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On the meaning of and relationship between dragon-kings, black swans and related concepts

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ABSTRACT

Different metaphors have been introduced to reflect the occurrence of rare and surprising types of events with extreme impacts, including black swans, grey swans and dragon-kings. Despite considerable research on clarifying the meaning of these concepts, their relationship still remains unclear. The present paper aims to meet this challenge, by reviewing current definitions and interpretations found in the literature and referred to in practice, analysing these definitions and interpretations, and providing a structure for improved understanding of the differences and similarities between the various metaphors. The paper also discusses some of the implications the use of these concepts has for risk management and decision-making.

1. Introduction

Rare and surprising events with extreme impacts have been given a substantial amount of attention in scientific environments for decades. Examples of such events are the terrorist attacks on September 11th 2001, the financial crisis in 2008 and the Fukushima nuclear accident in 2011. Common to these events is that we failed to predict them: their chain of events came as a surprise, and our existing mechanisms for prevention were insufficient.

Events of this type are found across numerous fields, from engineering and technology, to finance and social science. This wide-ranging relevance has led to efforts from multiple disciplines to examine and understand the nature of these events and how they can be confronted.

There are several metaphors aimed at describing this type of events. The most well-known is the 'black swan', popularized by Taleb in his book, *The Black Swan – The impact of the highly improbable* [78]. Its origin is usually linked to a Dutch expedition to Western Australia in 1697, discovering black swans on the Swan River. Up to that point in time, all observed swans in the Old World had been white. As discussed by Taleb [78] and Hammond [30], the metaphor was also used earlier – it is, for example, stated that, in 16th⁻century London, the black swan was a common metaphor used to describe the impossible.

Taleb [78] refers to a black swan as an event with three attributes: firstly, it is an outlier, lying outside the realm of regular expectations, as nothing in the past can convincingly point to its possibility. Secondly, it brings an extreme impact. Lastly, despite its outlier status, it is rendered explainable and predictable in retrospect. Inspired by Taleb's work, many risk researchers have further discussed the meaning of a black swan. For example, Aven [5–7] looks more closely into three possible interpretations:

1 An unknown unknown with extreme consequences
2 A surprising extreme event relative to one's beliefs/knowledge
3 A surprising extreme event with a very low probability ([6], p. 12) (1.1)

Following the black swan metaphor, Taleb [78] introduced the related concept of 'grey swans'. Several authors have referred to this metaphor when discussing rare and surprising events with extreme impact (e.g. [1, 54, 74]). Taleb describes them as "modelable extreme events" ([78], p. 272), events whose occurrence is rare, but not unexpected. Other authors refer to grey swans as 'known unknowns', e.g. Hole and Netland state that "A grey swan is a metaphor for a large-impact and rare event that's somewhat predictable, yet many overlook it. It's the 'known unknown', a rare event that some know is possible, but no one knows when or whether it will occur" ([33], p. 21).

Other interpretations of grey swans seem to link them more to a subset of 'known knowns', resembling the last (1.1) of the black swan interpretations discussed by Aven [6]. Examples of this are the practical understanding and use of the metaphor in financial markets; see, for example, the definition given by Investec [34] and Liberto [42]. Another example is Lin and Emanuel, who interpret grey swans as high-impact,

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low-probability events with a degree of predictability:

> Some high-consequence events that are unobserved and unanticipated may nevertheless be predictable (though perhaps with large uncertainty). Such to-some-extent-predictable, low-probability, high-impact events may be referred to as "grey swans" (or, sometimes, "perfect storms"). ([43], p. 106)

In their interpretation of grey swans, Lin and Emanuel link the grey swan concept to another metaphor: 'perfect storms'. This metaphor originated from the occurrence of a category-one hurricane in 1991, later named "The Perfect Storm" and made famous by Sebastian Junger [38] in his book of the same name. This storm arose from meteorological phenomena that were known to occur, but the conjuncture of the different weather systems resulted in a storm with extreme dimensions. In medical science, the metaphor of perfect storms is often used to describe scenarios where we face synergetic effects between multiple well-known medical phenomena (see e.g. [18, 83]).

Catanach Jr. and Ragatz describe a perfect storm as "an unexpected dramatic event resulting from a confluence of unpredictable circumstances. No individual contributing factor is powerful enough to create the resulting 'storm'; collectively their confluence creates an effect that is exponentially more devastating and unimaginable" ([16], p. 20).

The metaphor of perfect storms has been discussed in relation to black swans by Paté-Cornell [59] and Aven [6]. Aven states that "In relation to perfect storms, the variation in the phenomena is known and we face risk problems where the uncertainties are small; the knowledge base is strong and accurate predictions can be made" ([6], p. 122).

We see that the metaphor of perfect storms has been related to events that can be accurately predicted, events that can be predicted to some extent, and even events with circumstances that are unpredictable. Some of the interpretations link perfect storms to a rare combination of known events, whereas other definitions emphasize the effects of a synergetic relationship between the events.

Another metaphor used to describe these rare, surprising and extreme events is the "dragon-king" [69]. This metaphor is composed of two terms: 'dragon' and 'king'. The term 'king' was introduced by Laherrère and Sornette [40] to describe extreme outliers that strongly deviate from an overall pattern of events, much as the fortune of kings greatly exceeds the wealth of the population in general. Sornette later coupled this term with 'dragon' to incorporate the extraordinary characteristics of these events "whose presence, if confirmed, has profound significance" ([69], p. 5). The term 'dragon' is also linked to the unknown, for example by the Latin phrase 'hic sunt dracones' (translated to 'here be dragons'), often used in ancient maps as a reference to unexplored territory.

The use of metaphors in general contributes to creating discussion and attention around important issues, so also within the risk field. When the black swan concept was introduced, there followed an "increased interest and enthusiasm for discussing risk issues" ([5], p. 49). Metaphors do not only make complex and abstract concepts comprehensible; they also influence the way we perceive the phenomena. A study conducted by Thibodeau and Boroditsky [79] concluded that the metaphors we are presented with "can have a powerful influence over how people attempt to solve complex problems", and, notably, they found that "People do not recognize metaphors as an influential aspect in their decisions" ([79], p. 10). The metaphors also need to be used carefully because of features like "highlighting and hiding", sometimes referred to as "partiality of insight" [51], which means that, "in allowing us to focus on one aspect of a concept (…), a metaphorical concept can keep us from focusing on other aspects of the concept that are inconsistent with that metaphor" ([41], p. 10). Reasoning from the logic of Lakoff and Johnson, applying multiple metaphors (black swan, grey swan, dragon-king, perfect storm) to describe a single phenomenon (rare, surprising and extreme events), allows us to highlight different aspects of the phenomenon, contributing to a more complete understanding. However, in order to understand the contribution from each metaphor, we need to understand how the metaphors are related, their similarities and differences. The above discussion has shown that this is difficult, given the many existing definitions and interpretations used. It is observed that different metaphors are applied to the same event. For example, the Macondo accident in 2010 has been referred to as a black swan by Aven [6] and Murphy [52], and a grey swan by Yang et al. [86] and Murphy and Conner [54]. The nuclear disaster at Fukushima in 2011 is also referred to by multiple metaphors: a black swan [68], a grey swan [1] and even a dragon-king [84]. Many of these overlaps can be explained by different definitions and interpretations, but there is also a need to question the underlying rationale for these metaphors. For example, how should a grey swan be defined and relate to a black swan? To what extent is it meaningful to associate grey swans with, for instance, known unknowns? The scientific risk literature has only to some extent clarified the meaning of and relationship between these metaphors. The current situation is somewhat chaotic and hampers the effective communication of risk related to rare, surprising and extreme events. From a risk science point of view, it can be argued that the field is suffering from a rather high degree of inconsistency and lack of stringency in relation to important risk concepts.

In the present work, we will look more closely at these challenges. The main aim of the paper is to present a logic and structure for

Table 1
Definitions and interpretations of the black swan metaphor.

