The ambiguities of uncertainty:

A review of uncertainty frameworks relevant to the assessment of environmental change

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Abstract

As awareness of deep uncertainties in many disciplines has grown over the last half-century, researchers have developed many frameworks, typologies, and taxonomies to understand, analyse, and communicate them. Uncertainty analysis is critically important in fields of study that deal with large, complex, societally-coupled problems, such as those dealing with environmental change. However, as of yet, no wide-ranging review exists that systematically compares the features of these frameworks. This paper surveys a very large number of uncertainty frameworks (N=156) relevant to the assessment of environmental change, identifying their key features and highlighting the conceptual foundations of these frameworks. It shows that although many authors have employed very similar methods of classification, significant ambiguities may exist because of overlapping concepts or polysemous terminology. Further to this, philosophical inconsistencies are pervasive in the frameworks. This paper argues that the synthesis of these frameworks into one with general applicability is likely unachievable, and given the ambiguity of the meaning of much of the uncertainty lexicon, a more fruitful approach would be to start by examining the conceptual understandings of practitioners themselves.

1 Introduction

1.1 The use of uncertainty frameworks

Uncertainty undergirds many aspects of public life, often referred to in media as some amorphous evil, an anathema to business and a frequent subject of discourse during turbulent political times. Perceptions of uncertainty have been exploited by opponents of environmental policy to bring the edifice of science into disrepute and stymie political action on environmental issues such as climate change, acid rain and ozone depletion (Björnberg et al., 2017; Lewandowsky et al., 2015; Oreskes and Conway, 2012).

To analyse uncertainty in their research, many authors writing in both theoretical and applied literature over the years have turned to the production of frameworks, typologies, categorisations and taxonomies. For example, in environmental modelling, frameworks may help identify opportunities for model development. However, many uncertainty typologies only have relevance in narrow fields; *there is no one uncertainty framework to rule them all.*

1.2 Aims

There is a very substantial corpus of literature containing uncertainty frameworks; this literature is not homogeneous and aspects of uncertainty are conceptualised differently. This paper aims to take an overarching view on what these frameworks are and how they employ different concepts. The following questions, therefore, guide our review:

- *How are uncertainty frameworks typically structured?*
- *What are the most important conceptual features of uncertainty frameworks in literature, and what distinctions are typically made between different kinds of uncertainty?*
- *How do these conceptual distinctions relate to one another?*

Frigg et al. (2015) describe the field of uncertainty typologies as *pre-paradigmatic*.
Whilst I agree that the landscape of this literature is fractured and riven with confusion, I do not believe that a paradigm in uncertainty classification is achievable; it is hoped instead that the reader will be provided with a clearer map of some of the more prominent features of this terrain and will be better able to navigate the conceptual rifts that run through it.

1.3 The importance of understanding uncertainty frameworks

Uncertainty frameworks are particularly important in fields lying at the nexus of multiple disciplines and addressing significant societal problems, such as climate change-related studies. Through the alignment of terminology, they standardise the communication of uncertainty, which is important for decision-making (Morgan and Henrion, 1990). Thus *uncertainty guidances* are used by organisations such as the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2005a; Mastrandrea et al., 2010; Moss and Schneider, 2000), the Netherlands Environmental Assessment Agency (PBL) (Petersen et al., 2013; van der Sluijs et al., 2003), the World Meteorological Organization (WMO) (Gill et al., 2008) and the US Environmental Protection Agency (EPA) (Krupnick et al., 2006). Given the prominence of these uncertainty frameworks and their role in communicating scientific findings to both decision-makers and lay audiences, it is important that they are well understood.

Uncertainty frameworks have various important purposes in different research contexts. Inventories of uncertainties have been used variously for:

- Identifying opportunities for improvement of the work through further research (e.g. Walker et al., 2003)
- Providing a basis for decision-making on complex issues (e.g. Morgan and Henrion, 1990; Walker et al., 2003),
- Identifying risks (e.g. NRC, 1994)
- Aligning work with ethical values such as transparency (e.g. Hamel and Bryant, 2017)
- Identifying appropriate tools and techniques for uncertainty analysis (e.g. Dreier and Howells, 2019; van der Sluijs et al., 2003; Ricci et al., 2003; Stirling, 1998)

Uncertainty frameworks also play a role in standardising the treatments of uncertainty in a particular research area, creating semantic alignment to ensure similar issues receive consistent treatment (Moss and Schneider, 2000). Furthermore, they may provide the first step in guiding appropriate communication of findings among scientists, policy analysts, decision-makers, lay audiences and other end-users (Fischhoff and Davis, 2014; IPCC, 2005b; Petersen et al., 2013; van der Sluijs et al., 2003; Walker et al., 2003)

1.4 Previous research

Several previous papers have conducted literature reviews in this area, focussing on the conceptualisations of uncertainty. These are summarised in Table 1, below.

Table 1: Summary of previous reviews of uncertainty conceptualisations, the number of frameworks reviewed and their approaches.

Reference	**N**	**Thematic Focus**	**Approach**
Walker et al. (2003)	13	Model-based decision support/ Integrated Assessment	The authors present a highly influential framework for uncertainty that brings together several concepts. This has been variously described in literature as a review. They identify 13 papers from literature but do not explicitly identify divergences; instead, "*the aim of this paper is to highlight the agreements*".
Krupnick et al. (2006)	18	Environmental Protection, Regulation	As part of this report for the US EPA they review several uncertainty typologies that have influenced discussions of uncertainty in EPA documents. This is then used to build their own typology. It is unclear how sources were selected.
Kwakkel et al. (2010)	12	Model-based Policy analysis	The authors specifically review uncertainty frameworks influenced by Walker et al (2003). They reviewed citations of the original paper and selected those relevant for analysis.
Skinner et al. (2014)	30	Environmental Risk Assessments (ERAs)	The methodology for selection of uncertainty typologies is unclear. However, they later conduct a separate review of how ERAs use uncertainty using a novel systematic technique.
Baustert et al. (2018)	14	Ecosystems Services, Integrated Environmental Models (IEMs)	They review several frameworks relevant to IEMs. They acknowledge their review is partial and the original corpus is unclear; but select frameworks that have at least a classification and recommendations for uncertainty handling.
Doyle et al (2019)	35	Disaster Risk Management	A broader systematic review of papers on the topic of *communicating model uncertainty*. They identify the categorisation of uncertainty as one of the themes within this corpus and review some frameworks. They identify styles of classifications, including those specifically for spatial uncertainties and matrix-type typologies. Their thematic focus is *disaster risk management* but include

			literature from a broad array of disciplines such as health and visualisation.
Kirchner et al. (2021)	16	Integrated Modelling	They review several uncertainty conceptualisations relevant to Integrated Assessment Modelling. The authors conducted initial searches using several key terms. Following the identification of key articles, they then employed a snowball method to gather more relevant publications.

Six of the seven previous reviews identified have subsequently developed their own synthesis framework or improvements on an original framework. Most arrive at dimensions frameworks such as that of Walker et al. (2003). The reviews identified utilise either opaque literature selection methodologies (Baustert et al., 2018; Krupnick et al., 2006; Skinner et al., 2014; Walker et al., 2003), search for citations of one existing framework (Kwakkel et al., 2010) or employ a limited snowball approach (Kirchner et al., 2021). Doyle et al. (2019), as part of a broader review on the communication of model uncertainty in disaster risk planning, identify a number of frameworks containing categorisations but do not analyse the concepts used in these frameworks.

1.5 Review approach

This paper's core is a review of literature spanning multiple disciplines. The literature base's fragmentary nature and the inconsistency of terminology renders highly systematic keyword searches ineffective and vulnerable to significant omissions. Instead, an extensive snowball approach was employed: literature was initially found through searches of *Scopus* and the *Web of Science*, manually sorted to include frameworks relevant to environmental change-related studies. From this initial sample, other papers containing frameworks referenced were found and recursively analysed in turn in a branching manner until leads were exhausted. Such systematic snowball approaches are commonly employed when terminology is not consistently used across sources (Lecy and Beatty, 2012) and can yield larger corpora than keyword searches alone (Wohlin, 2014). This technique has been used to a much more limited extent in this subject area by Kirchner et al. (2021).

Appendix A gives a detailed account of the review process and an overview of the literature reviewed. Appendix B contains summaries of the uncertainty frameworks in each of the sources reviewed.

Limited unintentional omissions are unavoidable given the thematic and structural diversity of sources that could be included in such a review. However, manually exhausting all leads from an initial corpus produces a very extensive corpus, and conceptual exhaustion was noted. Resultingly, this review incorporates a far greater body of literature (N=156) than previous reviews and is far more extensive in its analysis.

1.6 Structure

The literature review is presented in two phases. *Section 2* considers *what these frameworks classify* and *how they are generally structured* to clarify exactly *what are* the conceptual frameworks reviewed. *Section 3* analyses the content of these frameworks through identification of key conceptual features and offers an emerging account of the considerable number of epistemic issues described in these frameworks. *Section 4* discusses these issues and presents challenges to consider for those using, developing or selecting from frameworks. *Section 5* then concludes this review.

2 The *structure* of uncertainty frameworks

2.1 How is uncertainty defined?

Uncertainty is one of the more capricious terms in the modern scientific lexicon and is defined variously by different authors for different purposes. Its polysemous nature has been recognised by a number of authors (Dequech, 2011; Kwakkel et al., 2010; Milliken, 1987). Table 2 gives some of the definitions on offer in the literature reviewed.

Table 2: A selection of definitions of uncertainty available in the literature reviewed

Reference	**Definition of *Uncertainty***
Walker et al (2003)	"…any departure from the unachievable ideal of complete determinism."
Brown (2004)	"…our inability to resolve a unique, causal, world, either in principle or in practice…"
Brouwer and De Blois (2008)	"… limited (incomplete or imperfect) knowledge and information about current or future environmental, social, economic, technological, political and institutional conditions, states and outcomes and the implications or consequences of these current or future conditions, states and outcomes"
Brugnach et al. (2008)	"we consider uncertainty impinging on a decision situation has no meaning in itself, but acquires meaning through the relationships established between the decision maker and the socio-technical environmental system. […] Uncertainty then becomes a property of how an individual in a social context relates to a system through certain practices and activities […] involving knowledge of different types."
Sigel et al. (2010)	"A person is uncertain if he/she lacks confidence about his/her knowledge relating to a concrete question"

Most generally, uncertainty definitions vary in three ways. *Firstly,* uncertainty is conceptualised as existing in different sites: either as something truly existing in nature, as a property of one's mental state (*psychological)* (e.g. Sigel et al (2010)), or as an object of social construction (*sociological)* (e.g. Brugnach et al., 2008; Wynne, 1992).

Secondly, the idealised yet unachieved epistemic state to which the uncertainty is constructed in reference varies. This may be a state of complete understanding (Brugnach et al., 2008), knowledge of some particular outcome, determinism (Petr et al., 2019; Walker et al., 2003; Warmink et al., 2010), knowledge sufficient for a particular purpose (Sigel et al., 2010) or confidence in one's knowledge (Kirchner et al., 2021).

Thirdly, uncertainty may be in reference to different possible knowable things: past, present and future states of systems (Brouwer and De Blois, 2008); future trends and events (Kutiel, 2019); the outputs of models (Kann and Weyant, 2000); answers to concrete questions (Sigel et al., 2010); the relationships laws or mechanisms that drive the behaviour of systems (Bergman et al., 2010); the consequences of actions both in terms of material outcomes and human subjective evaluation of these outcomes (Brouwer and De Blois, 2008). In the context of futures studies, one may differentiate types of claims by whether they are truth claims about future system states or explanations of mechanisms driving system behaviour (Bergman et al., 2010).

Furthermore, when used as a noun, 'uncertainties' may refer to facts or propositions about a situation that lead to a position of uncertainty.

2.2 The ontology of frameworks

The frameworks examined in this paper take various forms. The earliest are simple definitions that clarify key concepts such as risk, probability, uncertainty, ignorance and ambiguity (e.g. Ellsberg, 1961; Keynes, 1921; Knight, 1921). The complex relationship between these has seen an exchange of ideas over the last century, with conceptual boundaries frequently renegotiated.

The next level of framework complexity involves listing sorts of uncertainty that one may face. These categories of uncertainty may be distinct (e.g. Funtowicz and Ravetz, 1990) or non-exclusive (a single uncertainty can be given multiple labels) (e.g. Smith and Stern, 2011; Wynne, 1992). Increasing in complexity are 'taxonomies' which organise uncertainties in hierarchical categories, frequently represented by dendrograms (e.g. Ascough II et al., 2008; Faber et al., 1992; Suter et al., 1987).

The most complex class of frameworks conceptualise uncertainties as having orthogonal traits, different *dimensions* defining scales or categorisations (Bradley and Drechsler, 2014; Davies et al., 2014; Ekström et al., 2013; Faucheux and Froger, 1995; van der Sluijs, 1997; Walker et al., 2003). Many of these are influenced by Walker et al.'s (2003) highly prominent paper. Dimensions may be exclusive (e.g. Warmink et al., 2010) or allow overlaps, with individual uncertainties inhabiting multiple points in the space constructed by these dimensions, in which case the categories may be best described as *traits* (e.g. Petersen, [2006] 2012). These systems are also frequently represented by *uncertainty matrices*. Norton et al. (2006) point out that matrices with a small number of classes along each dimension (such as that of Walker et al., 2003) can be better described as taxonomies.

3 The *content* of uncertainty frameworks

We now consider the most prominent categorisations of uncertainty within these frameworks and how distinctions are made. The features of uncertainty frameworks identified in this section include:

1. *The aleatoric/epistemic divide:* two fundamental species of uncertainty are often described, yet in different ways.
2. *Levels of uncertainty* that generally range from complete indeterminacy to determinacy.
3. *The division of uncertainty by one's cognisance* (or lack thereof) of the uncertainties and their causes (varieties of ignorance and its border).
4. *The location (or source)* of an uncertainty within a knowledge production or decision-making process.
5. Uncertainties due to *difficulties in communication or forming consensus within social groups*; and
6. The incorporation into frameworks of *human values, subjectivity and normativity*: ethical, moral, epistemic and political.

3.1 The aleatoric/epistemic divide

Perhaps the most common and abiding feature of uncertainty discussions is a separation between two different fundamental species of uncertainties, in contemporary literature most generally labelled *aleatoric* and *epistemic* uncertainty. There is a loose correspondence between these fundamental types in the literature, though their divide is inconsistently described. We identify four means by which these two types of uncertainty are generally distinguished from one another:

- *Measurability* (measurable versus non-measurable)
- *Meta-uncertainty* (described uncertainty versus *uncertainty about that uncertainty*)
- *Nature* (due to variability in a system versus due to a lack of knowledge)
- *Reducibility* (non-reducible versus reducible)

Measurability

The most famous early elucidation of this divide came from Frank Knight (1921) in his book *Risk, Uncertainty and Profit*: *Risk* is measurable, while *True Uncertainty* defies attempts to measure it. Either an uncertainty is known *a priori*[1] (like a dice roll), or we cannot know the probabilities of outcomes (Sakai, 2016, p. 15). This distinction is often called 'Knightian Risk or Uncertainty'.

Keynes[2] made a similar distinction between *probability* and *uncertainty* (Carvalho, 1988) in his *Treatise on Probability* (Keynes, 1921). *Probability* for Keynes also includes probability intervals (e.g. 10–20% chance), likelihood ordering (e.g. p(a)>p(b)>p(c)) and non-orderable likelihood judgements (e.g. subjective statements) (Sakai, 2016). Probability links a set of premises one holds to possible conclusions: "As our knowledge or our hypothesis changes, our conclusions have new probabilities, not in themselves, but relatively to these new premises" (Keynes, 1921, p. 7). This interpretation of probability has been subject to contestation, famously by Ramsey (2016 [1931]), who criticised these probability relations as not existing in reality (Runde, 1994).

Uncertainty, on the other hand for Keynes, has its generation in the capriciousness of human behaviour (so-called *animal spirits*), with an unknowable or unimaginable range of outcomes (Sakai, 2016). Keynes also is known for the concept of the *weight of evidence* in which one apportions more importance to premises containing more relevant evidence. Keynes relates this to the "degree of completeness of information" (Runde, 1990), which some subsequent authors have related to a degree of certainty (Runde, 1990 after Lawson, 1985).

