UNIVERSITY OF LEEDS

This is a repository copy of *Expert Elicitation of Directional Metocean Parameters*.

White Rose Research Online URL for this paper:
http://eprints.whiterose.ac.uk/132293/

Version: Accepted Version

Article:

Astfalck, LC, Cripps, EJ, Gosling, JP orcid.org/0000-0002-4072-3022 et al. (2 more authors) (2018) Expert Elicitation of Directional Metocean Parameters. Ocean Engineering, 161. pp. 268-276. ISSN 0029-8018

https://doi.org/10.1016/j.oceaneng.2018.04.047

© 2018 Elsevier Ltd. This is an author produced version of a paper published in Ocean Engineering. Uploaded in accordance with the publisher's self-archiving policy. This manuscript version is made available under the Creative Commons CC-BY-NC-ND 4.0 license http://creativecommons.org/licenses/by-nc-nd/4.0/

Reuse

This article is distributed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs (CC BY-NC-ND) licence. This licence only allows you to download this work and share it with others as long as you credit the authors, but you can’t change the article in any way or use it commercially. More information and the full terms of the licence here: https://creativecommons.org/licenses/

Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing eprints@whiterose.ac.uk including the URL of the record and the reason for the withdrawal request.

White Rose
university consortium
Universities of Leeds, Sheffield & York

eprints@whiterose.ac.uk
https://eprints.whiterose.ac.uk/

Expert elicitation of directional metocean parameters

L.C. Astfalck[a], E.J. Cripps[b], J.P. Gosling[c], M.R. Hodkiewicz[a], I.A. Milne[d,*]

[a]*School of Mechanical and Chemical Engineering, The University of Western Australia, Perth, Australia*

[b]*School of Mathematics and Statistics, The University of Western Australia, Perth, Australia*

[c]*School of Mathematics, University of Leeds, Leeds, UK*

[d]*Centre for Offshore Foundation Systems, The University of Western Australia, Perth, Australia*

Abstract

Probability distributions that describe metocean conditions are essential for design and operational decision making in offshore engineering. When data are insufficient to estimate these distributions an alternative is expert elicitation – a collection of techniques that translate personal qualitative knowledge into subjective probability distributions. We discuss elicitation of surface currents on the Exmouth Plateau, North-Western Australia, a region of intense oil and gas drilling and exploration. Metocean and offshore engineering experts agree that surface currents on the plateau exhibit large spatio-temporal variation, and that recorded observations do not fully capture this variability. Combining such experts' knowledge, we elicit the joint distribution of magnitude and direction by first focusing on the marginal distribution of direction, followed by the conditional distribution of magnitude given direction. Although we focus on surface currents, the direction/magnitude components are common to many metocean processes. The directional component complicates the problem by introducing circular probability distributions. The subjectivity of elicitation demands caution and transparency, and this is addressed by embedding our method into the established elicitation protocol, the Sheffield Elicitation Framework. The result is a general framework for eliciting metocean conditions when data are insufficient to estimate probabilistic summaries.

Keywords: expert elicitation, directional elicitation, metocean, Exmouth Plateau, surface currents

1. Introduction

Complex interactions between waves, winds and currents are central to design and operation decision making in offshore engineering. For example, metocean conditions are used for design risk assessments associated with extreme events (Jonathan and Ewans, 2013), to identify important relationships for condition maintenance (Xia, 2012), to estimate expected operation time windows (Chen et al., 2002), and to assess computational modelling of physical systems (Tahar and Kim, 2003). Since metocean conditions are inherently uncertain, probabilistic descriptions are necessary to formalise such design and decision issues (Bitner-Gregersen et al., 2014). Ideally, recorded observations would be available, but sometimes this is not the case, as when proceeding with design analyses for new exploration projects. In these situations, alternate sources of information must be harnessed, and the knowledge belonging to subject-matter experts is a natural choice.

---

[*] Corresponding author
Email address: `ian.milne@uwa.edu.au` (I.A. Milne)

The offshore engineering literature has reported on the use of expert knowledge and judgement to inform Bayesian networks for the risk assessment of shipping accidents (Afenyo et al., 2017; Hänninen, 2014; Hänninen et al., 2014; Zhang and Thai, 2016), utility curve construction in structural shipping design (Knight et al., 2015), and 'abandon ship' procedures (Akyuz, 2016). However, the above literature concentrates on point estimates and is not concerned with quantifying probability distributions that also describe the experts' uncertainty.

The process of translating experts' qualitative knowledge and uncertainties into subjective quantitative probability distributions is known in the literature as expert elicitation (Cooke, 1991; Meyer and Booker, 1981). It normally involves the interaction of a facilitator knowledgeable in uncertainty, probability and statistics and domain specific experts (O'Hagan et al., 2006; Goossens et al., 2008). The interaction can be complex, often lasting days, until both the facilitator and experts are content with the outcome (Garthwaite et al., 2005). In short, the role of the facilitator is to (a) extract knowledge from the experts in the form of probabilistic judgements and (b) fit probability distributions to their judgements.

Experts are often untrained in probabilistic reasoning, impelling the facilitator to pose questions in terms of basic statistical summaries such as ranges and quantiles, as opposed to more obscure summaries such as variances and expected values. The potential of loose vocabulary to distort results is real and when experts gather as a group, social dynamics come into play (O'Hagan et al., 2006). More subtle problems stem from cognitive heuristics and biases when individuals estimate probabilities (for a review see Kynn (2008)).

Expert elicitation researchers have provided protocols to optimise the elicitation process and stress the need for transparent documentation of the interactions between the facilitator and experts that led to the results. The current state of affairs is that, when carefully prosecuted, elicitation can be a very powerful tool. Evidence of this claim can be found in the publications, across many disciplines, that usefully employ elicitation. It has found its way into reliability engineering (Ioannou et al., 2017), energy (Chan et al., 2011), meteorology (Johnson et al., 2015), agriculture (Krayer von Krauss et al., 2004), health (Batz et al., 2012), conservation biology (Runge et al., 2011), ecology (Murray et al., 2009), geology (Lark et al., 2015), decision making for public policy (Gosling et al., 2012) and climate science (Kennedy et al., 2008). O'Hagan et al. (2006) provides an excellent review of the many more applications prior to 2006. However, to the best of our knowledge, elicitation has not been applied to metocean quantities.

We elicit surface currents (defined here as up to 10 m below the mean water level) at the Exmouth Plateau, in North-Western Australia. The Exmouth Plateau is a region of intense oil and gas drilling and exploration where distributions of winds, waves and currents are vital as, for example, when characterising the input space to physical models such as vessel motions (Milne et al., 2016), side-by-side offloading (Zhao et al., 2014), and oceanographic studies (Rayson et al., 2011). Of these metocean conditions, surface currents have proved to be the most difficult to numerically model (Dhanak and Xiros, 2016) and to comprehensively measure because the Exmouth Plateau's large spatio-temporal variability necessitates an extensive and costly implementation of mooring monitors. High spatial variability implies many mooring monitors are required to yield representative data. High temporal variability over seasons and years necessitates lengthy measurement campaigns.

We gathered six metocoean and offshore engineering experts drawn from both industry and academia. The experts agreed that surface currents on the Exmouth Plateau exhibit large spatio-temporal variation, exacerbated by extreme local eddies, internal waves, cyclonic forcing, and multiple generative processes counteracting or reinforcing one another, but that recorded observations do not fully capture this variability. The elicitation workshop was conducted over two days at The University of Western Australia, facilitated by a statistician experienced in the elicitation process.