Source	Definition/interpretation
Taleb ([78], p. xvii)	"First, it is an outlier, as it lies outside the realm of regular expectations, because nothing in the past can convincingly point to its possibility. Second, it carries an extreme impact. Third, in spite of its outlier status, human nature makes us concoct explanations for its occurrence *after* the fact, making it explainable and predictable."
Makridakis et al. ([46], p. 795)	"(…) rare and unique events that are completely unexpected, and even outside the realm of our imaginations."
Hole and Netland ([33], p. 21)	"A black swan is a metaphor for a large-impact and rare event that comes as a total surprise to everybody. This type of event is the 'unknown unknown', a rare bombshell event that no one has considered."
Catanach Jr. and Ragatz ([16], p. 20)	"A low-probability, high-impact occurrence that can be either positive or negative in its effect, that is prospectively unpredictable but that everybody could see coming after it occurs."
Marsh and Pfleiderer ([48], p. 2)	"(…) what has come to be known as the problem of 'unknown unknowns' or 'black swan events', i.e., extreme events that are not well enough understood for their probabilities to be accurately modelled."
Yukalov and Sornette ([87], p. 54)	"The concept of black swan is essentially the same as Knightian uncertainty, i.e., a risk that is a priori unknown, unknowable, immeasurable, not possible to calculate."
Aven ([5], p. 49) Aven ([7], p. 83)	"a surprising extreme event relative to the present knowledge/beliefs". "a surprising extreme event relative to one's knowledge/beliefs"
Yang et al. ([86], p. 102)	"[Black swans] are unforeseeable and catastrophic events."
Murphy ([53], p. 13)	"(…) black swans are rare, catastrophic and unpredictable events."
Baldassarre et al. ([11], p. 1754)	"Some of these unknown unknowns may occasionally result in the so-called 'black swans': unexpected events with an extremely high impact on the system, which are essentially impossible to forecast."
Faggini et al. ([20], p. 106)	"(…) outlier's events, the risks of which cannot be anticipated, are referred to as Black Swans."
Ale et al. ([3], p. 3)	"The unknown unknowns are the most problematic and the most discussed. These are the real black swans."
CFI [17]	"A black swan event, a phrase commonly used in the world of finance, is an extremely negative event or occurrence that is impossibly difficult to predict. In other words, black swan events are events that are unexpected and unknowable."

clarifying and enhancing our understanding of these metaphors. By doing so, we believe the paper can provide a contribution to the process of further developing these concepts and their meaning and use in a risk context. In this way we also believe the paper can make a contribution towards a more a uniform use of language related to the concepts discussed in this paper.

The paper is organised as follows. First, in Section 2, we provide an overview of some of the most common definitions and interpretations of the different metaphors, following up and systematizing the discussion in this introduction section. In Section 3, we present the above announced structure, and, in Section 4, we discuss the implications the use of these metaphors has for risk management and decision-making. Lastly, some conclusions are drawn in Section 5.

2. Overview of current definitions and interpretations

In this section, we provide an overview of definitions and interpretations of the four metaphors: black swan, grey swan, perfect storm and dragon-king. The overview is not all-inclusive but considered sufficient to show how these metaphors are commonly understood and used.

2.1. Black swans

Table 1 presents a set of definitions and interpretations of black swans found in the literature

As seen from the list of interpretations and definitions in Table 1, the black swan is often linked to the so-called ‘unknown unknown’. However, authors interpret the ‘unknown unknown’ concept in different ways. Hole and Netland [33] use the expression to describe something “no one has considered”. According to Aven and Krohn [8], ‘unknown unknown’ events are “unthinkable and/or unknown to the scientific community” ([8], p. 9). Haugen and Vinnem [31] have a similar interpretation, stating that an ‘unknown unknown’ is an event that “no one really can foresee is possible at all, regardless of probability (…)” ([31], p. 2).

Others refer to the ‘unknown unknowns’ as “unexpected events” ([11], p. 1754) or “not well enough understood for their probabilities to be accurately modelled” ([48], p. 2).

The latter two interpretations represent scenarios where some sort of expectation exists regarding the event; the event has been identified in the risk assessment, but the variation in the phenomena is subject to large uncertainties and inaccurate modelling. However, if the ‘unknown’ is in fact unknown, no expectations will exist, as we do not have anything to base our expectations on.

Another interpretation of ‘unknown unknowns’ is proposed by Feduzi and Runde [22], who describe them as events “that the decision-maker does not imagine and therefore does not even consider” ([22], p. 270). By relating ‘unknown unknowns’ to the knowledge of the decision maker alone, we discount the possibility of the knowledge existing elsewhere. It could be an unknown known: unknown to the decision maker but known to others. Unlike the ‘unknown unknowns’ described by Aven and Krohn [8], ‘unknown knowns’ are potentially identifiable through a more thorough risk analysis.

As defined by Taleb [78], a black swan is retrospectively predictable. After its occurrence, the sequence of events leading to the black swan is exposed, rendering it explainable and foreseeable in hindsight. From several of the interpretations in Table 1, this attribute has developed into the assumption that black swans are prospectively *unpredictable* [16, 53]. However, this assumption can be questioned (e.g. [6, 44]). It may be unpredictable using probabilistic risk assessments, as we cannot rely on large amounts of reliable data from past events or detailed modelling of relevant phenomena. However, other types of risk assessments based on signals and warnings could give predictions of such events, though they may be inaccurate and subject to deep uncertainties.

The terrorist attacks on September 11th have been referred to as a black swan by several authors (e.g. [55, 58, 78, 86]. This event undoubtedly came as a surprise for many, both laymen and security professionals [6]. It was, however, well-known to the terrorist group responsible for planning and executing the attack. In the aftermath of the event, it became clear that the government had been made aware of Islamic terrorist groups planning an attack on US territory by hijacking aircraft [67]. The possibility of the aircraft being used as missiles was certainly apparent, as several similar attempts had been made during the 1990s [13]. Although the details of such a potential attack were difficult to predict, such as the exact location, targets and scope, it can be argued that “Government agencies and officials had all of the data they needed to know of dangerous deficiencies in airline security that could be exploited” ([13], p. 366). The knowledge of such a scenario was available but did not trigger any preventive measures. Hence, the event was a ‘known known’ to the terrorist organizations, as well as to government officials, but an ‘unknown known’ to the airport security officers. This example illustrates that the interpretation of the black swan is contingent on whose knowledge we are referring to, and at what time. The definition of a black swan by Aven ([6], p. 116) as “a surprising extreme event relative to the present beliefs/knowledge” captures this aspect. Based on this definition, Aven [6] distinguishes between three categories of black swans:

Table 2
Definitions and interpretations of the grey swan metaphor.

Source	Definition/interpretation
Taleb ([78], p. 37)	“They are near-Black Swans. They are somewhat tractable scientifically – knowing about their incidence should lower your surprise; these events are rare but expected.”
Nafday ([55], p. 193)	“(…) the random uncertainty of probabilistic models (what Donald Rumsfeld called ‘known unknowns’ or Taleb refers to as ‘grey Swans’).”
Hole and Netland ([33], p. 21)	“A grey swan is a metaphor for a large-impact and rare event that’s somewhat predictable, yet many overlook it. It’s the ‘known unknown’, a rare event that some know is possible, but no one knows when or whether it will occur.”
Nuñez and Logares([58], p. 17)	“Grey Swans may be associated with events that are rarer than White Swans, with consequences ranging from large to irrelevant.”
Murphy and Conner ([54], p. 110)	“The Black Swan pathway plus the recognition of similar pathways constitute some of the most valuable lessons-learned from a Black Swan event. Unfortunately, these valuable lessons-learned are often forgotten over time and the white swan becomes greyer and greyer unless efforts are made to keep the lessons-learned fresh.”
Stein and Stein ([74] p. 1281)	“(…) they are better viewed as ‘grey swans’ that—although novel and beyond recent experience—could have been foreseen and mitigated.”
Khakzad et al. ([39], p. 1336)	“(…) grey swan (GS) is used to address accident events that are predictable but with larger uncertainties.”
Lin and Emanuel ([43] p. 106)	“Some high-consequence events that are unobserved and unanticipated may nevertheless be predictable (though perhaps with large uncertainty). Such to-some-extent-predictable, low-probability, high-impact events may be referred to as ‘grey swans’ (or, sometimes, ‘perfect storms’).”
Gholami et al. ([28], p. 32, 037)	“A grey swan is a metaphor for a partially-predictable, high-impact, and rare (PHR) event, which is disregarded by many people.”
Akkermans and Wassenhove ([2] p. 10)	“Grey swan events are still very unlikely, but have occurred before, (…), and can in principle be foreseen by management.”
Investec [34]	“Unlike their cousins, grey swan events are possible and knowable, even though they may be regarded as unlikely. Like black swans though, their impact can be huge. In short, probabilities can be assigned to such events and so, presumably, their potential impact can be measured.”

