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Expert judgements of sea-level rise at the local scale

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Whilst local projections of sea-level rise are necessary to facilitate targeted climate change adaptation and communication strategies, downscaling from global climate models can be problematic. Here, we use expert probability judgement to elicit a suite of local projections, and associated uncertainties, for future sea-level rise on the Severn Estuary in the southwest of the UK. Eleven experts from a range of policy and academic backgrounds took part in a structured probability elicitation exercise for the years 2050, 2100 and 2200. In addition to the quantitative elicitation, the experts' reasoning during the task was qualitatively analysed. Quantitative analyses show that although there is consensus that sea levels will rise on the Estuary in future, there is wide variation between judgements and much uncertainty regarding the magnitude of future rise. For example, median estimates of sea-level rise (compared to the 2011 level) range from 9.6cm to 40cm in the year 2050; 20cm to 100cm in 2100; and 35cm to 300cm in 2200. Fifty percent confidence intervals and ninety percent confidence intervals vary even more. Qualitative analyses indicate that experts' judgements may have been influenced by their choice of methods and information sources, the ways in which they thought about the future, and heuristics. The study shows the merits of integrating qualitative and quantitative methods to explore the reasoning behind uncertainty judgements. We conclude that where expert probability judgements are to be used to characterise uncertainty such reasoning should be made explicit.

Keywords: uncertainty; sea-level rise; expert judgement; probability

Introduction

The provision of information about local sea-level rise (SLR) is a key research priority for the climate change planning and adaptation community (MCCIP 2014). However, while projections of mean future global SLR are numerous (e.g. IPCC 2007a, Nicholls, Marinova, et al. 2011), local projections can be problematic due to spatial variability and difficulties with downscaling. This paper therefore reports findings of an expert judgement study for local SLR, presenting estimates for the Severn Estuary in the southwest of the UK (Figure 1).

The Severn Estuary is a unique environment. It has the second largest tidal range in the world, with an average mean spring tidal range of 12.3m (Langston, Jonas, and Millward 2010), and it drains the UK's longest river. It is of high ecological significance (Severn Estuary Coastal Group and ATKINS 2010), and is a designated Special Protection Area, Special Area of Conservation and Ramsar site. There is a mixture of urban and rural land uses around the Estuary, and its shores are home to around one million people (Severn Estuary Partnership 2011). It is also the location for major infrastructures, and may in future become a key source of renewable energy (House of Commons 2013, Tidal Lagoon Cardiff 2015).

[Figure 1 here]

Sea-level measurements from tide gauges, satellites and proxy data show that global mean sea level rose during the 20th century and is continuing to do so (IPCC 2007b, Gehrels et al. 2007, IPCC 2013a). As the world continues to warm with climate change, mean global SLR is inevitable (Nicholls, Hanson, et al. 2011) through thermal expansion (changes in water volume due to temperature change) and glacio-eustacy (changes in water volume due to additions from melting land-ice). Indeed, records show

that the mean sea level on the Severn Estuary is gradually rising (Phillips and Crisp 2010), and has been throughout the current interglacial period (Environment Agency 2006).

Future SLR on the Estuary is expected to cause increased flooding and erosion risks, leading to various social, economic and physical impacts. The scale of such impacts will depend on the rate and magnitude of this SLR, which will be forced by both global and local factors acting over short and long timescales. Many of these factors are uncertain, and although sea levels are expected to continue to rise in future (e.g. Phillips and Crisp 2010, UK Climate Projections 2012), the amount of rise is unknown.

Despite these uncertainties, policy decisions will still need to be made in order to plan adaptation measures; and without assessments of the scale, magnitude and likelihood of future events, policy makers will make their own assumptions about the probability of different outcomes (Mastrandrea and Schneider 2004). An aim of the present study was to address this issue using established elicitation methods to provide local probability assessments for SLR, and compare them with projections in the literature. We also provide long timescale projections, and explicitly represent the uncertainty implicit in experts' projections, in order that such uncertainty can be acknowledged in decision making. Finally, we carry out an exploratory thematic analysis of interview transcripts to identify factors that may influence how experts make their judgements of SLR.

We begin by augmenting these aims and considering how expert probability judgements can address them. We then present the methodology used to elicit these judgements, before discussing the quantitative and qualitative results and their implications.

Study aims

The first aim of this study was to provide local probability estimates of SLR on the Severn Estuary, which will be of potential interest to researchers, the public, adaptation planners and policy makers. The UK Climate Projections¹ provide such estimates for locations on the Severn Estuary, and other projections are also available (e.g. Phillips and Crisp 2010, Severn Estuary Coastal Group and ATKINS 2010). We were interested in how experts would utilise these projections and how their own projections would compare. As such, our analysis reveals the range of expert estimates that may be omitted from aggregate, official estimates.

Our second aim was to provide long timescale projections. With one notable exception (Titus and Narayanan 1996), few authors have considered SLR projections further into the future than 2100, beyond which the magnitude of climate change and the resulting impacts are likely to be very large (Houghton 2009). This is important because management decisions made now have consequences beyond 2100 (Lenton et al. 2006). Coastal developments and infrastructures that are built today can be expected to endure through the 22nd Century, and some marine renewable energy projects proposed for the Estuary, such as a Severn Barrage tidal scheme, would be expected to have a lifespan of 120 years or more (DECC 2010, House of Commons 2013). The importance of long timescale projections is now being increasingly recognised (Lenton et al. 2006, Winkelmann et al. 2012), including in the latest reports by the Intergovernmental Panel on Climate Change (IPCC 2013a). In order to explore the feasibility of eliciting subjective probabilities for such long timescales (a methodological question relevant to both SLR and climate change projection more

¹ The UKCP09 projections are a suite of climate projections for the UK, providing climate information for those planning climate change adaptation (UK Climate Projections 2012).

generally) we therefore elicited estimates for 2200 as well as for the more usual time horizons of 2050 and 2100, with which climate experts are familiar.

