation, using data from the UK. The focus of the current work is on ways of communicating changes in flood risk.

An aspiration is to develop a seamless approach that merges the statistical analysis of past floods with the physics-based modelling of future changes, using dynamic statistical models. This would account for the physical drivers of change, including both climatic effects and catchment land use. Dr Slater has previously applied dynamic statistical models using the North American multi-model ensemble (Slater and others, 2019a; 2019b).

In such models, the physics-based projections from climate models can be used as covariates to update the parameters of statistical distributions, and therefore predict probabilistic changes in event magnitudes and frequencies, over sub-seasonal to multi-decadal timescales. Dynamic statistical approaches take advantage of the ability of physical models to predict large-scale phenomena and the strengths of non-stationary statistical models to estimate probabilities of extreme events conditioned on observed data, offering a realistic approach for projecting the changing properties of environmental extremes into the future.

The proposed research could potentially fill a major gap in current methods of non-stationary flood frequency estimation, which describe past changes but are not able to predict future changes and are difficult to reconcile with future scenarios from climate models.

A related project (Kelder and others, 2019), also involving Loughborough University, UK Centre for Ecology and Hydrology (UKCEH), the European Centre for Medium-Range Weather Forecasting (ECMWF) and the Norwegian Meteorological Institute, is looking at using hindcasts from weather forecasting models to help detect non-stationarity and potentially better understand its cases and estimation of design values under non-stationary conditions. Using 100 alternative modelled versions of modelled weather during the period 1981 to 2015, the projected fitted non-stationary rainfall frequency distributions for Norway. This is a novel application of the UNprecedented Simulated Extremes using ENsembles (UNSEEN) modelling framework.

### 6.1.3 Newcastle University

Newcastle has several projects that are looking at changes in flooding, generally taking a more physically-based approach, for instance using a national physically-based system SHETRAN-GB, the idea being that it is more robust than calibrated models for climate impacts and ungauged catchments.

The CONVEX project is using observational evidence and process understanding, including from numerical weather prediction models, to improve predictions of change in extreme rainfall.

Along with many other universities and institutes around the world, Newcastle is involved in the INTENSE project. INTENSE (INTElligent use of climate models for adaptatioN to non-Stationary hydrological Extremes) is creating a global sub-daily rainfall data set, incorporating information from satellite and radar observations. The project will explore drivers of change in rainfall, but the focus is mainly on trend detection rather than attribution.

Related work at Newcastle includes projects on understanding large-scale drivers of rainfall extremes over Europe (sub-hourly and hourly), for example, using weather types and other large-scale atmospheric variables, and work on the intermittency of UK rainfall and producing updated storm profiles for design based and statistical rainfall event models that account for dependencies between event design and magnitude.

### 6.1.4 Lancaster University

Staff in the mathematics and statistics department at Lancaster have played a leading role in developing extreme value statistics, including non-stationary methods. The REA included some of this research, including an article on a random effects model fitted to describe non-stationarity in the sizes of peak over threshold (POT) floods at gauges in the UK (Eastoe, 2019). Random effects, or latent process, models provide a way to model inter-year variability, capturing both long-term trends and fluctuation about these trends, without the need to specify covariates or a functional form for the trend. The random effect can be viewed as an approximation to any unobserved processes (such as precipitation, soil moisture or climate indices), which cause year-to-year changes in the probability distribution of the data.

Current aspirations at Lancaster for future development of random effects models are focused on applications likely to be useful to practitioners, including:

i. rolling out random effects models on a wider range of applications such as rainfall, sea levels and/or river levels

ii. developing software that adds the random effects model as a tool to sit alongside more familiar non-stationary regression models

iii. exploring and defining different concepts and/or measures of risk that can be inferred from either/both of the random effects and regression modelling approaches, along with the uncertainties tied to these measures and how to communicate this risk

Funding sources for these areas of work have not yet been identified.

Along with the JBA Trust, Lancaster is seeking funding sources for a PhD project to look at a more spatially structured modelling basis for non-stationary random effects models. This will involve explicitly modelling and quantifying spatial similarity in the effects across neighbouring regions.

## 6.2 Met Office

The Met Office acknowledges the presence of non-stationarity in the climate in its annual Statement of the Climate reports[5]. It typically presents annual climate data relative to 30-year standard reference periods, for example, 1961 to 1990 and 1981 to 2010, noting that there are differences in the climate between the reference periods. However, they also present the annual data relative to shorter, 10-year non-standard reference periods, noting "in a non-stationary climate 1981 to 2010 averages may already be partially out of date" (Kendon and others, 2017). Within each time slice the climate is assumed to be stationary.

The Met Office Hadley Centre performs research into non-stationarity, mainly within the group led by Dr Simon Brown (Lead Scientist and Climate Extremes Research Manager). This non-stationary research work will be used operationally with the forthcoming UKCP18 extremes products, due to be released in 2020. These products will consist of probabilistic projections of extreme rainfall (1-day and 5-day durations) for return periods 20, 50 and 100 years, on a 25 km grid across the UK.

The approach used is based on previous work by Brown and others (2014), which aimed to address a limitation of UKCP09 that provided little information on future changes in extremes. The analytical approach allows some or all of the parameters in an extreme value distribution to depend on covariates, be they time, global temperature or atmospheric indices like the North Atlantic Oscillation (NAO). An advantage of using global temperature rather than time as a covariate is that it is agnostic with respect to emission scenario, that is, a single statistical model can be applied irrespective of the rate of increase of temperature.

The method combines both modelled and observed rainfall data, fitting a single extreme value model (GEV) to both. The model includes one covariate that functions as an indicator variable to distinguish between modelled and observed data. This introduces an opportunity for bias correction, after which global temperature is introduced as a covariate. The approach assumes that the bias between the observed and modelled variables is constant over time.

[5] https://www.metoffice.gov.uk/research/climate/maps-and-data/about/state-of-climate [accessed 16 July 2020] [Accessed 22 July 2020]

Probabilistic projections of extreme rainfall are obtained from the GEV model, by sampling probability distributions of future global temperature along with distributions of the temperature-variant components of the GEV parameters. The latter account for climate model uncertainty, using a statistical emulator that relates variables of interest (such as rainfall) to functions of climate model parameters.

The group has invested considerable time in this approach and would generally recommend it. It provides one way of bridging the gap between statistical modelling of observed data and physics-based modelling of future change.

The 2014 paper was not picked up in the REA given that its title does not mention trend or non-stationarity. A related paper was included in the REA: Brown (2018); this fitted non-stationary GEV distributions to gridded observed rainfall in the UK, pooling parameter values between grid squares. Covariates included time and indices of atmospheric circulation.

Other more speculative work at the Met Office, some in conjunction with Exeter University, is looking at spatial dependence in extremes and at non-stationarity models applied to spatial fields, such as estimating parameters of a generalised Pareto distribution on the basis of quantities, including latitude, longitude, elevation and time. This may provide a way of estimating rainfall from non-stationary models at locations other than rain gauges.

## 6.3 UKCEH

UKCEH does not currently have any plans for funding future work on non-stationarity that it is able to share publicly.

## 6.4 National Oceanography Centre

### 6.4.1 Thames Estuary sea levels

Dr Ivan Haigh at the National Oceanography Centre recently carried out research in the Thames Estuary, which included investigating changes in tidal ranges and sea level rise acceleration. This work was carried out on behalf of the Environment Agency and reviewed by the UK Met Office. The report has not yet been finalised and email correspondence confirmed that we would not be able to access the report until it was finalised, therefore it has not been possible to include further details in this study.

### 6.4.2 Storm surges

The vast majority of studies on storm surge extremes have estimated event probabilities on a site-by-site basis, which means that estimates are based on very few extreme data at each location and, as a result, are subject to large uncertainty. Recent work (Calafat and Marcos, 2020) published after the rapid evidence assessment was completed presents a new spatiotemporal model for estimating the probabilities of storm surge extremes that exploits spatial dependencies in extremes to compensate for data sparseness. This model allows extreme event probabilities and their changes with time at any arbitrary location (not just tide gauges) to be estimated with less certainty compared with traditional approaches. This new approach provides the first observation-based probabilistic reanalysis of storm surge extremes in Europe, spanning the period 1960 to 2013. The uncertainties associated with estimates of event probabilities are up to three times smaller than those in traditional site-by-site analyses. This model shows a north-south dipole in trends in the probabilities of surge extremes for the period 1960 to 2013, with positive trends of up to 1 mm/year along northern and central coastlines of the UK and negative trends of similar magnitude along southern parts of the UK, as shown in Figure 6-1. Note that these trends are comparable in magnitude to trends in relative mean sea level at many tide gauges over the same period. For example, the sea-level trends at Wick, Aberdeen, North Shields, and Immingham are, respectively, 1.17, 1.43, 1.66, and 0.50 mm/year.