Table 3
Definitions and interpretations of the perfect storm metaphor

Source	Definition/interpretation
Merriam-Webster's Dictionary [60]	"A critical or disastrous situation created by a powerful concurrence of factors."
Reinstein and McMillan ([63], p. 955)	"(…) a "perfect storm" – a concurrence of unpredictable, rare and unusual conditions that combined to create a unique, devastating event."
Gardiner ([27], p. 398)	"(…) an event constituted by an unusual convergence of independently harmful factors where this convergence is likely to result in substantial, and possibly catastrophic, negative outcomes."
Emanuel and Fuchs ([19], p. 2789)	"A 'perfect storm' occurs when a confluence of many factors or events—no one of which alone is particularly devastating—creates a catastrophic force. Such confluence is rare and devastating."
Catanach Jr. and Ragatz ([16], p. 20)	"An unexpected dramatic event resulting from a confluence of unpredictable circumstances. No individual contributing factor is powerful enough to create the resulting 'storm'; collectively, their confluence creates an effect that is exponentially more devastating and unimaginable."
Frederick and Monsen ([25], p. 187)	"A perfect storm is when several remotely possible and individually innocuous events occur at the same time, which then feed off each other and lead to a dramatic and possibly disastrous event."
Paté-Cornell ([59], p. 1824)	"'Perfect storms' involve mostly aleatory uncertainties (randomness) in conjunctions of rare but known events."
Aven ([6], pp. 120–122)	"Rare event that may occur, where we understand the underlying phenomena: known variation of these phenomena described by frequentist probabilities."

a) Events that were completely unknown to the scientific environment (unknown unknowns)
b) Events that were not on the list of known events from the perspective of those who carried out the risk analysis (or another stakeholder), but known to others (unknown knowns)
c) Events on the list of known events in the risk analysis but not believed to occur because of negligible judged probability

In relation to c) it is tacitly understood that the supporting knowledge for the judged probability is also considered relatively strong [10].

2.2. Grey swans

Table 2 presents a set of definitions and interpretations of grey swans found in the literature

In his book, Taleb [78] relates the black swan to its more scientifically tractable cousin – the grey swan. The grey swan does not represent an analogy per se; the meaning of the metaphor builds on the black swan. Taleb [78] describes them as "near-Black Swans", events that are "rare and consequential, but somewhat predictable, particularly to those who are prepared for them and have the tools to understand them" ([78], p. 37).

The definition by Taleb [78], as well as several of the other interpretations in Table 2, relates grey swans to the 'known known'. They are described as foreseeable and predictable but unlikely to occur. Some authors relate grey swans to incidents that are known to have occurred before (e.g. [2, 54]), while others describe them as "beyond recent experience" [74] or even "unobserved" [43]. Hence, the background knowledge supporting the predictions may differ, but the predictions are in any case uncertain.

According to some of the definitions in Table 2, the grey swan metaphor reflects the 'known unknown'. With such an interpretation, the black swan/grey swan metaphors are combined by the known/unknown taxonomy. However, in order to justify this classification, we need to be clear on what the 'known' and 'unknown' in this expression are referring to. Judging from the interpretations in Table 2, there is large consensus that grey swans represent events that we know could occur, i.e. events that have been identified in the risk analysis. This justifies the 'known' in the partitioning. Based on the definition by Hole and Netland, an event being 'unknown' is taken to mean that "No one knows when or whether it will occur" ([33], p. 21), whereas Gholami et al. [28] relate grey swans to the following interpretation of 'unknown' events: "When probabilities cannot be assigned to at least part of the space (i.e., outcomes are specified but probabilities are not), the situation is unknown" ([28], p. 32037). Nafday [56] takes a similar approach, describing grey swans as known events with unknown likelihood.

The interpretation from Gholami et al. [28] requires some further consideration. It is stated that grey swans can be categorized as events where we can specify outcomes but not probabilities. This statement cannot be justified, as subjective (also known as knowledge-based) probabilities can always be assigned. Hence, no such scenario exists where probabilities cannot be assigned to known outcomes. However, the subjective probabilities could produce poor predictions, as the knowledge supporting the probabilities could be weak. We are in a state of what Stirling [75] calls "incomplete knowledge", in which attempts to assign probabilities "are neither rational nor 'science-based'" ([75], p. 310). Using probabilities alone to describe uncertainties for this type of situations is not sufficient [24].

2.3. Perfect storms

Table 3 presents a set of definitions and interpretations of perfect storms found in the literature.

As mentioned in Section 1, the origin of the 'perfect storm' expression was the category-one hurricane that hit the east coast of the United States in 1991. It developed into a case of several rare but well-known phenomena, each of large but not devastating magnitude, appearing in an unusual conjunction, where the interactions between the phenomena gave a synergistic effect that resulted in a devastating event. Hence, building on the original meaning of the metaphor, perfect storms can be interpreted as events where, although each event as well as the conjunction of events can be considered rare, we can make accurate predictions about the phenomena and their combinations. However, we may experience surprises relative to our knowledge, due to the synergistic effects of the conjunction.

The metaphor has become a popular expression in both scientific and non-scientific literature. In Google Scholar, a search for "perfect storm" yields over 68,000 results. A closer look at the different contexts where the perfect storm metaphor is applied reveals some discordance as to how the term is understood.

In all the interpretations in Table 3, perfect storms are related to the concurrence of events. However, when we dive further into each separate event constituting the combination, the interpretations diverge. In some cases, they are described as unusual or even unpredictable. Others refer to them as rare but known. If we consider how the perfect storm metaphor is applied in medical science literature, the events involved are in many cases well known to occur. For example, the metaphor is used to describe the relationship between phenomena like cancer and diabetes [76] and puberty and obesity [36], none of which can be considered rare or unexpected.

Furthermore, the combination of these events is subject to different interpretations. While some refer to the combination as rare and unusual, many applications of the perfect storm metaphor concern events that are closely related and known to occur at the same time. For example, the metaphor is used to describe the combination of different risk factors in adolescent driving [4], including the propensity for risky behaviour and peer influence. A combination of these factors is not rare, several references to the connection between these factors are found in the scientific literature (see e.g. [64]). In this case, the perfect storm is used to describe a scenario where the conjuncture of known, related events creates a negative outcome that is amplified by the interactions between the different factors.

Table 4
Definitions and interpretations of the dragon-king metaphor

Source	Definition/interpretation
Sornette ([69], p. 1)	"dragon-kings (…) refer to the existence of transient organization into extreme events that are statistically and mechanistically different from the rest of their smaller siblings."
Sornette and Ouillon ([71], p. 2)	"extreme events that do not belong to the same population as the other events."
Ale et al. ([3], p. 5)	"the existence of transient organization of phenomena that can emerge into extreme events. These extreme events lead to so-called meaningful outliers. These are events or data points that coexist with series of similar events that are distributed according to a regular distribution such as a power law."
Faggini et al. ([20], p. 112)	"[dragon-kings] are the result of the same system properties that give rise to the power law, but they violate the power law because those properties have been arranged in such a way as to create severe instability, producing a systemic risk. Moreover, the presence of a positive feedback mechanism 'creates faster-than-exponential growth, making them larger than expected'."
Janczura and Weron ([35], p. 79)	"[dragon-kings] are the result of positive feedback mechanisms that make them much larger than their peers. Being outliers to heavy-tailed behaviour, these dragon-kings are unaccounted for by power law."
Wheatley et al. ([35], p. 108)	"[Dragon-king] is a double metaphor for an event that is both extremely large in size or impact (a 'king') and born of unique origins (a 'dragon') relative to other events from the same system."
Süveges and Davison ([77], p. 131)	"The catastrophe could justly be called a 'Dragon-King': apparently impossible from scientific extrapolation or common sense based on the past."

The synergy in the concurrence of events is emphasized in several of the interpretations in Table 3, as well as in many of the examples from medical science literature. The extent to which these synergistic effects are understood may vary, depending on our knowledge of the phenomena.

The perfect storm is thus related to the 'known knowns', events that have been identified in the risk analysis, where some sort of judgement has been made about the possibility/likelihood of occurrence. Hence, there is a link to both black swans and grey swans. The perfect storm metaphor has been discussed in relation to the black swan metaphor by Paté-Cornell [59], who distinguishes between the two by relating them to different types of uncertainties: "'Perfect storms' involve mostly aleatory uncertainties (randomness) in conjunctions of rare but known events. 'Black swans' represent the ultimate epistemic uncertainty or lack of fundamental knowledge" ([59], p. 1827). In line with this reasoning, Aven [6] discusses perfect storms in relation to the type c) black swan mentioned in Section 2.1 (surprising, extreme events not believed to occur because of very low judged probability), stating that perfect storms are events that can be predicted (using frequentist probabilities) with large accuracy and small uncertainty, whereas black swans of type 3 are described using subjective probabilities and cannot be predicted with this level of accuracy.