The third aim was to explicitly represent uncertainty. The literature does not always represent the nuances and wide range of opinions held by experts, and local climate change impact studies particularly lack comprehensive appraisals of uncertainty (Dessai and Hulme 2004). Research shows that experts can hold vastly different views about the same topic (Nordhaus 1994, Vaughan and Spouge 2002, Zickfeld et al. 2010, Zickfeld et al. 2007, Arnell, Tompkins, and Adger 2005), but such diversity is not always represented in consensus reviews such as IPCC reports, where much of the focus lies in central tendencies (Kunreuther et al. 2013). The elicitation of probability distributions discourages such simplification and allows for questions like ‘what physically could not happen?’ or ‘what is the worst that could happen?’ (as per Hulme, Pielke, and Dessai 2009, 127).

Our final aim was to explore how SLR projections may be influenced by heuristics (cognitive aids or mental shortcuts). The effects of heuristics on probability judgements have been well documented (e.g. Kahneman, Slovic, and Tversky 1982), and research has explored how cognitive processes affect experts’ judgements about other risks (e.g. Donovan, Oppenheimer, and Bravo 2012), but none have addressed such themes in relation to quantitative projections of SLR. Thus, the expert interviews have also been analysed qualitatively in order to explore the reasoning behind judgements. Our mixed-methods approach is a particular strength of the present study and acknowledges the value of one-to-one discussion as part of elicitation processes (Spetzler and Stael Von Holstein 1975), as well as the need to understand factors that may contribute to divergent expert judgements (Sjöberg 1999).

Expert probability judgement

Arnell, Tompkins, and Adger (2005) discuss three ways of estimating the likely occurrence of future events: looking at past records, using computer models to simulate future conditions, and using expert judgement. They remind us that the first method assumes that the events in question have occurred in the past, and that the conditions were the same then as they will be in future; and that the second method relies upon the underlying assumptions of the models. Indeed, both of these methods to some extent require the judgements of experts, either explicitly or implicitly (Fischhoff et al. 1981, Pidgeon et al. 1992). The third method uses these expert judgements directly, and is the one employed here.

Probability elicitation techniques aim to 'draw out' personal judgements of likelihood and systematically quantify perceptions of uncertainty. Such methods have been used to provide estimates of uncertain outcomes in many fields, from estimating engine sales and crop yields to making clinical diagnoses (O'Hagan et al. 2006). In the climate change arena they have been used to estimate the likelihood of rapid climate change (Arnell, Tompkins, and Adger 2005), tipping points in the climate system (Lenton et al. 2008), and uncertainties in future polar bear populations (O'Neill et al. 2008), amongst others. While expert judgement is not a substitute for further empirical study, it can provide valuable insights for decision makers while research is ongoing. Directly eliciting experts' most up-to-date knowledge and views also avoids consulting literature that may not be comprehensive, locally relevant, or fully endorsed by the scientific community.

Elicitation methods vary in their means of engaging experts and in their focus on achieving consensus or plurality. One way of engaging experts with the task is to conduct individual face-to-face interviews (e.g. Zickfeld et al. 2010). Although resource-intensive, this method benefits from the rapport built between interviewer and

interviewee, which allows participants to discuss the meaning of questions (Watson and Buede 1987), and raise new concepts or concerns. This is especially useful when eliciting judgements for complex risks like SLR.

Another way of engaging experts requires them to convene as a group. The Nominal Group Technique (NGT) is one such approach, which facilitates the 'structured sharing of ideas' before a group decision is reached by pooling votes from each participant (Delbecq, Ven, and Gustafson 1975, 8). While this method benefits from direct discussion and debate, judgements can be biased towards the most reputed or respected members of the group. The process also relies on all of the participants being available in the same place at the same time, which is often unfeasible.

The Delphi method circumvents this problem by engaging a group of experts remotely, while still facilitating interaction through written exchanges. The method was initially developed by the RAND Corporation in the 1950s to obtain consensus opinions for military purposes (Dalkey and Helmer 1963), but proved highly popular and has since been utilised in fields as varied as healthcare and real estate (Gupta and Clarke 1996). There are many methodological variations (Linstone and Turoff 2002), but the protocol generally involves a number of iterations whereby: i) experts are asked for their opinions; ii) these opinions are summarised and shown to the experts again to allow for revisions of their earlier answers; iii) the process is repeated, usually leading to a convergence towards a 'consensus' answer (though see Turoff 2002).

The RAND Appropriateness Method extends the Delphi method to incorporate panel discussions, which, like the NGT, provide participants the opportunity to discuss the problem and reflect on other experts' views. The procedure begins with a literature review and a synthesis of the evidence, and is followed by a two-round 'modified

Delphi' process consisting of an individual survey and a panel group meeting (Fitch et al. 2001).

Once an engagement approach has been chosen, there are a number of ways to elicit and encode judgements. To aid the conceptualisation of probabilities, judgements can be elicited indirectly, whereby choices are made between bets (Savage 1972). However, while this method is more intuitive for participants unfamiliar with the notion of probability, it carries the risk that gambling behaviour will affect judgements (see Morgan and Henrion 1990 for a discussion). Where experts are familiar with probability, they can be asked to directly state numerical probabilities (for example as fractions, decimals or percentages). Judgements can be encoded as single point estimates, confidence intervals or continuous distributions.

Once judgements have been elicited, it may be desirable to combine results from all or some of the experts to provide one refined judgement (e.g. Titus and Narayanan 1996, Vaughan and Spouge 2002, Bamber and Aspinall 2013). A single probability distribution can be more useful for decision makers than a number of separate ones, and it has long been argued that combining judgements can lead to aggregate assessments that are 'better' than any individual's (Galton 1907). There are a number of ways of combining experts' opinions. Some are based on Bayes' theorem and require the decision maker to provide a prior probability, while others are based on psychological scaling methods that allow more qualitative assessments via pairwise comparisons (see Cooke 1991, for a review). Another class of methodologies weights the contributions of experts according to factors such as a given preference, the expert's own self-reported expertise, or their demonstrated abilities in quantifying uncertainty. The Classical Method (Cooke 1991) is a popular approach, whereby weights are based on the expert's ability to estimate quantities of known 'seed variables' from their own field.

The choice of methodology for engaging experts and eliciting their judgements is dependent upon the aims and constraints of the research. On account of the elicitations reported in this study forming part of lengthier one-to-one interviews about various aspects of SLR, a face-to-face approach was most appropriate. Due to our intention to explore plurality rather than reach consensus, interactions between experts was not essential, and we did not combine judgements. Probabilities were elicited directly, but a probability wheel² was on hand as an optional visual aid if participants so desired.