The ideas of Ellsberg dovetail, to an extent, with those of Keynes and Knight. *Ellsberg's paradox* observes that individuals prefer gambles with known probabilities over *ambiguity*[3] in which probabilities are unknown, despite equal expected utility (Ellsberg, 1961, p. 656). Within Ellsberg's ambiguity, subjects are able to make judgements on the strength of information affecting their beliefs (Ellsberg, 1961, pp. 657–8). Thus, *uncertainty* and *ambiguity* are separated by their *measurability,* and *ambiguity* describes a sort of *meta-uncertainty* (uncertainty about uncertainty).

Meta-uncertainty

If we can produce a measurement or estimate of uncertainty, may we be confident in it? Funtowicz & Ravetz (1990, p. 22) define uncertainties as having three sorts: *inexactness*, a measure of the spread of some data; *unreliability,* a measure of confidence in a quantitative statement; and *border with ignorance* in which fundamental ignorance is unavoidable. The difference between inexactness and unreliability is therefore a kind of *meta-uncertainty*, i.e. the confidence one has about some uncertainty that is described. Similarly, Suter et al. (1987) separate using *meta-*

[1] This could apply to situations where probability distributions may be stable over some relevant temporal or spatial period.
[2] The interpretation of Keynes' ideas about uncertainty are subject to some forthright contestation (e.g. Brady, 2014); it is described here in a broad sense in order to convey the difference with Knight.
[3] An example of *ambiguity* is the outcome of a bet on the colour of a ball drawn at random from an urn: in the first situation an urn contains 50 red and 50 black balls; in the second situation the number of black and red balls is unknown. This latter situation Ellsberg describes as '*ambiguity*' as the probability distribution is unknown. People are said to prefer the former situation to the latter, even though the expected utility may be equal.

uncertainty with *defined uncertainty* about a fact and *undefined uncertainty* about one's level of ignorance. Van der Blés et al. (2019) separate uncertainty directly expressed about a fact and that about one's level of ignorance (see also Gaudard and Romerio, 2020). A form of meta-uncertainty may be the difference between *error* (the actual difference between an estimate and a value) and *uncertainty* (the estimate of the error) (Henrion and Fischhoff, 2014).

Nature

In recent literature, uncertainty is often described as being *aleatoric*[4]*/ontic*[5] *or systematic/epistemic* (Kwakkel et al., 2010; Petersen, 2006; Rotmans and van Asselt, 2001; Spiegelhalter and Riesch, 2011, p. 4731; van Asselt et al., 2001, pp. 17–19; van Asselt and Rotmans, 2002a, pp. 78–80; Walker et al., 2003). This divide is labelled as '*nature*': there is an incommensurable difference between uncertainty due to the fundamental nature of a system and its variability or indeterminacy, and uncertainty due to a limited knowledge state. Authors are often in disagreement as to whether ontic uncertainty includes uncertainty due to social structuring within the system or whether this nature of the system is simply physical variability (Knol et al., 2009). This terminology originated in Hacking's (1975) distinction between *aleatory and epistemic probabilities* and is particularly prevalent in frameworks influenced by Walker et al. (2003).

Reducibility

The final distinction is *reducibility*: whether uncertainties are reducible through the acquisition of more knowledge (See for example Ascough II et al., 2008; Kelly and Campbell, 2000). This perhaps provides a simpler method of distinguishing between two types; however, the acquisition of more knowledge may increase uncertainty.

A loose yet highly imperfect coherence can be seen between these four mechanisms; many measurable uncertainties are also characterised as aleatoric, non-reducible and measurable, and vice versa. Table 3 summarises a number of these two-type uncertainty separations, the nomenclature used and the mechanism that separates them.

Table 3: Selected fundamental divisions of uncertainty into type-1 and type-2.

Author(s)	**'Aleatory' Label**	**'Epistemic' Label**	**Mechanism of Separation**
Knight (1921) Luce & Raiffa (1957)	Risk	Uncertainty	*Measurability*: Risk is measurable, uncertainty is not
Keynes (1921)	Probability	Uncertainty	*Measurability* (Broadly): Probabilistic (in a very broad sense) information is organisable (either numerically, ordinally or some kind of non-numerical degree of belief may be affixed). Uncertainty has origin in capriciousness of human behaviour.
Shackle (1955)	[Unnamed]	True Uncertainty	*Measurability*: Probabilities (frequency ratios) of outcomes cannot be known *a priori* or through repeated trials
Ellsberg (1961)	Uncertainty/Risk	Ambiguity	*Measurability (and Meta-*Uncertainty): In former, probabilities are known. In ambiguity probabilities are not known and is a "quality depending on the amount, type, reliability and 'unanimity' of information, giving rise to one's degree of 'confidence' in an estimate of relative likelihoods"
Einhorn & Hogarth (1986)	Uncertainty	Ambiguity	*Meta-Uncertainty and Measurability:* Ambiguity is "uncertainty about uncertainty" and is associated with families of possible probability distributions.

[4] The connotation of 'aleatoric' – which refers to the Latin *alea*: 'bone' or 'dice' – is uncertainty that is statistical or stochastic in nature.
[5] The connotation of 'ontic' – which refers to the Greek *on*: 'being' – is uncertainty that is related to the way of being of the system, in particular being intrinsically indeterminate or variable.

Suter et al. (1987)	Defined Uncertainty	Undefined Uncertainty	*Meta-Uncertainty:* "Defined uncertainty is uncertainty about a state of the world; undefined uncertainty is uncertainty concerning one's actual level of ignorance."
Funtowicz & Ravetz (1990)	Inexactness	Unreliability	*Meta-Uncertainty:* Unreliability gives an assessment of confidence of a given spread in results.
Helton (1994)	Stochastic Uncertainty	Subjective Uncertainty	*Nature:* Subjective Uncertainty a property of the analyst
Hoffman & Hammonds (1994)	Type B Uncertainty	Type A Uncertainty	*Nature and Measurability :* "when the assessment end point is a fixed quantity, distributions of values obtained from repeated observations represent uncertainty of Type B". Type A is associated with knowledge state and B is associated with variability.
Ferson & Ginzburg (1996)	Variability	Ignorance	*Nature and Reducibility"* Variability (due to stochasticity in underlying system) and Ignorance (due to underlying knowledge state); also Ignorance is described as reducible.
Paté-Cornell (1996)	Aleatory Uncertainty	Epistemic Uncertainty	*Nature:* Aleatory represents randomness, Epistemic is due to lack of knowledge
Kelly & Kolstad (1999) Kann & Weyant (2000) Peterson (2006)	Stochastic Uncertainty	Parametric Uncertainty	*Nature:* "Parametric uncertainty, which arises due to imperfect knowledge, and stochasticity, which is due to natural variability in certain processes." Kelly & Kolstad (1999)
Van der Sluijs et al. (2003) Meijer et al. (2005)	Variability-Related Uncertainty	Knowledge-Related Uncertainty	*Nature:* Knowledge related being that which is a property of the decision-maker.
Hayes et al. (2007)	Variability	Incertitude	*Nature and Reducibility:* Incertitude is due to lack of knowledge and is reducible
Refsgaard et al. (2007)	Stochastic Uncertainty	Epistemic Uncertainty	*Nature:* due to imperfect knowledge versus due to inherent variability
Van der Keur et al (2008)	Ontological Uncertainty	Epistemic Uncertainty	*Nature:* due to imperfect knowledge versus due to inherent variability
Ascough et al. (2008)	Variability Uncertainty	Knowledge Uncertainty	*Reducibility* and *nature:* Knowledge uncertainty may be reduced with additional research
Warmink et al. (2010)	Natural Variability	Epistemic Uncertainty	*Nature:* "…natural variability as random system behaviour that cannot be adequately explained great the available resources."
Petersen ([2006] 2012), Knol et al. (2009)	Ontic Uncertainty	Epistemic Uncertainty	*Nature*: Ontic is indeterminacy or variability associated with inherent nature of the system, epistemic is due to knowledge state
Smith & Stern (2011)	Imprecision	Ambiguity	*Measurability and Meta-uncertainty (also Nature) :* Imprecision is statistical and where PDFs can be provided. Ambiguity is where PDFs cannot be given and also is related to uncertainty about a PDF. They also liken ambiguity to 'un-nature' and the inadequacies of knowledge.
Dequech (2011)	Weak Uncertainty	Strong Uncertainty	*Measurability:* Weak uncertainty has complete and reliable probability distribution, strong does not
Beven (2016)	Aleatory Uncertainty	Epistemic Uncertainty	*Measurability*: Aleatory uncertainty has stationary statistical characteristics
Van der Bles et al. (2019)	Aleatory Uncertainty	Epistemic Uncertainty	*Nature:* Epistemic uncertainty as product of knowledge state. Aleatoric due to variability
	Direct Uncertainty	Indirect Uncertainty	*Meta-uncertainty:* Direct relates to a particular fact, Indirect relates to underlying knowledge base

3.2 Scales of uncertainty

Often some of the particularly intractable epistemic uncertainties of the above two-type systems are described as 'strong' (Dequech, 2011), 'radical' (Kay and King, 2020), 'severe' (Ben-Haim, 2019, 2006) or 'deep' (Marchau et al., 2019; Walker et al., 2013). This adjectivisation implies some dimension along which some uncertainties are more challenging or problematic than others. *Scales of uncertainty* may be used to characterise the depth of uncertainty by defining the specificity with which the possible states of a system and their probability distributions may be described (Risbey et al., 2002 call this *predictive capability*). Several uncertainty frameworks thus conceptualise uncertainties falling between extremes of indeterminacy and determinacy, with intermediate states falling between them (Rotmans and van Asselt, 2001; van Asselt and Rotmans, 2002b). This classification has significant overlap with *measurability* described previously and has been identified by some authors as descendant from Knight's original risk-uncertainty distinction (Enserink et al., 2013).

Walker et al. (2003) describe levels of knowledge ranging from *deterministic knowledge* (unachievable) to *indeterminacy/total ignorance*. They define four levels along this spectrum of *statistical uncertainty* (uncertainties can be described in statistical terms), *scenario uncertainty* (possible outcomes and mechanisms for arriving at those outcomes are not well defined), *recognised ignorance* (fundamental relationships unknown) and *total ignorance* (we do not know what we do not know).

Warmink et al. (2010, p. 1521) and Refsgaard et al. (2007) add a level to the Walker et al. (2003) scale, including *qualitative uncertainty*: non-quantifiable statements can be made, expressing expert opinion, linguistic probabilities and ambiguities between people. They also omit total ignorance as what is not known cannot be known. Harremoës (2003) uses the Walker et al. system but describes two reasons for indeterminacy: practical (too many functional relationships) and theoretical (relationships inherently undefinable) indeterminacy. Kwakkel et al. (2007) attempt to reduce confusion in the original Walker et al. (2003) and other subsequent frameworks by clarifying the mathematical structures behind the levels described.

Bradley & Drechsler (2014) include 'magnitude of uncertainty' as one of their three fundamental dimensions of uncertainty. They differentiate their levels by one's ability to make a judgement: *ignorance* (no judgement possible), *severe uncertainty* (partial judgement possible), *mild uncertainty* (judgement possible) and *certainty* (outcome of judgement known).

Another framework that does not include probability as a discriminator between different levels of uncertainty is that of Courtney et al. (1997), with levels based on what can be known about outcomes*: a single outcome can be known*, *a discrete set of outcomes known*, or a *range of outcomes known* or *true ambiguity* (no way to forecast the future).

Table 4 presents a list of levels systems approximately aligned along 'increments' on these scales, though equivalences are imperfect, as discussed in *section 4.2*

Table 4: An eclectic selection of author's labels for 'levels' of uncertainty and how they may be seen to line up against one another. This is an imperfect comparison and as will be discussed in Section 4, these levels are not directly commensurable.

Knight 1921	**Keynes 1921**	**Courtney et al 1997**	**Walker et al. 2003**	**Kandlikar et al. (2005)**	**IPCC (2005a)**	**Kwakkel et al. 2010**	**Warmink et al. 2010, Refsgaard et al. 2007, Brown 2004, Van Der Keur et al. (2008)**	**Van der Bles et al. 2019**
		Single Clear Future	(Determinism)					
Risk	Probability (numerical)		Statistical Uncertainty	PDF Given	PDFs given	Shallow Uncertainty	Statistical Uncertainty	Full PDF Defined
					Indicative probabilities given			A summary of a distribution
	Probability (Comparable)					Medium Uncertainty		A Rounded number, range
								A predefined categorisation of uncertainty
Uncertainty	Probability (non comparable)	Alternate futures	Scenario Uncertainty	Bounds given	Range given	Deep Uncertainty	Scenario Uncertainty	A list of possibilities or scenarios
		Range of futures		Order of Magnitude	Order of magnitude estimate			
				Expected Trend identified	Expected trend identified		Qualitative Uncertainty	A qualifying verbal statement
	Uncertainty		Recognised Ignorance	Ambiguous trend	Ambiguous relationships	Recognised Ignorance	Recognised Ignorance	Informally mentioning the existence of uncertainty
		True Ambiguity	Total Ignorance	Effective Ignorance				No mention of uncertainty
								Denial that uncertainty exists

In addition to describing the predictive legitimacy of a situation, levels may be used as a diagnostic tool used to select appropriate analytical techniques for a given situation (see the matrix of Stirling, 1998). They may also help classify how uncertainties are described (legitimately or not) in practice (see for example Paté-Cornell, 1996; Tennøy et al., 2006). Levels may also mix modalities of what *can* be stated and what *is* stated in practice (Enserink et al., 2013).

In essence, most of these scales categorise ways of enumerating or describing possible states of a system and making statements relating to their likelihood, probabilistic or otherwise. A list of these is given in Table 5.

Table 5: A number of ways in which state spaces and probability statements are typically expressed in different uncertainty frameworks that utilise level concepts. Original analysis based on literature reviewed.

Ways of Describing the State/Possibility Space	**Ways of attaching likelihood estimations to states**
Exhaustive yet limited set of possible states described	Full probability density function
Range of states given	Ordinal ranking of states in terms of probability
Some (but not all) possible states given	Interval Probabilities given
Some states excluded	Central estimate with spread given
Order-of-magnitudes estimated	Fuzzy categories described (likely, unlikely, possible etc.)
Direction of a trend given	Qualitative description of the likelihood of those states

3.3 Known-unknowns: Meta-knowledge, Cognisance and Ignorance

On the border of some of the level systems described above are many varieties of *ignorance*. These scales of uncertainty have described what is and can be known about states and probabilities, but several frameworks go further and taxonomise the boundary with what is *not known*.

> "… there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones."
>
> - Donald Rumsfeld, February 2002.

> One who knows and knows that he knows…
> His horse of wisdom will reach the skies.
> One who knows, but doesn't know that he knows…
> He is fast asleep, so you should wake him up!
> One who doesn't know, but knows that he doesn't know…
> His limping mule will eventually get him home.
> One who doesn't know and doesn't know that he doesn't know…
> He will be eternally lost in his hopeless oblivion!
>
> -14th Century Persian Poet Ibn Yamin. Translation by Niayesh Afshordi

The above quote from Donald Rumsfeld is ubiquitous in lay discussions of uncertainty, though said to be a paraphrasing of 14th-century Iranian poet Ibn Yamin. Frameworks like this *Rumsfeld-Yamin system* organise uncertainties by one's awareness of them or one's ability to gain an awareness of them. Of particular interest are ideas about ignorance and the limits of knowledge, both from the point of view of an individual and that of an epistemic community (see e.g. Knorr-Cetina, 1999). Of particular importance is the idea of cognisance: do you know what you do not know?

A prominent early classification in this style is that of Faber et al. (1992), who present an extensive dendrogram that separates *ignorance* from *uncertainty and risk*. Ignorance is further subdivided into *open* (recognised) and *closed* (unrecognised) ignorance, and the latter is then classified as reducible (may be lessened) and irreducible. Figure 1 lays out their framework as an illustration.

