"The Science of Global and UK Sea-Level Projections: Progress, Challenges and Future Directions" Workshop Report

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Executive Summary

A two-day virtual meeting was held on Monday 20th and Tuesday 21st September 2021 that included 50 registered participants from key UK Government stakeholder organisations and representatives from the UK and wider sea level science community.

The workshop aims were:

1. Understand the current state of sea-level projections, including knowledge gaps identified in IPCC AR6
2. Bring together UK research community to promote future scientific collaboration, identify research priorities and new opportunities
3. Inform plans around the next set of UK climate projections and explore ways in which the wider UK research community could contribute

The workshop programme was structured as follows (see Appendix 1). Session 1 included a general introduction to the science of sea level projections, followed by three UK government stakeholder perspectives on their information needs. Sessions 2 and 3 delved into specific science topics relevant to sea level projections to review the state-of-the-art and highlight some of the key uncertainties and research needs. Session 4 had the theme of integration, and focussed on discussion of the UK Earth System Model and the information needs for coastal planning. All sessions included plenary discussions and there was a targeted group activity in Session 4 on identifying research gaps and stakeholder needs.

The session presentations and discussions are summarised in this report in sections 1-4. Section 5 includes a summary of the research gaps and stakeholder needs identified by workshop participants. An important outcome that arose from workshop discussions is the following statement on the status of the UK Tide Gauge Network (see Appendix 3):

Tide gauge observations around the UK are critical to our understanding of contemporary and future coastal flood hazard, and the associated climate impacts. Currently, fewer than 30% of the UK tide gauge network sites provide measurements suitable for climate applications. There is an urgent need to restore and advance UK tide gauge observing capability, in-line with internationally agreed standards, to reflect both current and future societal needs.

Met Office Hadley Centre | University of Exeter | National Oceanography Centre British Oceanographic Data Centre BODC | University of Bristol | NIOZ

1. Introduction and Stakeholder Perspectives

Session 1 started with an introduction to the science of sea level projections, followed by three perspectives on stakeholder needs from the department for Business, Energy & Industrial Strategy (BEIS), the Environment Agency (EA) Thames Estuary 2100 project and the Climate Change Committee (CCC). The presentations were followed by a panel Q&A and plenary discussion.

1.1 Presentation Summaries

Introduction to sea level projection science - J. Gregory & M. Palmer

- Mean sea level change is the dominant driver in changes in coastal flood hazard - a relatively small change in the average sea level can have a big effect on the likelihood of coastal flooding.
- Observations clearly show that global average sea level has been rising since circa 1900 with a marked acceleration since the 1960s. Global sea level has increased by about 20 cm since 1900.
- UK-average sea level has increased broadly in-line with GMSL, but degradation of the tide gauge network over the last few years means that the UK sea level index was NOT updated in 2020.
- Sea level projection science brings together both global and local processes using state of the art model simulations and scientific understanding.
- The contributions to global average sea level rise include: thermal expansion of the oceans; loss of land-based ice from glaciers and ice sheets; changes in land water storage.
- Processes that additionally affect local sea level change include: ocean dynamics; changes in Earth's gravity, rotation and solid-Earth deformation arising from land-based ice and water changes; the response of the Earth system to the last deglaciation ("glacial isostatic adjustment"); and local vertical land motion from, e.g., subsidence and plate tectonics.

Sea Level Rise, UK and Global: a BEIS perspective - J. Davey

- Public perception vs "reality": people and Ministers understand flooding but perhaps the link to sea-level rise is not well-understood? Politicians and citizens are unlikely to distinguish between coastal and inland flooding, but they understand "floods".
- Governments largely rely on the IPCC and are generally - at senior levels - only familiar with key SPM findings as provided in briefings.
- Emphasis on Net Zero means that resilience, impacts and adaptation could be seen as "2nd class citizens" in climate policy right now.
- The (poorly understood) risk "Multiple risks to the UK from climate change impacts overseas" made the top 8 areas for urgent action, as set about by the Climate Change Committee this year.
- From a policy user perspective I do not care what sea level rise will be in 20XX. I care what the direct and indirect impacts on UK prosperity and security will be, of that rise.
- The IPCC estimates of sea level rise remain wide, slow and, in political terms, likely of low salience (e.g. 1m in a century doesn't feel like a big rise).. But flooding has deep salience and is a real concern.
- We need to better understand the direct and indirect impacts of sea-level rise on UK prosperity and security. By better understanding we can make better decisions to strengthen our resilience.

The Thames Estuary 2100 perspective - A. Robotham & A. Beverton

- Thames Estuary 2100 is a long-term flood risk management plan for a region including 1.4 million people, £321 billion worth of residential property and over 3,000 flood walls and embankments.
- The plan makes use of sea level projections in an "adaptive pathways" approach to determine which flood risk management interventions are most appropriate and the deadline for completing them.
- The projections used consider the period to the end of the 22nd century due to the 100 year lifespan of any new infrastructure recommended for construction by 2070.
- Challenges involved with using sea level projections involve 3 broad themes: uncertainty; communication; and data application.