Judgements were encoded as cumulative density functions (CDFs). These provide detailed representations of experts' beliefs in the form of a 'well-understood and convenient distribution' (O'Hagan et al. 2006, 100), and can be more useful than point estimates for decision makers who need to be flexible to multiple outcomes. To elicit these distributions, we used a procedure based on the Stanford/SRI protocol (Spetzler and Stael Von Holstein 1975). The protocol consists of five phases (see 'Probability elicitation methods', below) designed for the expert to work in ways they find most comfortable or familiar and thus reduce 'mental acrobatics' (Spetzler and Stael Von Holstein 1975, 343). Forty years after the protocol was developed, variants continue to be used to elicit probabilities of uncertain quantities (e.g. Bistline 2014), and the protocol is cited by the IPCC as 'good practice' in eliciting expert judgements (IPCC 2006).

² A probability wheel is a device for visually representing probabilities. The arms of the wheel can be moved to represent larger or smaller slices of the wheel, like a pie chart, and a spinning pointer is anchored in the centre of the wheel.

Methods

Elicitations formed part of two-hour individual face-to-face interview sessions regarding SLR on the Severn Estuary, held during the summer of 2011. The 11 participating experts held academic, consultancy and governmental roles with expertise in sea-level processes, impacts and adaptation responses on the Severn Estuary. This number of experts was deemed sufficient for our study as it covered all relevant fields and included leading figures in sea-level rise on the Severn Estuary. The sessions were facilitated by the lead author, who –besides being trained in qualitative interview techniques– had previously studied and modelled SLR, and spent six months researching SLR on the Severn Estuary prior to the interviews. This provided sufficient expertise to enable full engagement with the participants and the task.

Sampling

There is ‘no agreed definition of what constitutes an “expert”’ (Lowe and Lorenzoni 2007), and expertise can be described using a variety of criteria. An expert can be defined by the way in which they approach a problem (O'Hagan et al. 2006), how they work with the topic (e.g. through interacting with it or contributing to it) or through their lived experience (Collins and Evans 2002). Alternatively, an expert can be anyone whose knowledge we want to elicit (Garthwaite, Kadane, and O'Hagan 2005). For this study, interviewees were selected on the basis of their professional expertise in relation to a broad series of key questions regarding local SLR on the Severn Estuary (c.f Rice 2010). These questions related not only to the extent of future SLR, but also to its impacts, physical and social vulnerabilities, mitigation measures and adaptations.

Due to the complexity of SLR processes and impacts on the Estuary, the experts covered a wide range of backgrounds and disciplines. This allowed experts without specific expertise in SLR processes, but with other relevant expertise, to participate in

the research (c.f. Lowe and Lorenzoni 2007). The views of less specialised experts are significant, not only because their input can add value to exercises such as this (Tichy 2004), but because their roles (e.g. government, consultancy) mean their judgements may influence risk management decisions and policy recommendations.

Experts were identified through a literature review and through recommendation. A snowball sampling procedure was also used, whereby each participating expert was asked to suggest others in the field who might be willing to take part. The experts consisted of six academics (specialising in coastal processes, hydrological modelling, climate change, coastal engineering, estuarine systems and meteorology), two national government officials, one local government official, one Environment Agency coastal engineer and one marine environmental consultant (Table 1).

[Table 1 here]

Probability elicitation methods

Each expert participated in three elicitations: one for 2050, one for 2100 and one for 2200. The interview protocol was adapted from the Stanford / SRI Assessment Protocol (Spetzler and Stael Von Holstein 1975) and from Watson and Buede (1987). It ran as follows:

(1) Motivation

Rapport was developed between the interviewer and the participant during a semi-structured interview prior to the probability elicitation, and the objectives of the elicitation were made clear. Participants were made aware of common heuristics and biases in order that such biases might be reduced. These heuristics can include: anchoring, where an initial estimate is used as an anchor on which to base subsequent estimates, biasing judgements towards the initial anchor

(Tversky and Kahneman 1974); overconfidence, which is common both in expert and non-expert judgements and can result in probability distributions that are too narrow (e.g. Baddeley, Curtis, and Wood 2004); and herding, where other peoples' opinions are incorporated into the participant's own, leading to problems if the 'herd' is led down the wrong path (Baddeley, Curtis, and Wood 2004).

(2) Structuring

The conditions of the probability elicitation were specified so that each estimate was as 'accurate' as possible. The conditions specified in this study were that the judgements should be for sea-level change³ in 2050, 2100 and 2200 on the Severn Estuary relative to 2011 levels. Two experts responded by providing multiple judgements for conditions with divergent parameters under 'business as usual' and alternative scenarios. No other constraints were set, and experts were free to make estimates as large or small as they felt appropriate. This is in contrast to subjective probability elicitations of SLR projections carried out by Titus and Narayanan (1996), where experts were consulted regarding the probabilities of each separate parameter in a SLR model, and the results aggregated, thus constraining projections by model parameters.

(3) Conditioning

The participant was asked to talk about the information, scenarios and anchors they used, and assumptions they made. Participants were free to refer to the literature throughout the elicitation. Some elicitation studies encourage experts to consult literature and other materials during the elicitation in order to obtain

³ The term 'sea-level change' was used throughout the interviews to prevent biasing answers towards sea-level *rise* if participants felt sea-level *fall* was possible.

the expert's 'carefully considered opinion' (Zickfeld et al. 2010, 12456), but it could be argued that this practice encourages anchoring. During the first interview it became apparent that the experts' roles and self-perceived competencies in carrying out the task meant that some would feel more comfortable consulting the literature (as they would if they were considering projections in a normal work situation). Whether they referred directly to the literature or not, participants were encouraged to talk about which sources they drew upon (Table 3). Throughout the elicitation, participants were also asked questions such as 'how might extreme values come about?' and 'is there no way at all that sea-level change could be more/less than that?' to increase the robustness of estimates.