2.4. Dragon-kings

Table 4 presents a set of definitions and interpretations of dragon-kings found in the literature.

As mentioned in Section 1, the dragon-king metaphor is twofold: the 'king' part of the metaphor is related to the extreme size and impact of the event, while the 'dragon' describes its unique origin, i.e. the extraordinary generating mechanisms of the event [84].

According to Sornette [69], "The key idea is that catastrophic events involve interactions between structures at many different scales that lead to the emergence of transitions between collective regimes of organization" ([69], p. 11). Hence, we are talking about complex system structures, in which the interactions cause the system to move towards a state of instability. Dragon-kings emerge as a result of a phase transition, tipping point or bifurcation generated by this gradual maturation of the system. Sornette uses boiling water to illustrate this characteristic: when water is heated, it follows a gradual, predictable increase in temperature, until it reaches the boiling point (what Sornette refers to as the tipping point), after which the behaviour of the water becomes unstable, i.e. transforms into vapour. Sornette [69] argues that these bifurcations and tipping points create some early warning signals that give these events a potential for predictability.

The definition presented when the metaphor was introduced has created less room for diverging interpretations of the metaphor. However, although the references from scientific literature indicate a large level of consensus on the meaning of the metaphor, its relationship to the black swan and grey swan metaphors remains unclear.

According to Yukalov and Sornette [87], black swan events are inherently unpredictable, due to their shared properties with the rest of the population. From this view, "A great earthquake is just an earthquake that started small … and did not stop" ([69], p. 5). The only property distinguishing these extreme events from similar ones with lower impact is their size.

We struggle with the understanding of this reasoning. If black swan events are seen as part of the same population as the rest of the observations, can they be termed outliers? Recall the interpretation of a black swan by Yukalov and Sornette [87] as "a priori unknown, unknowable, immeasurable, not possible to calculate" ([87], p. 54). This statement essentially defines black swans as 'unknown unknowns', and the comparison of black swans and dragon-kings is made based on this perspective. However, if black swans are unknowable, how can we state that they have shared properties with the rest of the population?

The dragon-king, the black swan and the grey swan are all described as outliers. But what is an outlier? According to Hawkins [32], an outlier is "an observation that deviates so much from other observations as to arouse suspicion that it was generated by a different mechanism" ([32], p. 1). Rousseeuw and Hubert [66] have the following interpretation of outliers:

In real data sets, it often happens that some observations are different from the majority. Such observations are called *outliers*. Outlying observations may be errors, or they could have been recorded under exceptional circumstances, or belong to another population. ([66], p. 73)

These definitions are rather vague. However, they both indicate that an outlier is an observation stemming from a different population from the one studied. This leads us to considerations of probability models supporting the observations. If the data we observe come from a distribution F, the outlier comes from a distribution G, which could strongly deviate from F. The interpretation of probability models in the case of rare and surprising events is, however, not straightforward. Can such models at all be justified? These models are based on frequentist types of probability which require a population of a huge number of similar units.

When it comes to the dragon-king metaphor, outliers are interpreted as events found "beyond the extrapolation of the fat tail distribution of the rest of the population" ([69], p. 5). Based on such a perspective, outliers are not only extreme values in the distribution, they deviate from the distribution as a whole. Again, we need to interpret the definition in terms of probability models. However, to identify the observations that deviate from the model, the generating mechanisms of the phenomena must be well understood. If we consider some of the examples provided by Sornette [69], dragon-king outliers are identified in distributions of French cities, earthquakes and financial drawdowns. For each of these systems, we can rely on a thorough understanding of the phenomena involved, as well as large amounts of accurate and reliable data. In a rank-size distribution of French cities, Paris is seen as an outlier, found beyond the tail of the distribution. Referring to the outlier definition by Rousseeuw and Hubert [66], this observation is neither due to an error nor recorded under exceptional circumstances; hence,

Table 5
Overview of metaphor characteristics for black swans (BS), grey swans (GS), perfect storms (PS) and dragon-kings (DK)

	BS	GS	PS	DK
Knowledge				
Known/unknown (Categories within the taxonomy that are related to the metaphors)	**Unknown unknown Unknown known Known known**	**Known unknown Known known**	**Known known**	**Known known**
Available data/theory (The existence of historical data, observations and scientific theories)	**No/yes** Data/theory may be available, but reliability is limited	**No/yes** Data/theory may be available, but reliability is limited	**No/yes** Reliable data/theory on each individual event is available; data/theory on the concurrence could be limited	**No/yes** Reliable data/theory on the system is available; data/theory on each individual event could be limited
Understanding of phenomena (Inter alia knowledge on the underlying mechanisms causing the extreme events, triggering factors and the interplay between system components)	**Weak/medium** Underlying mechanisms of events are undisclosed but may be attainable by applying available data/theory	**Weak/medium** Underlying mechanisms of events are undisclosed but may be attainable by applying available data/theory	**Medium/strong** We have strong knowledge of the mechanisms and behaviour for each contributing event. Knowledge on the concurrence may be weaker	**Medium/strong** Knowledge on the mechanisms and behaviour of the system as a whole may be strong but could be influenced by a weaker knowledge on the mechanisms of each part
Knowledge base (The collection of knowledge on which risk assessments are based)	**Weak/medium**	**Weak/medium**	**Medium/strong**	**Medium/strong**
Predictability				
Prediction methods (Methods used to disclose the development of extreme events)	**Signals and warnings**	**Signals and warnings**	**Signals and warnings or probabilistic risk assessments**	**Signals and warnings or probabilistic risk assessments**
Prediction accuracy (The degree to which the prediction models reflect the actual state of the world)	**Low/medium** Predictions are based on subjective judgements and limited amounts of data/theory	**Low/medium** Predictions are based on subjective judgements and limited amounts of data/theory	**Medium/high** Predictions on each individual factor are based on reliable data and theories and can be modelled with large accuracy. For the confluence, the prediction models may rely on a weaker knowledge base, depending on the existence of relevant data/theory for the interplay	**Medium/high** Predictions are based on large amounts of relevant and reliable data/theory for the concurrence, but the accuracy of the prediction models may be influenced by a weaker knowledge base regarding the contributing factors

according to the argumentation above, this indicates that Paris belongs to a different population.

The dragon-king metaphor is largely focused on the dynamic process that causes the event to become an outlier. According to Yukalov and Sornette [87], there are amplifying mechanisms that are specific to dragon-kings, and, as a consequence of these, the events may be knowable and predictable using precursors. These precursors are found by observing dynamic variations in the phenomena. In order to analyse the behaviour of a phenomenon over time, it is implied that the phenomenon involved is known, understood, and that some sort of data exist to build the analysis on. Hence, dragon-kings concern the 'known knowns', events that we know could occur, where there is available historical data to support the assumptions made.

3. A structure for improved understanding of the differences and similarities between the various metaphors

Similarities and differences between the metaphors are discussed in relation to two of the most central aspects of rare, surprising and extreme events: knowledge and predictability. A general overview of the main differences and similarities is highlighted in Table 5.

3.1. Knowledge

Knowledge can be interpreted as "justified beliefs" [73] and constitutes an essential element in the understanding of, and distinguishing between, metaphors for rare, surprising and extreme events. All risk assessments are contingent on some background knowledge, covering "inter alia assumptions and presuppositions, historical system performance data and knowledge about the phenomena involved" ([23], p. 11). Knowledge captures some important aspects of rare, surprising and extreme events: whose knowledge we are talking about (what is known by person X may not be known by person Y) and at what time (what is unknown today, may be known tomorrow) ([6], p. 16). Another dimension of knowledge is the strength (or weakness), which is determined by factors such as availability of relevant data, degree of understanding of the phenomena involved and the existence of accurate models ([6], p. 103).

When we refer to black swans as 'unknown unknowns', they represent a "lack of fundamental knowledge (…), where not only the distribution of a parameter is unknown, but in the extreme, the very existence of the phenomenon itself" ([59], p. 1824). However, as argued in Section 2, other interpretations can be justified (represented as black swans of type b) 'unknown knowns' and c) 'known knowns'), where the knowledge exists, but we either fail to attain it (as in the case of the former) or our "justified beliefs" turn out to be false (as in the case of the latter). While the 'unknown knowns' are first and foremost related to black swans, the category of 'known knowns' can be used for all four metaphors. Initially, this may seem like a uniting feature, but, at closer inspection, large variations in knowledge can be found within this single category.