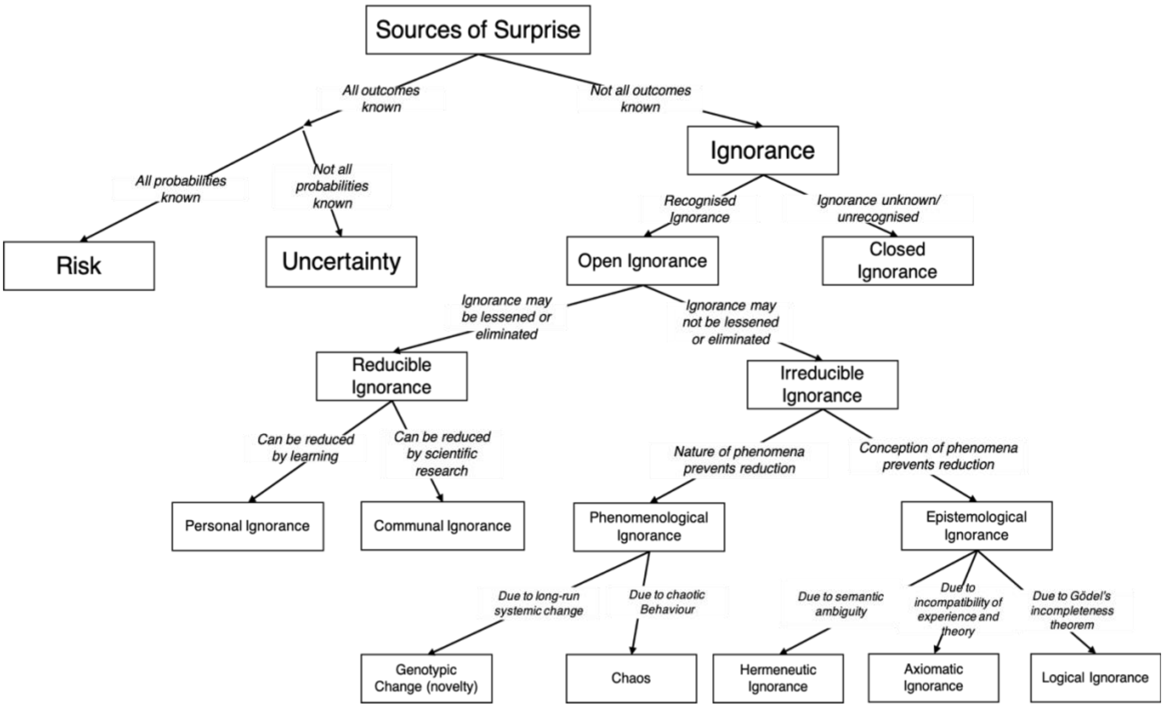

Figure 1: Compiled framework for ignorance in Faber et al. (1996) with distinctions added

The relationship between *ignorance* and *uncertainty* is contentious. Funtowicz & Ravetz (1990) describe the *border with ignorance* as including the gaps in one's knowledge that cannot be characterised statistically or through confidence statements, i.e. probing the edge of what is knowable. Wynne (1992) builds upon their work and limits *ignorance* to not knowing what one doesn't know. Petersen's framework ([2006] 2012) classes *recognised ignorance* as acknowledgeable and does not include unrecognised ignorance. Chow & Sarin (2002) define *known, unknown* and *unknowable uncertainty* by one's ability to know probabilities of outcomes. In other cases, variously: the term *ignorance* is used for *epistemic uncertainty* (Ferson and Ginzburg, 1996), *uncertainty* is considered a subcategory of *ignorance* (Dovers et al., 1996), ignorance is considered a subset of uncertainty (Smithson (1989)), ignorance is considered something that can be acknowledged (Faber et al., 1992) or something that is inherently unacknowledgeable (Brown, 2004).

Some typologies of uncertainty that interrogate ideas around ignorance have seen intellectual exchange with typologies of *surprise*. Perhaps, *surprise* could be considered the fruit that uncertainty bears. Typologies that study of the phenomenology of surprise answer questions such as 'how does the surprise appear to occur?' (Brooks, 1986), 'what caused it?' (Schneider et al., 1998) and 'was it anticipatable?' (Toth, 2009).

3.4 Source and location of uncertainty

The concepts of *source* and *location* of uncertainty are frequently used in uncertainty frameworks: how we conceptualise where uncertainties reside, originate from, or enter an analysis.

The *source of the uncertainty* either refers to the ultimate generator of the state of uncertainty itself (and hence trivially synonymous with 'an uncertainty'), or to a set of generalised causes of uncertainty. The latter conceptualisation will often involve listing some common causes of uncertainty in the given setting of the analysis, be it resolution errors, measurement instability, alignment errors, and the instability of human behaviour. For example, Manning & Petit (2004) describe five fundamental origins of uncertainty: incomplete observations, incomplete conceptual models, inaccurate understandings of processes, chaos and lack of predictability.

Location – sometimes also confusingly called *source* – has two general interpretations:

- In an analysis involving decomposable or interacting target systems, the aspect of a system regarded as uncertain (e.g. economic uncertainty in a coupled economic-biosphere model). Van der Keur et al. (2008) call this *context*.
- The point in the process of the knowledge production, model process or assessment process where uncertainty enters, is identified or is experienced (e.g. during model parameterisation or collection of data) (Zumwald et al., 2020)

These two conceptions of location may also end up blending in some typologies where different stages of the assessment process correspond to different interacting target subsystems, each receiving its own technical treatment (e.g. Beven et al., 2014).

Location as sub-system

The former conceptualisation may be particularly intuitive in environmental assessment, which involves the cascade of knowledge and concepts across the boundaries of different systems. Meijer et al. (2006) (after Milliken. 1987) define the *source* as the "domain of the organisational environment which the decision-maker is uncertain about". In futures studies dealing with socio-technical change and scenarios, the use of interacting subsystems of analysis is common; for example, Hughes et al. (2013) present a model of interacting systems of actor dynamics and technical systems dynamics and separate those uncertainties that lie outside of actor's control and those which are uncertain due to actors not having yet made strategic decisions.

Examples of uncertainty locations in studies from climate economics may be: emissions scenarios, climate response, climate impacts and optimal policy responses (Gjerde et al., 1999; Peterson, 2006). This echoes the format of climate assessments such as IPCC assessment reports and their three-working-group structure. Wilby & Dessai (2010) describe a cascade of uncertainties in the assessment of climate adaptation options that broaden the *envelope of uncertainty* as one moves between these stages of an assessment. Such cascading conceptualisations of uncertainty are prominent in work describing coupled models or multi-stage assessments (Refsgaard et al., 2016).

These sub-systems can also be conceptualised as having broad thematic categories (e.g. Wätzold, 2000). This approach is common in environmental economics. Examples include Heal and Kriström (2002), who define *scientific, impact* and *policy uncertainty* (see also Heal & Millner, 2017, and Brouwer & De Blois, 2008, who separate uncertainties into *environmental, economic* and *political*.

Typologies may be adapted to the particular modelling problem of specific disciplines; in population ecology some typologies thus consider *phenotypic, demographic, environmental* and *spatial* uncertainty sources (Burgman et al., 1993; Shaffer, 1987).

Uncertainties may also be categorised as endogenous or exogenous to the system one is modelling, organisational theorists have organised uncertainties in this way concerning the organisation under study (Dreier and Howells, 2019; Duncan, 1972).

Location as a point in the knowledge production process

Many frameworks describe *location* as the point at which uncertainty is experienced in a knowledge production process. Some view *location* as a part of a linear process of knowledge creation, while others may consider knowledge creation as part of a flow between different elements of a system (e.g. (Ekström et al., 2013; Link et al., 2012; Peterman, 2004; Zumwald et al., 2020)).

The uncertainty in climate models is organised by Hawkins & Sutton (2009) as due to the internal variability (of the climate system), model uncertainty (different responses of models) and scenario uncertainty (different emissions forcing scenarios). Similar formulations listing selections of scenario, climate response, model structure, parametrisation and initial condition uncertainties are common in the climate-related modelling literature (Cheung et al., 2016; Knutti et al., 2008; Kutiel, 2019; Linkov and Burmistrov, 2003; Monier et al., 2015; Stainforth et al., 2007).

Examples of locations of uncertainty within a model, or 'model uncertainties', are described in Table 6. Sources are inconsistent about relevant locations, but most commonly, *model structural uncertainty, parametric uncertainty, scenario uncertainty* and *model implementation uncertainty* are described.

Table 6: Table detailing common locations of modelling uncertainty in the literature with some general definitions. General Location has been introduced by this paper as an approximate organising concept.

General Location	**Model-related Uncertainty**	**General Description**	**Cox & Baybutt (1981)**	**Vesely & Rasmuson (1984)**	**Hall (1985)**	**Alcamo & Bartnicki (1987)**	**Suter et al. (1987)**	**Beck (1987)**	**Finkel (1990)**	**NRC (1994)**	**Ferson & Ginzburg (1996)**	**Cardwell & Ellis (1996)**	**Van der Sluijs (1997)**	**Huijbregts (1998)**	**Kann and Weyant (2000)**	**Rotmans & van Asselt (2001)**	**Huijbregts et al. (2001)**	**Linkov & Burmistrov (2003)**	**Walker et al. (2003)**	**Petersen (2006)**	**Pappenberger et al. (2006)**	**Hawkins & Sutton (2009)**	**Parker (2010)**	**Mirakyan & De Guio (2015)**	**Refsgaard et al. (2016)**
Conceptual Model	Model Choice	The effect of choices made by modellers												√											
	Modell***er*** Uncertainty	Difference in interpretation of the model problem																√						√	
Conceptual/ mathematical Model	Structural Uncertainty (conceptual)	Uncertainty in the correct relations between variables or mathematical forms. Sometimes this is just called *model uncertainty*	√	√	√	√	√	√		√	√	√			√	√		√	√	√	√	√	√	√	√
	Model Completeness	Are all relevant variables included?	√	√	√				√					√		√									
Mathematical Model	Model Boundaries	Uncertainty due to selection of boundary conditions					√														√		√		
	Parametric Uncertainty	Uncertainty in setting/ calibrating of parameters.	√		√	√	√		√	√	√	√		√	√	√		√	√	√	√		√	√	√
	Model Aggregation	Errors due to the aggregation of model elements					√																		√
Technical Implementation	Data Uncertainty	Uncertainty in the data used in model construction, calibration and tuning, including descriptions of terrain etc	√	√	√												√		√	√	√				√
	Model Implementation	Uncertainty introduced due to the computational implementation of a model, including numerical approximations		√		√							√		√	√			√	√	√			√	√
Model Driving	Initial Conditions	The effect of varying initial conditions in model settings				√		√															√		
	Model Forcing/ Scenario Uncertainty	Assumptions about conditions exogenous to the model system that drive behaviour.			√	√												√	√	√		√		√	√
Interpretation of model as a whole	Internal Variability (of model)	Spontaneous fluctuations in the model condition due to complexity of relationships			√																				
	Internal Variability (of system)	Spontaneous fluctuations in the system under study due to natural stochasticity					√															√			√
	Model Output Interpretation	Difference in interpretation of processed model outputs																	√	√				√	
	Inter-model Uncertainty	Difficulty in interpretation of result of alternative models										√													

3.5 Ambiguity, quality, dis-consensus and linguistic uncertainty

Uncertainties may arise due to difficulty communicating ideas or reaching consensus in epistemic communities. *Ambiguity* is most often used to refer to these kinds of uncertainty. However, the term is used inconsistently and not all authors agree it should be included in uncertainty frameworks (Bedford and Cooke, 2001).

Linguistic uncertainty

Linguistic uncertainties originate in the non-specificity of language or the lack of reliable conceptual representation in communication (Ascough II et al., 2008). Regan et al. (2002) define five kinds: *vagueness* (borderline cases in scientific vocabulary), *context dependence*, *under specificity* (unwanted generality), *ambiguity* (multiple meanings) and *indeterminacy of theoretical terms* (see also Elith et al., 2002; Hayes et al., 2007*). Linguistic uncertainty* may also be known as *semantic uncertainty* (Lane and Maxfield, 2005) or *translational uncertainty* (Rowe, 1994). In some cases it is identified as a form of epistemic uncertainty (e.g. Kirchner et al., 2021).

Multiple knowledge frames

Ambiguity may also refer to conflicting evidence, knowledge frames or epistemic values (Brugnach et al., 2008; Ekström et al., 2013; Enserink et al., 2013; Warmink et al., 2010). This could form a sort of meta-epistemic uncertainty or could be identified with epistemic uncertainty itself. Alternatively, ambiguity may be conceptualised as a third 'nature' of uncertainty (Brugnach et al., 2008; Petr et al., 2019).

Social reliability and pedigree

The NUSAP system is a notation system for the communication of quantitative and qualitative uncertainty, intended for science for policy (Funtowicz and Ravetz, 1990), which has been adopted by various authors (Fischhoff and Davis, 2014; Pye et al., 2018). The final letter of the acronym denotes *pedigree* – a description of the quality of the underlying science behind a statement. 'Indirect uncertainty' in van der Bles et al.'s (2019) uncertainty communication system is directly analogous. *Pedigree* may be somewhat ambiguously defined, and a description of the pedigree of knowledge may be a matter of expert assessment. The IPCC has produced a succession of frameworks for uncertainty communication, with statements assessed along two qualitative dimensions: *amount of evidence* and *level of agreement* (Mastrandrea et al., 2010; Moss and Schneider, 2000).

Smith & Petersen (2014) (also Petersen, 2006 [2012]) describe how the reliability of a piece of evidence can be referred to in three ways: its statistical reliability (*$reliability_1$*), its methodological reliability (*$reliability_2$*) and its social reliability (*$reliability_3$*).

There is some difficulty in extricating these forms of social uncertainty from one another. Uncertainties at the group level manifest themselves at the individual level and vice versa. Dovers et al. (1996) offer a partial solution by making the scale of the social unit at which the uncertainty manifests a dimension of uncertainty.

3.6 Values-related uncertainties

In his famous "Beauty Contest Example", Keynes (1936, chap. 12) described a contest in which a panel of judges compete to choose the most popular face amongst the panel itself, rather than their personal preference. Thus, the judges must attempt to anticipate the subjective preferences of the other judges. Authors have long noted how the variety of human evaluations is an aspect of uncertainty. Human values are an important part of our social reality and come into play in various ways in scientific investigations, modelling and decision-making processes. Different people hold different values about various topics such as epistemology, politics and ethics. Conflicting values create uncertainties even within the minds of individuals, as reflected in some uncertainty frameworks. We identify four ways in which values-related uncertainties are incorporated into uncertainty frameworks (cf. Figure 2):

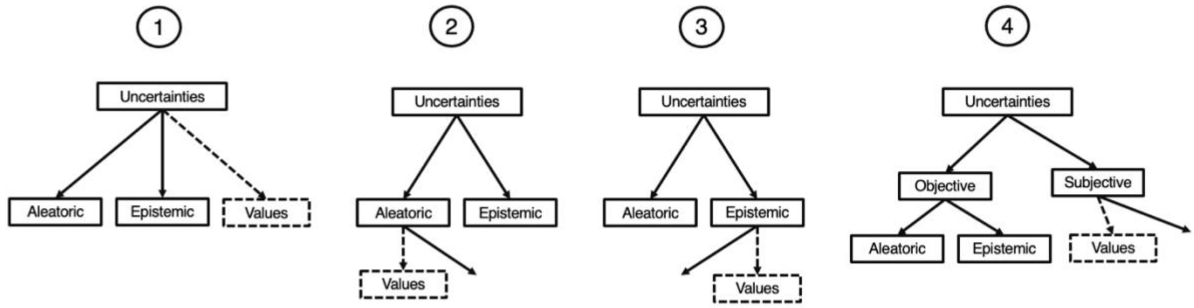

Figure 2: Summary of different methods of incorporating value-based uncertainties into frameworks

1) As an additional fundamental nature of uncertainty, Beven (2016) describes 'ontological' uncertainty[6] (associated with different belief systems) as separate from epistemic and aleatoric uncertainty. Bradley & Drechsler (2014) defines 'normative uncertainty' as a fundamental nature of uncertainty.

2) As just another aspect of the natural variability of the world. Knol et al. (2009) thus includes, 'normative uncertainty' as a sub-category of ontic (aleatoric) uncertainty which results from "a multitude of 'socio-ethical-normative' considerations within a society". Other classifications call this 'value diversity' (Rowe, 1994) and Smith & Stern (2011) describe a difference in values contributing to the indeterminacy of some variables.

3) As relevant assumptions that affect knowledge production to be identified and frankly acknowledged in the process of an assessment. In this way there is implicit normativity in epistemic frameworks used by people. Values are integrated into our way of knowing and are an integral aspect of epistemology. For example, Petersen (2006 [2012]) includes uncertainties that are due to *value-laden assumptions* in an uncertainty matrix. This is congruent with ideas from Post Normal Science (PNS) which advocates a frank inventory of values and assumptions in science.