Model storm surge simulations for the 21st century, carried out for UKCP18, suggested that the climatology of storm surges would not change significantly and, based on the modelling results, proposed a best estimate of zero change in storm surge (skew surge) over the 21st century. The UKCP18 findings suggest that the trends in Figure 1 are likely due to internal climate variability. Regardless, they have important implications for coastal protection against flooding, given that the trends are for a relatively long period (54 years) comparable to the lifespan for infrastructure.

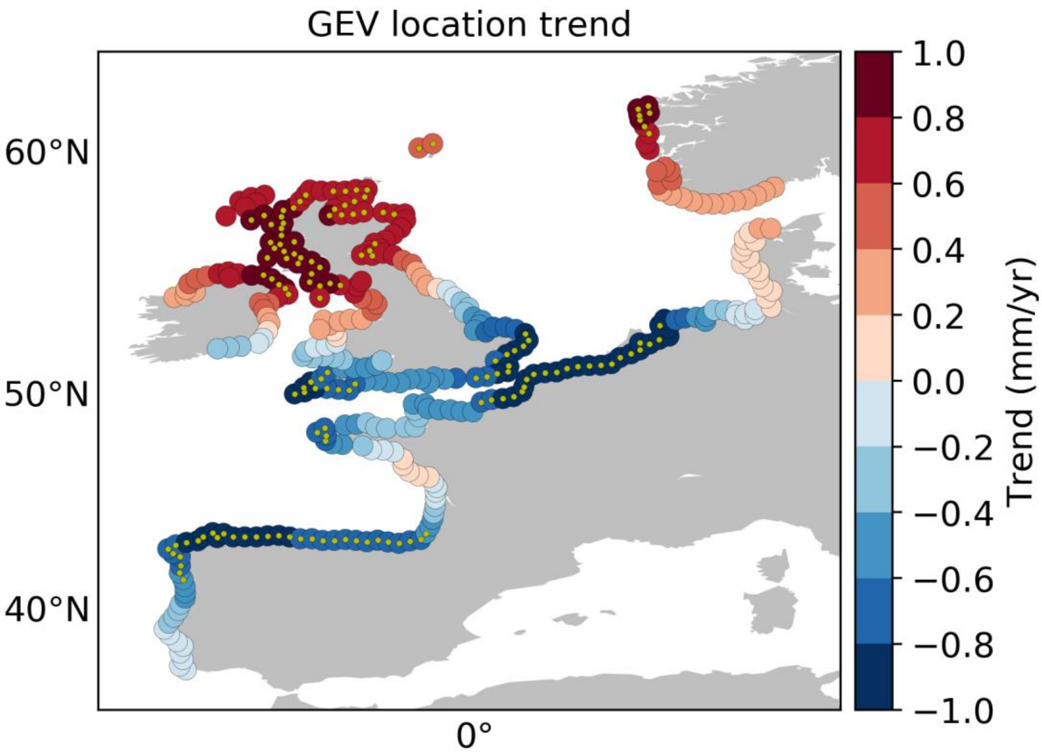


***Figure 6-1: Trends in the location parameter of the GEV distribution over the period 1960 to 2013 for storm surge extremes as estimated from the probabilistic reanalysis described by Calafat and Marcos (2020). Yellow dots denote locations where the trends are significant with 1-sigma confidence. Note that since the extremes model assumes the GEV scale and shape parameters to be constant with time, the trends in the map translate directly into trends in return surge levels.***

## 6.5 Marine Climate Change Impacts Partnership

The Marine Climate Change Impacts Partnership (MCCIP) report card on storms and waves (Wolf and others, 2020) updates on the review published by Woolf and Wolf (2013) by summarising the results of the IPCC AR5 report for storms and waves and then including more recent work published since 2013. There are similar conclusions:

wave-model results are controlled largely by the quality of the wind data used to drive them, and the forcing climate models have slightly improved in accuracy as well as resolution. In general, trends are obscured by large natural variability and a low signal-to-noise ratio. Assessment of changes in storminess and waves over the last 200 years are limited by lack of data, while future projections are limited by the accuracy of climate models.

All wind and wave time-series data show a great deal of variability, including inter-annual and inter-decadal fluctuations, but in some cases a distinct persistent trend can be observed within the variability, over various time periods. In the late 20th century there was a period of increasing wave heights over the North-East Atlantic, while trends in wind speed around the UK were much weaker. Therefore, most of the increase in wave heights is attributed to Atlantic swell (waves generated far outside of UK waters but propagating here from the ocean) rather than locally generated wind sea. Wave heights may have been enhanced by an increase in persistence of westerly winds.

There is evidence for an increase in North Atlantic storms at the end of the 20th century. Some projections for North Atlantic storms over the 21st century show an overall reduced frequency of storms and some indication of a poleward shift in the tracks in the northern hemisphere (NH) winter, but there is substantial uncertainty in projecting changes in northern hemisphere storm tracks, especially in the North Atlantic. Projections for waves in the North Atlantic show a reduction in mean wave height, but an increase in the most severe wave heights. There is a likelihood of larger wave heights to the north of the UK as the Arctic sea ice retreats and leads to increased fetch.

Models and observations from ships show an increase in annual and winter mean significant wave heights in the north-east Atlantic since the 1950s. Over the past 50 years, a poleward shift in mid-latitude depressions is evident during the winter. The strongest mid-latitude depressions may be increasing in intensity but becoming less frequent. High natural variability, and low understanding of climate change mechanisms, mean these observed trends in storms and waves cannot directly be attributed to climate change.

## 6.6 Wave climate projections

Climate change could affect storms and waves in the North Atlantic, but natural variability will continue to dominate in the near future. Under a high emissions scenario, there could be an overall reduction in mean significant wave height in the North Atlantic by 2100, although the most severe waves could increase in height. The retreat of Arctic Sea ice will extend the winter wave season, and combined with increased fetch (distance travelled), is likely to lead to larger wave heights to the north of the UK. The chance of severe storms reaching the UK during autumn may increase if tropical cyclones become more intense, and their region of origin expands northwards.

### 6.6.1 Global model ensembles

The Coordinated Ocean Wave Climate Project (COWCLIP) recently published a large ensemble of 148 members of global wave climate projections. They identify ocean regions with robust changes in annual mean significant wave height and mean wave period of 5 to 15% and shifts in mean wave direction of 5 to 15°, under a high-emission scenario. Approximately 50% of the world’s coastline is at risk from wave climate change, with ~40% revealing robust changes in at least 2 variables. However, uncertainty in current projections is dominated by climate model-driven uncertainty, which can contribute up to ~50% of the total associated uncertainty. Figure 6-2 summarises the findings of multi-model analysis of Morim and others (2019).