The grey swan is, by several definitions, referred to as a 'known unknown'. Consider the development of vaccines as an example. Based on similar situations concerning the development of new drugs/vaccines, there is strong knowledge that a novel vaccine could have some type of side effect. However, in the early phase of development, we cannot know what these side effects are or when they will occur. In this sense, we can talk about a 'known unknown': we have justified beliefs that the vaccine will carry some side effects (known), but we cannot say in advance what these side effects will be and when they will occur (unknown).

The generating mechanisms for black and grey swans are not clearly specified in any of the definitions from Section 2. The interpretations of these metaphors are first and foremost centred around characteristics that relate to our knowledge of their occurrence. Ricci and Sheng state that "Black Swans are observed and obtain from an undisclosed underlying physical mechanism" ([65], p. 7). The unknown mechanism of these events is part of the "lack of fundamental knowledge" ([59], p. 1824) associated with black swans. In fact, it is this very lack of knowledge that gives rise to them; "Surprising extreme events may occur as we do not fully understand what is going on" ([5], p. 46).

Recall the definition of a black swan by Aven [5] as "a surprising event relative to our present knowledge/beliefs" ([5], p. 49). Regardless of whether an event is driven by complex or simple mechanisms, we may experience black swans because our knowledge is poor, we do not have a thorough understanding of the system and its behaviour, and, consequently, surprises may occur relative to our beliefs. Nevertheless, a link exists between the swan metaphors and complex mechanisms; for risk problems characterized by large (deep) uncertainties, as in the case of black and grey swans, complexity could be a contributing factor, as "Uncertainty may result from an incomplete or inadequate reduction of complexity" ([9], p. 12).

When it comes to the second group, constituting the perfect storm and dragon-king metaphors, the focus shifts towards system complexity and interactions. The distinction between a 'known known' perfect storm and a 'known known' dragon-king lies within the understanding of the system as a whole.

The perfect storm is used to describe situations where we have several (well-known) phenomena occurring together, creating a (less known) interplay. Hence, we have strong knowledge about how the separate parts of the system behave, but the knowledge about how this interplay affects the total may vary. For dragon-kings, however, we can rely on large amounts of data on the performance/behaviour of the system as a whole. The distinction touches upon an important idea in the theory of complex systems: a system is more than the sum of its parts. In order to illustrate the difference: consider a stock market. In a perfect storm situation, we have knowledge of the different factors that influence the behaviour of the stock market, such as politics, unemployment and inflation. We can use this knowledge to make some judgements about how the stock market will behave, but these judgements are only based on what we know about each factor separately. Hence, behaviour that emerges from the interaction of these factors may be subject to weak knowledge. When referring to the dragon-king metaphor, on the other hand, we approach the problem from a different angle; the starting point is our knowledge about the behaviour of the stock market, and we may use this information in an attempt to obtain knowledge on how the contributing factors influence the system. Hence, we may have data on the behaviour of the system as a whole, but we do not necessarily understand how the different factors contribute to the behaviour of the system or their interrelations.

For perfect storms and dragon-kings, the focus is mainly on the mechanisms that cause events to cascade into extreme events. As seen from the definitions in Section 2, perfect storms are often referred to as a confluence of events, whose interplay amplifies the effects and causes a disastrous outcome. Dragon-kings are related to a similar interaction, where the behaviour of the system is shaped by "positive feedback mechanisms that lead to faster-than-exponential unsustainable growth regime" ([69], p. 8). Both metaphors are associated with scenarios where we face a number of different elements whose synergistic effects shape the behaviour of the system as a whole.

The perfect storm is focused on the mechanisms leading up to the conjunction, at which point the system causes mechanisms that we may have weaker knowledge about. Consider, for example, the Fukushima nuclear accident. In March 2011, an earthquake struck the north-eastern coast of Japan, creating a massive tsunami. The Fukushima Nuclear Power Plant was flooded, resulting in the meltdown of three reactors, and causing a major release of radiation. The event was not unforeseen; both the initial earthquake and the following tsunami were known types of phenomena, and when the Fukushima plant site was designed and built in the 1960′s, countermeasures against a possible tsunami were taken based on the prevailing assumptions and scientific knowledge at that time. This knowledge indicated the impact of a possible tsunami to be low (3.1 m) for that particular coastline. However, 18 years before the accident, new scientific knowledge surfaced, suggesting the potential impact of a tsunami to be significantly higher (15.7 m) than previously forecasted. Both government and the operator were aware of this new knowledge, but had yet to initiate any measures to mitigate risk [85]. Regardless of this new knowledge, the probability was judged as negligible, and so the government and the operator of the nuclear power plant "were reluctant to invest time, effort and money in protecting against a natural disaster which was considered unlikely" ([6], p. 8). However, assessors had not considered how the concurrence of these events could amplify the consequences, and the designed solutions and emergency response strategies were not adapted to the catastrophic interplay that arose from the concurrence [85]. Hence, the plant was to some extent prepared to handle the mechanisms of each event separately but failed to handle the mechanisms that emerged when the earthquake and the tsunami occurred adjacently.

The mechanisms of dragon-kings are extended to include the system behaviour beyond the confluence; the growth caused by positive feedback mechanisms will lead to a maturation of the system, in which a tipping point is reached and the system will change regime (e.g. the bursting of financial bubbles) [71]. By monitoring the mechanisms of the phenomena over time, important knowledge can be attained on the system behaviour. This knowledge may be used to identify useful precursors that could provide information on when and how the instability in the system will occur and, furthermore, how to prevent it. The financial drawdown of 2007 cascaded into a global economic recession, due to the "transient bursts of dependence between successive large losses" ([69], p. 7). These dependencies caused the financial system to follow complex mechanisms of positive feedback and amplifications, all of which could be observed in real time by modelling the large amounts of data available. However, at that time, the observed financial growth was thought to be sustainable, and these mechanisms were not recognized as paths to financial instability. The generating mechanisms of the event were not sufficiently understood, and crucial information contained in the behaviour of the system was left undisclosed [72]. This example illustrates how our lack of knowledge on the contributing factors influences our understanding of the system as a whole. Furthermore, it shows that if our knowledge of the system is weak, it limits our ability to identify and interpret relevant precursors that could have provided valuable information prior to the event.

Dragon-kings often represent the situations where we can rely on large amounts of data, which can be used to decipher the phenomena. One of the main characteristics of these events is the slow maturation towards instability, where dependencies have an amplifying effect and cause the system or event to take off into unsustainable growth. Hence, in order to identify these events, we need to understand the existing dependencies and how they influence the system, as well as when the unsustainable growth causes the system to reach its maturation point, and the crisis occurs. Such an understanding may be unattainable for some cases of rare, surprising and extreme events, where the phenomena are not understood to this extent. Let us again consider the September 11th terrorist attacks. Surely, there existed knowledge on the development of Islamic extremism, the formation of terrorist groups and the increasing enmity between Western society and parts of the Muslim world. However, the development of radical Islamism is a synthesis of factors, ranging from social and behavioural phenomena to foreign policies and the expanding role of the Internet [61]. Furthermore, Ranstorp states that

"Understanding the processes of radicalization and recruitment is a complex task as there are no single causes or mechanisms that are transferable from case-to-case. Rather it is the complex interplay between these factors being played out simultaneously across the global and local levels and across different geographic contexts down to the individual level." ([61], p. 3)

Similarly, we can consider compound climate risks, where "Extreme weather and climate events and their impacts can occur in complex combinations, an interaction shaped by physical drivers and societal forces" ([62], p. 611). External influence from climate change contributes to this complexity. A particular challenge arises when dealing with events that evolve gradually from incremental changes occurring over many years, referred to as 'slow-onset events' [81], as these events represent a difficulty in assigning temporal and spatial borders, i.e. difficulty in defining and limiting the scope of the event. Thus, "Slow onset climate change impacts create particular complexity due to the need for these threats to be treated as both 'risks across space' as well as 'risks across time'" ([45], p. 13). Take, for example, loss of biodiversity. There is a strong body of literature addressing some of the main drivers for biodiversity loss, such as habitat loss, over-exploitation and hunting [12, 82]. In recent years, there has been an increasing focus on how the effects of climate change influences biodiversity loss [14, 26]. However, "Our understanding of the effects of global climate change on biodiversity and its different levels of response is still insufficiently well developed" ([14], p. 368). Furthermore, there is a lack of knowledge on the relationship between main drivers of biodiversity loss and climate change, leading to uncertainties concerning the potential impacts on the ecological system, as "our understanding of the implications of these interactions for ecological systems are limited, and have generally been based on broad assumptions about what the interaction might look like, rather than empirical data about interactions" ([47], p. 103).