4) As belonging to a separate class of uncertainty entirely, along with other subjective uncertainties. Tannert et al. (2007, p. 894) thus propose a taxonomy in which *epistemic* and

---

[6] Not to be confused with the *ontic* uncertainty of other classifications. Here this means differences in belief systems (one's ontological beliefs) rather than due to the ontology of a system.

aleatoric are separate from *subjective uncertainty*[7], which includes as a sub-class of *moral uncertainty*. Sigel et al. (2010) divide uncertainty into factual and normative uncertainty, though the latter is mostly concerned with regulation and legality. Other authors, perhaps following trends in policy sciences, may describe issues of factual uncertainty separate from 'normative dissent' (Grin et al., 2004). *Subjective* uncertainties may include other uncertainties experienced by decision-makers or more broadly, 'human-dimension' uncertainties (Baecher and Christian, 2020; Moser, 2005, 1997).

One may further ask what *kind* of values are being incorporated: epistemic values (what is valued as knowledge), ethical/moral values, political values, aesthetic values? The interaction of different values with knowledge production is rarely considered in these frameworks.

4 Discussion: Challenges in uncertainty studies

Having reviewed the most important categorisations of uncertainty in the literature, this section presents several challenges to the current state of affairs in uncertainty studies. It considers whether conceptual synthesis between frameworks is achievable and suggests routes forwards to more productive uncertainty dialogues.

4.1 The fundamental nature of uncertainty and its inconsistencies

Frameworks for uncertainty analysis and the definitions they employ should be philosophically robust to have applicability across different domains, even within environmental assessment.

This paper has reviewed many systems that posit the two fundamental types of aleatoric and epistemic uncertainty and identified four ways to distinguish them: *measurability, meta-ness, reducibility* and *nature*. Despite these ways of separating being often inconsistent, this conflation exists commonly in the literature.

This paper suggests that this confounding of different ways of separating uncertainties may be due to the experience of different kinds of prediction tasks, such as weather- and climate-like tasks. Weather forecasting is a paradigmatic repeatable task in which system dynamics are well understood and can generally produce reliable probability distributions of future weather states in the short term. Yet the chaotic nature of the system prevents exact foreknowledge of the weather state and uncertainty is practically irreducible. In non-repeatable tasks like climate-like forecasting, the system drivers (such as anthropogenic emissions) cannot be known, and feedback processes (such as due to aerosols) are not well-defined (see also Smith, 2002). Thus, these situations abound with epistemic-type uncertainties.

More specifically, the use of *nature* itself, though predominant in recent literature, is imperfect for several reasons. Triaging a given uncertainty between epistemic and aleatoric uncertainties is indeed often difficult practically; expert opinion and analytical convenience may determine the classification used (Baecher and Christian, 2020; Beven et al., 2015; Hora, 1996; Walker et al., 2003). Moreover, conceptually, the idea of a fundamental separation between mind/epistemology and system/ontology implies a specific view of metaphysics.

[7] Tannert et al (2007) link this to Durkheim's idea of *anomie:* a state in which societal values become clouded and ambiguous.

Oftentimes the variability in a system is not easily attributed to some true system variability or to some hitherto unknown process. Skinner et al. (2014) therefore define an intermediate category to overcome this difficulty in judgement. Others may describe individual sources of uncertainty as having both epistemic and aleatoric components (Beven et al., 2015).

This uncertainty triage is particularly fraught when considering the unreliability of human behaviour and social systems. Individuals may disagree about the extent to which regularities of human behaviour could be eventually knowable. If knowable, these behaviours may yield epistemic uncertainty; otherwise, the human-system yields aleatoric uncertainty. In essence, this depends on one's view on the nature of human or social behaviour.

Chaotic systems seem a paradigmatic case of the effect of aleatoric uncertainties. However, in situations where an effect is due to some hidden emergent phenomena, we may not be able to recognise it as such. The epistemic/aleatoric divide is thus influenced by one's attitude towards different possible positions regarding determinism. If one views nature as purely deterministic with all outcomes inevitable given the antecedent nature of the world (what Gigerenzer et al., 1989 call *metaphysical* or *epistemic determinism*), then all uncertainty is ultimately epistemic (Riesch, 2012). For researchers with a more Bayesian strand of thinking, the divide is ultimately false and purely useful for instrumental purposes (Bedford and Cooke, 2001; Winkler, 1996). More subtle versions of determinism, such as the *effective determinism* (Gigerenzer et al., 1989), may see determinism coexisting with indeterminism as the two can apply at different levels of analysis. Thus, the level of aggregation and the domain of a study or model can allow the two natures of uncertainty to coexist pragmatically without making strong claims about the ultimate nature of a system.

Many issues described here have their origin in the difficulty of partitioning epistemology and system ontology. This divide ignores that knowledge creation occurs, in part, through a dialectic between epistemology and a system; the way one intervenes, measures and conceptualises a system is based on epistemic assumptions. Perhaps a more useful approach considers the epistemic capacities available in a situation: would improving data, conceptual, intellectual and computational resources improve understanding?

4.2 The value of scales of uncertainty

Organising uncertainty into levels is an attractive idea. In situations where the likelihood of different outcomes are difficult to estimate, it allows for a representation of knowledge and indicates appropriate analytical tools (e.g. scenario analysis in situations of *deep uncertainty*). However, this idea of uncertainties being rank-orderable should be understood as a helpful metaphor only, as underlying it are profound inconsistencies.

'Level-systems' do not imply that some uncertainties are 'larger' in some abstract sense, but they do encode information about the state space of possibilities and their probability. While it seems intuitively legitimate to have two poles of knowledge states, full determinism and complete indeterminacy, we cannot draw a straight line between them with stops along the way. Even individual level frameworks are inconsistent as to what is tracked in transition between uncertainty levels (Kwakkel et al., 2010; Norton et al., 2006). What these do in fact track one's ability to enumerate and describe possible states of a system and make statements relating to their likelihood, probabilistic or otherwise, as shown in Table 5.

Several other inconsistencies compromise the robustness of level-based organisations of uncertainty. *Firstly*, we may be able to only partially define both state spaces and probability distributions: we can give probabilities to some outcomes but not others. For example, in 'Black Swan' situations the likelihood and nature of day-to-day occurrences is well known, but unexpected events with unknowable probabilities have large impacts (Taleb, 2007).

Secondly, one must caution against the propensity to transform deep uncertainties into something more tractable such as probabilities (Derbyshire, 2017; Shackley and Wynne, 1996). According to Van der Bles et al. (2019), the deepest uncertainty level is an explicit denial of the existence of uncertainty – this seems circular as it may be impossible to distinguish a denial of uncertainty and a legitimate claim that significant uncertainties do not exist.

The conceptualisation of how our knowledge of state/possibility spaces may be constrained is a powerful organisational principle, but more textured descriptions of our knowledge states are possible. As acknowledged since the time of Keynes, we may also make less formal probability judgements, such as ordinal probabilities, interval probabilities, fuzzy sets, or qualitative judgements. Scenarios themselves can fulfil predictive, explorative and normative purposes (Börjeson et al., 2006). It is common to make value-based judgements over scenario sets in the form of worst- and best-case scenarios.

4.3 The ambiguity created by multitudinous frameworks

This paper has explored how concepts such as *nature, level* and *ignorance* intersect with one another. This may create confusion for those uninitiated in the esoteric teachings of uncertainty studies.

The profusion of uncertainty lexicography also creates a form of linguistic ambiguity – similar to the linguistic uncertainty described in section 3.5. The terms *ambiguity* and *uncertainty* themselves are ambiguous and uncertain (Milliken, 1987), and analysts may struggle to remember all terminology (Casman et al., 1999). While the ambiguous meaning of probability terminology has been well examined (e.g. Morgan and Henrion, 1990), that of uncertainty terminology more broadly has been less so.

If linguistic ambiguities already exist, framework constructors should reflect whether applying such labels to the uncertainties they identify is productive. It may be best to use terminology with the smallest risk of creating confusion.

4.4 The relevant boundary for inclusion of uncertainties within a framework

A huge number of issues have found their home in uncertainty frameworks. As quotidian difficulties in research practice have been framed as *uncertainty*, the term has perhaps become inflated. In attempting to be as comprehensive as possible, uncertainty frameworks may be insufficiently clear as to the range of analytical activities to which they have relevance.

Firstly, including concepts such as *risk, ambiguity* and *ignorance* within the boundary of uncertainty is contentious in the literature. Why particular concepts to include in uncertainty frameworks is a matter of analyst choice. If one is designing a framework to describe all hindrances to achieving a desired knowledge state, then exhaustiveness is desirable. But at this point, the term 'uncertainty' seems too petty for the summary of knowledge and potential defects thereof that is being produced. Perhaps some other more all-encompassing term is required.

Secondly, uncertainty frameworks may be insufficiently clear as to what parts of the system of knowledge production are within the bounds of analysis. For example, a typology for summarising uncertainties associated with an environmental model may limit its scope to uncertainties endogenous to the model and in the mind of the individual modeller. But the model is not immune to uncertainties within the epistemic community that its creator inhabits. Modelling involves the appropriation of elements from a wide variety of domains (Boumans, 1999), and drawing a boundary around the model process may be conceptually challenging.

4.5 The challenge of meaningfully incorporating values

Many frameworks do not account for how different values, epistemic, moral, ethical, political and otherwise, contribute to uncertainty. Others attempt to include values somehow, though very few delve deeply into these mechanisms rather than treating values as an afterthought.

The inconsistency in the treatment of values may be, partly, due to philosophical divergence over what roles values and normativity have in informing scientific and decision-making processes. Many philosophers of science argue that values are inextricable from scientific assessments and modelling processes in their methodological design and interpretation, while positivists wish to imagine a firebreak between human subjectivity and science.

Normative uncertainties are frequently brought up in commentary of the difficulties of Integrated Assessment (e.g. Giampietro et al., 2006). Disagreements over the selection of important variables such as *pure rate of time preference* and the *marginal utility of consumption* have origins in fundamental differences over moral values (Davidson, 2015). Heal & Millner (2017) call for some process of preference aggregation to move past an impasse over "primitive ethical questions". However, ethical preferences involve complexly interacting disagreements over how the world is and how it should be. Values are inherently unamenable to aggregation, else politics and collective decision-making would be no more than an optimisation exercise.

The theory and practice of Post Normal Science (PNS) advocates a form of strong candour about one's values and assumptions (Giampietro et al., 2006; Kønig et al., 2017). Perhaps frameworks should consider better what role values play and form appropriate accommodations, rather than considering them tokenistic additions.

4.6 Productive routes forward

A changing environment impacts many coupled environmental, human, technological and economic systems and requires studies that lie at their nexus. Addressing uncertainties found in the spaces between disciplines requires the collaboration and communication of individuals from different epistemic communities.

This paper has examined how frameworks are espoused in the theoretical sections of literature, but not necessarily how these frameworks are operationalised in the resulting literature which uses these concepts. The existence of uncertainty concepts in the literature does not necessarily mean that researchers in general conceptualise uncertainties in these ways.

Skinner et al. (2014) note that the development of frameworks for uncertainty analysis is often a crystallisation of the opinion of an individual researcher. If we wish interdisciplinary researchers to be able to communicate effectively with each other, we should start by examining empirically how researchers themselves relate to uncertainty in their work and understand it conceptually.

From this firmer ground of understanding, bridges can then be built to aid interdisciplinary collaboration on complex issues.

This paper has demonstrated that underlying epistemic values and philosophical commitments have a role to play in the development of frameworks. There are several well-known theoretical disagreements on topics such a probability, caricatured in some quarters as a tribal argument between Frequentists and Bayesians. Comprehensive genealogies exist for *probability* as a concept (e.g. Hacking, 1975), but scant research traces the conceptual roots of uncertainty concepts prominent in contemporary discourse. Tracing the heritage of these ideas could help account for the epistemic values and contingency of ideas underlying the uncertainty analysis frameworks reviewed in this paper.

We should understand frameworks for uncertainty analysis as collections of conceptual tools that allow us to examine, identify and communicate uncertainties in imperfect yet improved ways. Our ability to understand uncertainties in a system will be as imperfect as our knowledge of that system itself. We should recognise the possibility for different aims of uncertainty handling: are we trying to reduce perceived uncertainty, make our predictions more reliable, make our decisions more robust or justify predetermined positions? If our aim is to improve interdisciplinary collaboration, perhaps we should begin with engaging with uncertainty as *it is understood,* rather than *how we think it should be understood.*

5 Conclusion

This review has examined a large corpus of frameworks for the analysis of uncertainty of relevance to environmental change studies from disciplines including environmental economics, ecology, climate science, environmental assessment, integrated assessment, energy studies, risk theory and decision-making theory. This corpus is highly heterogeneous with different forms, aims and intended applicability, yet is recognisable as a body. Common features have been analysed and organised, such as the use of levels and scales to describe uncertain situations, the different meanings of *ambiguity* and the divide between *epistemic* and *aleatoric uncertainty.*

Presenting a series of challenges to the broader status of the literature, this paper has then suggested a route forward: engaging with uncertainty more empirically to investigate meanings and conceptual models employed by practitioners in their daily work and lives. Using this empirical basis, uncertainty handling can be described in a way more sympathetic to the real needs of researchers.

This review has conveyed the sheer inconsistency of treatments of uncertainty. While this inconsistency may hamper communications efforts with peers, policymakers and other stakeholders, this is hardly surprising given the range of epistemic issues represented under the banner of uncertainty.

Uncertainty frameworks deal with the forms knowledge can take and the conditions for drawing inferences from that knowledge to the past, present or future states of systems. *Uncertainty analysis* can seem almost too parochial a term for the act of accounting and describing one's knowledge state while accounting for the values inherent in decision-making. *Un*-certainty seems to imply that certainty is to be expected; in studies of the changing environment, uncertainty is inescapable. Perhaps a defunct term such as *gnosiology* could be resurrected to refer to the practical process of accounting for and describing one's knowledge state when assessing complicated systems.

Do not mistake the map for the terrain: the uncertainties described in uncertainty frameworks are not complete descriptions of all the ways in which we may be surprised. Let us recognise frameworks for uncertainty analysis for what they often are: imperfect but useful conceptual tools.

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APPENDIX A: Summary of Review Process

In this review a systematic backwards snowball approach was used that built on an initial corpus of papers. Pure literature keyword searches were deemed unsuitable for several reasons:

- Only small numbers of uncertainty typologies are gleaned from keyword searches
- Different disciplines and sub-disciplines frequently use inconsistent nomenclature
- Uncertainty frameworks often appear at different levels of prominence within sources: from papers that have uncertainty frameworks as their centrepiece, to papers that utilise an uncertainty framework as part of some larger piece of analysis to literature that only passing proposes uncertainty frameworks without further application
- Some influential uncertainty frameworks do not occur in journal articles, but also books and other literature, such as governmental reports.

Such systematic snowball approaches are commonly employed when terminology is not consistently used accords sources (Lecy and Beatty, 2012). They can also yield larger corpuses than keyword searches alone (Wohlin, 2014). They come with the limitation of being highly laborious due to the inefficiency of manually searching references and articles and requiring literature selection criteria that prevents overgrowth of the corpus examined (Wohlin, 2014). This technique has been used to a much more limited extent in this subject area by Kirchner et al. (2021).

The process utilised was as follows:

1) An initial search of Scopus and Web of science yielded several uncertainty frameworks. Search terms included a thematic indicator such as "climate", "energy", "environment" or "ecosystem" with *terms denoting typologies such as "uncertainty taxonomy".* This was combined with a small corpus of papers already known to the author.
2) Papers were read and short summaries were produced that described their uncertainty frameworks. These summaries are available in Appendix B. An excel spreadsheet was used to collate these notes and additional columns were created to compare similar aspects of different frameworks (for example if and how the authors distinguished between aleatoric and epistemic uncertainty).
3) Influences from or references to other frameworks were noted down and the sources for these were added to a backlog for potential inclusion in the corpus.
4) These were triaged in turn for uncertainty frameworks relevant to environmental change and analysed in the same way if found to be suitable.
5) This was continued until all leads were exhausted. Conceptual exhaustion, where additional frameworks were not yielding novel concepts, was also achieved.

Figure 3 explains this recursive snowballing approach.