Similar to wind and waves, surface currents are most commonly described in terms of magnitude (denoted by v) and direction (denoted by θ). Although modelling Cartesian coordinates can be more straightforward statistically, the experts preferred discussing v in meters per second, and θ as measured clockwise from North on $[0, 360)$. The article therefore elicits the joint probability of θ and v, $p(\theta, v)$. For reasons given in the article's main body, the experts were most comfortable with first discussing direction, followed by the magnitude associated with that direction. The problem was therefore decomposed into $p(\theta, \upsilon) = p(\theta)p(\upsilon|\theta)$. Marginalising over θ yields $p(\upsilon)$. On the advice of the experts, we elicited $p(\theta, \upsilon)$ for the Wet (November–April) and Dry (May–October) seasons separately.

For magnitude, the experts were asked to make plausible range and quantile judgements. This is known as the variable interval method, and is common practice in the elicitation literature (Garthwaite et al., 2005). We then fitted gamma and log-normal distributions to these judgements. Directional quantities have not yet been elicited in the literature and are more difficult because $\theta = 0$ and $\theta = 360$ are equivalent. We describe a variant of roulette elicitation (Gore, 1987), a graphical method whereby experts are asked to deposit chips into intervals to represent the probabilities of each interval's occurrence. Circular distributions are then required to fit the directional judgements. We allow for the possibility of the von Mises (Fisher, 1995), generalised von Mises (Gatto and Jammalamadaka, 2007) and asymmetric generalised von Mises (Kim and SenGupta, 2013) distributions. The final results are presented as the asymmetric generalised von Mises distribution.

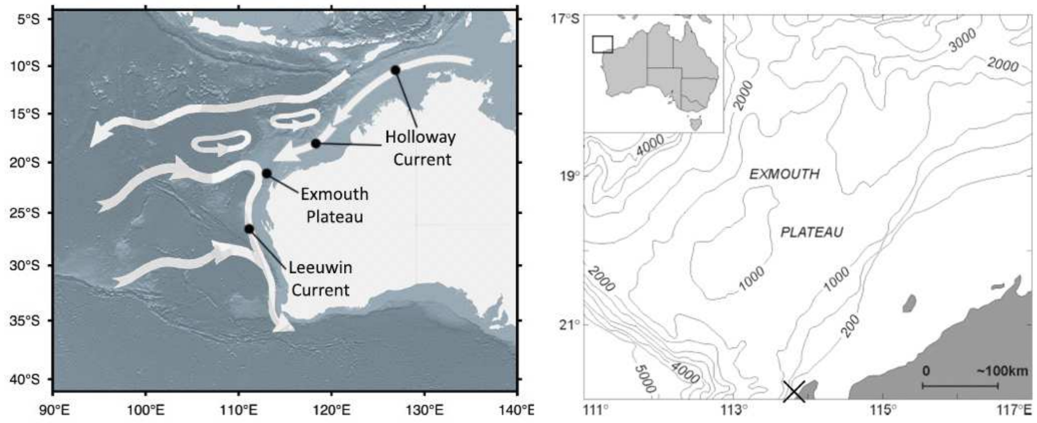
The elicitation protocol described in this article follows the SHeffield Elicitation Framework (SHELF) (Gosling, 2018) and its accompanying software (Oakley and O'Hagan, 2010). SHELF has been successfully implemented in many other studies: for instance, Lark et al. (2015) and Ren and Oakley (2014). However, SHELF does not yet include circular distributions. In this paper, we present a general method to elicit distributions of directional quantities, where the joint distribution of the angle and the magnitude is desired, that can be used when quantitative characterisations of uncertain metocean inputs is required.

The article proceeds as follows. Section 2 provides a review of the surface currents at the Exmouth Plateau. Section 3 describes the design of the elicitation and workshop process, with an emphasis on how the directional component is elicited. Section 4 presents the elicitation results and distributional fits, and Section 5 offers the conclusions from this research.

2. The Exmouth Plateau

The Exmouth Plateau forms part of the North–West Shelf of Australia as shown in Figure 1a. It is the second largest marginal plateau of offshore Australia with an area of 150 000 km^2 located approximately 300 km offshore from North–Western Australia (Exon and Willcox, 1980). The water depth varies from 3500 m along its base, to 1500 m atop the plateau, and as shallow as 100 m on the Eastern shelf-slope (see Figure 1b). It is one of the most economically significant maritime regions in Australia. Over 86 wells have been drilled since hydrocarbon exploration commenced in the late 1940s (NOPTA, 2017) and future activity is expected. The majority of the Floating Production Storage and Offloading (FPSO) facilities, which are utilised for much of the hydrocarbon production in the region, weathervane in response to the local meteorological and oceanic conditions. Critical to the design and safe operation of these facilities is an understanding of local surface current conditions and their variability.

On a global scale, the Exmouth Plateau is affected by the Leeuwin and Holloway currents. The Holloway Current originates North of the Exmouth Plateau from the Indonesian Throughflow, and flows southward to meet the head of Leeuwin Current at the Exmouth Plateau region (D'Adamo et al., 2009). In this region the global currents predominately flow towards the South–West, however seasonal flow reversals are common (Holloway and Nye, 1985). Localised temporal variation at the Exmouth Plateau stems from multiple sources. Semi-diurnal tidal currents govern short term variability (Holloway, 1988). Mid-term variability comes from the Wet/Dry seasonal effects of meteorological conditions such as winds, waves and tropical cyclones (Condie and Andrewartha, 2008). Climate drivers such as El Nino/La Niña cycles inject long term variability (Feng et al., 2003). The natural spatial variation is complicated by steep regional bathymetry. Internal waves are generated resulting from the interaction of the shelf slope and the barotropic tidal currents (Van Gastel et al., 2009), and extreme localised eddies can persist for several days (Morrow et al., 2003).



(a) (b)

Figure 1: (a) Mean surface paths of the Leeuwin and Holloway currents on the West Australian coast. (b) The bathymetry of the Exmouth Plateau in metres (image adapted from Exon et al. (1992)). The marked cross at the bottom of Figure 1b shows the location of the moorings in Lowe et al. (2012).

To install, maintain and record data from a single mooring monitor on the Exmouth Plateau for a year will cost in the order of hundreds of thousands of dollars. This factor coupled with the size of the Exmouth Plateau means that comprehensively observing the spatio-temporal variability the region's surface currents is difficult. However, some observational and modelling studies have been conducted in attempt to capture surface current behaviour on the Exmouth Plateau and in surrounding regions. As these studies inevitably inform our experts' opinions, some of these results are now discussed.

Indications of the magnitudes of the contributions of the global currents in the region can be inferred from measurements by Lowe et al. (2012). Two moorings were deployed on the 50 m and 100 m isobaths at the inner shelf of the North–West Cape immediately South of the Exmouth Plateau (marked by the cross at the bottom of Figure 1b) and data were measured over a six year period from 2004 to 2009. Currents were measured at roughly 5 m and 8 m above the seabed for the 50 m and 100 m moorings, respectively. Measurements of the Leeuwin Current predominately ranged from 0.1 and 0.2 $\mathrm{m\,s^{-1}}$; however, currents were subject to large transient flow reversals due to wind forcing, and speeds of over 0.5 $\mathrm{m\,s^{-1}}$ were measured in the Wet season. The semi-diurnal tidal component is generally well understood from numeric modelling (Holloway, 2001; Condie and Andrewartha, 2008), with Brewer et al. (2007) estimating average magnitudes varying from 45 $\mathrm{mm\,s^{-1}}$ in the Wet season to 57 $\mathrm{mm\,s^{-1}}$ in the Dry season.

In contrast, the contributions to the surface currents from other phenomena in the region are more challenging to ascertain. Holloway (1988) measured currents across the Exmouth Plateau over a three month period at four distinct mooring locations, providing one of most comprehensive studies of the plateau's current dynamics. This study reinforces the notion that the surface currents are spatially highly variable, providing evidence that the current directions can change by up to 90° between moorings 100 km from each other. Holloway (1988) further measured persistent high-frequency internal waves, noting they are highly variable across measurement locations.