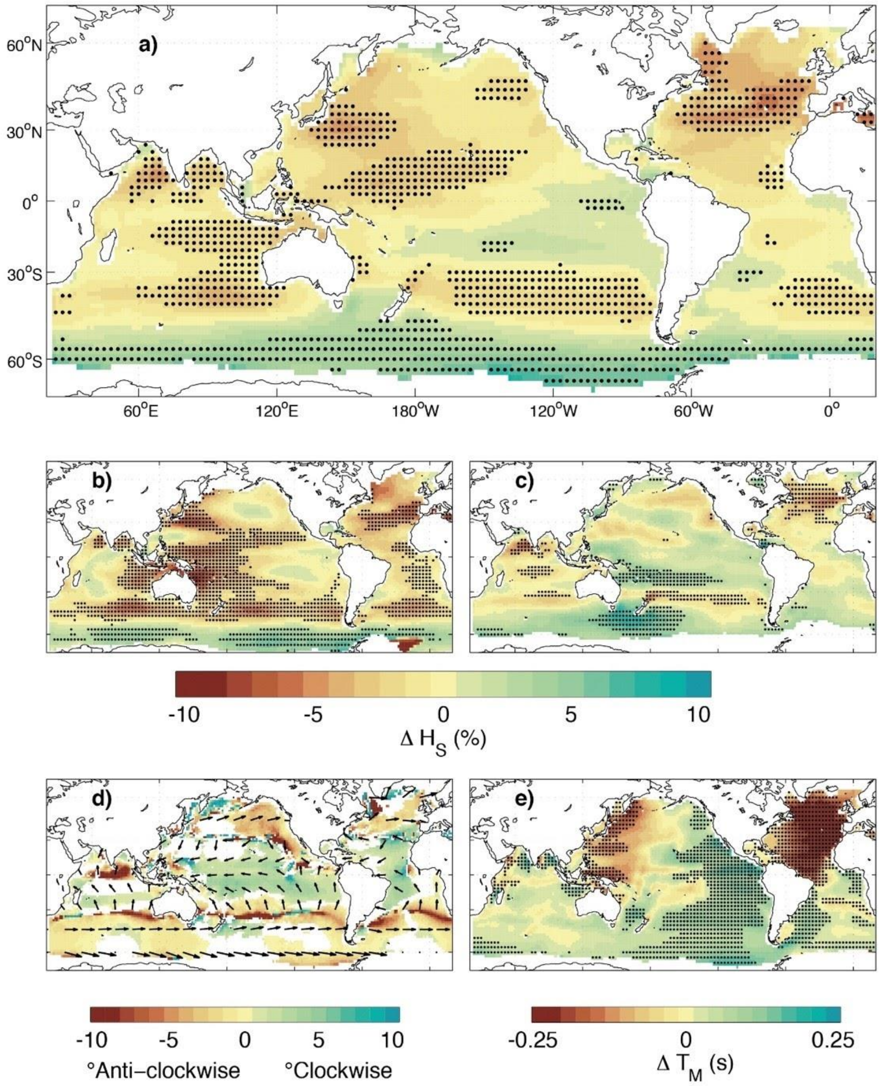


*Figure 6-2: reproduced after Morim and others (2019) Projected changes in wind–wave conditions (~2075 to 2100 compared with ~1980 to 2009) derived from the Coordinated Ocean Wave Climate Projection (COWCLIP) Project (Hemer and others, 2013). (a) Percentage difference in annual mean significant wave height (SWH). (b) Percentage difference in means of January to March SWH. (c) Percentage difference in means of July to September SWH. Hashed regions indicate projected change is greater than the 5-member ensemble standard deviation. (d) As for (a), but displaying absolute changes in mean wave direction, with positive values representing projected clockwise rotation relative to displayed vectors, and colours shown only where ensemble members agree on sign of change. (e) As for (a), but displaying absolute changes in mean wave period. The symbol ~ is used to indicate that the reference periods differ slightly for the various model studies considered.*

### 6.6.2 European shelf seas

Morim and others (2020) collated the latest projections available from CMIP5 climate model driven wave simulations. Analysis of a subset of these models (Figure 3) shows a consensus of reduction in mean SWH across most NW European seas. High resolution wave simulations suggest that the changes in wave climate over the 21st century on exposed coasts will be dominated by the global response to climate change. However, more sheltered coastal regions are likely to remain dominated by local weather variability over the 21st century.

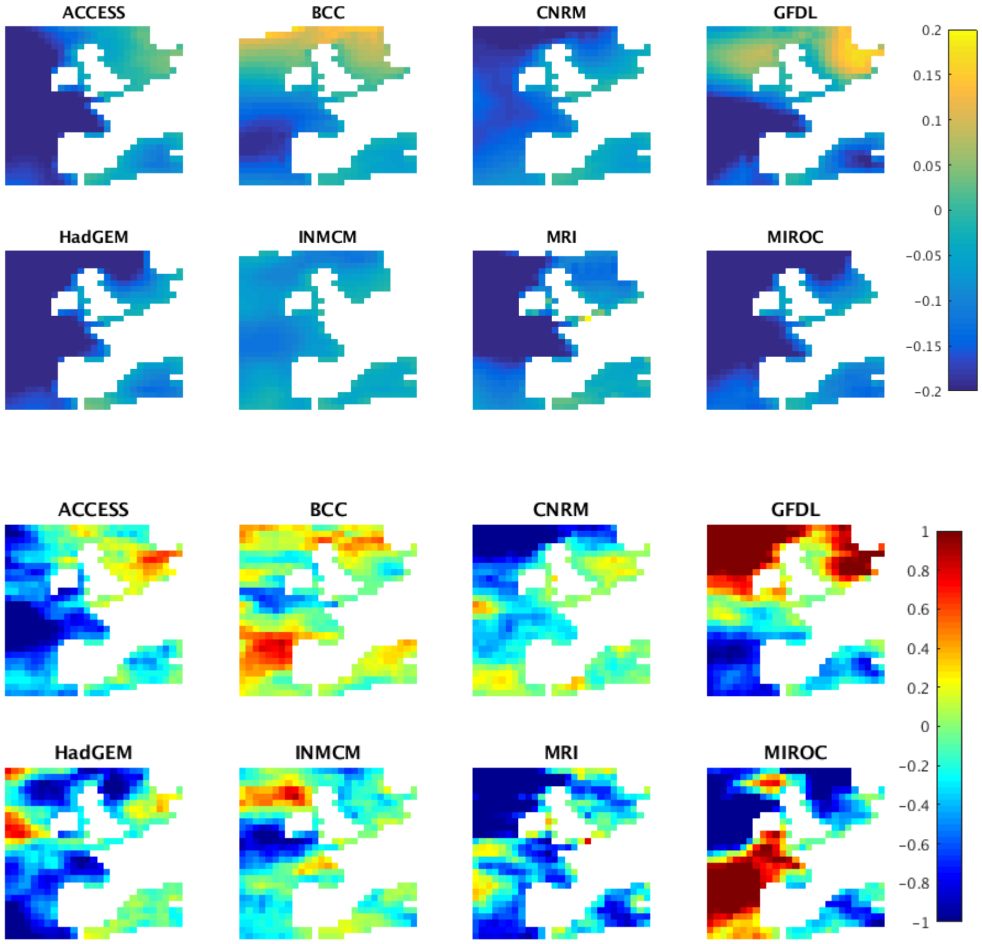


*Figure 6-3: Changes in SWH around NW Europe from eight models in the COWCLIP ensemble. The absolute difference between RCP8.5 (2070 to 2099) and historical (1970 to 1999) information is shown: (a) mean SWH, (b) mean annual maximum SWH. Model abbreviations. ACCESS1.0 (sister model of ACCESS 1-3), BCC-CSM1.1, CNRM-CM5, GFDL-CM3, HadGEM2-ES, INMCM4, MRI-CGCM3, and MIROC5*

# 7 Recommendations for future research and practice

The recommendations in this section are intended to draw out some priorities for future applied research on non-stationarity in UK flood hazards. The focus is on areas that are expected to directly benefit flood risk management, developing approaches that practitioners can readily apply. However, some recommendations require more fundamental research before a clear path towards user application can be identified.

The recommendations do not all necessarily relate to research that is funded by Environment Agency/Defra R&D. Some aspects may be more likely to be funded by research councils, the water industry or insurers.

## 7.1 Rivers

A project to develop interim guidance on non-stationary fluvial flood frequency analysis for England and Wales was completed in March 2020 (Environment Agency, 2020). Its outputs provide practitioners with tools and guidance for fitting non-stationary flood frequency distributions at sites with suitably long series of annual maximum flow data.

The 'interim' in the project title implies something of a stop-gap measure. Although the project included some in-depth development of methods, not all of the strands of investigation could be developed far enough to be recommended for widespread application. In addition, the focus was largely on adapting the existing approach applied by practitioners rather than making any fundamental changes.

One limitation of the interim guidance project was that it focused almost exclusively on annual maximum flows. Peaks over threshold data provide a more complete picture of the fluvial flood hazard; after all, flood defences can be overtopped by events that are not annual maxima. The REA located some research on POT, including a recent analysis of non-stationarity in the sizes of POT floods at over 800 gauges in the UK (Eastoe, 2019). Other initiatives (for example, at the University of Bath, see section 6.1.1) have made limited progress. A challenge for any future analysis at a national scale would be the need to compile consistent nationwide data sets. For example, POT data, although included in the National River Flow Archive, are known to be subject to numerous problems such as unreported gaps or inconsistencies.

We suggest that 2 other major gaps left to fill are the need:

- for a method that can be applied on ungauged catchments and reduces the uncertainty associated with single-site frequency analysis
- to reconcile modelling of past trends with projections of climate change impacts

The 2 sections below suggest some ways forward, drawing on recommendations made in the project report.

An important strand for any future investigation would be to look into non-stationarity of aspects other than the magnitude of annual maximum flows. This is expanded on in section 7.1.3.

### 7.1.1 Developing a practical method that can be applied on ungauged catchments and reduces the uncertainty associated with single-site frequency analysis

There are several ways that this could be approached. The one most in line with current UK practice is to develop non-stationary methods of pooled or regional flood frequency estimation. The interim guidance project included an investigation of pooled non-stationary analysis using methods similar to those in the Flood Estimation Handbook. This looked at:

- how to account for trend when forming pooling groups, developing a new similarity distance metric
- how to estimate index floods and flood growth curves that incorporate trend

For the latter, 4 options were tested, in which none, one, or both of the index flood and growth curve were modelled as non-stationary. The performance of these approaches was tested in a simulation study using an artificially-generated data set with known trend and realistic spatial dependence structure. This found that, when correctly specified, pooling methods can give good estimates of the true value of at-site parameters. However, when models are mis-specified (assigning trend where there is none, or vice versa), this can lead to poor fitting. Pooling groups making use of non-stationary index floods seemed the most promising of the options.

The investigation concluded that further work would be needed before pooled non-stationary analysis could be applied, apart from in limited circumstances such as where all stations in a pooling group have similar trend.