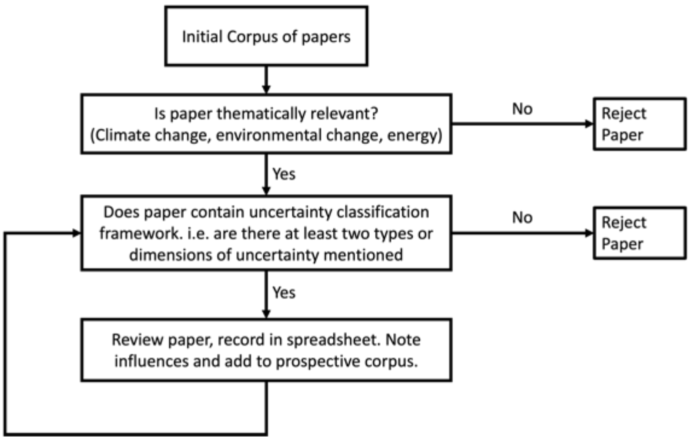

Figure 3: Flow chart showing snowball approach for corpus assembly from an initial sample of uncertainty frameworks.

This process resulted in the analysis of 156 distinct sources containing frameworks, primarily in the form of journal articles (115), but also in books or book chapters (21), reports (7), guidance documents (6), doctoral theses (3), working papers (3), a conference proceeding and a magazine article. The distribution of publication dates is shown in Figure 4.

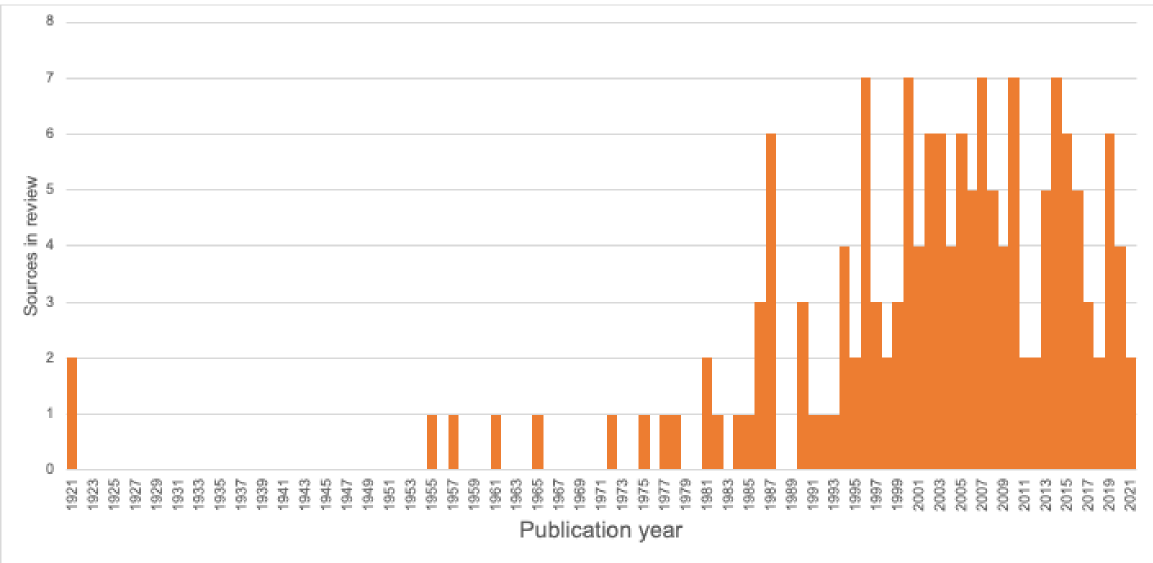

Figure 4: Distribution of publication year of literature reviewed in this paper

APPENDIX B: Summaries of Reviewed Literature

The table below summarises the literature reviewed in this article and some of the distinctive features described therein.

Authors	Year	Source	Type of Framework	Context	Brief Description of Notable Features
Knight	1921	Book	Definition	Economics	A definition of risk (probabilities can be known) and uncertainty (unknown probabilities).
Keynes	1921	Book	Definition	Economics	A fundamental distinction between uncertainty and probability. Probability is disaggregated into i) numerical ii) non-numerical yet comparable and iii) non-comparable
Shackle	1955	Book	Distinction	Economics	A key text in the consideration of uncertainty in economics. The definition of Knight is restated/ refined. Further examination of the nature of experiments and repeatability is explored. Divisible experiments are defined as those whose result is comprised of multiple experiments. *Seriability* exists in situations where experiments can be repeated. This all leads to his concept of 'potential surprise' as key decision-making variable.
Luce & Raiffa	1957	Book	Distinction	Decision Theory	Part of a classic tome on decision theory, based around a utility model of decision making. They distinguish between *risk* (one set of outcomes, probabilities known) and *uncertainty* (known outcomes, unknown probabilities). This is almost identical to Knight's definition. They also describe situations (such as statistical inference) where both risk and uncertainty are present in a mix. They describe utility theory as dealing with decisions under risk and game theory dealing with a mixture of risk and uncertainty as the decisions of others are considered as separate decision-under-risk problems.
Ellsberg	1961	Journal Article	Definition	Decision Theory	A classic article on decision theory that displays an inconsistency (paradox) between people's choices and evaluations subjective expected utility. An ambiguity aversion is identified where subjects prefer gambles where odds can be known, rather than gambles where odds are ambiguous (even if they may be larger).
Emery & Trist	1965	Journal Article	Typology of uncertain environments (for organisation)	Organisational Theory/ Management	A classic article that considers the types and complexity of environments that organisations find themselves in. i) Placid environment: goals unchanging and uncertainties are local and random, ii) strategy is required as imperfect competition exists between actors, iii) 'disturbed-reactive' highly competitive environments, iv) uncertainties arise not only from other actors but from the 'turbulent field' itself
Duncan	1972	Journal Article	Dimensions	Management Studies	A framework for understanding environmental uncertainty (that exogenous to an organisation). Two dimensions of the factors affecting uncertainty in an organisations external environment are: 1) Simple vs Complex- number of components in decision environment to consider 2) static-dynamic- do factors in the decision environment change in time?. A third dimension is also given in less detail regarding ability to assign probabilities to outcomes. They also develop a measure of uncertainty that uses all three of these.
Hacking	1975	Book	Conceptual Distinction	History of Science	As part of Hacking's famous history of the concept of probability he defines two senses of probability: aleatory and epistemic probability. This terminology is later picked up and applied in a number of uncertainty classifications.
Rowe	1977	Book	Definition of Risk	Risk Studies	A book examining the concept of societal risk which includes a classic definition of risk as "the functional combination of the probability of occurrence and its value to the risk taker."
Howell & Burnett	1978	Journal Article	Three distinctions for uncertain events for cognitive uncertainty	Psychology, decision-making	A typology of uncertain events for understanding human decision-making under uncertainty. Three distinctions made: 1) is the event frequency related, 2) is the underlying process causing the event stochastic, 3) is the event outside of the control of the observer?
Kaplan & Garrick	1981	Journal Article	An influential anatomy of Risk	Risk Studies	An influential conceptualisation of risk that characterises it as comprising a set of triplets: *scenario* (what can happen), *probability,* and *consequence* (what is the result of what happens).
Cox & Baybutt	1981	Journal Article	Sources of Model uncertainty	Risk Analysis	Towards the beginning of this paper they explain a number of sources of model output uncertainty: *parameters* (may be due to data, expert opinions or "uncertainties about uncertainties", *which sub-model is correct, statistical sampling variability, completeness of the analysis in a model.*
Kahneman & Tversky	1982	Journal Article	Typology	Decision-making, Psychology	A framework that builds on Howell & Burnett (1978). They recognise that uncertainty may be attributed to either the external world (dispositions) or the internal world (ignorance). External judgement of uncertainty may be distributional (relative frequencies may be estimated) or singular (probabilities assessed from propensities of case at hand). Internal uncertainty may be reasoned (deducing answer from other knowledge) or introspective (confidence in answers that seem familiar).
Vesely & Rasmusson	1984	Journal Article	Typology	Nuclear Risk Assessment	Firstly, a distinction between physical variability and knowledge uncertainties are made. Then three kinds of knowledge uncertainties are described: parameter, knowledge, and completeness. Parameter uncertainty is described as having a variety of sources. Model uncertainty is described as either due to model comprehensiveness (are all relevant variables included) or characterisation (the relationships between variables in the model. Completeness uncertainty concerns whether all relevant phenomena have been considered.
Hall	1985	Report Section	Types of Uncertainty	Climate Modelling	Description of several sources of uncertainty in climate modelling: process (uncertainties in data), model, statistical (fluctuations in the model or the world)-, forcing. Describes uncertainties to communicate validity of physical assumptions (structural), model completeness, parameterisation. Recognises that there can be both quantitative and qualitative expressions of uncertainty.

Einhorn & Hogarth	1986	Journal Article	Conceptual Distinction	Decision making, Economics	They examine Ellsberg's concept of and attempt to formalise and explain it with a new model of ambiguity. They describe ambiguity as 'uncertainty about uncertainties'. They also associate ambiguity with families of distributions "ambiguity results from the uncertainty associated with specifying which of a set of distributions is appropriate in a given situation".
Henrion & Fischoff	1986	Journal Article	Two conceptual distinctions.	Physics	Overall the paper is an application of psychological ideas to a new area to show the fallibility of error estimates in physics. Argues that uncertainty is not just probabilistic. Separates *Error* (the actual difference between an estimate and a value) and *Uncertainty* (an estimate of this error). Also discusses random error/uncertainty versus systematic error/uncertainty.
Brooks	1986	Book Section	Typology of Surprise	Policy, Environment	Describes three types of surprises: unexpected discrete events (e.g. reactor meltdown), discontinuities in trends, and the emergence of new information/knowledge.
Shaffer	1987	Book Chapter	Types of uncertainty	Ecology	A list of major types of uncertainty for consideration in conservation biology: *demographic uncertainty* (randomness in the survival of individuals), *environmental uncertainty* (randomness in the environmental setting), *natural catastrophes* and *genetic uncertainty* (random changes in genetic makeup).
Alcamo & Bartnicki	1987	Journal Article	Typology (they call it taxonomy)	Atmospheric Modelling	They present a typology of model uncertainty: *model structure uncertainty*, *parametric uncertainty, forcing functions* (the forcing from time and space dependent functions), *initial state* and *model operation* (due to implementation of model processing). They also distinguish between *diagnostic uncertainty* (model description of past or present conditions) and *prognostic uncertainty* (model use for forecasting). They describe uncertainties as either having diagnostic, prognostic or both components.
Beck	1987	Journal Article	Taxonomy	Water Quality Modelling	Reviews a number of approaches to uncertainty in water quality modelling. Borrows 'taxonomy' of uncertainty terminology from Alcamo & Bertnicki (1987). Examines several kinds of uncertainty and sorts them into those associated with *prior knowledge, identification* and those associated with *prediction*. Prior knowledge uncertainties: aggregation errors, numerical errors, model structure. Identification uncertainties: errors in field data for input, parameter error, state errors, initial state errors. Prediction errors: propagation of uncertainty errors.
Bogen & Spear	1987	Journal Article	Conceptual Distinction	Environmental Health and Risk Analysis	They attempt to design a framework for modelling both uncertainty and variability for Risk Assessments (rather than approaches that rely on tabulations of risks). *Uncertainty* is a lack of knowledge concerning some characteristic. *Variability* in this context is interindividual heterogeneity with respect to some risk. *Risk* is the probability of harm from a particular cause.
Suter et al	1987	Journal Article	Taxonomy	Environmental Impact Assessment	Adapts risk frameworks of Rowe (1977) and Fairley (1975) with a three-level dendrogram of uncertainty. Fundamental distinction is between defined and undefined (a form of meta-uncertainty). Defined uncertainty is then split between being either *identity* (uncertainty over victims of impacts) and *analytical*. Analytical uncertainty is either due to *model error, natural stochasticity or parameter error*. These are then subdivided as well.
Milliken	1987	Journal Article	Typology	Management Studies	Identification of three types of environmental uncertainty relevant to management(uncertainty about environment exterior to an organisation). Argues that previous authors had considered sources, but it will consider types. The types are: 1) *State uncertainty*- the inability to predict how components of environment are changing (authors stress not same as not defining pdf). 2) *Effect uncertainty* - inability to predict how environmental changes affect ones organisation. 3) *Response uncertainty*- uncertainty about what response options one has and effects of response choice (close to decision theorists).
Finkel	1990	Report	Typology	Risk Assessment	A report defining techniques for decision-making under uncertainty. The typology at the highest level gives four principal kinds of uncertainty: parameter uncertainty, modelling uncertainty, decision-rule uncertainty and variability. Parametric uncertainty is due to measurement errors, systematic errors or random errors. Model uncertainty is due to surrogate variables, excluded variables, abnormal conditions or incorrect model form. Decision-rule uncertainty is related to the choice of risk variables, acceptable risks, utility functions, aggregation of individual utility functions and temporal discounting. Variability is described in some way being separate from uncertainty and being some kind of separate dimension of an uncertainty analysis.
Morgan & Henrion	1990	Book	Taxonomy	Policy and Risk Analysis	As part of a book on the topic of policy and risk analysis a typology of uncertainties for policy relevant models is given. At the highest level there are uncertainties in quantities and in model form. Different types of quantities are described (defined constants, decision variables, value parameters, index variables, model domain parameters, state variables, outcome criteria). Empirical quantities are classified by sources of uncertainty: random error/statistical variation, systematic error/subjective judgement, linguistic imprecision, variability, randomness/unpredictability, disagreement and approximations.
Funtowicz & Ravtez	1990	Book	Multiple	Philosophy of Science	This book contains a number of ideas that have had a great deal of influence in this space. First of all they distinguish between different *sorts* of uncertainty: • *Inexactness*: the spread in a value • *Unreliability*: the confidence given in a quantitative statement • *Border with Ignorance*: gaps in knowledge not encompassed by inexactness or unreliability. Their NUSAP acronym is intended for the communication of uncertain information. It is thus: Number (the estimated quantity of a variable), Unit (the unit the number is given in), Spread (a measure of the range of uncertainty around the number given), Assessment (a judgement about the information such as significance level or qualitative judgement), Pedigree (evaluation of the production of the evidence and the intended use of the information) They also define different domains of decision-making: basic science (where systems uncertainties and stakes are low), consultancy (where they are moderate) and post normal science (where they are high).