(4) Encoding

Although the probability elicitations were mainly directed in terms of percentage probability (e.g. a 95% chance of SLR being greater than X) or as a decimal (e.g. a probability of 0.95 that SLR will be greater than X), judgements were not constrained in this way and participants were encouraged to think of probability in the way they were most comfortable. For example, Expert 7 described small probabilities as fractions. A probability wheel was available but most participants did not utilise it. The encoding process was as follows:

- First, the participant was asked to think about what the extreme values might be and give the absolute upper and lower bounds (the range) of possible sea-level change, however small the probabilities. This reduces the possibility of anchoring on a mean or central estimate (Morgan and Henrion 1990) and counteracts central bias (the tendency to choose data points around the middle of the distribution) (Spetzler and Stael Von Holstein 1975). The maximum and

minimum sea level values were marked onto graph paper, and a scale was drawn between them to create an x-axis.

- Next, the participant was asked to assign cumulative probabilities to sea level values within that range. Each response was marked onto the graph (marked with an 'X' on the example in Figure 2), the y-axis of which had been prepared prior to the interview. This process was repeated until around eight points were spread out on the distribution. Any inconsistencies were checked and corrected if necessary.
- A line (marked 'A' in Figure 2) was then drawn between the points to produce a CDF.
- The sea level values corresponding to the median and the 50% and 90% confidence intervals were then read from the graph (example marked with a B in Figure 2), and the distribution adjusted if necessary until the respondent was satisfied that it summarised their own probability assessment.
- Finally, the participant was asked 'If I had £1000 and would give it to you if you made exactly the right estimate of sea-level change by [year], what would your absolute best estimate be?' In practice, participants usually view their 'best estimate' as the median (Spetzler and Stael Von Holstein 1975), but this is not always the case (Morgan and Henrion 1990).

(5) Verification

Throughout the elicitation, estimates were checked to ensure the participant actually believed their distribution. For example, if the probability of 50cm or more SLR was 0.7, the probability of it being less than 50cm was checked to be 0.3.

[Figure 2 here]

CDFs were converted into box plots (c.f. Morgan, Pitelka, and Shevliakova 2001, Morgan and Keith 1995) (Figure 3) so that experts' judgements could be compared and contrasted.

Thematic analysis

Although subjective elicitations of SLR have been carried out previously (Titus and Narayanan 1996, Bamber and Aspinall 2013), none to our knowledge have been thematically analysed to explore factors that may have influenced experts' judgements. Therefore, experts were encouraged to talk through their thoughts as they worked through the elicitations, and the process was audio-recorded, transcribed and coded to capture the dominant themes emerging from the transcripts (c.f. Moser et al. 2011). A grounded approach was used (Glaser and Strauss 1967, Henwood and Pidgeon 1992), whereby concepts 'emerged' from the interviews, and the codes were developed to fit the data. NVivo (a computer-assisted qualitative analysis program) was used to aid the coding, sorting and organisation of data.

Results and discussion

Quantitative findings

The box plots in Figure 3 summarise the distributions of expert estimates of SLR for 2050, 2100 and 2200. They show the range of judged possible values, the 5th and 95th percentiles, the interval spanned by the 50% confidence interval, the median and a 'best estimate'. Wider spreads indicate greater uncertainty.

[Figure 3 here]

The box plots show that all participants projected a high likelihood of future sea-level rise on the Severn Estuary, with three experts asserting very low probabilities ($\leq 2\%$) of sea-level *fall* for 2100 or 2200. The plots also show that despite strong

consensus that there will be SLR on the Severn Estuary, there is wide variation between judgements. For example, the upper 95% confidence levels for the year 2050 range from 10.7cm to 95cm (i.e. there is an estimated 5% chance that SLR will exceed this value); median estimates for 2100 range from 20cm to 100cm; and 'best estimates' for 2200 range from 25cm to 280cm, more than an order of magnitude difference.

There was also considerable variation regarding how much SLR is thought to be *possible* on the Severn Estuary: while Expert 8 perceived a very remote possibility ($1/10^9$ chance) of 70m SLR by 2050, Experts 1, 4 and 11 projected an absolute maximum of 0.5m. Levels of confidence also vary: for example while some experts were willing to state absolute maximum and minimum values (e.g. Expert 10), others were not (e.g. Expert 7).

Consistent with a recent expert judgement study (Bamber and Aspinall 2013), the results indicate a wider diversity of opinion than that shown in often cited reports such as the IPCC and UKCP09, a selection of which are summarised in Table 2. Notably, while median estimates of SLR - which ranged from 9.6cm to 40cm in the year 2050, 20cm to 100cm in 2100, and 35cm to 300cm in 2200 - were of the same order of magnitude as the IPCC's Fourth and Fifth Assessment Reports (IPCC 2007a, 2013b), the experts in this study typically made high estimates that were much greater than these ranges. These findings support work by Kriegler et al. (2009), who found that in many cases, experts' probability judgements relating to tipping points in the climate system were considerably higher than those in current climate change assessments; as well as classic psychological studies showing group decisions can be more conservative than individual ones (Zajonc, Wolosin, and Wolosin 1972). They also support recent work that shows a majority of experts believe that the 2013 IPCC assessment may be too optimistic about SLR (Vision Prize 2014). It should be noted that the Fifth Assessment

Report's *likely* SLR range of between 0.52 and 0.98m by 2100 is *not* a worse case upper limit (Church et al. 2013), and is for global rather than local SLR so is not directly comparable. Furthermore, the Fifth Assessment estimates, which draw upon a variety of models and literature sources, are an area of considerable disagreement, particularly in terms of their low confidence in semi-empirical models (Rhamstorf 2013, Grinstead 2013).

[Table 2 here]

Qualitative findings

Our qualitative analyses support previous work (e.g. Tversky and Kahneman 1974) showing that judgements are influenced by a great many factors including the methods and sources that participants used, their heuristics, and the ways in which they thought about the future.

Methods, sources and heuristics

Consistent with Spetzler and Von Holstein's (1975) observation that people tend to place more confidence in a single piece of 'representative' information than in a larger body of more generalised information, seven of the 11 experts directly or indirectly used UKCP09 (see UK Climate Projections 2012) to guide their judgements (Table 3). This is to be expected considering that UKCP09, a suite of UK climate projections providing information for adaptation planning, itself consists of probabilistic distributions from an ensemble of climate models. However, and despite UKCP09 being particularly popular, few experts based their projections solely on a single data source. Other sources included experts' own measurements, satellite observations, IPCC projections (IPCC 2007a), the Severn Estuary Shoreline Management Plan (Severn Estuary Coastal Group and ATKINS 2010) and papers published about local and regional SLR (see Table 3).