Important elements of any further work in these areas would include:

- developing an approach for estimating metrics of non-stationarity at ungauged sites. This would probably be either a procedure based on catchment descriptors, a spatial model or some combination of the two. A related strand of the research found that spatial statistics offered a promising way of reducing the heterogeneity seen in maps of trend results. A useful starting point might be to examine relationships between non-stationarity and catchment properties
- further work on simulation testing, using more realistic record lengths to assess the performance of various approaches to forming pooling groups and fitting non-stationary distributions
- considering the pros and cons of incorporating physical covariates into pooled non-stationary models, and developing techniques to do this
- considering the choice of distribution; developing a distribution test suitable for non-stationary conditions
- developing software tools so practitioners can apply pooled non-stationary analysis

The project team is not aware of any current or planned work in the UK in these areas.

There are other potential alternative approaches to achieving this aim such as those that rely more on modelling of river flow on the basis of rainfall. Refer to section 7.2 for some possibilities.

We recommend that a project is taken forward to address the above.

### 7.1.2 Integration of modelling past and future non-stationarity

The interim guidance project took a statistical approach to modelling past non-stationarity, developing models that are purely descriptive and have no power to predict the future without making assumptions that are difficult to justify. Yet flood risk management needs to focus on planning for the future. The scope of the project did not cover attributing trends. The interim guidance recommends that future climate change is accounted for using the standard approach based on the output of climate models.

Without knowing what is driving trends we have little chance of knowing how they will evolve in the future. For robust trend attribution, it is necessary to demonstrate that the observed trends are consistent with the proposed cause, that they are inconsistent with alternative causes, and to provide a measure of confidence in the attribution (Merz and others, 2012). A first step towards attribution would be to test for trends in extreme rainfall over the same period of record as peak flows (see the next section).

A more seamless modelling approach would be desirable, merging the statistical analysis of past floods with the physics-based modelling of future changes. One promising way forward would be to apply dynamic statistical models, which could potentially account for the physical drivers of change, including both climatic effects and catchment land use.

In such models, the physics-based projections from climate models can be used as covariates to update the parameters of statistical distributions, and therefore predict probabilistic changes in event magnitudes and frequencies, over sub-seasonal to multi-decadal timescales. Dynamic statistical approaches take advantage of the ability of physical models to predict large-scale phenomena and the strengths of non-stationary statistical models to estimate probabilities of extreme events conditioned on observed data, offering a realistic approach for projecting future changes in flood frequency.

It would also be desirable to explore a hybrid approach to uncertainty assessment (for example, to help partition between uncertainties associated with future radiative forcing scenarios, climate model structures, internal variability and observation noise).

The research could build on recent and ongoing work at the Met Office (see section 7.2) in which non-stationary models have been fitted to both modelled and observed rainfall data using global temperature as a covariate.

The need for this research has been (provisionally) identified in the emerging flood hydrology roadmap. The research topic relates to advice contained within the 2016 National Flood Resilience Review, which recommended closer linking of global and regional weather models to hydrological and flood models. If adopting an approach to flood frequency estimation that is more closely based on process models, it will be important not to lose sight of the value of long records of river level and flow, including historical information and other types of local data, that provide a vital anchor for any modelled estimate of flood frequency, notwithstanding the presence of non-stationarity.

There are some synergies between this recommendation and projects that are proposed or aspired to at UK universities, in particular Oxford, also Bath and Lancaster (see section 6.1).

Another related initiative, carried out several years ago, is Future Flows Hydrology (Prudhomme and others, 2013), which provided modelled daily river flow projections for 150 flow-gauged river monitoring sites throughout England for 1951 to 2098, that is, covering the typical period of observed river flow records and also extending far into the future. The modelling was based on scenarios from UKCP09 and so could be replaced with something based on UKCP18. The REA included several articles that used the results of Future Flows to examine impacts of climate change.

This topic is important and could potentially meet a major need in flood risk management. At the same time, it requires some fairly fundamental research before a clear path towards user application can be identified.

### 7.1.3 Non-stationarity of other aspects of floods

Floods are much more than peak river flows. The frequency of floods, their tendency to cluster, their duration, and hydrograph shapes and volumes can all have an influence on the damage, disruption and economic costs associated with flooding. Including them in research on non-stationarity would enable a more holistic, multivariate appreciation of the way in which flood hazard is changing.

The REA captured some research on these aspects. A small number of articles looked at trends in the duration of flooding, its seasonality, the speed of rise of floods or their spatial extent.

An alternative, less reductive, way of investigating non-stationarity in these various 'dimensions' of the fluvial flood hazard might be to take a more holistic approach. This might model flow as a continuous variable, either in isolation or linked to modelling of climatic variables. Alternatively, it might focus on aspects that are closely linked to flood hazard, such as water levels, flood extents or measures of economic loss.

Additionally, it could be that the more physics-based modelling approaches outlined in section 7.1.2 lead to outputs that help answer some of the questions raised in this section.

This topic may be less urgent than those listed above to many practitioners, who are perhaps more comfortable with techniques with which they are already familiar gradually evolving. However, faced with the fundamental problem of managing flood risk in a changing world it seems important to broaden the focus. We recommend that these aspects are considered in any plans for future research.

## 7.2 Rainfall and run-off

Many aspects of flood risk management rely on rainfall frequency analysis rather than analysis of peak flow series. Rainfall frequency statistics, coupled with rainfall-run-off models are used for:

- dam safety assessments
- urban drainage studies
- surface water flood studies (run-off for these is nearly always modelled on the basis of rainfall)
- flood studies on some rivers, such as lowland, pumped, tide-locked rivers, also some urban catchments and others where circumstances lead to preference for a rainfall-run-off method

If extreme rainfall is non-stationary, as we would expect from our understanding of climate change impacts, then it could be important to account for such non-stationarity in rainfall frequency statistics.

The articles included in the REA gave rather mixed messages about non-stationarity in UK extreme rainfall: 40% of studies reported an increase in extreme precipitation, with most others either reporting a mix of increases and decreases or no change. One of the most comprehensive studies analysed 223 daily rainfall data sets in the UK with data from 1961 to 2009. It found significant increases in annual maximum rainfalls (with durations 1 to 10 days), particularly in the west.

It would be valuable to update this analysis with another 11 years of data, and to extend it to shorter duration rainfalls. Another worthwhile objective would be to increase the record length by adding pre-1960 rainfall data, one possible source being the CEH-GEAR (gridded) rainfall data set, which extends back to 1890 (although it is possible that trend signals may be confounded by inhomogeneity in the station network).

Currently, UK practitioners use the FEH 2013 rainfall frequency statistics (Stewart and others, 2013). They incorporate rainfall data up to about 2006 and assume stationarity. Revising the handbook to incorporate non-stationary methods would be a major task in light of the complexity of the FEH rainfall frequency analysis. Challenges would include:

- how to define and interpolate the index rainfall (RMED) in a non-stationary framework
- how to apply the FORGEX method of pooling rain gauges if networks contain gauges with a variety of trend characteristics
- whether the model for spatial dependence in extreme rainfall, which is an ingredient of FORGEX, would be compatible with non-stationary methods

We suggest that a useful way forward may be to commission a scoping study that looks at:

- trends in annual maximum rainfalls, using up-to-date records and extending from durations of one hour up to several days
- options for incorporating non-stationarity in UK rainfall frequency analysis, including approaches closely based on the FEH methodology, those applied by the Met Office as part of UKCP09 and UKCP18 (see section 6.2), projects such as CONVEX and Future storms (see section 6.1.3) and any others that appear promising
- the need to merge modelling of past trends and future expected climate change. This links to the section above (section 7.1.2). The UKCP18 outputs include transient data and high-resolution rainfall grids. It could be valuable to explore these outputs when comparing past and future non-stationarity, as the Met Office is currently doing
- it may be that there are some useful lessons to learn from the Canadian FloodNet research initiative, which is planning to include recommendations on non-stationary rainfall frequency (see section 4.2)
- a project currently being procured by the Environment Agency, which is scoping a method for revising the estimation of probable maximum precipitation (PMP) and probable maximum flood (PMF). This may include considering trends (past or future) in extreme rainfall
- storm rainfall is only one factor in the modelling of flood flows or run-off. Others include soil moisture, influenced by evapotranspiration and longer term rainfall accumulations, and land surface parameters. Any of these could also be affected by non-stationarity. For instance, one consideration could be that parameters of rainfall-run-off models estimated from past data do not necessarily apply under present or future conditions. However, we suggest that a focus on non-stationarity of extreme rainfall would be a useful starting point when considering the types of flood studies listed at the start of this section.

## 7.3 Estuaries

No research was found in the REA or follow-on work investigating potential changes in dependence relationships between fluvial and coastal events. Note the original REA search included keywords that would pick these studies out. Previous Environment Agency research (FD2308) has shown dependence between river flows and storm surge in some areas. However, in the UK extreme sea levels are dominated by astronomical tide levels and therefore dependence between storm surge and river flows can translate to very weak dependence between extreme sea levels and river flows which are the variables of interest for flood risk. We have found no evidence of a non-stationary dependence parameter between fluvial and coastal flows being used in practice. The recent Environment Agency National Tidal Loading Project assumed stationary dependence between fluvial and coastal flows.