More recent studies have measured internal waves to induce currents of over 0.6 $\mathrm{m\,s^{-1}}$ at neighbouring locations on the North–West Shelf (Lowe et al., 2012; Van Gastel et al., 2009). Eddies in the region can persist for several days and have been measured to give rise to surface currents greater than 0.8 $\mathrm{m\,s^{-1}}$ (Morrow et al., 2003). Whilst these eddies were previously believed to occur only during the Wet season when wind-driven currents caused upwelling events, recent studies have shown that they can be present throughout the year (Rossi et al., 2013). Cyclones further contribute to the surface current extremes. Since the 1940's at least 126 tropical cyclones have been recorded passing through the region (Australian Bureau of Meteorology, 2017). An average of five cyclones form in the warmer North-West sea of Australia during the Wet season, of which typically two cyclones make landfall.

These studies only provide a guide to the behaviour of the surface currents at the Exmouth Plateau. None of these reported measurement campaigns are fully representative as they are either too short in duration to capture seasonal and inter-annual effects, such as Holloway (1988), or were spatially located near but not on the Exmouth Plateau, such as Lowe et al. (2012). Further, many of the current generating phenomena exhibit localised complex dynamics, so numerical modelling is not accurate in describing this behaviour. Due to these difficulties, reliably measuring current at the Exmouth Plateau would be a timely and costly process.

Lastly, it is important to acknowledge that longer duration private monitoring campaigns on the Exmouth Plateau have been undertaken by exploration companies, but these data are not publicly accessible. These private monitoring campaigns are generally site specific and individually do not capture the spatial variation of surface currents across the Exmouth Plateau.

3. The Elicitation Process

This section proceeds in three stages. First, we outline some of the ideas and theory behind expert elicitation and why we chose to follow the SHELF protocol. Second, the design of our process is discussed, including the development of eliciting directional quantities. While it is vital to prepare thoroughly for an elicitation workshop, it important to understand that once the workshop has commenced strategies may evolve, depending on how the experts are most comfortable expressing their judgements. The last stage of this section therefore summarises how the execution of the workshop contributed to finalising our goals.

3.1. Expert Elicitation and the SHELF protocol

Expert elicitation is the structured process of translating expert knowledge about an uncertain quantity into a probability distribution. The science, however, is not exact. Elicited probabilities from one expert may well be different from that obtained from another and in group settings social dynamics may influence the outcome (O'Hagan et al., 2006). Experts are also prone to cognitive heuristics and biases when it comes to probabilistic reasoning (Kynn, 2008). The three main biases considered in the elicitation literature are the tendencies of experts to (1) over-emphasise an initial judgement, biasing all subsequent judgements (described in Winkler (1967) as *anchoring* and *adjustment*), (2) link the probabilities of an event to the frequency with which the individual can recall it (described in Tversky and Kahneman (1973) as *availability*) and (3) inadequately assess the tails of a distribution (described in Wallsten and Budescu (1983) as *overconfidence*). Finally, the fact that an expert in the specified domain is usually not an expert in probability and uncertainty means the process must proceed with caution, lest the experts be uncomfortable with, or misunderstand, the language used to elicit the quantities (Kadane and Wolfson, 1998).

To mitigate the above problems, the establishment of elicitation protocols has received a lot attention, based on the experiences of statistical pioneers in the field, often in collaboration with psychologists (Garthwaite et al., 2005). This article opts for the SHELF protocol and accompanying software because of the following reasons. First, to instil confidence in the results we included an experienced facilitator – Dr Gosling, an author of this article – to manage the workshop. Second, to minimise the potential loss of information we gathered a group of experts, as opposed to an individual expert. Third, we wished for the method to be generalisable to other metocean quantities so as to be useful to further offshore engineering research. The SHELF protocol meets these requirements and has been successfully implemented in multiple studies (for example, see Higgins et al. (2012); Lark et al. (2015); Lee et al. (2013); Ren and Oakley (2014)). Gosling (2018) distinguishes SHELF from other elicitation frameworks by five essential elements:

1. *Judgement aggregation* - SHELF aggregates expert judgements via behavioural aggregation, as opposed to mathematical aggregation. Experts first make individual judgements, and then are provided with the opportunity to discuss their differences and share opinions and expertise. Finally a consensus judgement is made as a group.
2. *The SHELF workshop* - The discussion and group consensus phases of the elicitation require the group of experts to be together. Typically, experts are organised together in a room, though other arrangements such as video conferencing are acceptable.
3. *The rational impartial observer (RIO)* - It is not expected that the group will be able to reach complete agreement. Instead the group is asked what an RIO may believe after viewing their individual judgements and hearing their discussion. By taking the perspective of the RIO, experts can reach agreement on a distribution that represents a rational impartial view of their combined knowledge.
4. *The facilitator* - The elicitation is lead by an experienced facilitator, who aids the experts in obtaining accurate judgements, manages the group discussion, and helps experts apply the RIO perspective.
5. *SHELF templates* - SHELF templates are documents that help structure the elicitation workshop, direct individual and group elicitations, and document the elicitation process. They are based on extensive practical elicitation experience, and employ findings from research in the psychology of judgement to reduce the effect of biases.

3.2. The design of surface current elicitation process

A direct application of the SHELF protocol to surface currents constitutes defining the quantities of interest, eliciting magnitude, interactions with the experts and the execution of the workshop. However, eliciting directional quantities is new, and Section 3.2.3 provides a method to do so.

3.2.1. Defining the quantities of interest

First, we defined our quantities of interest as follows. Denote by v the random variable describing surface current magnitude, $v > 0$, and by θ the random variable describing surface current direction, $\theta \in [0, 360)$. v and θ describe those aspects of surface currents that exist in the top 10 m of the water column. The spatial and temporal domains of v and θ are the Exmouth Plateau as described in Section 2. Since it is unlikely that θ and v are independent, it was necessary to consider their joint distribution. Factorising the joint distribution as the product of marginal and conditional distributions, we opted to ask the experts during the workshop which form they would prefer to elicit, $p(\theta, v) = p(\theta)p(v|\theta)$ or $p(\theta, v) = p(v)p(\theta|v)$.

3.2.2. Eliciting surface current magnitude

Two methods are available to elicit judgements about continuous quantities: fixed interval and variable interval methods (Garthwaite et al., 2005). Fixed interval methods require the facilitator to ask experts to state their probabilities that a quantity will lie within a defined interval. Variable interval methods ask experts to make quantile judgements, such as providing medians, quartiles, and plausible limits (often defined as the 1st and 99th quantiles). For v, we decided to follow Hora et al. (1992), which argues that the variable interval method is more appropriate for assessing tails or extremes of continuous quantities. Experts are first asked to establish a range of plausible limits that v may take, then to bisect this range into regions of equal probability, obtaining an estimate of the median. Further bisection of the lower and upper regions provide lower and upper quartile judgements. Using a least squares procedure, SHELF has a variety of common distributions such as the gamma, log-normal, log-Student-t, exponential, Weibull, truncated normal and truncated Student-t that can be fit to these judgements.

3.2.3. Eliciting surface current direction

As θ is directional, and defined on the circle, eliciting quantiles is far from intuitive. Instead, we decided upon a variant of the fixed interval method known as roulette elicitation (Gore, 1987). Translating roulette elicitation to a directional quantity, the support of θ is partitioned into m distinct wedges (or bins) on the circle. For example, if $m = 4$ the bins may correspond to the four standard quadrants of a circle. Experts are asked to distribute n chips between the bins. The choice of m and the location of the bins are determined by the experts, with the first bin centred on the experts' most likely value of θ (i.e. its mode, θ_{mode}) and all bins are of equal size. We write

$$B_i = \left[\theta_{\text{mode}} + (i-1)\frac{360}{m} - \frac{360}{2m}, \theta_{\text{mode}} + (i-1)\frac{360}{m} + \frac{360}{2m}\right), \tag{1}$$

for $i \in \{1, ..., m\}$, and denote by $[B_i]$ the congruence class of all numbers in B_i, modulo 360. The proportion of chips allocated to each bin represents the probability of θ lying in that bin. To fit distributions to the experts' allocation of chips, we must consider families of circular probability distributions (Mardia, 2014).