- In order to provide clear guidance on the timing of its interventions, the Plan requires continuous projections covering the relevant timescales.
- A challenge with more general use of climate projections is that required variables are not always available, e.g., information on future peak river flows.

The CCC needs for information on future sea-level rise - R. Millar

- The Climate Change Committee (CCC) carries out an independent assessment of UK climate risk every 5 years to inform National Adaptation Programmes (NAPs).
- The CCC needs information on current exposure to coastal flooding and erosion, and the possible climate futures, including long-term sea level rise commitment.
- CCRA3 highlighted numerous risks associated with sea-level rise that require more action or further investigation. These include: aquifers and agriculture land; coastal species and habitats; transport networks; viability of coastal communities; businesses and infrastructure.
- Future work and evidence needs:
    - A vision for a well-adapted UK coastline.
    - A more quantified progress monitoring framework for the deployment of coastal adaptation plans.
    - A better understanding of the role of policy in managed retreat and abandonment
    - Timescales: when might certain sea level rise levels be reached and how do these compare to infrastructure/asset lifetimes?

1.2 Discussion

The main topics discussed in the session 1 discussions were:

1. The need for information about the potential direct and indirect impacts of sea-level rise (e.g., potential damages)
2. Interpretation, communication, and application of high-end sea-level scenarios (e.g., UKCP09 H++)
3. The requirement for continuous sea-level projections beyond 2100, rather than values for a particular year (e.g., the AR6 sea-level projection values for 2150)
4. The importance of tide gauge measurement for monitoring the trajectory of UK sea-level rise

The terms used when communicating the science of sea-level rise and information from sea-level projections do not have salience with government stakeholders. Sea-level rise does not have salience with the public and government stakeholders, whereas impacts such as flooding and damages do have salience. Generally, the distinction between inland and coastal flooding does not matter to government stakeholders. The relevant metrics for governments would translate sea-level rise into potential damages. Given the global remit of the IPCC, this information would not be expected to come through in the summary for policymakers. Information on changes in recurrence periods due to sea-level rise would be more relevant to policy makers.

There were discussions about the formulation and use of “reasonable worst case” sea-level rise scenarios such as the H++ scenarios from UKCP09 and the “low-confidence” sea-level projections from IPCC AR6. In the UK the H++ scenarios are used by risk-averse stakeholders involved in critical infrastructure planning, are used by government stakeholders for adaptation strategy but are not used in the planning of specific adaptation projects. There was an acknowledgement that there had been progress in this area, with attention on H++ type scenarios in the most recent UKCCRA and IPCC reports. Stakeholders involved in adaptation and nuclear regulation also expressed a need for continuous sea-level projections beyond 2100 but the most recent IPCC projections stop at 2150.

Finally, there was agreement about the need to restore and enhance the UK sea-level monitoring capability. UK tide gauges no longer meet the accuracy standards required for climate research and monitoring by the Permanent Service for Mean Sea-level. The tide gauge observations are crucial for assessing if actual rates of sea-level rise are within the range of tolerance for different adaptation measures and adjusting plans if necessary. The ability to evaluate adaptation measures and make flexible adaptation decisions is dependent on the quality of the sea-level monitoring systems.

2. IPCC AR6 and projections of future ice loss

Session 2 began with a presentation on the latest assessment of future sea level rise from the recent Intergovernmental Panel on Climate Change Sixth Assessment Report of Working Group I (IPCC AR6). This was followed by three presentations on projections of sea level rise associated with ice mass loss from Greenland, Antarctica and mountain glaciers. These presentations were followed by a panel Q&A and plenary discussion.

2.1 Presentation Summaries

Assessment of sea level rise in IPCC AR6 – Helene Hewitt

- It is virtually certain that sea level will continue to rise throughout the 21st century and beyond – deep and rapid cuts in emissions are the route to minimise sea level rise (particularly risk of large loss from Antarctic ice sheet)
- Sea level rise at 3C by 2100 is 62cm (50-81cm) (*medium confidence*) BUT
    - extreme flooding events that happened once per century will occur annually in more locations at higher warming levels (60% versus 80%)
    - higher sea level rise, approaching 2m, by 2100 cannot be excluded due to ice sheet processes
    - 3C warming would have significant implications for sea level rise post 2100, reaching levels > 15 m by 2300 (*low confidence* due to uncertain ice sheet processes)
- Deep uncertainty is associated with ice sheet processes and this area should be a priority to reduce uncertainty in the projections beyond AR6

Projections of Greenland ice sheet – Sophie Nowicki

- The Greenland ice sheet will continue to lose mass throughout this century under all emissions scenarios (*virtually certain*)
- Surface melt has become the dominant mass loss component in the last decade
- The likely contribution of the Greenland ice sheet at 2100 ranges from 0.01-0.10 m under SSP1-2.6 up to 0.09-0.18 m under SSP5-8.5.
- One of the main challenges is assigning weightings to the "zoo" of ice sheet model projections. Reproducing the past successfully can give us an indication of the success into the future, but this is hindered by uncertainty in historical observations.