Due to the weak dependence between extreme sea levels and fluvial flows, non-stationarity in dependence between storm surges and fluvial flows would have minimal impact on the results of flood risk assessments. We therefore recommend other research recommended in this report is prioritised over research into this topic.

## 7.4 Non-stationarity of astronomical tides

The current practice of the Environment Agency when assessing future flood risk is to assume that astronomical tidal ranges and tide curve shapes are the same in the future as they are now. The REA findings do not support this assumption, especially if sea level rise is large. Numerous observational studies have used tide gauge data to show significant trends in tidal levels at many locations around the world, comparable in magnitude to the rate of sea-level rise at some locations (see recent review paper by Haigh and others, 2020). Changes in tides observed at tide gauge records reflect a combination of all contributions, including the effect of sea-level rise on tides, but also that of other human activities that alter the shape of the coastlines such as building tidal barrages. Furthermore, a number of recent modelling studies have suggested changes in tidal range resulting from future changes in mean sea level (Pickering and others, 2017; Ward and others, 2012, Pelling and others, 2013; Wilmes and others, 2017). These modelling studies all suggest that changes in tidal range will be approximately plus or minus 10% of any changes in mean sea level, with large spatial variability. Although small compared to the mean sea level changes, altered tidal ranges could enhance (or reduce) coastal flooding at some locations.

These changes in tidal levels caused by sea-level rise are predictable to the extent that they could be incorporated into coastal protection plans. However, an important caveat is that a number of independent regional model simulations should all give the same spatial interpretation of tidal changes (that is, an ensemble of European shelf models should agree on the locations of increased and decreased tidal range): this is not currently the case.

To address this gap, we recommend firstly reviewing the modelling already carried out to identify possible causes of differences between results. For example, comparing the model boundary conditions used, do they allow coastlines to flood with sea level rise or assume coastlines are defended? Following this investigation, we recommend a multi-model ensemble of astronomical tides under future sea level rise is run, with the models set up so the results can be compared by using the same boundaries, bathymetry and other factors identified in the first stage. Finally, we recommend the robustness of the results to model resolution is tested. The findings of this research will inform future flood risk assessments of which areas are sensitive to changes in future astronomical tides, and if increases in mean sea level rise will increase or decrease astronomical tidal levels.

Until such an ensemble of models is available, we recommend planners include the likelihood of tidal range changes in their sensitivity studies.

As well as the peak sea level, flood inundation is sensitive to the shape of the tidal curve (as it affects the duration extreme sea levels exceed defence crest heights). Articles on tidal changes due to mean sea level rise have concentrated on the impact on tidal heights but the data they produced could be reanalysed to investigate the impact on tidal curves. We recommend this reanalysis is carried out. The authors of this study hypothesise that the changes in the tidal curve will be more consistent between different models as the tidal curve is the result of the addition of all tidal harmonics. The results of this research would enable the Environment Agency to advise if changes in the tidal curve shape need to be considered in flood risk assessments of future epochs or if it would be reasonable to scale the existing shape up/down to test changes in the tidal range.

## 7.5 Storm surges

Modelled projections of future storm surges show no significant changes. This lack of evidence does not rule out future changes due to changes in windiness, storm tracks and other factors. There is still much uncertainty around the present and past variability of storm surges (for example, as shown by the NERC project, Synthesising Unprecedented Coastal Conditions: Extreme Storm Surges). The REA supported the current methodology for assessing extreme coastal conditions if sufficiently long observations were available. The observations need to be long enough to represent the natural variability. In many locations tide gauge observations cover only a few decades, therefore we recommend further research to better quantify the natural variability of storm surges and investigate how to account for this at locations with shorter observational time series.

Potential methods to better quantify the natural variability of storm surges are:

- quantify long-term changes (for instance, using the new model of event probabilities published in Calafat and Marcos, 2020) and try to link them to modes of natural variability
- use a combination of observations and ensembles of climate simulations to try to separate the forced signal from the internal variability
- investigate storm surge variability using a large Monte Carlo ensemble of highly idealised extratropical storms (as has been done for tropical cyclones, for example, Lin & Emmanuel, 2016)

## 7.6 Sea level rise acceleration

Sea level rise acceleration is already accounted for when considering future epochs. It is not accounted for when statistically analysing historical data (a linear trend is used). The REA recommended the assumption of a linear trend be reviewed regularly against the latest science as climate change studies predict an acceleration.

Recent studies have demonstrated using satellite altimetry observations that global average sea level has been accelerating since at least 1993 at a rate of about 0.084 mm/year$^2$ (Nerem and others, 2018), which is in line with what dynamical models project for this century. Extrapolation of this acceleration to the end of this century roughly doubles the amount of sea level rise relative to projections that assume a constant rate of sea level rise of 3 mm/year (the current global rate). If the global average sea level has been accelerating, then it follows that local sea level has also likely been accelerating at many locations, even though detection of sea level accelerations at a local scale has proven challenging due to the presence of substantial climate noise associated with internal climate variability. Nevertheless, recent studies have shown that the pattern of regional sea level accelerations has started to emerge (Dangendorf and others, 2019; Hamlington and others, 2020). In particular, Dangendorf and others (2019) showed, using a combination of tide gauge and satellite altimetry observations, that the acceleration of global sea level detected in the altimetry record in fact started in the 1960s and it is also detectable in reconstructed historical sea levels at a local scale.

Extreme sea levels for flood risk studies in the UK are taken from the Coastal Flood Boundary and the State of the Nation data sets. Consultants preparing flood maps for the Environment Agency do not normally need to do their own extremes analysis and therefore would not be required to implement alternative detrending techniques. Given the results from Dangendorf and others, 2019 and other recent papers, we recommend that when either the Coastal Flood Boundary or State of the Nation data sets are next updated, sea level rise trends from UK tide gauges are recalculated 'cleaning' the time series by removing known atmospheric variability, to see if an acceleration emerges as the records get longer. It should be noted that even if acceleration can be detected, the impact of removing a non-linear trend versus a linear trend on the resulting extreme sea levels is likely to be small until the acceleration is large/has been continuing for an extended period. For this reason, periodic reviews are appropriate.

## 7.7 Waves

There is considerable uncertainty about changes to the future wave climate. Climate change modelling produces information on offshore waves. We recommend that national sensitivity testing is carried out to ascertain how sensitive inshore conditions are to changes in offshore parameters. We propose 2 sensitivity tests:

- Firstly, test the importance of changing offshore wave direction (as identified in COWCLIP projections). Perform sensitivity tests to quantify the resulting change in wave incident direction at the toe of defences occurring from an offshore change in wave direction of around 5 to 15 degrees. Since waves refract as they approach the coastline we hypothesise that, at least in some locations, this testing will show low sensitivity of nearshore wave conditions to these changes. This knowledge would help reduce uncertainty in our overtopping estimates for future climates.

- There is some evidence of future increases in wave energy at longer periods changing the spectral shape offshore and the peak/mean wave period. Flood risk studies perform extreme assessments on the spectrum statistics, for example, peak period and mean period. Local wave modelling must therefore use a design spectrum (usually JONSWAP) with these parameters. For this reason, it would not be possible to implement changes in the boundary wave spectrum except through these parameters. We recommend sensitivity testing is performed to assess the impacts of changes in offshore wave period: quantifying the translation from offshore changes to inshore changes, for example, does a 1s increase offshore equal a 1s increase inshore, and then translating this impact into wave overtopping and erosion. The impacts on wave overtopping and erosion would also depend on other parameters, therefore, we recommend testing on a variety of locations to quantify the range of response.

Understanding the sensitivity of nearshore wave conditions to changes in different aspects of offshore conditions would enable future research to be more targeted.

## 7.8 Data

This report has focused on methods used to account for non-stationarity. However, it should be kept in mind than any statistical assessment is only as reliable as the data on which it is based. The REA only supported current practice for calculating coastal extremes on historical data when there was a sufficiently long time series due to inter-decadal variability. The following recommendations reflect this:

- It is critical that the current networks of tide, river and rain gauges are maintained to allow for future flood risk assessments. Longer records will mean inter-decadal variations can be better characterised, and data over the next few decades will be important in identifying effects such as sea level rise acceleration. A crucial part of this for tidal gauges is frequent geodetic levelling (surveying) to ensure a reliable and consistent vertical datum, without which it is impossible to estimate mean sea level trends or even produce a reliable tide table.
- The State of the Nation project which provides extreme wind, wave and water level data sets for nearshore coastal flood risk modelling is based on observed water level but modelled wind and waves. Ideally, future assessments would use observed conditions to remove modelling errors. This requires high quality, long duration wave observations in suitable locations.
- As mentioned above, ideally, we would base extreme assessments on wave observations. In the interim, while we wait for these observational data sets to be long enough, we recommend an assessment of the mismatch between observed and hindcast waves, to quantify systematic biases in the wave modelling. This should be followed by the development of a methodology to correct/blend hindcast and observed data (for example, uplift of underpredicted high waves under storm conditions). This would improve the quality of the hindcast data used in statistical analysis.
- The length of the WaveWatch III hindcast (starting in 1980) is shorter than many tide gauge records. Analysis of surges at Newlyn where there is 100-years of observations shows inter-decadal variation in extreme surges. This variability may not be captured in the wave hindcast due to its length. We therefore recommend running a high resolution UK scale long wave hindcast based on ERA-5 winds (1950 to 2020).