Dosi & Egidi	1991	Article	Distinction / Matrix	Economics	The principle distinction made is between procedural (lack of capacity to solve problems) and substantive (lack of information about the environment one is in) uncertainty. Substantive uncertainty is subdivided into weak substantive uncertainty (probabilities known and analogous to risk and strong substantive (analogous to Knightian uncertainty).
Wynne	1992	Article	Typology	Environment	In this article Wynne reworks the ideas of Funtowicz & Ravtez to reject the implicit scale. Says that four categories of uncertainty are risk (odds known), uncertainty (odds unknown), ignorance (unknown unknowns), indeterminacy (causal chains or networks open).
Burgman et al	1993	Book Section	Typology	Ecology	A typology of uncertainties in ecology that classifies by the specific source: *phenotypic* (variation between individuals in population), *demographic* (variation of average chances of survivorship), *environmental* (changes in environment through time) and *spatial* (variation between patches of habitat).
Helton	1994	Journal Article	Distinction	Risk Assessment	A distinction between *stochastic* and *subjective uncertainty*. Also adaptation of a risk framework to use for probabilistic risk assessment uncertainties.
Rowe	1994	Journal Article	Dimensions	Risk Assessment	Distinguishes four classes or dimensions of uncertainty: *temporality* (uncertainty in past, present or future states), *structural* (uncertainty due to the complexity of the system), *metrical* (uncertainty in measurement) and *translational* (uncertainty in explaining uncertain results). Variability is described as contributing to all four classes. Various factors contributing to all of these classes are given.
Hoffman & Hammonds	1994	Journal Article	Conceptual Distinction	Risk Assessment	A conceptual distinction between *Type A* and *Type B* uncertainty is included in this paper. Type A uncertainty is immeasurable and associated with a lack of knowledge (and is captured in this paper by the choice of statistical distribution). Type B uncertainty is measurable, associated with variability and fixed the midpoint and tails of a distribution.
NRC	1994	Book	Typology	Risk Assessment	This book section reviews a number of approached to uncertainty management and the EPA's previous approach to uncertainty. It recommends a typology of uncertainties into *parameter* and *model* uncertainties. It also notes other typologies such as that of *bias* (result of study design), *randomness* (due to sample size) and variability (what risk assessors study).
Faucheaux & Froger	1995	Journal Article	Dimensions	Ecological Economics	Following the Knightian distinction they define a scale from *Ignorance, Strong uncertainty, Weak Uncertainty and Certainty*. These are displayed on the diagonal on a map of two dimensions of uncertainty: probability (imprecise to well defined) and reliability (low to maximum). This typology is also stated in Froger & Zyla 1995.
Myers	1995	Journal Article	Conceptual Distinction (two kinds of surprise)	Environment	A distinction between two kinds of surprise: discontinuities (sudden changes in the natures of a system) and synergisms (interacting factors lead to unexpected effects).
Hora	1996	Journal Article	Conceptual Distinction	Safety Engineering/ Risk Analysis	The paper uses example of permeability of geologic formation to discuss the separation between aleatory and epistemic uncertainty in risk analysis. The paper argues that sharp distinctions between the two do not normally exist. They argue that the classification between the two is somewhat determined by the purpose of the study and expert opinion.
Cardwell & Ellis	1996	Journal Article	Conceptual Distinction	Environmental Management	In this paper examining aggregation (multiple models) issues in water quality modelling. Defines Type-I Uncertainty as due to the simplifications necessary to form a mathematical model of a physical system. Type-II uncertainty is parameter value uncertainty.
Paté-Cornell	1996	Journal Article	Conceptual distinction+ List of 6 type of Risk Analysis	Safety Engineering/ Risk Analysis	Makes a distinction between epistemic and aleatory uncertainties. Then defines six levels of analysing uncertainty in risk analysis: 0. recognition of a hazard, 1. defining a worst-case scenario, 2. defining a plausibly worst-case scenario, 3. a central estimate of outcome, 4. provision of a probability density function, 5. families of PDFs
Winkler	1996	Journal Article	Distinctions (4)	Risk Assessment	The paper argues against the broad use of types of uncertainty, insisting that at root there are only two things: uncertainty and probability. It does however provide a number of distinctions that can be used to organise uncertainty: 1) uncertainty about observables vs about un-observables; 2) the separation between parametric uncertainty and model uncertainty; 3) different forms of information; 4) apparently/practically reducible vs irreducible uncertainties
Ferson & Ginzburg	1996	Journal Article	Matrix (2D)	Safety Engineering/ Risk Analysis	Makes distinction between *Variability* (due to underlying system) and *Ignorance* (due to underlying knowledge state); also Ignorance is described as reducible. Presents these in a table/matrix with two kinds of model uncertainty: *parameters* and *model formulation*.
Faber et al	1996	Book	Taxonomy	Ecological Economics	In this book on uncertainty analysis they classify sources of surprise in an extensive dendrogram. At the highest tier separating risk + uncertainty from ignorance by ability to know all outcomes. • Ignorance is then split into open (knowable) and closed (unaware) ignorance. • Open ignorance is split into reducible and irreducible. These are then further subdivides by the causes of the reducibility (personal or communal ignorance) or lack thereof (phenomenological or epistemological). • These categories are subdivided further
Dovers et al	1996	Article	Taxonomy/ Dimensions	Biodiversity and Conservation	Following Smithson (1989) describe uncertainty as a subset of ignorance. They then define three particular kinds of ignorance: apparently reducible, apparently irreducible and self generated (inadequate information management). They define some dimensions of ignorance as gradients: certainty-complete ignorance, individual-societal etc. A number of sources of ignorance are given.
Moser	1997	PhD Thesis	Loci of human-dimension uncertainties	Environmental Assessment	Reviews a number of previous taxonomies of uncertainty. Identifies that human-dimension uncertainties are often neglected and gives a number of 'loci' of human dimension uncertainties: epistemology, perception & human cognition; problem definition; science and analysis; decision-stakes & decision-making; policy goals, policy-making & strategy;

					management & implementation; human behaviour, actions & choices; values, preferences & goals; communication; emerging societal futures.
Courtney et al	1997	Magazine Article	Typology (Levels)	Business Strategy/ decision-making	An influential Harvard Business Review article in which four levels of uncertainty are described: a single outcome can be known, a discrete set of outcomes known, or a range of outcomes known or true ambiguity (in which there is no way to forecast the future).
van der Sliujs	1997	PhD Thesis	Matrix (2 dimensions)	Integrated Assessment Modelling	In chapter 6 of his PhD thesis he reviews a number of typologies of Uncertainty. He develops a framework which crosses Funtowicz & Ravtez's three sorts of uncertainty (inexactness, unreliability, ignorance) with Versely & Ramusson's types of modelling uncertainty (conceptual model structure, technical model structure, model completeness). This creates a 2D matrix of uncertainty types. Later in the thesis chapter (6.7) also describes a methodology for incorporating quality estimates in modelling).
Schneider et al	1998	Journal Article	Taxonomy of Surprise	Environmental Change	A paper that reviews a number of different typologies of uncertainty and surprise in. They develop a variant of the Faber et al 1992 typology that organises by the sources of expectations and considers impediments to preventing surprise. At the highest level, risk (probabilities known) & uncertainty are separated from imaginable surprise by whether all outcomes are known. Imaginable surprise is separated into those due to an unwillingness to change expectations and those where people are open to changing expectations. These open expectations are subdivided into those that are easy to enlarge (due to a lack of learning or research) and those that are harder (epistemological or phenomenological impediments).
Stirling	1998	Journal Article	Matrix	Risk Assessment	A typology that separates Risk, Uncertainty, Ambiguity and Ignorance along two dimensions: knowledge about outcomes (fuzzy outcomes, known outcomes) and knowledge about probabilities (no basis for probabilities, firm basis for probabilities).
Huijbregts	1998	Journal Article	Taxonomy	Life-Cycle Assessment	A list of types of uncertainty relevant for Life-cycle assessment. A fundamental distinction between uncertainty and variability is made at the highest level though the difference is not explicit. Uncertainty is *parameter uncertainty, model uncertainty* or *choice uncertainty*. Variability is *spatial, tempora*l or *between source and object* (in accounting for loadings in a life cycle analysis).
Gjerde et al	1999	Journal Article	Three uncertain areas.	Integrated Assessment	The paper details the use of an Integrated Assessment Model to model the possibility of catastrophic events is detailed. Describes three primary uncertainty aspects from an economist's point of view being GHG emissions, effectiveness of policies and damage from global warming. Catastrophes are a subset of damage uncertainties.
Kelly & Kolstad	1999	Journal Article	Typology	Integrated Assessment	The article focusses on reducing uncertainty through learning for policy and IAMs. Makes distinction between two main kinds of uncertainty being *stochastic* (due to variability) and *parametric* (reducible). They describe a third aspect of uncertainty being *learning*- which is associated with agents making imperfect decisions and adapting over time.
Casman et al	1999	Journal Article	Some conceptual distinctions	Integrated Assessment	Paper that considers the temporal domains of validity for different model complexities. They describe the epistemic/aleatoric divide as often. They mainly separate uncertainties into parametric uncertainties and model uncertainties. Model uncertainties can be assessed with variations in model structure. Different domains of model validity are defined: detailed model is relevant; order of magnitude mode is relevant; bounding analysis is relevant; total ignorance.
Baecher & Christian	2000	Conference Proceedings	Taxonomy	Risk Analysis in Water Resources	In this Conference paper they mainly consider the nature of the aleatoric epistemic divide. They also present a taxonomy with three major kinds of uncertainty each with sub-categories: • *Natural Variability* (Temporal, Spatial) • *Knowledge Uncertainty* (Model, Parameters) • *Decision Model Uncertainty* (Objectives, Values, Time Preferences)
Arentsen et al	2000	Journal Article	Distinction	Environmental Policy, Decision-making	They highlight two kinds of uncertainty in particular (seemingly taking some influence from Hempel): Uncertainty in Problem Definition and Uncertainty of Policy Response. They also introduce the idea of some normative confusion.
Streets & Glantz	2000	Journal Article	Reviews several Taxonomies of Surprise	Environmental Policy, Climate Change	As part of this paper, they review a number of taxonomies of surprise. Makes distinctions between closed (where someone is willing to admit there are unknown outcomes) and open ignorance (where someone is not willing to admit there are unknown outcomes)
Kann & Weyant	2000	Journal Article	Typology	Energy Systems Modelling	In this paper the authors describe a number of approaches to uncertainty analysis of large energy models. They sort uncertainty into two broad categories: stochastic and parametric uncertainty. They discuss additional categories of uncertainty values uncertainties (such as differences over discount rate) and model structure uncertainty. Model structure uncertainty is also described as relating to the choices that modellers make. They also describe probabilities as being the ideal outcome of a probability assessment.
Kelly & Campbell	2000	Journal Article	Distinction	Ecological Risk Assessments	In this article they emphasise the importance of distinguishing between uncertainty and variability. Variability is defined as the true spread of a variable, whereas uncertainty is the approximation of this true spread. They describe variability as irreducible. They also relate variability to the situation of having good quality data and uncertainty to bad.
Moss & Schneider	2000	Uncertainty Guidance	Dimensions	IPCC, Uncertainty Communication	Guidance document prepared for the Third Assessment report of the IPCC (TAR). Gives calibrated language for expressing confidence terms by probability. Recommends also qualitatively describing uncertainty along two axes: level of agreement and amount of evidence. This creates a 2 x 2 matrix.
Wätzold	2000	Journal Article	Dimensions (3 Criteria)	Environmental Economics, Risk Assessment	Gives three criteria with which to assess a given environmental uncertainty. 1) Behaviour (of emission in the environment): accumulation, diffusion in time and space, synergistic damage etc. 2) Extent of Knowledge: Risk or ignorance. 3) Number of actors involved (number of polluters)
Rotmans & van Asselt	2001	Journal Article	Typology + Scale	Integrated Assessment	Restatement and development of framework in van Asselt's (2000) PhD Thesis and combination of ideas from Funtowicz & Ravetz (1990) about epistemic, methodological and technical uncertainties. At a first level they

					distinguish between uncertainty due to variability and due to lack of knowledge. They then present three kinds of uncertainty that are practically faced: • *epistemological* (does model correspond to real world), • *methodological* (a lack of knowledge over appropriate analytical tools) • *technical* (due to quality and appropriateness of data). These types are then attached diagrammatically to a scale of uncertainties: • *Inexactness* • *Lack of Observations* • *Practically Immeasurable* • *Conflicting evidence* • *Ignorance* • *Indeterminacy* Particular issues in modelling are also diagnosed and related diagrammatically (such as model structure, model validity, parameter uncertainties etc.)
Bedford & Cooke	2001	Book Section	Types	Probabilistic Risk Assessment	5(6) sorts described: Epistemic, Aleatory, Parameter (uncertainty in the true parameter of the model), Model, Volitional (will an individual do what the have agreed to do), Ambiguity (considered not really a form of uncertainty)
Van Asselt et al	2001	Report		Environmental Assessment	In this report they distinguish at the highest level of aggregation between: • *Variability* having sources in the inherent randomness of nature, value diversity, human behaviour, socio-cultural dynamics and technological surprises • *Limited knowledge* is described as having a partial source in variability and existing on a continuum from inexactness, lack of observations, immeasurability, conflicting evidence, reducible ignorance indeterminacy to irreducible ignorance.
Huijbregts et al	2001	Journal Article	Taxonomy of Data Uncertainties	Life Cycle Analysis	Different data uncertainties present in Life cycle analyses. At the highest level this is due to *inaccuracy* or a *lack of specific data*. Lack of data may be due to *data gaps* or *unrepresentative data*.
Heal & Kristrom	2002	Journal Article	Types	IPCC, Economics	Discussion of economic uncertainties after the Third Assessment Report. It re-evaluates the five categories from TAR from economic perspective into: 'scientific', 'impacts' and 'policy'. Also includes brief mention of meta- uncertainties.
Risbey et al	2002	Journal Article	Levels	Climate Science	A set of scenarios for regional climate are developed in this paper. In order to describe the level of knowledge about the relationships between dynamical processes, five uncertainty levels are developed: • *Quantitative Estimate*: sign and magnitude of change can be given • *Definitive sign*: can give direction of the sign • *Ambiguous sign*: plausible arguments for sign going either way • *Speculative sign*: can give arguments for sign in one direction, but cannot rule out the other or provide arguments • *Ignorance*: cannot give arguments for either direction
Regan et al	2002	Article	Taxonomy	Ecology and Conservation Biology	Uncertainty is split into epistemic and linguistic uncertainty. Epistemic in this case also includes inherent randomness. • Epistemic (measurement error, systematic error, natural variation, inherent randomness, model uncertainty, subjective judgement) • Linguistic Uncertainty (vagueness (borderline cases in natural language). context dependence, ambiguity (polysemy of words), under specificity (unwanted generality), indeterminacy of theoretical terms)
Elith et al	2002	Journal Article	Taxonomy	Ecological modelling	This paper adapts and uses the typology from Regan et al 2002. They remove the categories of 'inherent randomness' and 'context dependence'. Each type of uncertainty is discussed in turn. The authors also discuss the compounding of uncertainty and discuss the appropriateness of confidence intervals for characterising certain epistemic uncertainties.
Chow & Sarin	2002	Article	Three Types	Psychology Decision Theory	For this psychological study they define three kinds of uncertainty: • Known uncertainty = probabilities known, • Unknown uncertainty= probabilities unknown, • unknowable uncertainty = probabilities unknown to everyone and unknowable
van Asselt & Rotmans	2002	Journal Article	Various schema	Integrated Assessment	A restatement and elaboration on the Rotmans & van Asselt 2001 typology. Additional content includes a more elaborated list of sources of variability: • Inherent randomness of nature • Value diversity • Human behaviour • Social, economic and cultural dynamics • Technological Surprises
Walker et al	2003	Article	Matrix/Dimensions	Model based science advice	In this highly influential paper the authors introduce a dimensions framework and matrix for understanding uncertainty in model-based decision support. Dimensions given are: • *Location*- where the uncertainty manifest in the process of modelling • *Level*- on a spectrum between deterministic knowledge and total ignorance • *Nature*- due to variability or imperfection of knowledge
van der Sluijs et al.	2003	Guidance Document	Matrix/ Dimensions	Environmental Assessment	This is the first detailed guidance for uncertainty assessment/communication for the Netherlands environmental assessment agency (PBL). It adapts the Walker et al (2003) framework, adding two extra dimension (or columns in the matrix: • *Qualification of knowledge base:* weak, fair or strong • *Value-ladenness of choices*: small, medium or large