Projections of Antarctic ice sheet – Tamsin Edwards

- Continued ice loss over the 21st century is *likely* for the Antarctic ice sheet
- Wide range of model projections to 2100, differences explained by:
    - Basal melt sensitivity to ocean warming
    - Ice sheet response to basal melt sensitivity and/or ice shelf collapse (e.g. inclusion of Marine Ice Cliff Instability – MICI)
- Taking the *medium confidence* processes, the contribution from the Antarctic ice sheet at 2100 ranges from 0.03-0.27 m under SSP1-2.6 up to 0.03-0.34 m under SSP5-8.5.
- The high end (*low confidence*) is up to 0.56 m by 2100 under SSP5-8.5.
- By 2300, > 15 m cannot be ruled out under SSP5-8.5 considering MICI.

Projections of mountain glaciers – Ben Marzeion

- Glaciers are important contributors to sea-level rise now and will remain important throughout the 21st century.
- Independent of emissions, they will continue to lose mass throughout the century
- Contribution is projected at a constant rate of 1 mm yr^{-1} for RCP2.6, increasing to 2.5 mm yr-1 at 2100 for RCP8.5 before levelling off (due to decreased glacier area)
- Disagreement between glacier models is greatest source of uncertainty until mid of the 21st century whereas scenario uncertainty dominates at the end of the 21st century

2.2 Discussion

A leading question throughout the discussion centred on how to improve communication of sea-level change to stakeholders, including funders, ministers and non-scientists. Figure SPM.8 in the IPCC AR6 WG1 Summary for Policymakers depicts low-likelihood, high-impact storylines under SSP5-8.5 for sea-level change to 2100 (2m) and at 2300 (>15m), relative to 1900. Timescales are causing difficulty in communicating sea-level changes. On one hand, past emissions have caused committed sea-level changes, such as glacier mass loss (GLACIERMIP2), and it is important to stress 'when' (not 'if') we will reach committed changes. However, emissions pathways do make a difference in the quantity of sea-level change, especially beyond 2100, and inspiring hope is key to driving down emissions. Highlighting our current trajectory path and mid-range (instead of focussing on high or low end) pathways could help put context to the projections. Whilst it was agreed long-term risk is well communicated in AR6, and that some user groups do look beyond 2300 (e.g. nuclear facility planners), ministers' and funders' interests tend to focus on nearer-term issues, such as fluvial flooding and storms. Using narratives and storylines, and framing in terms of 'warming levels' or other metrics of stakeholder interest, could help convey the importance of long-term risks. Upcoming IPCC working group reports will shed light on human impacts.

Discussions also looked at how to assess epistemic uncertainty in climate models and addressing 'the unknown unknowns'. From a palaeo-perspective, there have been processes (e.g. MWP-1a), which we have tracked in the geological record but are difficult to encode and explain. Structured expert judgement, which contributes to low confidence sea-level projections in AR6 have been used to capture what models cannot predict - allowing us to consider the 'space above projections'. Concerns remain on how confident experts can be on their judgement at the time, including personal biases, and whether past unknowns are relevant for the future.

There were calls for further consideration of the Greenland ice sheet, in addition to Antarctica, in terms of potential for accelerated future sea level rise and to reflect this in communication of uncertainties. There was some discussion around the representation of debris-covered glaciers in models, and how sensitive models might be to these features. A final point raised was that IPCC AR6 only provides continuous sea level projections to 2150, while there seems to be a need for continuous projections beyond this time-horizon for some stakeholders (e.g. Thames Estuary 2100 project).

3. Regional processes and palaeo perspectives

Session 3 of the workshop focused on regional processes of sea level change, including the solid-Earth response to the last deglaciation (glacial isostatic adjustment, GIA), ocean processes and their representation in models and the value of paleoclimate evidence for sea level projections. Four presentations on the various science aspects were followed by a panel Q&A and plenary discussion.

3.1 Presentation Summaries

Estimating relative sea-level change from glacial isostatic adjustment (GIA) - Pippa Whitehouse

- Key uncertainties:
  - Coastal land deformation due to GIA is modelled or interpolated from data
  - Changes in mean sea surface height depend on future cryospheric change
- Northern hemisphere ice loss is predicted to have a negligible impact on SLC around the British Isles, Antarctic ice loss will have a significant impact
- How to address current uncertainties:
  - Use modelling and observations to better understand (time-evolving) land deformation
  - Better predictions of cryospheric changes
  - Research into the impact of spatial variations in Earth rheology
  - Research into the ability of GIA to delay grounding line retreat in W-Antarctica

Ocean dynamical downscaling for sea-level change - Tim Hermans

- Global climate models (GCMs) have limited capability in shelf sea and coastal areas due to limited horizontal/vertical resolution and lack of tides.
- Ocean dynamical downscaling uses a higher resolution regional ocean model to improve the representation of costaline, bathymetry, currents and tidal processes.
- Downscaled simulations show better agreement with observations and can overcome limitations that lead to potential biases in GCM projections, such as associated with a closed English Channel for sea level changes on the European Shelf Seas.
- Dynamical downscaling can lead to substantial differences in the patterns and magnitude of sea level change compared to the parent GCM, especially for lower resolution GCMs that have crude representation of the coastline.
- So far only limited GCMs have been used for dynamical downscaling - partly an issue of modelling centres not providing the high-frequency data needed to drive the regional ocean model.