## 7.9 Summary of recommendations

### 7.9.1 Inland flooding

The following recommendations are made for future research and practice in relation to fluvial and surface water flooding:

1. Take a more holistic approach to non-stationary fluvial flood frequency estimation that looks beyond annual maximum peak flows to consider aspects such as the magnitude and frequency of all floods, their tendency to cluster, their duration, and hydrograph shapes and volumes.
2. Develop a practical method of non-stationary flood frequency estimation that can be applied on ungauged catchments and reduces the uncertainty associated with single-site frequency analysis.
3. Integrate the modelling of past and future non-stationarity in flood flows. This will include work to attribute observed trends.
4. Commission a scoping study that looks at trends in extreme rainfall, options for incorporating non-stationarity in UK rainfall frequency analysis, and the need to merge modelling of past trends and future expected climate change.

### 7.9.2 Coastal flooding

The following recommendations are made for future research and practice in relation to coastal flooding:

5. As part of the sensitivity testing in flood risk mapping, test the impact of increasing/decreasing the future tidal range by +/- 10% of the mean sea level rise being applied.
6. Further analysis of regional tidal models and their response to sea level rise, to reduce uncertainty around the local sign and magnitude of tidal changes.
7. Analyse the changes to future tidal curves from existing studies, investigating the impact of sea level rise on astronomical tides.
8. Better quantify the natural variability of storm surges.
9. Reassess tide gauge records for sea level rise acceleration when next updating either the Coastal Flood Boundary or State of the Nation data sets.
10. Test the sensitivity of inshore wave direction to changes in offshore wave direction.
11. Test the sensitivity of wave overtopping/coastal erosion to changes in wave period.

### 7.9.3 Data

The following recommendations are made to support future research and practice in assessing all sources of flooding:

12. Maintain the current networks of tide, river and rain gauges.
13. Acquire high quality, multi-decadal wave observations in suitable locations.

14. Research methods to correct/blend hindcast and observed data to improve wave hindcasts.
15. Run a high-resolution UK scale long wave hindcast based on ERA-5 winds (1950 to 2020).

# References


AghaKouchak A, Ragno E, Love C and Moftakhari H. 2018 'Projected changes in California's precipitation intensity-duration-frequency curves' California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CCCA4-CEC-2018-005. Available from: https://www.energy.ca.gov/sites/default/files/2019-11/CCCA4-CEC-2018-005_ADA.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

BAFU. 2017 'Stationsbericht Hochwasserstatistik, Leitfaden' Available from https://www.bafu.admin.ch/dam/bafu/en/dokumente/hydrologie/fachinfo-daten/leitfaden-stationsberichte-hochwasserstatistik-bafu.pdf.download.pdf/leitfaden-stationsberichte-hochwasserstatistik-bafu.pdf [accessed 15 July 2015] [Accessed 22 July 2020]

Brown SJ. 2018 'The drivers of variability in UK extreme rainfall' International Journal of Climatology, 38, pp. e119-e130

Brown SJ, Murphy JM, Sexton DMH, Harris GR. 2014 'Climate projections of future extreme events accounting for modelling uncertainties and historical simulation biases' Climate Dynamics, 43 (9-10), pp. 2,681 to 2,705

Bush E and Lemmen DS. editors 2019 'Canada's Changing Climate Report' Government of Canada, Ottawa, ON. 444 p. Available from https://changingclimate.ca/CCCR2019/ [accessed 15 July 2020] [Accessed 22 July 2020]

Calafat FM, Marcos M. 2020 'Probabilistic reanalysis of storm surge extremes in Europe' Proceedings of the National Academy of Sciences of the United States of America, 117 (4), pp. 1877 to 1883

Carpe Diem West. 2011 'Running the Climate Rapids – An Interview with David Behar' Carpe Diem West. Available from https://www.carpediemwest.org/running-climate-rapids-interview-david-behar/ [accessed 15 July 2020] [Accessed 22 July 2020]

Dangendorf S, Hay C, Calafat FM, Marcos M, Piecuch CG, Berk K and Jensen J. 2019 'Persistent acceleration in global sea-level rise since the 1960s' Nature Climate Change, 9, 705 to 710

DoD. 2018a 'Unified Facilities Criteria (UFC) Installation Master Planning' (UFC 2-100-01). Department of Defense. Available from https://www.wbdg.org/FFC/DOD/UFC/ARCHIVES/ufc_2_100_01_2012_c1.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

DoD. 2018b 'Unified Facilities Criteria (UFC) Installation Master Planning' (UFC 3-201-01). Department of Defense. Available from https://www.wbdg.org/ffc/dod/unified-facilities-criteria-ufc/ufc-3-201-01 [accessed 15 July 2020] [Accessed 22 July 2020]

Eastoe EF. 2019 'Nonstationarity in peaks-over-threshold river flows: A regional random effects model' Environmetrics, 30 (5), art. no. e2560

England JF Jr, Cohn TA, Faber BA, Stedinger JR, Thomas WO Jr, Veilleux AG, Kiang JE and Mason RR Jr. 2018 'Guidelines for determining flood flow frequency—Bulletin 17C' (ver. 1.1, May 2019): U.S. Geological Survey Techniques and Methods, book 4, chap. B5, 148 p., https://doi.org/10.3133/tm4B5 [Accessed 22 July 2020]

Environment Agency. 2020 'Development of Interim National Guidance on Non-Stationary Fluvial Flood Frequency Estimation' Environment Agency, report FRS18087 (in press)

Fleming P. 2012 'The Climate Change Imperative for Water Utilities: Management Responses' In: 9th International Water Supply Technology Symposium - Resilient Water Supply System, November 20 to 22, 2012, Yokohama, Japan. Available from http://www.jwrc-net.or.jp/aswin/symposium_archive/images/data/009_inv_an_Paul-Fleming.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

Griffis VW, Stedinger JR. 2007 'Incorporating climate change and variability into Bulletin 17B LP3 Model' Restoring Our Natural Habitat - Proceedings of the 2007 World Environmental and Water Resources Congress, 8 p. DOI: 10.1061/40927(243)69

Haigh ID, Pickering MD, Green JAM, Arbic BK, Arns A, Dangendorf S, Hill DF, Horsburgh K, Howard, T, Idier D, Jay DA, Jänicke L, Lee SB, Müller M, Schindelegger M, Talke SA, Wilmes SB, Woodworth PL. 2020 'The Tides They Are A-Changin': A Comprehensive Review of Past and Future Nonastronomical Changes in Tides, Their Driving Mechanisms, and Future Implications' Reviews of Geophysics, 58 (1), art. no. e2018RG000636

Hall JA, Gill S, Obeysekera J, Sweet W, Knuuti K and Marburger J. 2016 'Regional Sea Level Scenarios for Coastal Risk Management: Managing the Uncertainty of Future Sea Level Change and Extreme Water Levels for Department of Defense Coastal Sites Worldwide' U.S. Department of Defense, Strategic Environmental Research and Development Program. 224 pp. Available from https://climateandsecurity.files.wordpress.com/2014/01/regional-sea-level-scenarios-for-coastal-risk-management_managing-uncertainty-of-future-sea-level-change-and-extreme-water-levels-for-department-of-defense.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

Hamlington BD, Frederikse T, Nerem RS, Fasullo JT and Adhikari S. 2020 'Investigating the acceleration of regional sea level rise during the satellite altimeter era' Geophysical Research Letters, 47, e2019GL086528

Kelder T, Müller M, Slater L, Wilby R, Bohlinger P, Marjoribanks T, Prudhomme C, Dyrrdal A, Nipen T and Ferranti L. 2019 'UNSEEN trends: Towards detection of changes in 100-year precipitation events over the last 35 years' EGU General Assembly 2020, Online, 4 to 8 May 2020, EGU2020-521, https://doi.org/10.5194/egusphere-egu2020-521 [accessed 16 July 2020] [Accessed 22 July 2020]

Kendon M, McCarthy M, Jevrejeva S and Legg T. 2017 'State of the UK Climate 2016' Met Office, Exeter, UK

Knutson T, McBride J, Chan J and others. 2010 'Tropical cyclones and climate change' Nature Geosci 3, 157 to 163 https://doi.org/10.1038/ngeo779 [Accessed 22 July 2020]