The choice of a suitable distribution relies on the number of bins that are elicited and the flexibility required. The von Mises distribution (vM) (Fisher, 1995) is a possibility. The vM is described by

$$p(\theta) \propto \exp\left[\kappa \cos(\theta - \mu)\right], \tag{2}$$

where $\mu \in [0, 360)$ and $\kappa > 0$. Here, μ is a measure of location, κ is a measure of concentration (or $1/\kappa$ a measure analogous to the variance) around μ. If $\kappa = 0$ then θ is uniformly distributed. However, the vM distribution is symmetric and unimodal and there must be strong prior belief in these characteristics to use the vM distribution in elicitation.

Extensions to the vM that allow for bi-modality and asymmetry are the three parameter asymmetric generalised von Mises distribution (AGvM) (Kim and SenGupta, 2013) and the four parameter generalised von Mises distribution (GvM) (Gatto and Jammalamadaka, 2007). The AGvM is described by

$$p(\theta) \propto \exp\left[\kappa_1 \cos(\theta - \mu) + \kappa_2 \sin 2(\theta - \mu)\right], \tag{3}$$

for $\mu \in [0, 360)$, $\kappa_1 > 0$, $\kappa_2 \in [-1, 1]$. If $\kappa_2 = 0$ the parameters μ and κ_1 have a similar interpretation to the vM. Asymmetry, or skewness, of the AGvM is measured by κ_2. The mode(s) are the solutions to $\kappa_1 \sin(\theta - \mu) = 2\kappa_2 \cos 2(\theta - \mu)$ when $\kappa_1 \cos(\theta - \mu) > -4\kappa_2 \sin 2(\theta - \mu)$. For $\kappa_2 \neq 0$, when $\kappa_1 \geq 2|\kappa_2|$ the AGvM is unimodal but asymmetric. In this case, when $\kappa_2 > 0$ probability mass is moved clockwise from μ and when $\kappa_2 < 0$ mass is moved anti-clockwise from μ. If $\kappa_1 < 2|\kappa_2|$, the AGvM is bi-modal.

The GvM is described by

$$p(\theta) \propto \exp\left[\kappa_1 \cos(\theta - \mu_1) + \kappa_2 \sin 2(\theta - \mu_2)\right], \tag{4}$$

where $\mu_1, \mu_2 \in [0, 360)$ are two location parameters and $\kappa_1 > 0$, and $\kappa_2 \in \mathbb{R}$ are shape parameters. Obviously, if $\kappa_2 = 0$ we again obtain the vM described by Equation 2 and when $\kappa_1 = \kappa_2 = 0$ the uniform distribution results. The mode(s) of Equation 4 are the solutions to $\kappa_1 \sin(\theta - \mu_1) = 2\kappa_2 \cos 2(\theta - \mu_2)$ when $\kappa_1 \cos(\theta - \mu_1) > -4\kappa_2 \sin 2(\theta - \mu_2)$. The GvM supports a vast array of shapes and the reader is referred to Gatto and Jammalamadaka (2007) for more details.

As circular distributions are not supported by SHELF, an adaptive quadrature algorithm was written to estimate the cumulative distribution functions that correspond to Equations 2, 3 and 4. These were then fitted to the experts roulette judgements using least squares. The number of elicited bins and parameters in each distribution dictates which distribution can be fit. The vM can be fit when $m \geq 3$, the AGvM when $m \geq 4$, and the GvM when $m \geq 5$.

3.2.4. Selection, briefing and debriefing of the experts

The experts were chosen on the criteria that each individual had sufficient knowledge to express reliable judgements on the quantities of interest and that the range of expertise was such that a suitable coverage of opinion could be achieved. The second criterion is shown to be important in Clemen and Winkler (1999): they demonstrate that experts who are similar in discipline tend to provide redundant information, which may induce bias. The final panel comprised two industry metocean engineers, two academics researching internal wave monitoring, all with field experience at the Exmouth Plateau, and two academics researching wave-structure interactions for vessels located on the Exmouth Plateau.

Prior to the elicitation workshop, a briefing package, including an evidence dossier, was released to all experts, who were invited to provide additional material. Many of the articles presented in the finalised dossier are discussed in Section 2. The evidence dossier was made available during the workshop to help ensure that no relevant material was overlooked. The industry representatives may have seen privatised measurements not available in the evidence dossier. As such, their opinions may be informed by more comprehensive measurements than are available in the public domain. After completion of the workshop, a document outlining the experts' reasoning and distributional fits was released to the participating experts to invite feedback and confirm that they were satisfied with the results.

3.3. Execution of the elicitation workshop

The elicitation workshop was held over two days at The University of Western Australia in May 2017. In the introductory stage, the experts stated their role within industry/academia, declared potential conflicts of interest, and shared their expertise relevant to the elicitation. The group was then asked to identify its strengths and weaknesses as a collective. This information is solely used to help experts understand the characteristics of the group, and recognise their own expertise. It is not used to weight experts' judgements, as in elicitation protocols that use mathematical aggregation (for example, Cooke and Goossens (2000)).

Following the introductions, experts were provided with a primer on basic probability concepts including medians, quantiles, and plausible limits and a training elicitation, based on net rainfall for the month of May in Perth, Western Australia. Net rainfall was chosen due to its similarities with surface current, in the sense that it is a skewed and highly uncertain meteorological quantity. This provided the group with the opportunity to review their judgements. The facilitator used the training exercise to highlight and explain biases and heuristics that can affect the quality of elicitations (see Section 3.1), so that the experts could be cognisant of these effects during the actual elicitation.

Next, in conjunction with the experts, the scope of the elicitation was defined. Spatially, experts agreed to divide the Exmouth Plateau into two regions: the 'shelf-slope' region, defined as water depths less than 500 m, and the 'blue-water' region, defined as water depths more than 500 m. The elicitation was restricted to the 'shelf-slope' region as it is the region of primary industrial interest. Temporally, experts believed it optimal to distinguish between the Wet and the Dry seasons, for reasons discussed in Section 4 below. It was agreed that υ and θ were not independent and that is was most natural to discuss the seasonal effects first on surface current direction, then on magnitude given direction for that particular season. To clarify, denote by $p^w(\theta, \upsilon)$ and $p^d(\theta, \upsilon)$ the joint distribution for the Wet and Dry season respectively. The experts chose to consider $p^w(\theta, \upsilon) = p^w(\theta)p^w(\upsilon|\theta)$ and $p^d(\theta, \upsilon) = p^d(\theta)p^d(\upsilon|\theta)$.

After each round of individual judgements, each expert was invited by the facilitator to share their reasoning. A group discussion was then held to reach a consensus on what would be a rational impartial view of their combined knowledge. The facilitator took care to manage the group discussion so that each expert was engaged in the process and to ensure that no single expert dominated the conversation.

4. Elicitation results

The experts were asked to identify and consider the effects of the main phenomena which contribute to the surface currents. Four key phenomena were identified as eddies, internal waves, global currents, and wind-driven currents. Figure 2 shows the most common directions toward which they act in the Wet and Dry seasons. The diagrams in Figure 2 are excerpts from the workshop, and were used to help experts form a common mental model of the behaviour of the current generating phenomena.