For such situations, we neither possess sufficient knowledge and understanding of the system/phenomena nor can rely on large amounts of relevant data to use in our modelling.

Disclosing the mechanisms that give rise to rare, surprising and extreme events may contribute to enhancing our understanding of what triggers the formation of these events, enabling us "to learn about the mechanism that causes the extremes by examining the states that precede the extreme events" ([21], p. 8). However, as the knowledge base for the metaphors ranges from weak to strong, the path to obtaining this knowledge differs. For systems that are subject to large amounts of reliable data, disclosing the underlying mechanisms is considerably more tractable than for systems associated with scarce and unreliable data. Furthermore, it is important to emphasize that gaining knowledge on phenomena and mechanisms that can lead to extreme events will not result in perfect knowledge. Regardless of knowledge strength, there is a leap between our current knowledge and what could actually occur in the future. This is of particular relevance when it comes to extreme events, as these often have a unique combination of circumstances that have not been present in previous events. However, an enhanced understanding of the phenomena and the mechanisms that lead to extreme events will nevertheless increase the potential for disclosing similar patterns in future events. We refer also to the discussion in the coming section.

3.2. Predictability

In discussions of rare, surprising and extreme events, the predictability feature is given much attention. So, also, when it comes to the metaphors used to describe these events. The focus is partly directed towards the importance of prediction as a tool for managing the risk of such scenarios, but the feature is also frequently used to distinguish the different metaphors (e.g. black swans from dragon-kings [69] or grey swans from black swans [49]).

Although several of the metaphors discussed in this article have been characterized as unpredictable (from the definitions in Section 2), the theoretical potential for predictability exists in all metaphors. However, the methods of prediction will vary, as they are conditioned on the model accuracy, uncertainty representation and knowledge of the phenomena in question. Similarly, the strength and accuracy of these predictions will depend on the same factors.

The issue of prediction is linked to the knowledge dimension as "Accurate predictions require detailed knowledge of the present state of the system, which is usually unavailable. The partial knowledge of the current state together with the chaotic nature of the system leads to uncertainty in the future predictions" ([21], p. 1). As knowledge develops over time, the predictability of events will change. For instance, consider Taleb's notion of black swans as retrospectively predictable; the occurrence of the event has led to insights that strengthen our knowledge, and our ability to understand and explain the phenomena has increased. Thus, a posteriori, our state of knowledge allows us to concoct explanations that render the event predictable in retrospect. Hence, the predictability is not determined by the event per se, but by our knowledge of the phenomena involved. Before the event occurs, our knowledge could be very weak. Nevertheless, it can be argued that the knowledge is a priori *theoretically* available, even though we have not yet obtained it (e.g. we may not, at the present time, have tools that are sufficiently developed to interpret our data). As mentioned previously, it is acknowledged that the complex nature of these events makes the process of generating knowledge a challenge in practice. In situations characterized by large uncertainties, we will in practice be far away from being able to make accurate predictions. Yet it is possible to make a thought experiment: if the knowledge were available, we would be able to make accurate predictions. Depending on the type of black swan (refer to Section 2.1), the actual availability of knowledge will be different, and hence also the degree of predictability, see discussion below.

To further explain the logic, think about an event A and the associated knowledge K_1 of the assessor: If A occurs, it will come as a surprise relative to the assessor's knowledge K_1. The event cannot be accurately predicted based on K_1. Now suppose, as a thought experiment, that the assessor possessed a knowledge K_2: If A then occurs, it will not come as a surprise for the assessor; the event can in fact be accurately predicted. The concept of theoretical predictability of the event A builds on the idea that such a knowledge K_2 is in theory possible to obtain, although it is not available at the time of the assessment. This idea may raise a philosophical discussion; is such a knowledge always possible to obtain? However, our perspective is as much pragmatic as it is philosophical. As discussed above, the knowledge is available retrospectively and the event is retrospectively predictable. The thought experiment is based on the assumption that we possessed that knowledge at the time of the assessment. Consider for example the HIV epidemic, which can be seen as a black swan of the type unknown unknown. Following our reasoning the event was theoretically predictable, in the sense that accurate prediction could have been made say 50 years ago if we had the current knowledge then. For any knowledge base between K_1 and K_2, we may be able to make predictions, but with varying accuracy. The element of surprise will not be eliminated as the knowledge (and predictability) increases, but the potential for experiencing surprises will decrease. The metaphors involve a dimension of surprise relative to current knowledge at the assessment point, but knowledge generation is dynamic and what would have been a surprise at one specific point in time would not necessarily be later, as the knowledge base can change. For the risk management this is essential. There is a *theoretical potential* for obtaining the relevant knowledge which could lead to the avoidance of the events, refer to discussion in Section 4.

Black swans are often associated with risk problems categorized by large/deep uncertainties. For such scenarios, "An essential feature is the lack of justifiable prediction models" ([6], p. 149). However, black swans can also occur in situations characterized by moderate uncertainties, in which "Some dominating explanations and beliefs exist, but the knowledge base is considerably weaker than the category of small uncertainties" ([6], p. 162). In either case, we cannot ensure accurate predictions, as the judgements need to be based on a number of assumptions and hypotheses. The inherent uncertainty of black swan events has led to the presumption that black swans are prospectively unpredictable. This view has been challenged by several authors, including Paté-Cornell [59], Aven [5, 6] and Lindaas and Pettersen [44], arguing that these events can be predicted using signals and warnings: "Obviously, the truly unimaginable cannot be envisioned upfront, but signals (for instance, medical alerts that a new virus has appeared, or new intelligence information) can be observed, suddenly or gradually" ([59], p. 1825). Precursor signals and warnings can be used as a form of dynamic risk assessment, where information, observations and knowledge of the system are obtained, processed and reimplemented. In this way, the prediction model is subject to a continuous improvement process, ensuring that the assumptions and theory that the model is built on correspond with the system behaviour [6]. Furthermore, the process of scientific research may contribute to disclosing important information related to the occurrence of these events. For example, we may discover a new virus through medical research, despite there being no precursor signals or warnings of such a virus.

Lindaas and Pettersen [44] refer to the process of predicting black swans as "de-blackening" them, and they present two strategies for this purpose: the epistemological approach, where black swans are de-blackened by transferring knowledge from those who know to those who do not know. The second strategy, called "imaginative de-blackening", involves "transforming tacit knowledge – in a loose sense of the word – into explicit knowledge" ([44], p. 1238). For both strategies, communication plays an important part: "In an epistemic perspective, communication ensures the transference of knowledge; from an imaginative perspective, communication ensures the elicitation of ideas" ([44], p. 1239).

The predictability of grey swans is, unlike that of their black cousins, a less disputed topic. As seen from the definitions in Section 2.2, this feature is a recurring characteristic in the interpretations of grey swans, and often used to distinguish between grey swans and black swans (implicitly or explicitly interpreting black swans as unpredictable). However, as discussed above, depending on which type of black swans we are referring to, there are varying degrees of predictability for black swan type of events in practice. Recall our interpretation of a black swan of type c) as a surprise relative to our knowledge, where the event is known, but it is not believed to occur due to a negligible judged probability. For this type of black swan, as well as for grey swans, the event has been identified in the risk assessment. Hence, we have a stronger foundation of knowledge supporting our predictions; we have a justified belief that this event could occur. Black swans can, however, also be categorized as 'unknown unknowns' and 'unknown knowns' (referred to as types a) and b) in Section 2.1), in which cases the events have not been identified in the risk assessment; thus, the methods and accuracy of predictions are reflected by this.

In the definition by Taleb [78], grey swans are referred to as "somewhat predictable, particularly to those who (…) have the tools to understand them" ([78], p. 37). This captures an essential aspect of prediction, not only for grey swans but for all the metaphors in this article: the predictability of events needs to be seen in relation to the tools we apply to predict them.

For the perfect storm metaphor, the predictability becomes distinctively twofold. When assessing each contributing event separately, we find ourselves in a situation where "The variation in the phenomena is known and we face risk problems where the uncertainties are small, the knowledge base is strong and accurate predictions can be made" ([6], p. 122). When predicting aspects of the phenomena that concern the effects of the confluence, however, we may have weaker knowledge to found our assumptions on, and the methods of prediction need to be adapted accordingly. Consider, for example, the origin of the metaphor: The category-one hurricane that hit the coast of North America in 1991. The event consisted of three separate weather systems, each of which was known to occur regularly. Meteorologists were able to use precise probabilities to predict the behaviour of these phenomena accurately. However, when the separate weather systems merged to form what was later known as 'the perfect storm', meteorologists could not necessarily rely on similar situations, as the combination of these events was rare. Depending on the scientific strength of knowledge on this concurrence, more or less accurate predictions of the storm could be made.