Kopp RE, Andrews C, Broccoli A, Garner A, Kreeger D, Leichenko R, Lin N, Little C, Miller JA, Miller JK, Miller KG, Moss R, Orton P, Parris A, Robinson D, Sweet W, Walker J, Weaver CP, White K, Campo M, Kaplan M, Herb J and Auermuller L. 'New Jersey's Rising Seas and Changing Coastal Storms: Report of the 2019 Science and Technical Advisory Panel' Rutgers, The State University of New Jersey. Prepared for the New Jersey Department of Environmental Protection. Trenton, New Jersey. Available from https://www.nj.gov/dep/climatechange/pdf/nj-rising-seas-changing-coastal-storms-stap-report.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

Lin N, Emanuel K. 2016 'Grey swan tropical cyclones' Nature Climate Change, 6 (1), pp. 106-111. https://doi.org/10.1038/nclimate2777 [accessed 16 July 2020] [Accessed 22 July 2020]

Luke A, Vrugt JA, AghaKouchak A, Matthew R and Sanders BF. 2017 'Predicting nonstationary flood frequencies: Evidence supports an updated stationarity thesis in the United States' Water Resources Research, 53, 5469–5494, doi:10.1002/2016WR019676

Madsen H, Lawrence D, Lang M, Martinkova M and Kjeldsen TR. 2013 'A review of applied methods in Europe for flood-frequency analysis in a changing environment' COST Action ES0901: Flood frequency estimation methods and environmental change, technical report, CEH, UK, ISBN: 978-1-906698-36-2

Merz B, Vorogushyn S, Uhlemann-Elmer S, Delgado J and Hundecha Y. 2012 'More efforts and scientific rigour are needed to attribute trends in flood time series' Hydrology and Earth System Sciences, 16, 1379 to 1387

Ministry of Forests, Lands, Natural Resource Operations and Rural Development. 2018a 'Flood Hazard Area Land Use Management Guidelines' Available from https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/integrated-flood-hazard-mgmt/flood_hazard_area_land_use_guidelines_2017.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

Ministry of Forests, Lands, Natural Resource Operations and Rural Development. 2018b 'Legislated flood assessments in a changing climate in BC' Available from https://www.egbc.ca/getmedia/f5c2d7e9-26ad-4cb3-b528-940b3aaa9069/Legislated-Flood-Assessments-in-BC.pdf.aspx [accessed 15 July 2020] [Accessed 22 July 2020]

Morim J, Hemer M, Wang XL, Cartwright N, Trenham C, Semedo A, Young I, Bricheno L, Camus P, Casas-Prat M, Erikson L, Mentaschi L, Mori N, Shimura T, Timmermans B, Aarnes O, Breivik Ø, Behrens A, Dobrynin M, Menendez M, Staneva J, Wehner M, Wolf J, Kamranzad B, Webb A, Stopa J, Andutta F. 2019 'Robustness and uncertainties in global multivariate wind-wave climate projections' (2019) Nature Climate Change, 9 (9), pp. 711 to 718

Morim J, Trenham C, Hemer M, Wang XL, Mori N, Casas-Prat M, Semedo A, Shimura T, Timmermans B, Camus P, Bricheno L, Mentaschi L, Dobrynin M, Feng Y, Erikson L. 2020 'A global ensemble of ocean wave climate projections from CMIP5-driven models' Scientific Data, 7 (1), art. no. 105

Natural Resources Canada. 2019 'Federal Hydrologic and Hydraulic Procedures for Flood Hazard Delineation' Version 1.0. Available from http://ftp.geogratis.gc.ca/pub/nrcan_rncan/publications/ess_sst/299/299808/gip_113_en.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

Nerem RS, Beckley BD, Fasullo JT, Hamlington BD, Masters D and Mitchum GT. 2018 'Climate-change–driven accelerated sea-level rise detected in the altimeter era' Proceedings of the National Academy of Sciences of the United States of America, 115(9), 2022–2025. https://doi.org/10.1073/pnas.1717312115

Obeysekera J, Park J, Irizarry-Ortiz M, Trimble P, Barnes J, VanArman J, Said W, Gadzinski E. 2011 'Past and Projected Trends in Climate and Sea Level for South Florida' Interdepartmental Climate Change Group. South Florida Water Management District, West Palm Beach, Florida, Hydrologic and Environmental Systems Modelling Technical Report. July 5, 2011. Available from https://www.sfwmd.gov/sites/default/files/documents/ccireport_publicationversion_14jul11.pdf [ accessed 15 July 2020] [Accessed 22 July 2020]

Orton P, Lin N, Gornitz V, Colle B, Booth J, Feng K, Buchanan M, Oppenheimer M and Patrick L. 2019 'New York City Panel on Climate Change 2019 Report Chapter 4: Coastal Flooding' Annals of the New York Academy of Sciences, Vol 1439, Issue 1, pages 95-114. https://doi.org/10.1111/nyas.14011 [accessed 15 July 2020] [Accessed 22 July 2020]

Over TM. 2016 ‘Site and Regional Flood Frequency Analysis at USGS’ [blog]. 28 October. Available from: http://abouthydrology.blogspot.com/2016/10/site-and-regional-flood-frequency-at.html# [accessed 15 July 2020] [Accessed 22 July 2020]

Pelling HE, Mattias Green JA and Ward SL. 2013 ‘Modelling tides and sea level rise: To flood or not to flood’ Ocean Modelling, 63, 21 to 29

Pickering MD, Horsburgh KJ, Blundell JR, Hirschi JJ-M, Nicholls RJ, Verlaan M and Wells NC. 2017 ‘The impact of future sea-level rise on the global tides’ Continental Shelf Research, 142, 50–68. https://doi.org/10.1016/j.csr.2017.02.004

Prudhomme C, Haxton T, Crooks S, Jackson C, Barkwith A, Williamson J, Kelvin J, Mackay J, Wang L, Young A, Watts G. 2013 ‘Future Flows Hydrology: An ensemble of daily river flow and monthly groundwater levels for use for climate change impact assessment across Great Britain’ Earth System Science Data, 5 (1), pp. 101 to 107

Rijkswaterstaat. 2017 ‘Water veiligheid Begrippen begrijpen’ Available from https://www.deltacommissaris.nl/deltaprogramma/documenten/publicaties/2017/06/01/waterveiligheid-begrippen-begrijpen [accessed 15 July 2020] [Accessed 22 July 2020]

Rosenweig C and Solecki W. 2015 ‘New York City Panel on Climate Change 2015 Report Introduction’ Annals of the New York Academy of Sciences, Vol 1336, Issue 1, pages 3 to 5. https://doi.org/10.1111/nyas.12625 [Accessed 22 July 2020]

Slater LJ, Villarini G, Bradley A, Vecchi G. 2019a ‘A dynamical statistical framework for seasonal streamflow forecasting in an agricultural watershed’ Climate Dynamics, 53(12), 7429-7445, doi:10.1007/s00382-017-3794-7

Slater LJ, Villarini G, Bradley A. 2019b ‘Evaluation of the skill of North-American Multi-Model Ensemble (NMME) Global Climate Models in predicting average and extreme precipitation and temperature over the continental USA’ Climate Dynamics, 53(12), pp. 7381–7396. doi: 10.1007/s00382-016-3286-1

Stewart EJ, Jones DA, Svensson C, Morris DG, Dempsey P, Dent JE, Collier CG, Anderson CW. 2013 ‘Reservoir Safety – Long Return Period Rainfall’ Volume 1, R&D Technical Report WS 194/2/39/TR, Defra 2013

Storm Water Solutions. 2019 ‘Resiliency in the Big Apple’ Available from https://www.estormwater.com/software-data-management/resiliency-big-apple [accessed 15 July 2020] [Accessed 22 July 2020]

USACE. 2018a ‘Nonstationarity Detection Tool (NSD) - Home. US Army Corps of Engineers’ Available from http://corpsmapu.usace.army.mil/cm_apex/f?p=257:2:0::NO [accessed 15 July 2020] [Accessed 22 July 2020]

USACE. 2018b ‘Nonstationarity Detection Tool (NSD) – User Guide’ US Army Corps of Engineers. Available from http://corpsmapu.usace.army.mil/cm_apex/f?p=257:20:0::NO [accessed 15 July 2020] [Accessed 22 July 2020]

USACE. 2019a ‘Incorporating sea level changes in civil works programs’ Washington, Department of the Army Engineering Regulation No. 1100-2-8162. Available from https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/ER_1100-2-8162.pdf?ver=2019-07-02-124841-933 [accessed 15 July 2020] [Accessed 22 July 2020]

USACE. 2019b ‘Procedures to evaluate sea level impacts, responses, and adaptation’ Washington, Department of the Army Engineering Pamphlet No. 1100-2-1. Available from https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/EP-1100-2-1.pdf?ver=2019-09-13-141310-707 [accessed 15 July 2020] [Accessed 22 July 2020]

USACE. (undated) 'Climate Preparedness and Resilience' US Army Corps of Engineers. Available from https://www.usace.army.mil/corpsclimate/ [accessed 15 July 2020] [Accessed 22 July 2020]