Harremoës	2003	Journal Article	Levels of uncertainty	Integrated Assessment	Restates and explains the level dimensions of Walker et al (2003). The levels given are: • *determinism* (an unachievable ideal), • *statistical uncertainty* (outcomes and statistics known), • *scenario uncertainty* (range of outcomes but no statistics), • *recognised ignorance* (where we know we do not know the functional relationships), • *indeterminacy* (we do not know that we do not know some functional relationship) to absolute ignorance. Indeterminacy can either be *practical* (due to large number of parameters) or *theoretical* (knowledge impossible due to chaotic nature of system).
Ricci et al	2003	Journal Article	Levels	Environmental Decision-making	As part of this article examining different decision making frameworks they present levels of variability/ uncertainty and relate these to levels of representation of causal relationships: • Probabilities > Model Uncertainties • Probability distributions > Bayes Factors • Probability Bounds > Entropy of Information • Interval Analysis > Partial Ignorance • Other.. > Complete Ignorance
Harwood & Stokes	2003	Journal Article	Typology	Ecology	They identify four sources of epistemic uncertainty in ecological management: • *process stochasticity* (variability), • *observation error*, • *model error* (incomplete or misleading representation of system dynamics) • *implementation error* (the failure to implement a policy).
Linkov & Burmistrov	2003	Journal Article	Typology	Model based science advice	They present four kinds of uncertainty. Three are common to other frameworks: parameter uncertainty, model uncertainty and scenario uncertainty. In addition, they include modeller uncertainty which is due to uncertainty in the interpretation of a problem by the modeller.
Peterman	2004	Journal Article	Typology	Fisheries modelling/management	A number of types of uncertainty in fisheries management: *Natural Variability, Observation error, Communication difficulties, Unclear management objectives, Implementation error.* Also sources are described in a network diagram
Brown	2004	Journal Article	Taxonomy	Physical Geography	A framework taxonomy that distinguishes uncertainty (an expression of confidence in knowledge) from ignorance. Uncertainty can either be bounded (outcome space known) or unbounded (outcomes unknown). Bounded uncertainty can be divided by whether one known some, none or all probabilities of outcomes. Unbounded uncertainty is divided by whether no outcomes are known, some are known or whether some probabilities and outcomes are known.
Manning & Petit	2004	Working Paper	Types	Climate Science Assessment	As part of a consideration of the IPCC's handling of uncertainty ahead of AR4. The paper distinguishes between five key origins of component of uncertainty: 1. Incomplete or imperfect observations (this is a joint property of the system under study and our ability to measure it) 2. Incomplete conceptual frameworks (not all relevant processes included) 3. Inaccurate prescriptions of known processes (e.g. poor models or parameterisations) 4. Chaos (uncertainty is a property of the system being studied) 5. Lack of predictability (e.g. social systems)
Grin et al	2004	Journal Article	Conceptual Distinction	Foresight and Innovation	A fleeting conceptual distinction between informational uncertainty and normative dissent.
Brown et al	2005	Journal Article	Model of Locations of Uncertainty	Environmental Change	The authors present a conceptual model for where uncertainties can manifest in a data recording. They define three aspects to assessing uncertainties: • The empirical quality of data: magnitude of uncertainty and empirical quality • Sources of uncertainty: in the methods and concepts used • The fitness the data has for its application • The 'goodness of the uncertainty model. Furthermore, they differentiate between different kinds of data and the uncertainty (position and attrbutes).
Moser	2005	Journal Article	Study where sources and types of human-dimension uncertainty are identified	Coastal Management	Moser Interviews a number of scientists to identify oft-neglected human-dimension uncertainties present in coastal management decision making. Through the interviews, four groups of uncertainties are collated: human factors that determine sea-level rise, human factors that co-determine sea level rise impact assessments, uncertainties in policymaking/management processes, uncertainty in condition for policy change.
IPCC	2005	Guidance Note	A number of features	Climate Science Assessment	This is the guidance note for the IPCC's fourth assessment report (AR4). It contains a number of recommendations for dealing with and communicating uncertainty. They present a simple typology of uncertainty: • Unpredictability (not amenable to prediction) • Structural Uncertainty (inadequate models etc) • Value uncertainty (unknown parametric values etc.) Advice about language used to describe probabilities is given. The Moss & Schneider (2000) matrix is re-stated. They also provide different levels of information provision in a hierarchy: A. Direction of change is ambiguous B. An expected trend is identified C. An order of magnitude can be given for the degree of change D. A range can be given for the change E. Likelihoods can be given for representative outcomes F. Probability distributions can be given

Kandlikar et al	2005	Journal Article	Levels of Uncertainty	Climate Science Assessment	They critique uncertainty communication methodologies (such as in IPCC TAR) that attempt to separate likelihood and confidence as likely to create confusion. Instead they present a set of ways of representing deep uncertainty. They propose a cascade of steps for determining the way in which uncertainty can be described. This creates a hierarchy of treatments of uncertainty: 1. *Full PDF* (Q: is it reasonable to apply a full probability distribution) 2. *Bounds* (Q: is it reasonable to specify bounds for the outcome) 3. *First-order estimates* 4. *Expected sign or trend* 5. *Ambiguous sign or trend* 6. *Effective Ignorance*
Lane & Maxfield	2005	Journal Article	Typology	Innovation Economics	They identify three sorts of uncertainty: truth uncertainty (uncertainty in the truth of a proposition), semantic uncertainty (actors uncertainty related to the meaning of statements) and ontological uncertainty (uncertainty related to actors assumptions about the ontology of a system)
Meijer et al	2006	Journal Article	Dimensions	Foresight and Innovation	They organise uncertainties in socio-technical transformation by: • *Source*: technology, resources, supplier, consumers, politics • *Level*: low to high
Pappenberger et al	2006	Report	Typology	Hydrology, Flooding	In this report on flood risk, the authors distinguish five primary sources of uncertainty: • Model structure (choice of simplification of reality) • Numerical approximations • Definition of flow domain considered (specification of geometry of terrain etc) • Boundary conditions • Parameter choices
Peterson	2006	Journal Article	Typology	Economics and Environmental Assessment	A review paper that brings together a couple of conceptualisations of uncertainty. Makes a distinction between *parametric* (knowledge related, also includes functional forms in models) and *stochastic* (variability related) uncertainties. Then describes ways in which uncertainties can be organised by their position in the cascading climate problem: uncertainty in emissions path, uncertainty in climate response, uncertainty about impacts and uncertainty about optimal policies.
Tennøy et al	2006	Journal Article	Sources and Levels of treatment	Environmental Impact Assessment	They describe four explanatory factors for uncertainty, based on de Jongh (1988): *change in project, model error, data errors* and *bias*. They describe four levels for the treatment of uncertainty: • 0- no description of uncertainty; • X- uncertainty is suggested but not explicitly named; • XX- uncertainty indicated or estimate but not explained; • XXX- uncertainty is explained to some degree
Krupnick et al	2006	Report	Taxonomy	Resource management	Types of uncertainty are: • Variability (dispersion of values around a central tendency) • Parameter uncertainty (described as a subset of epistemic uncertainty) {measurement errors, unpredictability, conflicting data, extrapolation errors …} • Model uncertainty (subset of epistemic) {structural choices, simplification, incompleteness, choice of pdfs, correlations, system resolutions}; • Decision uncertainty (uncertainties that affect risk managers about valuing social objectives) {choice of risk measure, choice of discount rate, decisions about risk tolerance, utility functions, distributional considerations}
Petersen	2006 [2012]	Book	Matrix	Modelling in Climate Science and Policy advice	Adapts the Walker et al 2003 framework in a number of ways: • Splits off recognised ignorance from Walker et al's 'levels'. Levels are re-labelled as 'range'. • Adds two additional dimensions of 'methodological unreliability' (relevant to theoretical basis, empirical basis, other simulations and peer consensus) and 'value diversity' (epistemic, discipline bound, socio-political and practical). Also relates his framework to that of Funtowicz & Ravetz: e.g. identifies his 'location' dimension with their 'source'.
Stainforth et al	2007	Journal Article	Taxonomy of Sources	Climate modelling, decision-making	The authors describe a number of sources of uncertainty: • *Forcing uncertainty* • *Initial condition uncertainty* (ICU). Subdivided into microscopic ICU (small rapid mixing scales) and macroscopic ICU (slow large mixing scales) • *Model Imperfections*. The two types of this are (i) *model inadequacy* (shortcomings of models due to non-representativeness of model structure to target system) and (ii) *model uncertainty* in parameterisations which can be quantified with ensemble experiments.
Patt	2007	Journal Article	Distinction	Environmental Change, IPCC	The paper distinguishes and explored the difference between *model based* and *conflict based* uncertainty. The former relates to uncertainties in modelling in particular. The latter is conflicts due to the different opinions of experts.
Blind & Refsgaard	2007	Journal Article	Some Sources	Water Resources Management	Aside from using Brown et al (2004)'s framework, they identify and document a number of sources of uncertainty and issues that arose in a modelling process: • Modeller's understanding of input data • Lack of metadata on observations • Lack of consistent bias handling in data • Poor correction factors that account for unrepresentative samples • Complexity due to links of data streams to society
Pindyck	2007	Working Paper	Some Sources	Environmental Economics	Describes a number of sources of uncertainty relevant for environmental economics: uncertainty in costs, uncertainty in benefits and disagreement

					over discount rates. Some natures of uncertainties that make the issues worse ae *nonlinear damage functions, irreversibilities* and *long time horizons*.
Refsgaard et al	2007	Journal Article	Dimensions	Environmental Modelling	Adapts the Walker et al (2003) framework with influence from Brown (2004). • Relabels Walker et al's variability as stochastic uncertainty • Adds a level of qualitative uncertainty in the Walker et al's levels. Renames levels as type.
Tannert et al	2007	Journal Article	Taxonomy	Science and Society	Presents a dendrogram of uncertainty as 'the igloo of uncertainty' • At highest level knowable probabilities separates ignorance from knowledge. • Ignorance and knowledge are either open or closed. • Open knowledge and ignorance are within the 'field of uncertainty'
Hayes et al	2007	Book Chapter	Taxonomy	Ecological Modelling	They provide a general introduction to a number of uncertainty concepts and treatments. Their taxonomy identifies three primary kinds of uncertainty: • *Linguistic* (due to various ambiguities of language; examples: ambiguity, context dependence, underspecificity, vagueness) *,* • *Variability (*fluctuations in a process • *Incertitude* (lack of knowledge; example: model uncertainty and measurement error). This is largely adapted from Regan et al 2002.
Gill et al	2008	Guidance Document	Sources of Uncertainty	Weather Forecasting	A World Meteorological Organisation guidance document on the communication of uncertainty. Outlines the following sources of uncertainty: • Atmospheric Unpredictability • Data interpretation • Composition of the forecast (uncertainty in linguistic presentation of forecast) • Forecast interpretation
Ascough II et al	2008	Journal Article	Typology	Ecological Modelling/ Decision-making	Three fundamental categories of uncertainty: Knowledge, Variability and Linguistic. Each of these is subdivided and all contribute to decision uncertainty. Decision uncertainty also consists of goals and assessment criteria.
Brugnach et al	2008	Journal Article	Dimensions	Ecology, Natural Resource Management, Water Resource Management	A two dimensional system: • Three fundamental natures of uncertainty: *Unpredictability, Incomplete Knowledge and Multiple Knowledge Frames*. These natures are described in a relational way • They then separate three different objects of knowledge: natural systems, social systems and technical systems. This is then manifested in a 3x3 grid of types of uncertainties
Brouwer & De Blois	2008	Journal Article	Typology/Taxonomy	Environmental (Water) modelling and decision-making	Two lists of kinds of uncertainty given. Environmental, Economic and Political (subdivided into *goal* uncertainty and *yield* uncertainty). They take Brown's (2004) version of an uncertainty scale of statistical, scenario, qualitative and recognised ignorance.
van der Keur et al	2008	Journal Article	Dimensions of Uncertainty	Water management	They present a typology of uncertainty, adapted from Walker et al (2003) and Refsagaard et al (2007). They give four dimensions of uncertainty: • *Nature*: ontological or epistemic • *Type* (this is equivalent to what others call levels): statistical, scenario, qualitative, recognised ignorance, total ignorance • *Source*: data uncertainty, model uncertainty, multiple knowledge frames, boundary conditions • *Context*: natural technical or social
Knutti et al	2008	Journal Article	Contributions to Uncertainty	Climate modelling	In this review of uncertainty in global temperature rejections there is not an explicit framework, but uncertainty is divided up into four contributions: scenario uncertainty, climate feedback, carbon cycle feedback and structural uncertainty. The authors also distinguish between uncertainties that are the result of single methods and those the result of multiple methods.
Brown & Damery	2009	Book Section	Distinction	Environmental Geography	As part of a chapter discussing the differences between the concepts of Uncertainty and Risk, the authors identify a number of psychological, sociological and situational aspects of uncertainty and risk.
Toth	2009	Book Section	Taxonomy of Surprise	Environmental Assessment/ Scenarios	A taxonomy of surprises that summarises some previous literature. Described two dimensions to classify surprises: knowability and whether one expects them. This creates three general types of surprises: anticable, conjecturable, and out of the blue.
Hawkins & Sutton	2009	Journal Article	Typology	Climate Modelling	Thee kinds of uncertainty are identified: Scenario (associated with emissions scenarios), model (differences in model outcome due to model structure) and internal variability (due to inherent variability of the climate)
Knol et al	2009	Journal Article	Dimensions/ Matrix	Environmental Health	Adapts Petersen (2006) in *location* and to make more useful for specific application. *Normative uncertainties* are included in ontic uncertainty. *Contextual uncertainty* appears included in *location*
Kwakkel et al	2010	Journal Article	Dimensions/ Matrix	Model-based policy support	Reviews a number of uncertainty frameworks that built upon the Walker et al. framework. Based on criticisms of these they attempt a synthesis by: • Refining the *level* dimension to four levels. • Adding a fundamental nature of uncertainty of *ambiguity* (different interpretation with different frames and values) • Clarifying different locations of uncertainty in the model process
Mastrandrea et al	2010	Uncertainty Guidance	Guidance Document/ Report	IPCC, Communication	A guidance note from a workshop in advance of the IPCC's 5th Assessment report. They recommend: • A two-dimensional communication of evidence (low mid high) and agreement (low mid high) • Calibrated likelihood language to refer to specific probability intervals
Parker	2010	Journal Article	Typology	Philosophy of (climate) Science	Details three major kinds of representational uncertainty associated with climate modelling:

					• *Initial Condition uncertainty* • *Parametric Uncertainty* (uncertainty in parametrising processes) • *Structural Uncertainty* (uncertainty about the form of equations) Choice of boundary conditions are also mentioned as a source of uncertainty.
Spielgelhalter & Reisch	2010	Journal Article	Dimensions	Risk, Modelling	They describe a number of characteristics of uncertainty: • Object of uncertainty- they describe five levels: event, model, parameter, acknowledged and unknown inadequacies • The form of expression of uncertainty (another scale); • the Source of Uncertainty; • the Subject of uncertainty (whose uncertainty is is?); • Affect (feelings associated with uncertainty)
Warmink et al	2010	Journal Article	Dimensions	Environmental Modelling	The Walker et al. (2003) system is refined with a decision tree for each of the dimensions of uncertainty. Additional level of uncertainty is given. Additional nature of uncertainty due to competing evidence.
Sigel et al	2010	Journal Article	Typology	Environmental Decision-making	They describe two types of uncertainty: • Factual (relating to facts) a • Normative uncertainty (relating to legal or regulatory demands). The source of uncertainty is what the uncertainty relates to. Causes of uncertainty are variously given.
Wilby & Desai	2010	Journal Article	A cascade of sources of uncertainty	Climate Adaptation	They frame the uncertainties relevant to adaptation planning as coming from a cascade of uncertainties that create a growing envelope of uncertainty. The cascade described is: future society > GHG emissions > Climate Model > Regional Scenario > Impact Model > Local Impacts > Adaptation Responses
Dequech	2011	Journal Article	Dimensions	Economics	Builds on Dosi & Egidi and Knightian uncertainty. Adds own distinction between ambiguity and fundamental uncertainty. The three distinctions are: • Strong vs weak uncertainty (can pdf be defined); • substantive (due to lack of information) vs procedural (lack of capacity to gain information); • ambiguity (state space known)) vs fundamental (state space unknown)
Smith & Stern	2011	Journal Article	Typology	Climate Policy	They distinguish a number of (not mutually exclusive) types of uncertainty: • *Imprecision* – outcomes where probability can be provided • *Ambiguity* – outcomes may be known, probabilities cannot • *Intractability* – computations cannot be performed due to lack of mathematical or computational capacity • *Indeterminacy* quantities relevant for policy for which no precise value exists. This may occur when there is value diversity of a physical quantity does not really exist.
Riesch	2012	Book Chapter	Levels of Uncertainty	Risk Theory, Decision-making	Asks a number of questions: Why are we uncertain: aleatoric or ontological ; Who is uncertain?; How is uncertainty represented?; They describe three types of uncertainty within the modelling process and two without. They describe 5 non-exclusive levels of uncertainty in some detail. These levels do not describe pdfs, but describe model adequacy.
Link et al	2012	Journal Article	Typology	Ecosystem Models	They define types of ecosystem model uncertainty: • Natural Variability (inconsistency in a state variable); • Observation error (failures of observation); structural complexity (complexity of model due ot many parameters etc); • Inadequate communication (difficulty in conveying information between scientists); • Unclear management objectives (vagueness of objectives); • Outcome uncertainty (failure to implement a management plan)
Enserink et al	2013	Journal Article	Dimensions	Futures/ Climate Scenarios	This article discusses how creators and users of scenario studies deal with uncertainty. They present three dimensions of uncertainty, with similarities to the framework by Kwakkel et al (2010): • *Nature* (Epistemic, Ambiguity, Ontic) • *Level* (Five levels) • *Location* (Where in the model or object under study uncertainty is located)
Hughes et al	2013	Journal Article	N/A	Energy Policy	In this scenarios and futures-focusses paper the authors describe potential conceptualisations for low carbon scenarios and a methodology for constructing them. They describe how the design of scenarios can focus on unknow future elements that are either dependent on the actions of agents or not. The also distinguish between things with are uncertain "*because [they] lie beyond the control of system actors*" and those that are uncertain because "*actors have not yet decided upon their strategies in respect of it*".
Ekström et al	2013	Journal Article	Matrix	Climate Risk and Water	They adapt the Walker et al (2003) framework for water risk assessments. They include the Warmink et al (2010) added nature of *ambiguity*, but broaden it to include differences in understanding/interpretation. In addition, their matrix involves: • An accounting of the aims of the assessment • The stages of a climate vulnerability assessment form Füssel & Klein (2006)
Petersen et al	2013	Uncertainty Guidance	N/A	Environmental Assessment	The second edition of uncertainty communication guidance for the Netherlands Environmental Assessment Agency (PBL).
Parker	2013	Journal Article	Typology	Climate Science, Philosophy	As part of a review of Ensemble modelling practices defines the following types of climate model uncertainty: • *Scenario Uncertainty*- uncertainty about emissions and forcing