Patterns of warming and sea level rise - Laura Zanna

- Patterns of heat storage (and thermosteric sea level)
  - Historical Period: observed trends dominated by re-distribution; mixed results in CMIP-models.
  - Future trends: dominated by passive heat uptake (at least in coarse-resolution models)
- Uncertainty in projections
  - North Atlantic: redistribution plays a large role in inter-model spread
  - North Pacific: similar patterns but different mechanisms in projections
  - Southern Ocean: passive but mixing processes contribute to the spread in projections
- What’s next?
  - Effect of resolution vs parameterizations on patterns + spread
  - Relating interior changes to changes at the coast

Palaeo perspectives and high end scenarios - Natasha Barlow

- 3 key uncertainties:
  - Modelling ice sheet extent -> MICI (Marine Ice Cliff Instability); past ranges influence modelling of instabilities
  - Dynamic topography
  - GIA correction in previous warm periods
- What can palaeo tell us about future sea level?
  - Illustrates the lag of sea-level rise behind temperature forcing -> commitment
  - Long-term sea level commitment, of use for certain end users (e.g. nuclear)
- Takeaway:
  - Palaeo provides important model calibration
  - Uncertainty ranges need to be reduced
  - Palaeo can help contextualise high-end SL scenarios

3.2 Discussion

Glacial Isostatic Adjustment (GIA). Decay of GIA-related land uplift/subsidence rates will be minimal over the next 100 years. In the longer term we need to understand the processes driving changes to the rate and pattern of GIA-related land deformation around the UK. Steps forward in our ability to quantify spatial variations in the relaxation time of the solid Earth have the potential to slightly alter GIA predictions over a 100-yr timescale. GPS GNSS, i.e. direct observations of vertical land motion, not only helps us understand the rates of GIA but also think about other processes that we might not be accounting for in GIA models.

Dynamical downscaling. Selecting the most appropriate models from the ensemble is encouraged prior to analysis, for example by excluding models that perform poorly in certain areas or selecting those expanding the full range of boundary conditions to reduce the computational burden in regional downscaling. Biases in regional models should be mainly driven by the "parent" GCM that provides the lateral boundary conditions. Assumptions in dynamical downscaling exercises include: (i) regional ocean models resolve the ocean signals transmitted from the deep ocean onto the shelf; and (ii) the large-scale flow field is not altered. These could be tested with sensitivity studies.

H++ (high end scenario). It has always been specified as a range but the new Government guidance has narrowed it down to a single number. Storylines are good from a communication perspective. However, the difficulty with some of the storylines is that there is potentially an infinite number of them. Although we can't draw a complete distribution, there are some things we can say as part of the H++ narrative on the likelihood. This allows decision makers to start considering what that means in the decision process. There was some discussion on whether it is necessary to provide "ball-park" likelihood information for high-end scenarios (e.g. 1 in 100, 1 in 10,000,000?).

4. Integration of modelling and sea level information

Session 4 of the workshop was focussed on integration of sea level modelling in the UKESM, and integration of sea level projections/information to inform coastal decision making. There was a presentation on each of these topics followed by a dedicated plenary discussion. Finally, there was a breakout group activity to identify research gaps and stakeholder needs.

4.1 Presentation Summaries

Sea level in the UK Earth System Model: representation of projections and processes - Robin Smith

- The UK Earth System Model (UKESM) represents the UK contribution to CMIP and is a collaboration between the Met Office and NERC research community.
- UKESM is characterised by a high climate sensitivity, which has implications for thermal expansion, ice melt and increased snowfall in some regions.
- Interactive Greenland and Antarctic ice sheets are now available in model configurations of UKESM and is the only model that currently has two-way coupling to the Antarctic ice sheet, and includes representation of ice shelf cavities.
- Changes in climate in response to Greenland ice sheet changes are minimal over the 21st century but become important on longer timescales.
- While progress has been made in modelling Antarctica, important biases and limitations in the simulations remain, which mean that the model is best used for process studies rather than providing projections.
- A number of developments are "in the pipeline", including: collapse of Antarctic ice shelves; higher resolution regional configurations to inform improved parameterisations in the global model; and representation of glacier mass balance using Hydro-JULES.

Sea-level information for decision making - Gonéri Le Cozannet

- Sea-level rise will reshape coastlines for decades and centuries
    - Mitigation of climate change has been urgent for 30 years
- Sea-level rise adaptation is becoming urgent too: e.g. high-tide chronic flooding
    - Planning and implementing adaptation takes decades
    - Exposure and vulnerability generally continue to increase
- As users adapt to sea-level rise impacts committed for 2030-2050, they also need to anticipate the next steps
    - Provide information on the timing of impacts and adaptation; feasibility and effectiveness; residual risks
- Rather than uniform guidelines at national scale, scenarios targeted to the practitioner's profile can be delivered

4.2 Discussion

4.2.1 Sea level in the UK Earth System model

Uncertainty in the SLR contribution from the Antarctic ice sheet. At this stage, ESMs may be more useful for process understanding than for projections with meaningful uncertainty bounds.