A recurring issue when discussing the predictability of rare, surprising and extreme events is the limitations of using historical data to predict the future or what Sornette refers to as "the ubiquitous tendency to extrapolate new behaviour from past ones" ([69], p. 12). In fact, this argument forms the basis for his assertion of the inherent unpredictability of Taleb's swans: we cannot predict these events, because our predictions will be founded on the assumption that the events will behave in the same way as previous observations. However, what Sornette refers to as prediction by "the extrapolation of the power law distributions in their tail" ([69], p. 5) essentially means attempting to predict black swans based on probabilistic risk assessments. We share his scepticism towards this approach, which is why we argue that the prediction of black and grey swans needs to be founded on approaches that better highlight the dimension of knowledge, such as using signals and warnings, and adaptive risk analysis [6].

One of the challenges faced by risk assessors today is the increasing complexity of modern society and what Masys et al. [50] call the "engines of civilization", meaning an intricate framework of diverse networks (…), which are all built up of many (relatively) simple components (agents such as humans, power stations, businesses, airports etc.) that interact with each other leading to patterns of interaction exhibiting extreme (unlimited) complexity and potentially resulting in emergent forms of behaviour that are difficult (if not impossible) to predict. ([50], p. 134)

When discussing the predictability of dragon-kings, it is with regard to the idea that "There may be a set of basic universal rules (generic organizing principles) that would allow one to predict the emergent behaviour in a complex network" ([50], p. 135). The predictability of dragon-kings is associated with the identification of precursor signals and warnings, which can be obtained by understanding and monitoring these distinctive generating mechanisms. Hence, though Sornette [69] states that dragon-kings "may be forecasted probabilistically", in terms of simulation and modelling of the events, the use of signals and warnings represents an extended approach, much like the that of black swans, grey swans and perfect storms.

The fact that the simulation and modelling used to predict dragon-kings is also associated with uncertainty needs to be addressed. It has been argued that "Simulations may be questioned in terms of their representation, the rules encoded in the representation, and the data used for calibration and initial conditions" ([37], p. 37). This is also known as the "Can you trust it?" problem [15], which highlights some of the challenges faced when using simulation and modelling to predict the behaviour of complex systems, such as poor data, poor use of data and misinterpretation of results [37]. In order to acknowledge that there is a leap between models and the real world, we need to recognize the limitations of the models used; what Thompson and Smith [80] refer to as the "escape from model land". In relation to extreme events, it is particularly important to focus on the model's ability to capture surprising events: "this is precisely the information needed for high-quality decision support: a model-based forecast, completed by a statement of its own limitations (the Probability of a "Big Surprise")." ([80], p. 10). Furthermore, attempting to model extreme events will lead to difficulties in defining and constraining model parameters, as our knowledge of the phenomena, and the phenomena itself, could be changing. An example is natural disasters, where catastrophe modelling has become a common tool used by for example insurance companies to assess the potential losses related to events. However, as a consequence of climate change, the frequency and severity of these events is constantly developing [62]. The models, although sophisticated, may not be capturing such developments. The model output could provide inaccurate predictions. Some of these challenges can be met by model validation, evaluation and continuous improvement of our knowledge on the model input: "Even where we cannot test long-range model-based predictions, we can test how well our model can reflect (shadow) the past, and learn the phenomena with which they cope most poorly. This informs judgement as to how far in the future a given model is likely to be relevant to the evolution of the real world." ([80], p. 11).

4. Discussion

Metaphors have a powerful impact on the way we communicate and perceive a concept, as mentioned in the introduction. Black swans, grey swans, perfect storms and dragon-kings have become well-known terms in the risk literature and represent important contributions to the understanding and communication of rare, surprising and extreme events.

An important element in the understanding of these concepts is acknowledging that the characteristics of the metaphors need to be seen in relation to the current approaches we are applying to manage them. An event is not unpredictable per se, though it may be unpredictable using the risk assessment tools at hand. This acknowledgement triggers some central features within risk management: responsibility and accountability. These are terms that often arise when discussing the metaphors in the present article, but what do they actually mean in this context? Sornette and Ouillon [71] state that "In a world where catastrophes (…) are pure surprises, no one can be responsible" ([71], p. 2). Catanach Jr. and Ragatz [16] pose the rhetorical question: "If the event could not be predicted, or its causes were so unique, then how could anyone be held accountable for contributing to its occurrence?" ([16], p. 20). However, we cannot (and should not) dismiss responsibility and accountability on these grounds, as the surprise dimension, as well as the predictability feature, needs to be seen in relation to knowledge: a surprise occurs relative to some expectation of what is to come, and these expectations are built on our knowledge at the time. As in the case of Fukushima, our expectations could turn out to be based on poor judgments, e.g. due to misleading assumptions, lack of phenomena understanding or misinterpretation of data or information. Furthermore, the accuracy of predictions depends on the knowledge base. Whether we are dealing with an 'unknown unknown' black swan or a 'known known' dragon-king, we have a specific foundation of knowledge on the phenomenon, and the tools and strategies that we apply to manage the events should reflect this. We argue that responsibility and accountability are related to the ability to take the knowledge dimension into account when assessing and managing the risk of rare, surprising and extreme events: risk assessors are responsible for ensuring that the risk assessment techniques are performed in such a way that the knowledge and surprise dimensions have been sufficiently highlighted. We need to acknowledge that the predictability and knowability of events are properties that first and foremost depend on the limitations (or strengths) of the risk assessors. Furthermore, in what is referred to as managerial review and judgement, decision-makers are accountable for taking these limitations into consideration, along with evaluations of other aspects that may not have been captured in the assessment (such as political, strategic and ethical concerns) [6]. Based on this reasoning, the claim that events reflected by the black swan metaphor are merely an "act of God", for which no one can be held responsible or accountable, does not hold; lack of knowledge does not imply a lack of responsibility and accountability. Rather, it emphasizes the need for suitable approaches to address this lack of knowledge in risk assessment and decision-making.

Let us consider the September 11th terrorist attacks as an example. As argued in Section 3.1, the complex causality of this event makes it a challenging task to disclose its underlying mechanisms. The scenario is characterized by weak knowledge, as data is scarce and unreliable, and a large part of the system's mechanisms are not well understood. Taleb [78] states the following regarding the terrorist attacks: "Had the risk been reasonably *conceivable* on September 10, it would not have happened" ([78], p. x). In our view, the risk was *conceivable* but failed to be *conceived*, and here lies the essence of responsibility and accountability: a gap exists between the conceivable and the conceived, and this gap may be closed by applying tools and strategies that support the continuous enhancement of knowledge. According to this reasoning, the claim that there exists a theoretical potential for predictability in all the metaphors is highly relevant; by claiming that events are theoretically predictable, it is opened up for the notion that the inability to conceive them is a result of the inability to obtain the sufficient level of knowledge. By strengthening our knowledge, focusing on transferring and spreading information, questioning key assumptions and presuppositions, rigorously searching for new knowledge and counteracting our "optimistic illusions about the future that prevent us from envisioning looming catastrophes" ([13], p. 374), we may prevent these events from occurring. In the case of September 11th, the knowledge of a possible attack using airplanes as missiles existed, but a number of crucial assumptions were left unchallenged (e.g. that the largest threat towards aircraft security was the use of explosives; that terrorists were mainly concerned with negotiating the release of captive extremists, and suicide attacks would serve limited potential for this purpose; that it was most likely that future terrorist attacks would have similar methods and magnitudes to previous attacks) [57]. These were assumptions that, had they been confronted, could have been modified and corrected by obtaining available intelligence information. Furthermore, there was a failure to transfer knowledge to central decision-makers:

> At an organizational level, the 9/11 Commission Report documents that while the FAA [Federal Airline Administration] had a 40-person intelligence staff, [the] Administrator (…) and her deputy did not regularly review intelligence briefings, nor were they aware of the great amount of information on hijacking threats that existed within their own agency. ([13], p. 370)

The terrorist attack on September 11th came as a surprise relative to what was believed or known at the time; it was a black swan. However, no one seemed able to "connect the dots", and so the terrorists were able to carry out the most lethal terrorist attack ever experienced on US territory. The event was *conceivable*, in the sense that signals and warnings existed; they had even been clearly communicated to government officials [13]. Nevertheless, the event was not *conceived*, as decision-makers did not respond adequately to these signals and warnings, nor was necessary action taken to obtain new knowledge that could have provided essential information for preventing the event from occurring.