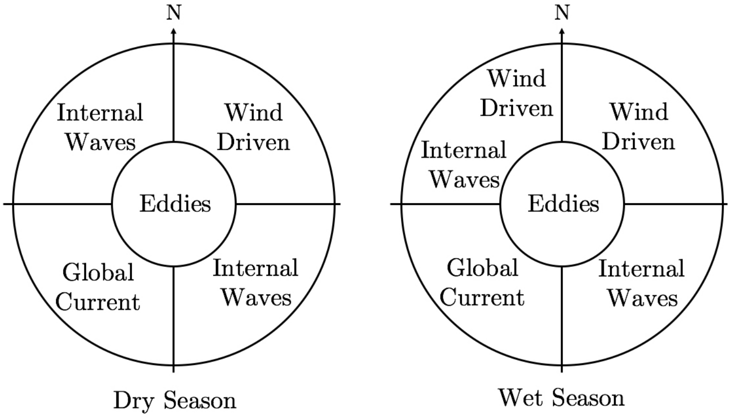


Figure 2: Prevalent identified phenomena contributing to the dominant directions for the Dry and Wet seasons. Phenomena act towards these directions.

In both the Dry and Wet seasons, the experts believed that the global current acts most commonly towards the South–West and wind driven currents most commonly towards the North–East, as a result of the transient South–West wind. In the Dry season, the opinion was that wind-driven currents are very infrequent and comparatively weak. In the Wet season, transient South–West wind-driven currents were thought to be frequent, comparatively strong and tending a little more North than the Dry season due to frequent depressions in the East. The result of the seasonal effects of these opposing forces suggested greater variability in the Wet than the Dry season, and the experts being more uncertain about eliciting overall surface current direction in the Wet season.

Directional effects of both internal waves and eddies were thought to be constant year-round. Internal waves predominantly act toward both the North–West and South–East quadrants. Eddies were considered to be quite unpredictable, but contributing to the extremes of surface current magnitude when in operation. Finally, cyclonic activity was believed to produce extreme currents shifts, both in direction and magnitude, and occurred during the Wet season.

4.1. Surface current direction

Experts identified the seasonal modal current directions as 225°during the Dry season, driven by the global current, and 45° for the Wet season, driven by the wind-driven currents. At first, 8 bins were considered but the experts were not comfortable eliciting surface current direction at such fine resolutions. Therefore, 4 bins were used throughout the workshop. In conjunction with the modal values, 4 bins result in the compass quadrants. Over a series of questions the experts were asked to distribute 100 chips among the bins.

Table 1 reports the elicited modes and bin probability judgements for each season. These results, as well as the bin orientations, are graphically shown in Figures 3a and 3b. Note that bin labels start at the quadrant containing θ_{mode} and proceeds clockwise. For example, the Dry season reports a mode of 225° so $B_1 = [180, 270)$ with $p^d(\theta \in [B_1]) = 0.525$ and $B_2 = [270, 360)$ with $p^d(\theta \in [B_2]) = 0.25$. Similarly, the Wet season reports a mode of 45° so $B_1 = [0, 90)$ with $p^w(\theta \in [B_1]) = 0.28$ and $B_2 = [90, 180)$

with $p^d(\theta \in [B_2]) = 0.22$. The elicited judgements were considered by the experts to be a satisfactory representation of the distribution of the directional effects of the main phenomena identified above.

		$p(\theta \in [B_i])$			
Season	θ_{mode}	$i = 1$	$i = 2$	$i = 3$	$i = 4$
Dry	225°	0.525	0.25	0.075	0.15
Wet	45°	0.28	0.22	0.23	0.27

Table 1: Seasonal modes and bin probabilities elicited by the roulette method. The range of each bin is calculated by Equation 1.

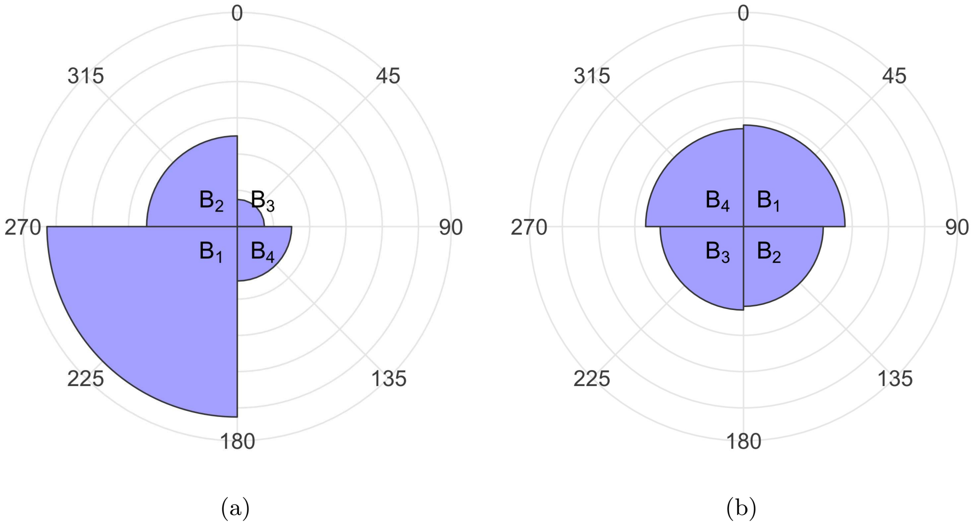


Figure 3: Elicitation results of the current direction in the (a) Dry season, and (b) Wet season.

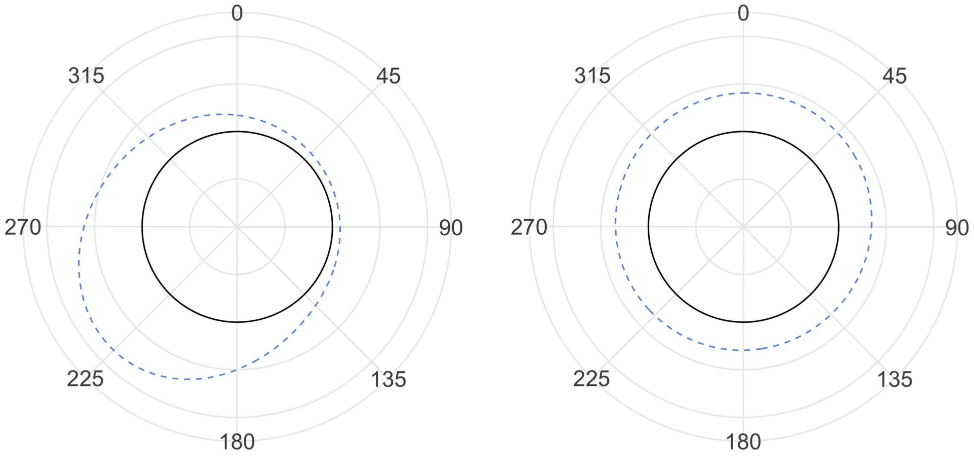
As the elicitation was conducted with 4 bins, we used the AGvM to provide a fit to the experts' judgements. The blue dashed lines in Figures 4a and 4b show $p^d(\theta)$ and $p^w(\theta)$ as fitted by the AGvM to the roulette elicitation results in Figures 3a and 3b. The parameter estimates resulting from the optimisation routine that give rise to $p^d(\theta)$ and $p^w(\theta)$ are reported in Table 2. Values of κ_1 are larger for $p^d(\theta)$ than $p^w(\theta)$, which represents higher concentration of probability mass about the mode in the Dry season. This reflects both the smaller variability of currents, and the higher degree of certainty held by the experts in their judgements for the Dry season. For the Dry season, $\kappa_2 = -0.166$ indicates skewness clockwise from the mode, with more mass allocated towards the North–West than the South–East. For the Wet season, skewness is not so pronounced with $\kappa_2 = 0.0279$. In both seasons $\kappa_1 \geq 2|\kappa_2|$, indicating that both seasons are unimodal.

	μ	κ_1	κ_2
$p^d(\theta)$	242	1.14	-0.166
$p^w(\theta)$	0.00	0.158	0.0279

Table 2: Parameters for the AGvM fits of surface current direction for each season.