Fidelity of models and climate forcing over/around ice sheets. Small ice shelves have a large effect on ice mass balance - BISICLES benefits from an adaptive mesh. Higher-resolution ocean models necessitate shorter simulations. Synoptic atmosphere events are important for surface mass balance but are not represented well.

Model evaluation (some discussion/debate). How useful is an ESM for looking at one component if another component is not represented well? It's important to study the interactions between components. But in practice, we are likely to struggle to find models that are good everywhere.

Weighting models based on emergent constraints (some discussion/debate). Emulators allow a fuller and more objective sampling of parameter space. The choice of constraint may be important. It can be useful to look in a global warming thresholds sense (rather than year in simulation) to even out effects of climate sensitivity between models.

Future model enhancements. In some locations the GIA time scale is decades - this could be included. It would be interesting (though a long way off) to include sediment dynamics, as this will change regional mean sea level patterns.

4.2.2 Sea level information for decision making

Time scales for adaptation measures (consensus). The time needed to invest in adaptations is very long, and adaptation measures may need to be applied in sequence, so we have to think about the next 100+ years.

Attribution of extreme sea level events and damages (some discussion/debate). Emergence of climate signal; establish responsibility (some participants expressed concern at the use of attribution for redress); provides a message to support adaptation investment (particularly for developing countries). Impact can be measured in financial currency (costs of adaptation vs damage). Attribution can be difficult for coastal systems (hard to disentangle non-climate processes).

Adaptation by small island states. A priority for many islands is the impacts of climate change on marine ecosystems because this has a direct and immediate impact on the economy (tourism, fisheries). SLR is often more perceived as a threat for the far future (e.g., beyond 2050). There is often a lack of precise understanding of sea level projections and confidence levels.

The coast is always changing. Need to be able to manage climate variability. Allowing the coastline to change may be difficult for megacities, but in some places, managed retreat may be preferable to costs of protection. Some areas with sufficient sediment supply could gain sediment, despite sea level rise.

Real-time observations. Tide gauges record extreme water levels, including tsunamis. Radar stations report on approaching storms for use in preparing for flooding and reservoir operations.

4.3 Research Gaps and Stakeholder Needs

The workshop participants were split into 3 breakout groups for a discussion session that made use of "jam boards", i.e., virtual noteboards where ideas/comments can be gathered in real time using virtual sticky notes. A summary of these sessions is presented below organised by some of the general topics that emerged from participant responses. The jamboards discussion focused on the question: *Where are the research gaps and what are the stakeholder needs?*

Figure 1: A "word cloud" generated using the jam board text submitted as part of the breakout discussions.

Attribution

- There is a clear need to understand the current drivers of sea level change, both globally and locally. For example, many locations around the world are subject to substantial tectonic activity or other vertical land motion influences.
- More work is needed on the attribution of observed changes to external forcings or internal variability - for example some of the large changes we have seen in the ice sheet contributions.
- There is a need to improve our understanding of what drives uncertainty in future projections of local sea level rise particularly for century timescales (workshop presentations showed that these can be location, timescale and scenario dependent).

Communication

- One of the key themes was the need for more discussion between scientists and stakeholders. This includes an appreciation of the range of different stakeholders and co-development of information to inform decision-making
- There is a more general challenge in making sea-level rise information to a range of stakeholders, including politicians and the general public. This could include more explicit links between modest increases in sea level leading to potentially large changes in recurrence of extremes and the utility of example extreme coastal flood events to demonstrate the future challenges we may face.
- Specifically for policy makers, there is a clear requirement to convert the units of mm / m into $ / £ / Euros and other units of "social currency" that are more readily understood. Overall, there was a sense that the societal importance of current and future sea level rise is not widely appreciated.
- The need for science workshops such as this one - that spans the various scientific disciplines that are relevant to providing sea level information on a range of timescales - to foster improvements in the information available to decision makers.

Extremes

- While the focus of the workshop was on mean sea level change, there is a need to include projections of extreme sea level events, which can occur from a number of drivers and their coincidences / interactions.
- More research is needed into compound events - e.g. combined high rainfall, river flow, high tide, storm surge and waves.
- The issue of non-stationarity in extreme sea level events should be considered, as well as projections of changes in sea level variability (e.g. seasonal cycle) and the potential for changes in tidal characteristics and mean sea level increases.

Impacts/Risks

- Coastal adaptation planning requires consideration of exposure and vulnerability as well as the environmental hazard.
- The international landscape is an important consideration, e.g., developing nations with large low-lying areas could see mass migration under future sea level rise, potentially leading to conflict and global implications.
- Impacts studies should consider multiple impact drivers, e.g. heatwaves, heavy rainfall, that may provide additional challenges to coastal adaptation. The impacts of adaptation options on the local environment / ecosystems should also be considered.