USEPA. (undated[a]) 'Climate Change Indicators in the United States' United States Environmental Protection Agency. Available from https://www.epa.gov/climate-indicators [accessed 15 July 2020] [Accessed 22 July 2020]

USEPA. (updated[b]) 'Adapting Water Infrastructure to Non-stationary Climate Changes' United States Environmental Protection Agency. Available from https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=330891 [accessed 15 July 2020] [Accessed 22 July 2020]

Ward S, Green JAM and Pelling H. 2012 'Tides, sea-level sea level rise and tidal power extraction on the European shelf' Ocean Dynamics, 62(8), 1,153 to 1,167

Wilmes S-B, Green JAM, Gomez N, Rippeth TP and Lau H. 2017 'Global tidal impacts of large-scale ice-sheet collapses' Journal of Geophysical Research: Oceans, 122, 8,354 to 8,370

Wolf J, Woolf D and Bricheno L. 2020 'Impacts of climate change on storms and waves relevant to the coastal and marine environment around the UK' MCCIP Science Review 2020, 132 to 157. doi: 10.14465/2020.arc07.saw

Woolf D and Wolf J. 2013 'Impacts of climate change on storms and waves' MCCIP Science Review 2013, 20-26, doi:10.14465/2013.arc03.020-026

WUCA. (undated [a]) 'Engineering case studies' Water Utility Climate Alliance. Available from https://www.wucaonline.org/adaptation-in-practice/engineering-case-studies/index.html [accessed 15 July 2020] [Accessed 22 July 2020]

WUCA. (undated [b]) 'New York City Department of Environmental Protection, Climate Resiliency Standard Operating Procedure' Water Utility Climate Alliance. Available from https://www.wucaonline.org/assets/pdf/engineering-case-study-new-york.pdf [accessed 15 July 2020] [Accessed 22 July 2020]

Yang YJ. 2010 'Precipitation Nonstationarity Effects on Water Infrastructure and Risk Management' Presented at Workshop on Nonstationarity, Hydrologic Frequency Analysis and Water Management, Boulder, CO, January 13 to 15, 2010. Available from https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NRMRL&dirEntryId=218793 [accessed 15 July 2020] [Accessed 22 July 2020]

# List of abbreviations

| | |
|---|---|
| AAL | Average annual loss |
| APA | Adaptation Action Plan |
| ARR | Australian Rainfall and Runoff |
| BAFU | Swiss Federal Office for the Environment |
| BoM | Bureau of Meteorology |
| cat | catastrophe |
| CSIRO | Commonwealth Scientific and Industrial Research Organisation |
| CMIP5 | Coupled Model Intercomparison Project Phase 5 |
| COWCLIP | Coordinated Ocean Wave Climate Project |
| DAS | German Strategy for Adaptation to Climate Change |
| DoD | Department of Defense |
| ECMWF | European Centre for Medium-Range Weather Forecasts |
| FD2308 | Joint probability - dependence mapping and best practice |
| FEH | Flood Estimation Handbook |
| FEMA | Federal Emergency Management Agency |
| FFA | Flood frequency analysis |
| FHWA | Federal Highway Administration |
| FORGEX | Focused Rainfall Growth Extension method |
| GEV | Generalised extreme value distribution |
| IPCC | Intergovernmental Panel on Climate Change |
| JONSWAP | Joint North Sea Wave Project |
| MCCIP | Marine Climate Change Impacts Partnership |
| MSLR | Mean sea level rise |
| NAO | North Atlantic Oscillation |
| NCCARF | National Climate Change and Adaptation Research Facility |
| NERC | Natural Environment Research Council |
| NOAA | National Atmospheric and Oceanic Administration |
| PACT | Protecting Against Climate Threats |
| PMF | Probable maximum flood |
| PMP | Probable maximum precipitation |
| POT | Peaks over threshold |
| PRA | Prudential Regulatory Authority |

| | |
|---|---|
| RCP | Representative concentration pathways |
| REA | Rapid evidence assessment |
| SFPUC | San Francisco Public Utilities Commission |
| SLR | Sea level rise |
| SWAN | Simulating waves near shore |
| SWH | Significant wave height |
| UKCEH | UK Centre for Ecology and Hydrology |
| UKCP09 | UK Climate Projections 2009 |
| UKCP18 | UK Climate Projections 2018 |
| USACE | US Army Corps of Engineers |
| USEPA | US Environmental Protection Agency |
| USGS | United States Geological Survey |
| WUCA | Water Utility Climate Alliance |

# Appendix A: Summary of coastal flood risk and flood management guidance in the UK, USA, Australia, Germany, and the Netherlands

| Country | Primary guidance (but see text below for further detail and exceptions) | Scientific basis at time of writing | Is guidance statutory? | Climatological assumption for tides, waves and storm surges |
|---|---|---|---|---|
| UK<br>England | 'Flood risk assessments: climate change allowances': https://www.gov.uk/guidance/flood-risk-assessments-climate-change-allowances. | IPCC AR5; UKCP18 | Yes | Simple allowances (+5%, +10% depending on epoch) are given for extreme wave heights. Stationarity is assumed for storm surges and tides. |
| UK<br>Scotland | 'Climate change allowances for flood risk assessment in land use planning, LUPS-CC1, Version 1, 2019'. https://www.sepa.org.uk/media/426913/lups_cc1.pdf | IPCC AR5; UKCP18 | Yes | Stationarity is assumed for storm surges and tides. A sensitivity test to a 10 to 20% increase in extreme offshore wave heights is recommended. |
| UK<br>Wales | Natural Resources Wales (2018). Flood Consequence Assessments: Climate change allowances. www.gov.wales/sites/default/files/publications/2018-11/flood-consequence-assessments.pdf | IPCC AR4; UKCP09<br>(being updated) | Yes | Stationarity is assumed for storm surges and tides. Precautionary sensitivity tests for offshore waves are recommended. |
| USA | Coastal flood policy and technical guidance is the responsibility of individual agencies, states or cities.<br>USACE guidance: Engineer Regulation 1100-2-8162: | IPCC AR5; SROCC<br>(applies to links in the previous column; not used in all | No<br>(with some exceptions) | Stationarity is assumed for storm surges, tides and waves (in all US guidance). |

| Country | Primary guidance (but see text below for further detail and exceptions) | Scientific basis at time of writing | Is guidance statutory? | Climatological assumption for tides, waves and storm surges |
|---|---|---|---|---|
| | https://www.publications.usace.army.mil/Portals/76/Users/182/86/2486/ER_1100-2-8162.pdf?ver=2019-07-02-124841-933<br>Kopp and others (2019)<br>https://www.nj.gov/dep/climatechange/pdf/nj-rising-seas-changing-coastal-storms-stap-report.pdf | cities or states) | | |
| Australia | Sea level rise planning guidelines are the responsibility of state governments rather than the federal government.<br>The most up to date scientific advice is the CoastAdapt data set: https://coastadapt.com.au/sea-level-rise-information-all-australian-coastal-councils | IPCC AR5; the CoastAdapt project | Variable by state | Stationarity is assumed for storm surges, tides and waves. |
| Canada | In Canada, land use, planning and zoning is typically governed at the provincial or municipal level. Most provinces use scenario-based regional sea-level rise projections to the end of the 21st century. For example:<br>British Columbia guidelines for "'flood hazard area land use':<br>https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/integrated-flood-hazard-mgmt/flood_hazard_area_land_use_guidelines_2017.pdf<br>For New Brunswick:<br>http://bathurstsustainabledevelopment.com/userfiles/Sea%20Level%20Rise-Coastal%20Sections-Daigle-2012.pdf<br>N.B. New national guidelines on coastal and flood risk assessment for building and infrastructure design applications will be published during 2020. | Ministry or consultancy reports based on IPCC AR4 | Variable by province or municipality | Stationarity is assumed for storm surges, tides and waves. |

| Country | Primary guidance (but see text below for further detail and exceptions) | Scientific basis at time of writing | Is guidance statutory? | Climatological assumption for tides, waves and storm surges |
|---|---|---|---|---|
| Germany | Adaptation Action Plan (APA) and German Strategy for Adaptation to Climate Change (DAS), and DAS 2015 progress report (progress report – in German) | IPCC AR5;<br>DWD Climate Model Ensemble | Variable by state | Stationarity is assumed for storm surges (after accounting for sea-level rise), tides and waves. |
| Netherlands | National Water Plan (2016-2021) http://www.helpdeskwater.nl | KNMI14 (based on IPCC AR5), or KNM06<br>(based on IPCC AR4) | Yes | Stationarity is assumed for storm surges, tides and waves. |

## Would you like to find out more about us or about your environment?

## Then call us on
**03708 506 506** (Monday to Friday, 8am to 6pm)

## email
**enquiries@environment-agency.gov.uk**

## or visit our website
**www.gov.uk/environment-agency**

## incident hotline **0800 807060** (24 hours)
## floodline **0345 988 1188 / 0845 988 1188** (24 hours)

Find out about call charges (www.gov.uk/call-charges)