4.2. Surface current magnitude

The conditional distribution of surface current magnitude, given direction, was elicited for each of the 4 bins for each season. Experts defined the plausible limits of all of distributions to be from 0 to $1.5\,\text{m}\,\text{s}^{-1}$. The common upper limit is indicative of the year round contribution of eddies. Although comparatively



(a) (b)

Figure 4: AGvM fits to the experts' judgements. Panel (a) reports $p^d(\theta)$ and panel (b) reports $p^w(\theta)$. The black solid line marks zero.

infrequent, eddies were thought capable of generating very large magnitudes. For $p^d(\upsilon|\theta \in [B_i])$ and $p^w(\upsilon|\theta \in [B_i])$, $i = 1, \ldots, 4$, expert judgements of medians ($p_{0.50}$), and lower ($p_{0.25}$) and upper ($p_{0.75}$) quartiles were elicited and are shown in Table 3. All judgements were skewed to the right, such that that the majority of the probability mass is concentrated around lower values, with heavy tails representing the possibility of large surface current magnitudes.

Using the SHELF software, the fitted distributions were presented to the experts in the workshop. This allowed the facilitator to further question the experts on their quantile beliefs. For instance, the 1st/5th and 95th/99th quantiles were frequently used to assess the probabilities of unlikely events. When the experts believed the tails were unrealistic, their judgements were adjusted so that the fitted tails were deemed representative of their beliefs. Questioning the experts on the tail probabilities frequently lead them to revise their judgements, suggesting that value was gained by having immediate access to the fitted distributions in the workshop. The quantile judgements presented in Table 3 are the finalised judgements, after revision of the fitted distributions.

Season	Direction	Bin	$p_{0.25}$	$p_{0.50}$	$p_{0.75}$
Dry	NE	B_3	0.05	0.15	0.25
	SE	B_4	0.12	0.15	0.22
	SW	B_1	0.15	0.25	0.33
	NW	B_2	0.12	0.21	0.33
Wet	NE	B_1	0.12	0.2	0.3
	SE	B_2	0.1	0.18	0.4
	SW	B_3	0.15	0.2	0.4
	NW	B_4	0.12	0.2	0.3

Table 3: Elicited quartile estimates for $p^d(\upsilon|\theta \in [B_i])$ and $p^w(\upsilon|\theta \in [B_i])$.

Gamma, log-normal, log-Student-t and truncated normal distributions were all shown to the experts for every set of judgements. Depending on the results, experts then selected the distribution they felt most appropriate. The gamma and log-normal distributions were sufficient to represent all of the experts elicited judgements. The log-normal is written as

$$p(v) = \frac{1}{v\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln v - \mu)^2}{2\sigma^2}\right), \quad v > 0, \quad \mu \in \mathbb{R}, \quad \sigma > 0,$$

with $\mathbb{E}[v] = \exp\left(\mu + \frac{\sigma^2}{2}\right)$ and $\mathrm{Var}[v] = [\exp(\sigma^2) - 1]\exp(2\mu + \sigma^2)$. We parameterise the gamma distribution as

$$p(v) = \frac{\beta^\alpha}{\Gamma(\alpha)} v^{\alpha-1} e^{-\beta v}, \quad v > 0, \quad \alpha > 0, \quad \beta > 0,$$

with $\mathbb{E}[v] = \frac{\alpha}{\beta}$ and $\mathrm{Var}[v] = \frac{\alpha}{\beta^2}$. The resulting fitted distributions are shown in Table 4. For the log-normal distributions "Para 1" denotes μ and "Para 2" σ. For the gamma distribution "Para 1" denotes α and "Para 2" β.

Season	Direction	Bin	Distribution	Para 1	Para 2	$\mathbb{E}[v]$	$\mathrm{Var}[v]$
Dry	NE	B_3	Gamma	0.976	4.99	0.196	0.039
	SE	B_4	Gamma	4.83	28.4	0.170	0.0060
	SW	B_1	Log-Normal	-1.45	0.601	0.281	0.034
	NW	B_2	Gamma	2.07	8.38	0.247	0.029
Wet	NE	B_1	Gamma	2.47	10.8	0.228	0.021
	SE	B_2	Log-Normal	-1.66	1.04	0.372	0.207
	SW	B_3	Gamma	1.81	6.46	0.280	0.043
	NW	B_4	Gamma	2.47	10.8	0.228	0.021

Table 4: Distributional fits, expected values and variances of $v|\theta \in [B_i]$ for the Wet and Dry seasons.

Comparison of the expected behaviour of v between quadrants and seasons can be made from the statistical summaries shown in Table 4. For instance, expected values and variances of v towards the North–East are $\mathbb{E}^d[v|\theta \in [B_3]] = 0.196$, $\mathbb{E}^w[U|\theta \in [B_1]] = 0.228$, $\mathrm{Var}^d[v|\theta \in [B_3]] = 0.039$ and $\mathrm{Var}^w[v|\theta \in [B_1]] = 0.021$. This implies that current magnitude towards the North–East is on average lower but more variable in the Dry season than the Wet season.

4.3. Marginal distribution of surface current magnitude

We also present $p^d(v)$ and $p^w(v)$ by marginalising $p^d(\theta, v)$ and $p^w(\theta, v)$, over θ. For binned values of θ, the marginal distribution in the Dry season is

$$p^d(v) = \sum_{i=1}^{m} p^d(\theta \in [B_i]) p^d(v|\theta \in [B_i]).$$

We calculate $p^w(v)$ similarly.

Figure 5 plots $p^d(v)$ and $p^w(v)$ and shows $p^d(v)$ allocates more mass to the interval (0.10,0.37) than $p^w(v)$. Conversely, $p^w(v)$ has higher density for $v < 0.10$ and $v > 0.37$. Statistical summaries are provided in Table 5. Quantiles are found computationally via Monte Carlo estimates, and the expected values and variances are calculated analytically. The statistical summaries presented in Table 5 show that $\mathbb{E}^w[v] > \mathbb{E}^d[v]$ and $\mathrm{Var}^w[v] > \mathrm{Var}^d[v]$. This implies that the Wet season experiences on average higher, more variable surface currents than the Dry season. This is further reflected in the percentile judgements listed in Table 5. Whilst the Dry and Wet seasons have very similar medians of $0.207\,\mathrm{m\,s^{-1}}$ and $0.204\,\mathrm{m\,s^{-1}}$, respectively, the larger variance in the Wet season is most clearly seen by examining the tails of the distributions. The 5th percentile reports values of $0.059\,\mathrm{m\,s^{-1}}$ and $0.045\,\mathrm{m\,s^{-1}}$, and the 95th percentile reports values of $0.584\,\mathrm{m\,s^{-1}}$ and $0.642\,\mathrm{m\,s^{-1}}$, for the Dry and Wet seasons. The higher concentration of mass around the median in the Dry season reflects less variability of surface current magnitude than the Wet season.

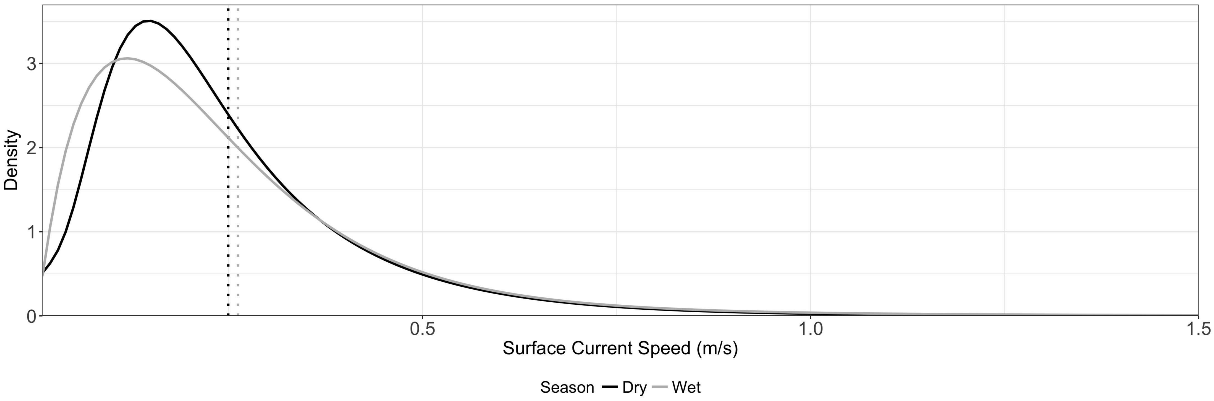


Figure 5: Seasonal marginal distributions of surface current, $p^d(v)$ and $p^w(v)$. The expected values of the distributions are marked by the dotted lines.