High End Scenarios

- Following the IPCC AR6 WG1 report, there is a need to update the UKCP09 H++ scenario for a range of timescales. This work could include "cascade risks" such as marine ice sheet instability leading to AMOC shutdown, for example.
- A range of high end scenarios suitable for stakeholders with different risk tolerances and timescales of interest is needed, along with guidance on how these can be used for risk assessment and adaptation planning.
- More research is needed specifically on ice sheet processes, including field observations and process/model studies. These aspects remain the primary concern for high end scenarios on century-and-longer timescales.

Modelling

- More evaluation needed of the suitability of global climate models to inform local sea level projections and limitations in their representation of key processes.
- Knowledge of 3D rheology is needed to improve our understanding of Earth-ice dynamic feedbacks (particularly important for future ice sheet changes).
- Research is needed to better understand the response of natural coastal systems under sea level rise (e.g. geomorphology, sediment transport etc).
- Model simulations of ice sheets beyond 2100 is a key gap in the literature, as are simulations that consider what happens if we were to return to pre-industrial levels of GHGs.

Observations / Palaeo Evidence

- There is a need to invest in suitable observations to monitor change signals and use them to develop improved models of the Earth system. One key aspect of this is the maintenance of "climate quality" tide gauge observations that include co-located vertical land motion measurements (e.g. GNSS).
- It is important to monitor sea level, including its component contributions, both globally and locally in order to track the real world trajectory in the context of state-of-the-art projections and inform adaptive planning approaches (e.g. TE2100 project).
- More work is needed to refine sea level information from palaeo records in order to calibrate model simulations on a range of timescales (not just interglacials)

Emissions Scenarios

- The rationale behind a choice of scenario could be discussed more explicitly. For example, RCP8.5 is seen as much less likely than RCP4.5 due to emissions reduction pledges as part of the Paris Agreement.
- Perhaps dialogues on future sea level rise could more usefully start with discussing the more likely emissions pathways (e.g. RCP4.5, RCP6.0).
- Low End Scenarios may be a useful approach to inform minimum adaptation requirements.

Timescales

- There is a need for projections on multi-century-to-millennia timescales for stakeholders that deal with very long asset lifetimes (e.g. Nuclear energy sector) or those studying coastal erosion. These timescales are also needed to inform the sea level rise commitment associated with temperature stabilisation targets.
- Some stakeholders require continuous local sea level projections well-beyond 2100. IPCC AR6 only provided this information to 2150.
- Only a limited number of CMIP climate model simulations are available beyond 2100. It would be very useful if more centres could provide simulations to 2300 or longer.

APPENDIX 1. Workshop Programme

DAY 1: MONDAY 20TH SEPTEMBER		
	SESSION 1	Chair: Matt Palmer
09:30-09:35	Welcome: Albert Klein-Tank (Director of the Met Office Hadley Centre)	
09:35-09:40	Workshop overview: Matt Palmer	
09:40-10:00	Introduction to sea level projection science: Jonathan Gregory	
10:00-10:15	Stakeholder #1: A BEIS perspective – James Davey	
10:15-10:30	Stakeholder #2: An Env. Agency perspective – Anna Robotham / Andy Beverton	
10:30-10:45	Stakeholder #3: A Committee on Climate Change perspective – Richard Millar	
10:45-11:10	B R E A K	
11:10-11:55	Questions + Panel Discussion	Rapporteur: Ben Harrison
11:55-12:00	SESSION 1 closing remarks: Matt Palmer	
12:00-14:00	L U N C H	
	SESSION 2	Chair: Anne Le Brocq
14:00-14:15	Science #1: Assessment of sea level rise in IPCC AR6 – Helene Hewitt	
14:15-14:30	Science #2: Projections of Greenland ice sheet – Sophie Nowicki	
14:30-14:45	Science #3: Projections of Antarctic ice sheet – Tamsin Edwards	
14:45-15:00	Science #4: Projections of mountain glaciers – Ben Marzeion	
15:00-15:25	B R E A K	
15:25-16:10	Questions + Panel Discussion	Rapporteur: Jenny Weeks
16:10-16:15	Session 2 closing remarks: Anne Le Brocq	
16:15	**CLOSE OF DAY 1**	

DAY 2: TUESDAY 21ST SEPTEMBER		
	SESSION 3	Chair: Liz Bradshaw
10:00-10:15	Science #5: Glacial isostatic adjustment – Pippa Whitehouse	
10:15-10:30	Science #6: Sea level change associated with ocean processes – Laure Zanna	
10:30-10:45	Science #7: Ocean dynamical downscaling – Tim Hermans	
10:45-11:00	Science #8: Palaeo perspectives and high-end scenarios – Natasha Barlow	
11:00-11:25	B R E A K	
11:25-12:10	Questions + Panel Discussion	Rapporteur: Victor Malagon Santos
12:10-12:15	Session 3 closing remarks: Liz Bradshaw	
12:15-14:00	L U N C H	
	SESSION 4	Chair: Jason Lowe
14:00-14:20	Integration #1: Sea level in the UK Earth System model – Robin Smith	
14:20-14:30	Questions + Discussion	Rapporteur: Lesley Allison
14:30-14:50	Integration #2: Sea level information for decision making – Gonéri Le Cozannet	
14:50-15:00	Questions + Discussion	Rapporteur: Lesley Allison
15:00-15:25	B R E A K	
15:25-16:00	Jamboard session (all participants): Sea level research priorities for science and stakeholders	Facilitator: Jenny Weeks
16:00-16:05	Session 4 closing remarks: Jason Lowe	
16:05-16:10	Workshop closing remarks: Matt Palmer	
16:10	**CLOSE OF WORKSHOP**	