Anchoring was evident throughout the interviews. While efforts were made to encourage participants to concentrate on ranges of possible outcomes rather than anchoring judgements on particular values, some preferred to calculate their distribution directly from values in the published literature (e.g. Expert 9 below). Herding was also a theme, with one participant remarking that he had been ‘institutionalised’, and another that she had been ‘brainwashed’. The implications are that judgements may be biased towards particular sources and particular values (Tversky and Kahneman 1974). This would lead to problems if these end up being wrong (Baddeley, Curtis, and Wood 2004).

‘I have been institutionalised, if you like. I’ve fed myself a diet of about 40 centimetres’ – Expert 3, Academic.

‘I’ve been brainwashed, haven’t I? By lots of clever scientists’ – Expert 5, Consultant.

We talk very much about one metre by the end of the [Shoreline Management] Plans, which is 100 years. So I don’t tend to do anything below that. I tend to talk about one metre in 100 years – Expert 9, Government.

[Table 3 here]

Experts chose different methods by which to construct their judgements. These included: calculating a linear rise from recorded rates of SLR on the Estuary (e.g. Expert 6); extrapolating from a range of emissions scenario graphs (e.g. Expert 10); thinking about extreme scenarios, feedbacks and time lags (e.g. Expert 2); ‘gut feelings’ (e.g. Expert 7); and using indicators from local geomorphology (e.g. Expert 3). It is feasible that these methods may have influenced the judgements. For example, Expert 6 used his own data and had higher confidence in his 2050 projections than any other expert, denoted by the narrowest confidence intervals. Expert 2, who thought about

extreme scenarios, feedbacks and time lags, had the widest confidence intervals of all 2200 judgements.

While the current dataset does not permit statistical comparisons, results indicate that experts' roles or backgrounds may have influenced the methods that they chose. Academics (e.g. Experts 1, 3, 6 and 10) tended to use rates from published sources, for example to extrapolate to future SLR. Those more involved with policy making (e.g. Experts 5 and 7) tended to cite more personal methods such as a general feel or semi-informed gut feelings, which can also be rational modes of reasoning (Slovic et al. 2004). These observations are consistent with research showing that scientists' methodological preferences are related to their academic backgrounds and experiences (Donovan, Oppenheimer, and Bravo 2012), as well as with wider literature describing the 'context-bound nature' of expert rationality (Wynne 1989, 36), and earlier work recognising that *ways* of teaching and learning shape the production of scientific knowledge (Wittgenstein 1953, Kuhn 1962, Foucault 1977). The findings also lend support to the notion that the views of a variety of experts can add value to foresight exercises (Tichy 2004) and that expert panels should include participants from a variety of relevant disciplines (Fitch et al. 2001).

Future thinking

Transcripts indicate that the ways in which experts think about the future may have influenced their probability judgements. This emerged as two themes: uncertainty and optimism. Uncertainty in empirical quantities such as sea levels arises from many sources, including statistical variation, inherent randomness, disagreement, approximation, linguistic imprecision and variability (Morgan and Henrion 1990). Table 4 lists the sources of uncertainty cited by participants. Some are aleatory uncertainties, arising from factors such as random variability within a system, and are not reducible by

further research. Others are epistemic, arising from things that could be known but are not, and can in theory be reduced by further research. These qualitative findings are supported by the quantitative data, which show that almost all judgements exhibit wide probability ranges and confidence intervals, indicating large uncertainties in projections.

[Table 4 here]

Experts tended to find it particularly difficult to think about the future beyond 2100, as shown in the quotes below. This is to be expected because uncertainties increase with time due to the chaotic nature of the climate system and unknowns such as emissions scenarios. Lenton et al. (2006, 2) suggest that the tendency to focus on short timescales also ‘surely reflects the human lifetime’ and our difficulty in contemplating the world ‘long after we cease to live in it’. Indeed, research shows individuals have difficulty imagining the future much beyond 15-20 years (Tonn, Hemrick, and Conrad 2006). Furthermore, most of the sources upon which experts based their judgements do not make projections beyond 2100.

‘What’s the purpose of the outlandish [2200 elicitation]?’ – Expert 3, Academic.

[2100] ‘There’s a problem here though, because it’s going to be so dependent on the futures, isn’t it. And so it gets less like simple probability. [It is now] conditional probability, which makes me very uncomfortable because it’s just like guessing’ ... [2200] ‘200 years and 1000 years, you know, it is really difficult to actually think that far ahead...’ – Expert 4, Academic.

‘[2200] It’s a stupidly long time’ – Expert 5, Consultant.

‘[2200] It’s all these ifs ifs ifs ifs ifs’ – Expert 6, Academic.

[2100] ‘Gosh we’re really guessing, aren’t we. That’s so far away that so many things can happen’ – Expert 7, County Council.

‘200 years. I have NO confidence in my estimates AT ALL that far ahead, because it’s just TOO far ahead to conceive of, really... It’s so far ahead in the future as to be completely meaningless... These are now WILD guesses’ – Expert 9, Government.

[2200] ‘For a median change, I feel- well, we’re getting into the realms of science fiction here’ – Expert 11, Academic.

Another way in which future thinking may have influenced judgements was optimism. Optimism can be described as a personal disposition; an inclination to believe that the world is the ‘best of all possible worlds’, or hopeful expectations in a given situation (Gillham et al. 2001, 53). Expert 4 made best estimates that were considerably lower than her median estimates. When she realised her inconsistency, she indicated that this was because she was optimistic⁴, stating ‘I just have this feeling that the nearer we get to those times, the more likely that people will actually wake up to do something about it’. The quotes below further indicate that an optimistic disposition may have influenced some participants’ judgements.

‘[It is the] optimism in me thinking that we’ll have hopefully curbed some emissions’ – Expert 3, Academic.

‘I’d like to think it would be nearer 20 than 50[cm]. So we had actually got a grip on it... We can do it... Fighting with my optimism and my pessimism.’ – Expert 5, Consultant.