Season	$\mathbb{E}[v]$	$\mathrm{Var}[v]$	$p_{0.05}$	$p_{0.25}$	$p_{0.50}$	$p_{0.75}$	$p_{0.95}$
Dry	0.249	0.031	0.059	0.132	0.207	0.318	0.584
Wet	0.262	0.069	0.045	0.117	0.204	0.332	0.642

Table 5: Statistical summaries of $p^d(v)$ and $p^w(v)$.

5. Concluding Remarks

This article considers the use of expert knowledge in offshore engineering with an emphasis on quantifying the associated uncertainty and likelihood of events via probability. Directional metocean parameters are the quantities of interest as in offshore engineering their probability distributions are central to Monte Carlo analysis, probabilistic decision making, risk assessment and constructing prior distributions in Bayesian modelling. Although direct measurements or metocean model outputs may be used to estimate these distributions, there are many situations when neither are adequate. This is particularly the case for localised currents because obtaining comprehensive measurements is expensive and numeric modelling of complex processes such as eddies, solitons and internal tides remains a challenge (Dhanak and Xiros, 2016).

It is important to recognise that the elicitation process specifically addresses the experts' subjective beliefs, at the time of the workshop. The results would very likely differ for a different group of experts or for the same group of experts on another occasion. However, quantification of the uncertainty or reliability associated with the resulting probability distributions is difficult. Rather, the success of the process is gauged by whether the experts are satisfied with the outcome and whether the outcome is useful. We argue this research meets both criteria. After eliciting surface currents on the Exmouth Plateau, we provided a document summarising the results for feedback from the experts. All experts indicated that the group elicitation workshop added to their own knowledge of surface current behaviour on the Exmouth Plateau. Furthermore, the experts were content that the results were satisfactory for use in Monte Carlo analyses of numeric models of vessel motions evaluated for the Exmouth Plateau. Ongoing research has commenced that combines hindcast data of winds and waves on the Exmouth Plateau with the elicited surface currents to provide a joint distribution of these model inputs.

By following the SHELF protocol and including an experienced facilitator, the process of eliciting magnitude was routine, albeit novel in offshore engineering. Direction, obviously important when describing many metocean parameters, has not yet been considered in the elicitation literature. We used a variant of roulette elicitation to elicit expert judgements for direction, and fitted these judgements using the asymmetric generalised von Mises distribution, although other circular distributions may be used. For metocean parameters that are commonly understood to a higher resolution (for example, wind) experts may be comfortable eliciting more than 4 bins. In such cases it is possible to harness the additional flexibility of the generalised von Mises distribution. The methodology is transferable to suit any directional metocean parameter and we embedded the process into the SHELF protocol. The result is a framework with which directional metocean parameters may be elicited.

6. Acknowledgements

This research was supported by the ARC Industrial Transformation Research Hub for Offshore Floating Facilities which is funded by the Australian Research Council, Woodside Energy, Shell, Bureau Veritas and Lloyds Register (Grant No. IH140100012)

References

Afenyo, M., Khan, F., Veitch, B., Yang, M., 2017. Arctic shipping accident scenario analysis using Bayesian Network approach. Ocean Engineering 133, 224–230.

Akyuz, E., 2016. Quantitative human error assessment during abandon ship procedures in maritime transportation. Ocean Engineering 120, 21–29.

Australian Bureau of Meteorology, 2017. Climatology of Tropical Cyclones in Western Australia. `http://www.bom.gov.au/cyclone/climatology/wa.shtml`. Accessed: 2017-11-08.

Batz, M.B., Hoffmann, S., Morris Jr, J.G., 2012. Ranking the disease burden of 14 pathogens in food sources in the United States using attribution data from outbreak investigations and expert elicitation. Journal of Food Protection 75, 1278–1291.

Bitner-Gregersen, E.M., Bhattacharya, S.K., Chatjigeorgiou, I.K., Eames, I., Ellermann, K., Ewans, K., Hermanski, G., Johnson, M.C., Ma, N., Maisondieu, C., et al., 2014. Recent developments of ocean environmental description with focus on uncertainties. Ocean Engineering 86, 26–46.

Brewer, D.T., Lyne, V., Skewes, T.D., Rothlisberg, P., 2007. Trophic systems of the North West marine region. Report to the Department of the Environment and Water Resources.

Chan, G., Anadon, L.D., Chan, M., Lee, A., 2011. Expert elicitation of cost, performance, and RD&D budgets for coal power with CCS. Energy Procedia 4, 2685–2692.

Chen, H., Moan, T., Haver, S., Larsen, K., 2002. Prediction of relative motion and probability of contact between FPSO and shuttle tanker in tandem offloading operation, in: ASME 2002 21st International Conference on Offshore Mechanics and Arctic Engineering, American Society of Mechanical Engineers. pp. 91–100.

Clemen, R.T., Winkler, R.L., 1999. Combining probability distributions from experts in risk analysis. Risk Analysis 19, 187–203.

Condie, S.A., Andrewartha, J.R., 2008. Circulation and connectivity on the Australian North-West Shelf. Continental Shelf Research 28, 1724–1739.

Cooke, R.M., 1991. Experts in uncertainty: Opinion and subjective probability in science. Oxford: Oxford University Press.

Cooke, R.M., Goossens, L.J.H., 2000. Procedures Guide for Structured Expert Judgment. Report EUR 18820, Brussels-Luxembourg.

D'Adamo, N., Fandry, C., Buchan, S., Domingues, C., 2009. Northern sources of the Leeuwin current and the Holloway Current on the North-West Shelf. Journal of the Royal Society of Western Australia 92, 53–66.

Dhanak, M.R., Xiros, N.I., 2016. Springer Handbook of Ocean Engineering. Springer.

Exon, N.F., Haq, B.U., Von Rad, U., 1992. Exmouth Plateau revisited: Scientific drilling and geological framework, in: Proceedings of the Ocean Drilling Program, Scientific Results, pp. 3–20.

Exon, N.F., Willcox, J.B., 1980. The Exmouth Plateau–stratigraphy, structure, and petroleum potential. 199-200, National Gallery of Australia.

Feng, M., Meyers, G., Pearce, A., Wijffels, S., 2003. Annual and interannual variations of the leeuwin current at 32 s. Journal of Geophysical Research: Oceans 108.

Fisher, N.I., 1995. Statistical analysis of circular data. Cambridge University Press.

Garthwaite, P.H., Kadane, J.B., O'Hagan, A., 2005. Statistical methods for eliciting probability distributions. Journal of the American Statistical Association 100, 680–701.

Gatto, R., Jammalamadaka, S.R., 2007. The generalized von Mises distribution. Statistical Methodology 4, 341–353.

Goossens, L.H.J., Cooke, R.M., Hale, A.R., Rodić-Wiersma, L., 2008. Fifteen years of expert judgement at TUDelft. Safety Science 46, 234–244.

Gore, S.M., 1987. Biostatistics and the medical research council. Medical Research Council News 35, 19–20.

Gosling, J.P., 2018. SHELF: the Sheffield elicitation framework, in: Elicitation. Springer, pp. 61–93.

Gosling, J.P., Hart, A., Mouat, D.C., Sabirovic, M., Scanlan, S., Simmons, A., 2012. Quantifying experts uncertainty about the future cost of exotic diseases. Risk Analysis 32, 881–893.