APPENDIX 2. Workshop Participants

Organising Committee

Matt Palmer	Met Office / University of Bristol
Rory Bingham	University of Bristol
Liz Bradshaw	British Oceanographic Data Centre
Anne Le Brocq	University of Exeter
Aimée Slangen	Royal Netherlands Institute for Sea Research (NIOZ)

Speakers - Session 1

Jonathan Gregory	University of Reading
James Davey	Dept for Business, Energy & Industrial Strategy
Richard Millar	Committee on Climate Change
Anna Robotham	Environment Agency
Andy Beverton	Environment Agency

Speakers - Session 2

Helene Hewitt	Met Office
Sophie Nowicki	State University of New York at Buffalo
Tamsin Edwards	King's College London
Ben Marzeion	University of Bremen

Speakers - Session 3

Pippa Whitehouse	University of Durham
Laure Zanna	New York University
Tim Hermans	Royal Netherlands Institute for Sea Research (NIOZ)
Natasha Barlow	University of Leeds

Speakers - Session 4

Robin Smith	University of Reading
Goneri Le Cozannet	French Geological Survey (BRGM)
Jason Lowe	Met Office / University of Leeds

Participants

Lesley Allison	Met Office
Robert Arthern	British Antarctic Survey
Jonathan Bamber	University of Bristol
Robert Barnett	University of Exeter
David Behar	San Francisco Public Utilities Commission
James Brand	Environment Agency
Sally Brown	University of Bournemouth
Peter Clarke	Newcastle University
Simon Engelhart	University of Durham
Ed Garrett	University of York
Mattias Green	Bangor University
Ivan Haigh	University of Southampton
Ben Harrison	Met Office
Stephan Harrison	University of Exeter
Angela Hibbert	National Oceanography Centre
Fiona Hibbert	University of York
Chris Hughes	University of Liverpool
Luke Jackson	University of Durham
Svetlana Jevrejeva	National Oceanography Centre
Rob Larter	British Antarctic Survey
Kirsty Lewis	Foreign, Commonwealth & Development Office
Victor Malagon Santos	Royal Netherlands Institute for Sea Research (NIOZ)
Robert Nicholls	University of East Anglia
Tony Payne	University of Bristol
Samantha Royston	University of Bristol
Fiona Turner	King's College London
Jenny Weeks	Met Office
Chris Wilson	National Oceanography Centre
Sarah Woodroffe	University of Durham

Appendix 3. The UK Tide Gauge Network: Current Status and Societal Needs

E. Bradshaw, I.D Haigh, S. Jevrejeva, M. Palmer, R. Nicholls and P. Whitehouse

1. Executive Summary

Tide gauge observations around the UK are critical to our understanding of contemporary and future coastal flood hazard, and the associated climate impacts. Currently, fewer than 30% of the UK tide gauge network sites provide measurements suitable for climate applications. There is an urgent need to restore and advance UK tide gauge observing capability, in-line with internationally agreed standards, to reflect both current and future societal needs.

The UK tide gauge network is currently funded and maintained by the Environment Agency, on behalf of the UK Coastal Flood Forecasting service (a partnership between the Environment Agency, Natural Resources Wales, the Scottish Environment Protection Agency and Northern Ireland Department for Infrastructure - Rivers), primarily to support flood forecasting activities. However, these observations are critical to a much wider set of operational and research activities that are fundamental to the development of weather and climate services on a range of timescales. Moving forward, there is an urgent need for a sustained UK tide gauge network that supports societal needs in a changing climate, and informs robust coastal decision making and adaptation planning.

2. Current Status of the UK Tide Gauge Network

Sea level observations in the UK from tide gauges started over 250 years ago, with the earliest recorded data available from the port of Liverpool. Coordinated national observations began when the UK National Tide Gauge Network was established, as a result of severe flooding in 1953 along the east coast of England. This provided a world-class dataset on sea levels around the UK including supporting flood warnings, analysis of the characteristics of major flood events (e.g., Haigh et al., 2016), and understanding sea-level rise and extreme sea level statistics.

Over the last decade there has been a significant decline in the quality of sea level data measured by the UK National Tide Gauge Network. The network is currently made up of 42 tide gauges around the coastline of Great Britain and Northern Ireland. However, the gauge installations are ageing and many sites are now operating long beyond their design lifespans. With budget cuts, there has been a decrease in site visits and maintenance. In particular, the regular leveling checks that are vital to ensure gauges record sea level to millimeter accuracy has not been undertaken with sufficient frequency. Sites are currently only being operated at the 0.1 m accuracy required for flooding forecasting, but not at the accuracy required for assessing long term changes in sea level. Less than 30% of the 42 government-operated UK Tide Gauge Network sites are now suitable for climate-related studies. Between 1990 and 2010, less than 10% of data was missing or of suspect quality across the network. However, after 2010 around 35% of data was missing or of suspect quality (Figure 1).