These findings are consistent with a growing body of research regarding the relationships between probability estimates, optimism and pessimism (Vosgerau 2010, Windschitl et al. 2010, McKenna 1993). Interestingly, those experts who vocalised their

⁴ Although there may be winners and losers with SLR, evidence strongly indicates that the negative implications of SLR will outweigh any potential benefits (IPCC 2014). Thus, projecting lower SLR would be optimistic.

optimism did not project especially low magnitudes of SLR (Figure 3). As Expert 8 remarked, ‘one man’s pessimism is another man’s optimism’ and such outlooks are subjective. Having said this, it is reasonable to suggest that if these participants were not being optimistic their SLR judgements may have been different. Such optimism has been documented in expert judgements before (e.g. Tichy 2004) and dispositional elements like these should be acknowledged as potential factors influencing risk communication and decision making.

Concluding discussion

We used expert probability judgement to elicit a suite of local projections for future SLR on the Severn Estuary in the southwest of the UK. We found strong consensus for a high likelihood of future SLR there. However, there is wide variation between judgements and much uncertainty regarding the magnitude of future rise. Importantly, while median estimates correspond to IPCC projections, top-end uncertainties are far greater.

Unlike frequentist probabilities, such as tossing a coin, or predictions that are easily tested after the event such as weather forecasts (Murphy and Winkler 1974), SLR projections for 2050, 2100 and 2200 cannot be calibrated. While it is clearly not feasible to design adaptation strategies that are robust to any point on the experts’ distributions, it is important to consider the plural nature of these projections - for one of the outliers among the respondents may be correct. Robust adaptation planning for SLR must therefore be flexible (Hulme, Pielke, and Dessai 2009), for instance employing ‘low-regrets’ measures such as early warning systems, risk communications and sustainable land management, that provide benefits under a range of future scenarios (IPCC 2012).

We explored the feasibility of eliciting subjective probabilities for long timescales (2200) as well as for time horizons that most climate experts are familiar

with (2050 and 2100). This was a methodological question relevant to both SLR and climate change projection more generally. Participants found long-timescale projections challenging, and questioned the utility of such an exercise. Though this finding is unsurprising (see Lonsdale et al. 2008), it is important because difficulties in thinking about the future may have implications for the ways in which long timescale SLR projections are made, communicated and utilised. It poses the question of whether key reports should more routinely include explicit long timescale projections, such as those provided by the most recent IPCC reports (IPCC 2013a), so that they are more readily available to experts. But it also poses the question of how useful such projections can be. More research is therefore needed to investigate the best ways in which to elicit long timescale projections. If it is not possible to do this in a way that is acceptable to expert participants while also providing useful projections, long-term SLR responses will have to focus on reactive or shorter term anticipatory management.

We thematically analysed interview transcripts to explore expert reasoning. These analyses indicated that experts' judgements may have been influenced by their choice of methods and information sources, heuristics, and the ways in which they thought about the future. These findings reiterate the merits of integrating qualitative and quantitative methods in uncertainty judgements, as recommended by Stirling (2010). They also imply that such qualitative factors should be acknowledged. Indeed, 'for post-normal science, the decision making process is as important as the research product' (Dessai and Hulme 2004, 120).

There are a number of limitations to this study. First, each expert's judgement depends on what they retrieve from memory (or their chosen source) at a particular time, and possibly on the order in which the information is integrated into a unified opinion (Wallsten and Budescu 1983). Each judgement is therefore a snap-shot of

opinion at the time the interview was carried out and may change in light of further deliberation or new information. The second limitation is linked to the first, and relates to our decision to allow participants to consult literature during elicitations. Such an approach encouraged an open discussion of anchoring and herding heuristics and highlighted the most popular sources of information; but it may in turn have *encouraged* anchoring and herding, thus leading to biased responses.

It should be reiterated that the experts participating in this research had varying levels and types of expertise in relation to SLR processes and rates. Although no participant refused to participate in the probability elicitation, some were not entirely comfortable with the procedure, and felt that they were not well qualified for such an exercise. One expert felt that the process was like ‘almost being asked to deny what other people have done and what other people think’. This reluctance to participate in expert elicitations should be recognised, and has been previously noted by Arnell, Tompkins, and Adger (2005).

Our final limitation relates to the number of experts that we sampled. While structured elicitations can be carried out with smaller numbers of experts (Cooke and Goossens 2004 suggest a minimum of four), a greater number of experts would have allowed a more thorough exploration of how different roles and experiences may influence judgements, and could facilitate statistical comparisons between groups. This would be a productive avenue for further research.

At this juncture, we can conclude that personal differences such as heuristics and future thinking were evident during elicitations of future SLR at the local scale, and may have influenced projections. Such personal differences cannot be eliminated from judgements, and nor should they be (e.g. Slovic et al. 2004, Tichy 2004). Instead, risk assessors must make explicit the reasoning behind judgements and the basis on which

they are made (Oppenheimer et al. 2007), minimise biases (Vosgerau 2010), and acknowledge subjectivity (Donovan, Oppenheimer, and Bravo 2012) to ensure that judgements are transparent. Provided this is done, subjective probability elicitation should remain a valuable tool for considering SLR at local scales.

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Table 1: Expertise, genders and years of experience of interviewees

Expert	Expertise	Gender	Experience in field (years)
1	Academic	Male	5-10
2	Government	Female	<5
3	Academic	Male	>20
4	Academic	Female	5-10
5	Consultant	Female	11-20
6	Academic	Male	11-20
7	County Council	Male	>20
8	Environment Agency	Male	5-10
9	Government	Female	<5
10	Academic & advisor to various organisations including local authorities and government organisations	Male	>20
11	Academic	Male	>20

Table 2: Selected global and local projections of sea-level rise

	Projection	Description
Global projections		
IPCC's Fifth Assessment Report (AR5)(IPCC 2013b)	26cm to 98cm by 2100	Model-based likely range for four Representative Concentration Pathway scenarios, compared to 1986-2005
IPCC's Fourth Assessment Report (AR4)(IPCC 2007a)	18cm to 59cm by 2100	Model-based range for six emissions scenarios, compared to 1980-1999
Titus and Narayanan (1996)	34cm by 2100 and 81cm by 2200	Aggregated median estimates of SLR from expert elicitations
Local projections		
MCCIP (2010)	21–68cm by 2095	SLR projected under a medium greenhouse gas emission scenario by 2095 for Cardiff, Severn Estuary
UKCP09 (see UK Climate Projections 2012)	44.4 cm by 2095	Medium emissions scenario for Cardiff, Severn Estuary