Hänninen, M., 2014. Bayesian networks for maritime traffic accident prevention: Benefits and challenges. Accident Analysis & Prevention 73, 305–312.

Hänninen, M., Mazaheri, A., Kujala, P., Montewka, J., Laaksonen, P., Salmiovirta, M., Klang, M., 2014. Expert elicitation of a navigation service implementation effects on ship groundings and collisions in the Gulf of Finland. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability 228, 19–28.

Higgins, H.M., Dryden, I.L., Green, M.J., 2012. A Bayesian elicitation of veterinary beliefs regarding systemic dry cow therapy: Variation and importance for clinical trial design. Preventive Veterinary Medicine 106, 87–96.

Holloway, P.E., 1988. Physical oceanography of the Exmouth Plateau region, North-Western Australia. Marine and Freshwater Research 39, 589–606.

Holloway, P.E., 2001. A regional model of the semidiurnal internal tide on the Australian North-West Shelf. Journal of Geophysical Research: Oceans 106, 19625–19638.

Holloway, P.E., Nye, H.C., 1985. Leeuwin current and wind distributions on the southern part of the Australian North-West Shelf between January 1982 and July 1983. Marine and Freshwater Research 36, 123–137.

Hora, S.C., Hora, J.A., Dodd, N.G., 1992. Assessment of probability distributions for continuous random variables: A comparison of the bisection and fixed value methods. Organizational Behavior and Human Decision Processes 51, 133–155.

Ioannou, I., Aspinall, W., Rush, D., Bisby, L., Rossetto, T., 2017. Expert judgment-based fragility assessment of reinforced concrete buildings exposed to fire. Reliability Engineering & System Safety 167, 105–127.

Johnson, J.S., Cui, Z., Lee, L.A., Gosling, J.P., Blyth, A.M., Carslaw, K.S., 2015. Evaluating uncertainty in convective cloud microphysics using statistical emulation. Journal of Advances in Modeling Earth Systems 7, 162–187.

Jonathan, P., Ewans, K., 2013. Statistical modelling of extreme ocean environments for marine design: A review. Ocean Engineering 62, 91–109.

Kadane, J., Wolfson, L.J., 1998. Experiences in elicitation. Journal of the Royal Statistical Society: Series D (The Statistician) 47, 3–19.

Kennedy, M., Anderson, C., O'Hagan, A., Lomas, M., Woodward, I., Gosling, J.P., Heinemeyer, A., 2008. Quantifying uncertainty in the biospheric carbon flux for England and Wales. Journal of the Royal Statistical Society: Series A (Statistics in Society) 171, 109–135.

Kim, S., SenGupta, A., 2013. A three-parameter generalized von Mises distribution. Statistical Papers 54, 685–693.

Knight, J.T., Collette, M.D., Singer, D.J., 2015. Design for flexibility: Evaluating the option to extend service life in preliminary structural design. Ocean Engineering 96, 68–78.

Krayer von Krauss, M.P., Casman, E.A., Small, M.J., 2004. Elicitation of expert judgments of uncertainty in the risk assessment of herbicide-tolerant oilseed crops. Risk Analysis 24, 1515–1527.

Kynn, M., 2008. The "heuristics and biases" bias in expert elicitation. Journal of the Royal Statistical Society: Series A (Statistics in Society) 171, 239–264.

Lark, R.M., Lawley, R.S., Barron, A.J.M., Aldiss, D.T., Ambrose, K., Cooper, A.H., Lee, J.R., Waters, C.N., 2015. Uncertainty in mapped geological boundaries held by a national geological survey: Eliciting the geologists' tacit error model. Solid Earth 6, 727.

Lee, L.A., Pringle, K.J., Reddington, C.L., Mann, G.W., Stier, P., Spracklen, D.V., Pierce, J.R., Carslaw, K.S., 2013. The magnitude and causes of uncertainty in global model simulations of cloud condensation nuclei. Atmospheric Chemistry and Physics 13, 8879.

Lowe, R.J., Ivey, G.N., Brinkman, R.M., Jones, N.L., 2012. Seasonal circulation and temperature variability near the North West Cape of Australia. Journal of Geophysical Research: Oceans 117.

Mardia, K.V., 2014. Statistics of directional data. Academic press.

Meyer, M., Booker, J., 1981. Eliciting and Analyzing Expert Judgement: A Practical Guide. New York: Academic Press.

Milne, I.A., Delaux, S., McComb, P., 2016. Validation of a predictive tool for the heading of turret-moored vessels. Ocean Engineering 128, 22–40.

Morrow, R., Fang, F., Fieux, M., Molcard, R., 2003. Anatomy of three warm-core Leeuwin Current eddies. Deep Sea Research Part II: Topical Studies in Oceanography 50, 2229–2243.

Murray, J.V., Goldizen, A.W., OLeary, R.A., McAlpine, C.A., Possingham, H.P., Choy, S.L., 2009. How useful is expert opinion for predicting the distribution of a species within and beyond the region of expertise? A case study using brush-tailed rock-wallabies Petrogale penicillata. Journal of Applied Ecology 46, 842–851.

NOPTA, 2017. National Offshore Petroleum Information Management System. `https://nopims.dmp.wa.gov.au/Nopims/Search/Wells`. Accessed: 2017-07-08.

Oakley, J.E., O'Hagan, A., 2010. SHELF: The Sheffield Elicitation Framework (version 2.0). Sheffield, UK: School of Mathematics and Statistics, University of Sheffield .

O'Hagan, A., Buck, C.E., Daneshkhah, A., Eiser, J.R., Garthwaite, P.H., Jenkinson, D.J., Oakley, J.E., Rakow, T., 2006. Uncertain judgements: Eliciting experts' probabilities. John Wiley & Sons.

Rayson, M.D., Ivey, G.N., Jones, N.L., Meuleners, M.J., Wake, G.W., 2011. Internal tide dynamics in a topographically complex region: Browse Basin, Australian North West Shelf. Journal of Geophysical Research: Oceans 116.

Ren, S., Oakley, J.E., 2014. Assurance calculations for planning clinical trials with time-to-event outcomes. Statistics in Medicine 33, 31–45.

Rossi, V., Feng, M., Pattiaratchi, C., Roughan, M., Waite, A.M., 2013. Linking synoptic forcing and local mesoscale processes with biological dynamics off Ningaloo Reef. Journal of Geophysical Research: Oceans 118, 1211–1225.

Runge, M.C., Converse, S.J., Lyons, J.E., 2011. Which uncertainty? Using expert elicitation and expected value of information to design an adaptive program. Biological Conservation 144, 1214–1223.

Tahar, A., Kim, M., 2003. Hull/mooring/riser coupled dynamic analysis and sensitivity study of a tanker-based FPSO. Applied Ocean Research 25, 367–382.

Tversky, A., Kahneman, D., 1973. Availability - A heuristic for judging frequency and probability. Cognitive Psychology 5, 207–232.

Van Gastel, P., Ivey, G.N., Meuleners, M.J., Antenucci, J.P., Fringer, O., 2009. The variability of the large-amplitude internal wave field on the Australian North West Shelf. Continental Shelf Research 29, 1373–1383.

Wallsten, T.S., Budescu, D.V., 1983. Encoding subjective probabilities: A psychological and psychometric review. Management Science 29, 151–173.

Winkler, R., 1967. The quantification of judgment: Some methodological issues. Journal of the American Statistician 62, 1105–1120.

Xia, J., 2012. FPSO design to minimise operational downtime due to adverse metocean conditions off North West Australia. Deep Offshore Technology (DOT), Perth, Australia .

Zhang, G., Thai, V.V., 2016. Expert elicitation and Bayesian network modeling for shipping accidents: A literature review. Safety Science 87, 53–62.

Zhao, W., Yang, J., Hu, Z., Tao, L., 2014. Prediction of hydrodynamic performance of an FLNG system in side-by-side offloading operation. Journal of Fluids and Structures 46, 89–110.