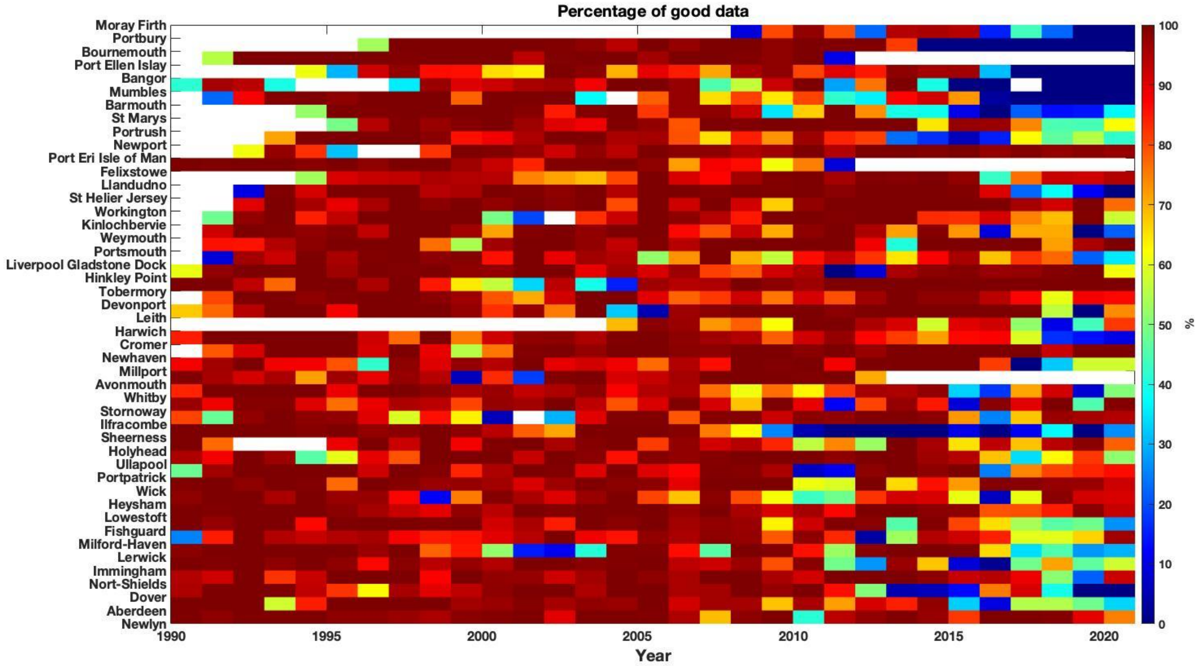

Figure 1: A visual summary of the % of good data available from tide gauge sites around the UK coastline during the period 1990 to 2020.

3. What are the Societal Needs?

Coastal flooding is a major issue for the UK with a long history of coastal floods such as 1607 in the Bristol Channel, 1953 along the East Coast, and the 2013/14 stormy season (www.surgewatch.org). Today, 520,000 properties in England are at risk of damage from coastal flooding. Coastal communities, infrastructure and landscapes are facing future threats due to sea level rise, changes in storm surges and waves in a warming climate. By 2100, up to 1,600 km of major roads, 650km of railway line with 92 railway stations are at risk of coastal flooding (CCC, 2018; Environment Agency, 2018). When compared with our European neighbours, the UK stands out as one of the most threatened countries to coastal flooding (Vousdoukas et al., 2020).

Information on extreme coastal water levels from tide gauge observations are essential to practitioners in a host of socially-relevant planning and decision making activities, including (Environment Agency, 2018):

• flood risk mapping
• flood risk assessments
• spatial planning
• coastal flood defence design
• flood warning
• port operations
• infrastructure decisions
• coastal erosion management
• climate change assessments
• informing emergency planning

4. What are the research needs?

Tide gauge observations have enormous value in a much wider set of societally-relevant research activities, for example:

- Evaluation and development of ocean and climate models
- Advancing our understanding of coastal sea level variability and extremes
- Development of sea level forecasts on a range of timescales (e.g. seasonal-to-decadal)
- Climate monitoring, including mean sea level and changes in tidal characteristics
- Advancing our understanding of the drivers of global and local sea level change
- To provide observational context to projections of future sea level changes
- Improving the accuracy of satellite-based sea level observations through calibration

In addition, the UK has international commitments to the Global Sea Level Observing System (GLOSS, gloss-sealevel.org) with several UK tide gauge sites part of the Core Network (Lerwick, Newlyn and Stornoway) and Long Term Trends network (Aberdeen, North Shields and Sheerness). These were selected based on the basis of geographic representivity and record length. Data rescue activities have extended the record at Liverpool, which is now the longest record in the UK. The National Oceanography Centre is currently upgrading the sites at Liverpool, Newlyn and Sheerness in-line with internationally agreed scientific standards.

Acknowledgments: This perspective document arose from discussions during the virtual workshop "The science of global and UK sea-level projections: progress, challenges and future directions" held on 20th and 21st of September 2021.

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