					• *Response Uncertainty*- the response of the climate system given a forcing, which has both epistemic and ontic components
Fischoff & Davis	2014	Journal Article	Protocol for Uncertainty Elicitation and communication	Climate Science	As part of this paper they describe an expert uncertainty elicitation protocol that is derived partially from the NUSAP system of Funtowicz & Ravetz 1990 (also from the CONSORT criteria for medical trials). The uncertainties to be elicited are: • *variability*, • *internal validity* (of a study in question), • *external validity* (how well can results be extrapolated), • *strength of science* (directness, empirical basis, methodological rigour and validation) and • *credible intervals* (a measure of both the variability in a situation and the strength of the underlying science to give an estimate of an interval).
Bradley & Drechsler	2014	Journal Article	Dimensions	Philosophy	Three dimensions of uncertainty: Nature, Object and Severity. • Nature is split between modal (what could be the case), empirical (what is the case) and normative (what is the case). • The object of uncertainty is either factual (about the world) or counterfactual (the way things could; or would be if they were different). • Severity is a scale of uncertainty.
Lehmann & Rillig	2014	Journal Letter to Editor	Distinction	Climate Change, Ecology	The letter proposes terminology to distinguish between uncertainty (a measure of unexplained variation) and natural variability (explained variation)
Gould et al	2014	Journal Article	Taxonomy	Ecology	Uncertainty is described as having three components: • Natural Variability • Measurement Error • Incomplete Knowledge They also give additional classes of: • Unpredictability of the future • Modelling error They describe a conceptual model that gives different sources (effectively locations) within species distribution models.
Davies et al	2014	Report	Dimensions	Energy Sector Planning	Adaption of the Funtowicz & Ravetz (1990) map of system uncertainties versus decision stakes for use in Energy systems planning. They then include Skinner et al's framework in this adapting the nature, location and level of uncertainty.
Skinner et al	2014	Journal Article	Taxonomy	Environmental Risk Assessment	A novel approach to forming a classification is employed. In which papers utilising uncertainty assessment frameworks in environmental risk assessments were assessed to see what locations of uncertainty were espoused. These locations were then organised into Epistemic, Aleatory and Combined (could be described as both) camps. These sources were then clustered.
Beven et al	2014	Report	Typology	Hydrology, Flood Mapping	In this report the authors provide and extensive framework and implementation guide for analysing uncertainty in fluvial flood risk mapping. They acknowledge a difference between epistemic and aleatoric uncertainties. They define a number of key sources of uncertainty: • Uncertainty in fluvial flood sources (essentially a collection of uncertainties that define the magnitude and nature of the causes of flood events) • Uncertainties in pathways (uncertainties in the way that flood events are modelled) • Uncertainties in receptors (Uncertainties in the vulnerabilities of systems to flood events) • Uncertainty due decisions of implementation (to the way uncertainty analysis is carried out)
Beven et al	2015	Journal Article	Typology	Hydrology, Flood Mapping	The authors describe various *sources* of uncertainty in flood risk mapping. Each of these sources is described as having *aleatory* (due to natural variability and treatable with probabilities) and *epistemic* components. This typology presented in this paper in tabular form is said to be adapted from of that of Beven et al 2014, though Beven et al 2014 do not sort epistemic and aleatoric components of uncertainties this way.
Watson et al	2015	Journal Article	Dimensions	Energy Policy	They combine a version of Funtowicz & Ravetz's (1990) two dimensions of uncertain situations from Davies et al (2014) with the Risk framework of Millar & Lessard (2008). They adapt the risk framework to include *instrumental* (relating to specific energy technologies) and *systemic* (that could have systemic impact). The end result is a framework which organises uncertainties on source (instrumental and systemic) and rates these on two dimensions of complexity and impact.
Grubler et al	2015	Journal Article	Types	Technological Forecasting	In this article the authors define a number of types of uncertainty. • Parametric uncertainties • Functional uncertainties (exact relationship between entities is not known) • Unknown Unknowns They also distinguish between three classes of uncertainty: • Epistemic (uncertainty data and/or models) • Linguistic Uncertainty (vagueness) • Contingency/agency (due to human intentionality)
Monier et al	2015	Journal Article	Typology	Climate Modelling	They describe there being four sources of uncertainty in the context of climate modelling: • Emissions projections uncertainty • Response of the climate system to changing GHG and aerosol concentrations • Natural variability • Model structure uncertainty
Mirakyan & De Guio	2015	Journal Article	Typology and levels.	Energy Planning	The define six categories of uncertainty, with five of these appearing to be mutually exclusive: linguistic uncertainty, Knowledge uncertainty, Variability uncertainty), Decision (similar to ambiguity with competing options) Uncertainty, Level of uncertainty and procedural uncertainty.

					They also define 4 *Levels*: Determinism, Risk, Uncertainty (sub levels: fuzzy probabilities, belief or plausibility function, and possibility membership function), Ignorance
Frig et al	2015	Journal Article	Set of questions	Philosophy of (Climate) Science	A philosophical article that among other things, considers how climate scientists have wrestled with uncertainty. They present a number of difficult questions left unanswered after Knightian the risk/uncertainty distinction: 1. Why are precise probabilities not possible in uncertain situations? Are there unknown unknowns? 2. Can uncertainty be quantified (not necessarily by quantitative measures)? 3. How can uncertainty be communicated to decisionmakers? 4. What is the rational way of making decisions under uncertainty?
Payne et al	2016	Journal Article	Typology	Marine ecosystems modelling	An adaption of Hawkins & Sutton's typology for use in marine ecosystems research. Structural (how model is built up), Initialisation/ Internal Variability (the combination of the variability of the model and complex model feedbacks), Parametric, Scenario
Refsgaard et al	2016	Journal Article	Uncertainty cascade	Hydrology and Climate modelling	The authors describe and conceptualise the uncertainty 'cascade' between different stages of the modelling process. The particular cascade they describe sees uncertainty flow between GHG emission scenarios -> to Climate models -> to Downscaling and bias correction -> to Hydrological models which then results in uncertainties in different relevant outputs. Within each of the model they also describe other sources of uncertainty such as natural variability, process equations, data & parameter values, discretisation numerics.
Cheung et al	2016	Journal Article	Typology	Marine resources, Climate change	The authors adapt Hawkins & Sutton's typology for use in marine ecosystems research. They describe four types: Internal Variability, Structural, Parametric, Scenario. They also make use of some use of the ideas of Link et al 2012 in their description of parametric uncertainty.
Usher	2016	PhD Thesis	Conceptual Distinction	Energy Systems Modelling	Following other authors, broadly describes there being two relevant sources of uncertainty: parametric and structural uncertainty. Describes the idea of *dynamic uncertainty* which involves the temporal development due to the agency of decisionmakers, learning and the interactions of variables.
Beven	2016	Journal Article	Taxonomy (2 levels)	Hydrological Modelling	4 fundamental types of uncertainty in hydrological modelling: • *Epistemic* is subdivided into three sub-classes (system dynamics, forcing and response data, disinformation) • *Aleatoric*- uncertainty with stationary statistical characteristics • *Semantic/linguistic*- uncertainty over meaning of statements • *Ontological*- differing belief systems
Hamel & Bryant	2017	Journal Article	Matrix	Ecosystems Services	This paper is primarily focussed on practical issues involved in uncertainty analysis in Ecosystems Services Modelling. They adapt the Walker et al (2003) framework for this use. They adapt the *locations* of the uncertainty to be specific to Ecosystems Services. They include an extra dimension of uncertainty of 'overall importance' to business cases, optimal design or impact estimates.
Schick et al	2017	Journal Article	4 Types	Ecosystem Health and Sustainability	They deploy the 'VUCA' system, an uncertainty accounting tool previously popular in strategy and leadership literature, in an ecology context. The VUCA mnemonic provides for dimensions to assess a strategic situation: • Volatility: the speed of change in the system • Uncertainty within the main drivers of the situation • Complexity: a high number of interlinkages within the system and with other systems • Ambiguity: multiple interpretations of current and future conditions
Heal & Millner	2017	Working Paper	Implicit taxonomy (2 Levels)	Ecological Economics	Uncertainty relevant to environmental economics is at the first level divided between scientific uncertainties and socio-economics (by system domain). Scientific uncertainties are subdivided into internal variability, model uncertainty and emissions uncertainty. Socio-economic uncertainties are divided into model uncertainties (including parameter uncertainties) and disagreements about values.
Baustert et al	2018	Journal Article	Dimensions/ Stages in Uncertainty Assessment	Ecosystems Services, Integrated Environmental Models	The authors review a number of conceptualisations of uncertainty for integrated modelling. They describe a number of dimensions of uncertainty that are identified with stages of an uncertainty analysis. *Location:* Which model element the uncertainty manifests in. This is subdivided into context, frame, variables, structure. *Identification:* How uncertainty is described by a number of dimensions, such as nature (epistemic or ontic) and level (a scale from complete knowledge to blind ignorance). *Characterisation*: How the uncertainty is represented using a mathematical structure *Treatment:* A calculation of the influence of one or more uncertainties *Communication*: Linguistic or visual communication of uncertainty in results
Benjamin & Budescu	2018	Journal Article	Taxonomy	Climate Science Communication	For this study examining participants responses to a number of different kinds of uncertainty, the authors divide uncertainty into *model uncertainty* and *Source uncertainty*. Model uncertainty is either due to structural uncertainty (difference between models) or judgemental uncertainty (different initial conditions). Sources of uncertainty are either conflict (difference between precise forecasts) or two identical imprecise forecasts.
Doyle et al	2019	Journal Article	Review	Disaster Risk Reduction	A broader systematic review of papers on the topic of *communicating model uncertainty* relevant to the field of disaster risk management. They identify the categorisation of uncertainty as one of the themes within this corpus and review. They identify styles of classifications, including those specifically for spatial uncertainties and matrix-type typologies.

					As part of the framing of the review they give sub-categories of model uncertainty of model structure uncertainty (uncertainty in how model describes system), model technical uncertainty (due to choices made in technical implementation), initial condition uncertainty, external driving force uncertainty, forcing data, parameter value uncertainty, scenario uncertainty, data uncertainty, and model outcome uncertainty. They collect together row and column categories from matrix-type classifications (table 15), including level, location, nature, qualification of knowledge base and value-ladenness of choice.
Derbyshire	2019	Journal Article	Distinction	Scenarios, Geography	This paper distinguishes between 'Epistemic' uncertainty and 'Ontological' uncertainty. The former is described as "the known and bounded inaccuracy of our knowledge". Ontological Uncertainty "stems … from the tendency of fundamental changes to disrupt our present knowledge". This uncertainty also includes the changes in attitudes, belief and behaviours of actors in the wake of these developments. The two kinds are described as existing on a continuum, with certain kinds of analysis being particularly problematic in situations characterised by ontological uncertainty.
van der Bles et al	2019	Journal Article	Aspects of uncertainty (essentially dimensions)	Uncertainty communication	They develop a model for communication of uncertainty four relevant aspects of uncertainty to communicate: • *Object* (what is uncertain), • *the Source* (the cause of the uncertainty), • *the level* (direct (about a fact) or indirect uncertainty (about underlying knowledge base)), • *the magnitude of uncertainty*
Marchau et al	2019	Book Section	Levels	Decision-making	They first provide an ontology of a decision support system to use in uncertainty analysis. Then then present 5 levels of uncertainty: • A clear enough future • Alternative futures with probabilities • A few plausible futures • Many plausible futures • Unknown future They relate each of these to appropriate system models.
Dreier & Howells	2019	Journal Article	Dimensions	Energy Modelling	The paper presents a new piece of software for stochastic energy systems modelling. They present two dimensions of uncertainty as a diagnostic tool to aide selection of uncertainty analysis technique. They classify uncertainty analysis techniques as to whether they are endogenous/exogenous to the model system and whether the technique is stochastic/deterministic.
Petr et al	2019	Journal Article	Dimensions	Climate and Forestry	They adapt the framework of Walker et al (2003), Refsgaard et al (2007) and Warmink et al (2010) to define three dimensions of uncertainty: • *Location*: Context & framing, driving forces, system, data, model structure, technical model (model selection, model implementation), parameter uncertainty, model output uncertainty (type of information output, information selection decision) • *Level:* statistical, scenario or recognised ignorance • *Nature*: Epistemic, Stochastic/Aleatory, Ambiguity They then use their framework in a review of the forest science literature to determine how often different locations of uncertainty appear.
Kutiel	2019	Journal Article	Typology	Climate Modelling	The article focusses on temporal uncertainties (changes in time). They give three contributions to uncertainty in climatic variables: natural variability, lack of sufficient data and erroneous scenarios. A taxonomy of temporal uncertainty is presented where it is split into long term trends, inter-annual uncertainty and intra-annual uncertainty.
Pye et al	2020	Journal Article	Matrix	Energy Systems	A paper in which the NUSAP framework is adapted and applied to Energy Systems Modelling. They create a matrix which plots uncertainties in a 2-d space with axes of strength of evidence (pedigree) and spread (influence on outcome).
Gaudad & Romero	2020	Journal Article	Dimensions	Energy Planning	Three dimensions of uncertainty (within a risk context) given: probability (low or high), doubt (confidence in that probability assessment; low or high) and impact (low or high). These are combined into a 16 point 'acuity scale', a term borrowed from medical vocabulary.
Zumwald et al	2020	Journal Article	Sources	Climate Datasets	They describe a framework to understand uncertainties in climate datasets. They describe a number of sources and sub-sources: 1a) How the data is measured 1b) How the data is processed (e.g. the model used to understand the measurement) 2) When and where a measurement is taken and how that relates to the phenomenon of interest e.g. biased samples) 3) The adequacy of the dataset to provide a description of the phenomenon
Kay & King	2020	Book	Various distinctions/ Dimensions	Economics	In this book, aimed at a popular audience, they make the Knightian distinction between 'resolvable' and 'radical' uncertainty. Radical uncertainty has a number of dimensions to it: • Obscurity • Ignorance • Vagueness • Ambiguity • Ill-defined problems • A lack of information that in some cases but not all we might hope to rectify at a later date They relate the resolvable/radical difference to aleatoric/epistemic (p23)
Workman et al	2021	Journal Article	Taxonomy	Integrated Assessment	At the highest level they separate those uncertainties that are within the modelling process and those between modelling and policy-making. Each has a number of sub types • Uncertainties in modelling: stochastic, epistemological, ontological (entities not in conceptual models), computational, scope (processes not within scope of

					model), judgement (expert decisions about parameters or convergence criteria), modelling errors • Uncertainty in policy: Endpoint uncertainties (required endpoint not certain), semantic uncertainties, implicit value judgements, implementation uncertainty, ethical uncertainties
Kirchner et al	2021	Journal Article	Dimensions/ Taxonomy	Integrated Modelling, Global Change	They review a number of uncertainty conceptualisations in the literature. They develop their own uncertainty matrix, based on the original Walker et al (2003) framework. They describe three dimensions of uncertainty: *Nature*: Epistemic or Stochastic – epistemic is said to be *reducible*. They subdivide these two into different sub categories Epistemic ={unreliability, structural, system understanding, linguistic}; Stochastic= {natural variability, human variability}. *Type*: is described as the way that uncertainty can be expressed. There are four types given: Statistical, Scenario, Qualitative Ignorance *Location*: where uncertainty manifests in the model process or framework. They give four major locations, each subdivided into minor locations: Context (System boundaries, system resolution) , Inputs (System Data, System Drivers) , Model (Parameter calibration, Structure, Hardware & Software) , Outcome (Linkage, Extrapolation, Decision Support).