Table 3: Sources and methods used by experts to estimate future sea-level rise on the Severn Estuary

Expert	Sources	Methods
1	Shennan and Horton (2002)	Recorded rates used to project future rise.
2	UKCP09	UKCP09 emissions scenario graphs taken ‘as rough guidelines and taking my own approximation from there’, and bearing in mind that the sources only include certain emissions scenarios. 2200: thought about processes such as feedbacks, ice caps melting, and high emissions scenarios.
3	UKCP09 and academic papers about local SLR	2050: UKCP09 and continuation on a trajectory, ‘just allowing what we know has happened to carry on happening’ 2200 minima: UK coastal geology.
4	IPCC (from memory)	Based on measured rates in the literature, plus a mental probability density function (PDF). Rates not worked out accurately, but used as a guide.
5	UKCP09 and the Severn Estuary Second Shoreline Management Plan (SMP2)	‘A general feel’. 2200: extrapolated from 2100, and compared what the world was like 200 years ago with what it could possibly be like in 200 years.
6	His own work, other data sets and IPCC estimates	Used geological record and his own sea level measurements to extrapolate rates into the future. Also used other data sets with longer time scales, and created a mental curve with an accelerated rise.
7	Shoreline Management Plans, UKCP09	‘Semi-informed’ gut feelings based on background knowledge. Once plotted, looked at the graph and spread it out to make it less steep.
8	UKCP09, Defra (UK Department for Environment, Food and Rural Affairs) and various others	Used historical rates, published projection graphs (including Defra and UKCP09), background reading and ‘general knowledge about what is happening from a climatic point of view’.
9	Severn Estuary Second Shoreline Management Plan (SMP2)	Extrapolated from the 2100 1m estimate used in the SMP2.
10	Variety of published sources, especially UKCP09	Used rates from published sources, extrapolating from a range of emissions scenarios; as well as thinking about extreme scenarios, time lags, and physical processes.
11	IPCC, literature, observations (including satellite).	Used rates and trends. Drew families of curves, using instincts for 2200, increasing the ranges due to greater uncertainties associated with making projections specific to the Severn Estuary.

Table 4: Sources of uncertainty cited by experts in their judgements of future SLR on the Severn Estuary

Expert	Sources of aleatory uncertainties
1, 2, 4, 5, 8, 10, 11	Uncertainties in future conditions e.g. emissions scenarios, impacts of a potential Severn Barrage on local sea level.
7	Unknowables
	Sources of epistemic uncertainties
2, 3, 6, 7, 8, 11	Process uncertainty, e.g. ice sheet response to warming, feedbacks, time lags, regime shifts
2, 3, 8, 10	Climate model uncertainty
7, 9	Availability of and confidence in data
2, 5	Unavailability / non-existence of projections for long timescales
8	Uncertainties about what parameters are included in published guidance projections

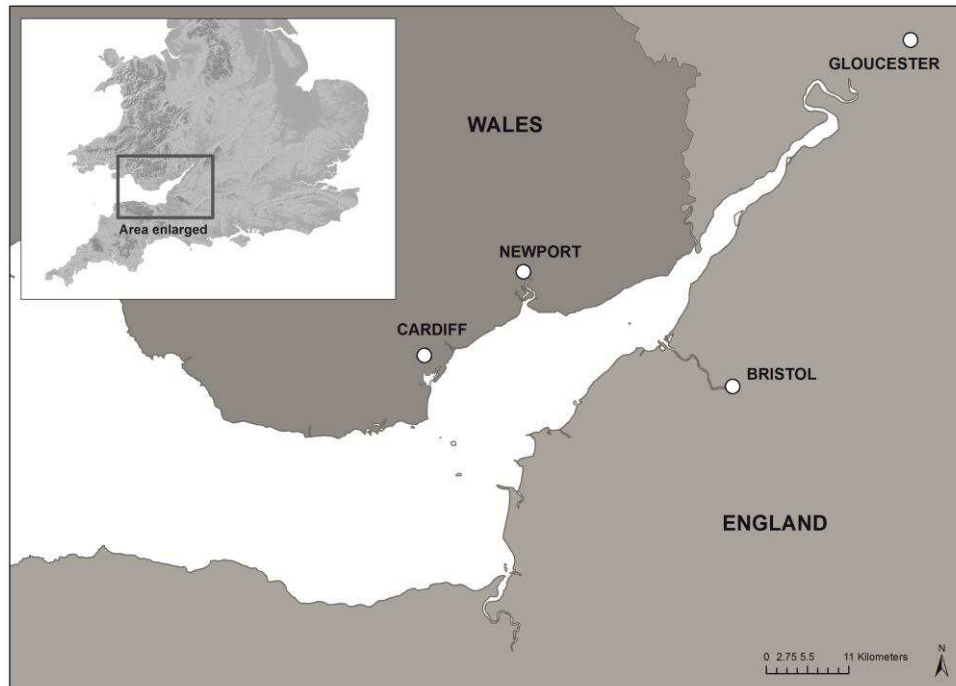


Figure 1: The location of the Severn Estuary (a) within the UK (inset, b)

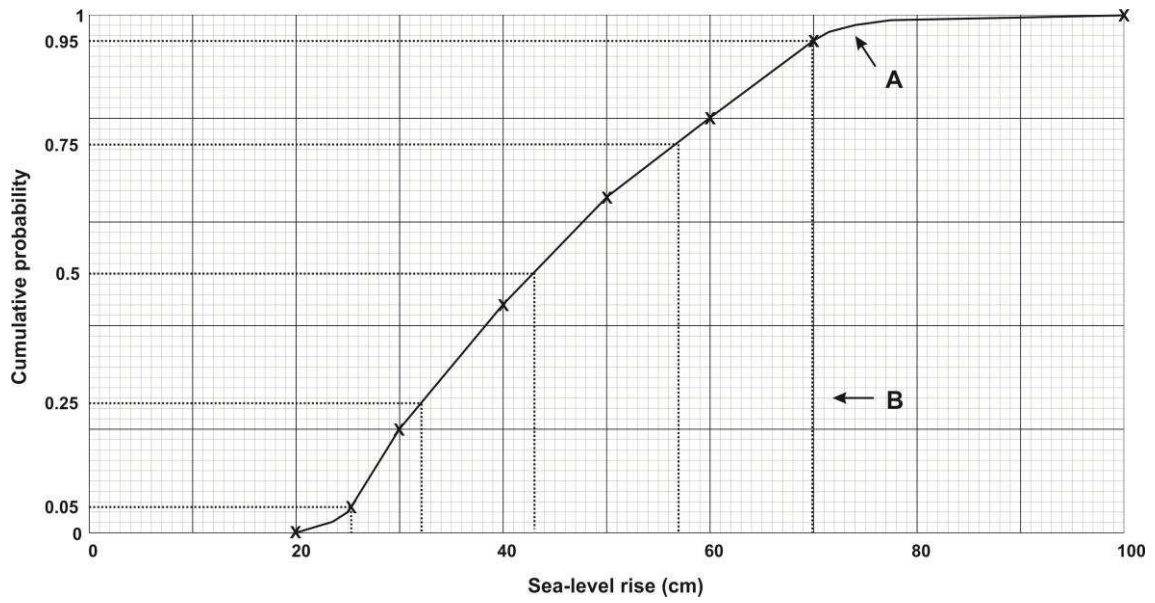


Figure 2: Example of points on an elicited subjective probability distribution. The points [X] are elicited from the expert, before a rough line (A) is drawn between the points. Sea levels corresponding to confidence intervals (B) are then checked with the expert.

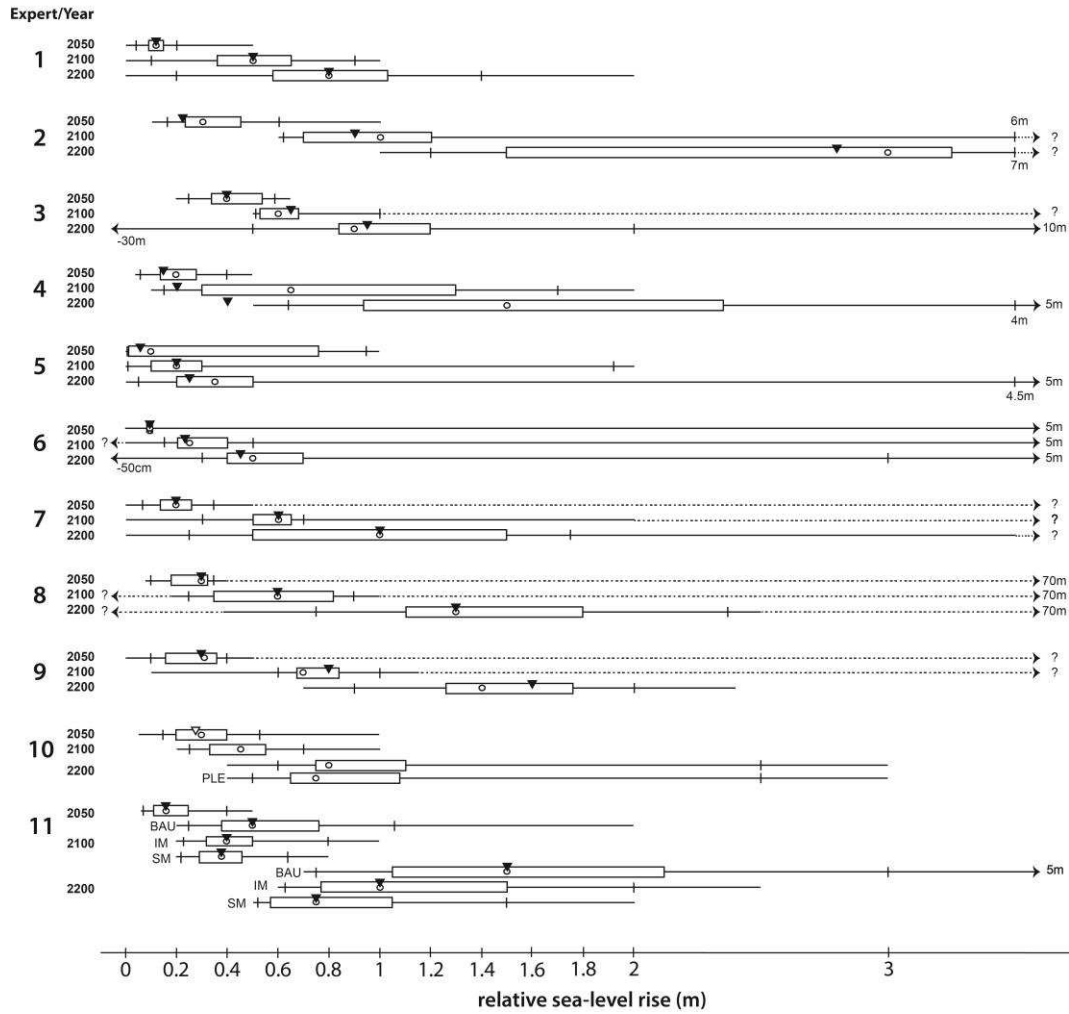


Figure 3: Box plots summarising expert subjective probability distributions. Box plots show results elicited for relative sea-level change on the Severn Estuary in 2050, 2100 and 2200. Vertical tick marks indicate 90% confidence intervals, and boxes denote 50% confidence intervals. Open circles indicate medians, solid triangles indicate ‘best estimates’ (value chosen if the expert were to bet money on it) and the open triangle indicates a reluctantly stated best estimate (Expert 10 was reluctant to give best estimates because he felt it defeats the object of a probability distribution). Question marks show where no absolute maximum or minimum was stated, and dashed lines show where no explicit probability or very low probabilities ($1/10^5$ to $1/10^9$) were estimated. PLE = possible low emissions scenario; BAU = business as usual scenario; IM = intermediate mitigation scenario; SM = stringent mitigation scenario.