The distinction between "conceivable" and "conceived" captures the essence of our statement at the beginning of this section; We need to understand the characteristics of the events in relation to how they are managed. The September 11th events were not conceivable using the approaches that were actually taken, but that does not make the event inconceivable per se; had the adequate tools and strategies been applied prior to the event, it could have been conceived. The same distinction needs to be emphasized for other words frequently used to describe the metaphors in this article (unpredictable vs unpredicted, unknowable vs unknown, unforeseeable vs unforeseen). Interpreting the metaphors as unpredictable, unknowable or unforeseeable not only removes much of the relevance these metaphors have for risk management (if an event is not only unknown but unknowable, is it even relevant to discuss this event from a risk perspective?), it also indicates that responsibility and accountability for these events do not exist: the events are essentially impossible to manage. Furthermore, it represents an inconsistency: by interpreting an event as inherently unknowable or unpredictable, predictability and knowability are seen to be objective properties of the event. However, as we have shown, the metaphors and their predictability are related to knowledge, and knowledge is not objective.

5. Conclusions

Using metaphors to describe phenomena can be effective in making complex information comprehensible. However, in the present paper, we emphasize that the implications of using metaphors go far beyond this; the use of metaphors can strongly influence how we perceive phenomena. Being aware of the promises and pitfalls of metaphors is essential in ensuring an effective but at the same time a cautious use of this powerful tool.

The metaphors presented in this article are commonly referred to when discussing rare, surprising and extreme events. Comparisons of the different metaphors are frequently made in scientific literature [3, 16, 20, 35, 50, 69]. However, the present use of the metaphors appears somewhat unsystematic, as the metaphors are subject to different interpretations and definitions, and their meaning and relationship have not been sufficiently clarified. To enhance our understanding of the main characteristics of the metaphors, we have reviewed and discussed a selection of interpretations and definitions. Based on this, we have created a structure in which we present some of the similarities and differences between the metaphors, centred around the knowledge and predictability features. Several authors have explored the meaning of the black swan metaphor in a risk context [5–8, 44, 59]. These efforts have contributed to relating the concept to general frameworks of risk assessment and risk management. We argue that the black swan should be seen as a surprising, extreme event relative to the present beliefs/knowledge [5], emphasizing that 'the present beliefs/knowledge' is that of the person(s) being surprised. Hence, the question of whether the event is a black swan or not is in the eye of the beholder. This interpretation is in line with the views of Taleb [78], as well as the historical context of the concept. In line with the definition by Aven [5], we may distinguish between three types of black swan, as presented in Section 2.1: 'unknown unknowns', 'unknown knowns' and a subset of 'known knowns'. When it comes to the term 'surprise', it clearly applies to 'unknown knowns' and 'known knowns', but is less obvious for 'unknown unknowns', as there may not exist a prior expectation for such events. However, when referring to a black swan as 'a surprising, extreme event relative to the present beliefs/knowledge', we include per definition also 'unknown unknowns'. See discussion on black swans in relation to surprises in Aven [6].

The history of the black swan metaphor not only provides a fascinating anecdote, it places the meaning of the concept in a broader perspective. The grey swan cannot be placed in a similar context; the grey swan per se does not represent something rare or extreme. The interpretation of grey swan events as rare, surprising and extreme is not meaningful, unless they are seen in relation to the black swan concept. Furthermore, the grey swan metaphor is based on the notion that black swans are 'unknown unknowns'. However, we have shown that limiting black swans to this category alone is not consistent with the meaning of the black swan metaphor in a risk context. A closer look at the September 11th events leads us to conclude that the black swan metaphor also reflects events belonging to the categories 'unknown knowns' and 'known knowns', in line with Aven [6].

As no metaphorical interpretation of the grey swan exists, we should avoid using this term as a metaphor. Grey swan events are covered by our recommended definition of black swans. Connecting grey swans to 'known unknowns' does not justify the use of the metaphor as a distinct genus of swans. For example, we may discuss the extent to which a 'known unknown' can be considered a surprise. Referring to the example of vaccines in Section 3.1, if we know that there will be a side effect, but we cannot say in what form, can it be termed a surprise when a side effect occurs? On the other hand, if we know that an event could occur, but not when and in what form, it could be termed an "anticipated surprise", in line with Gross et al. [29]. Furthermore, events can be interpreted differently (e.g. the side effects of a vaccine can also be interpreted as an 'unknown unknown': it was completely unknown that such a side effect would occur at that particular time or in that specific form), and the 'known' and 'unknown' in the expression may be subject to different interpretations, as mentioned in Section 2.2. We do not put forward these issues in an attempt to solve them but rather to highlight the complexity related to the known/unknown taxonomy and its application for rare, surprising and extreme events.

Like the black swan, the origin of the perfect storm metaphor can be placed in a historical context. The metaphor was coined by Junger [38] to describe the category-one hurricane that struck the east coast of North America in 1991. We argue that the definition of the metaphor should reflect the characteristics of the original event, which was a rare conjunction of well-known phenomena, whose interplay had an amplifying effect, resulting in an extreme event.

Can a perfect storm be classified as a black swan? As discussed in Aven [7], the answer depends on the perspective taken and how we more specifically interpret the perfect storm metaphor. If we have a situation with perfect knowledge about the variation of all the phenomena considered, the event should not come as a surprise. It is rare, but we know that the event will occur sooner or later. However, it is also possible to argue differently. With strong knowledge about the variation in all the phenomena considered, the event is judged so unlikely to occur in the next 100 years, say, that it is not believed to occur. Consequently, it can be viewed as a black swan of type c), if it should in fact occur. The fact that there could be uncertainties related to the interplay of phenomena supports this latter interpretation – there is an additional element of potential surprise. As commented above, we also need to be precise on who is potentially surprised. Take the original 'perfect storm' event. For the scientists, who had strong knowledge on the different weather systems that formed the concurrence, the event was, as the name implies, a perfect storm. The fishermen who were caught in the storm, however, did not have this strength of knowledge on the phenomena, and the event came as a surprise for them – a black swan.

The perfect storm metaphor is related to the dragon-king by their common, specified mechanisms of amplifying interactions between multiple factors, leading to an extreme event. We argue that perfect storms and dragon-kings represent different perspectives on these mechanisms, illustrated by the stock-market example from Section 3.1. The original definition of dragon-kings as "the existence of transient organization into extreme events that are statistically and mechanistically different from the rest of their smaller siblings" ([69], p. 1) is mainly a description of the specific mechanisms of these events. The dragon-king theory represents valuable insights into risk, but, in order to clarify how this metaphor contributes to enhancing our understanding of extreme events, we need to provide a clear definition of what the dragon-king metaphor means in a risk context. We argue that a dragon-king should be seen as an extreme event, resulting from emergent behaviour caused by the amplifying interplay of a confluence of uncertain factors. By this interpretation, dragon-kings are linked to perfect storms, as they describe similar phenomena. However, for perfect storms, the contributing events are well-known, while, for the dragon-kings, this may not be the case. Consider, for example, the bursting of a financial bubble. We may observe mechanisms such as explosive growth, ultimately resulting in a phase transition where the bursting of the bubble represents a dragon-king. However, what exactly triggers this development is not known, although several theories exist (see Sornette et al. [70] and references therein). Hence, it can be considered a dragon-king, as we have some knowledge on the system (the behaviour of the financial market), but we do not have strong knowledge on the contributing factors to this behaviour, as would be the case for the perfect storm.

A dragon-king can be considered a black swan (of type c)), as the event is known but there is a potential for surprises because of the uncertainties related to the emergent behaviour of the system.

Events can be characterized in different ways and may therefore also be described by different metaphors. The financial crisis of 2008 is an example. Which metaphor is used depends on the perspective: The event can be seen as a result of emergent behaviour of the system (dragon-

Table 6
Recommended definitions/interpretations of the metaphors, including examples.

Metaphor	Recommended definition/interpretation	Example
Black swan	A surprising, extreme event relative to the present beliefs/knowledge ([5], p. 49)	The September 11th terrorist attacks
Grey swan	Should not be used as a metaphor due to lack of metaphorical context	
Perfect storm	A rare confluence of well-known phenomena creating an amplifying interplay leading to an extreme event Can also be viewed as a black swan	The financial crisis of 2008
Dragon-king	An extreme event resulting from emergent behaviour caused by the amplifying interplay of a confluence of uncertain factors Can also be viewed as a black swan	The financial crisis of 2008

king) or as the result of the amplifying interactions between a confluence of events (perfect storm). Another example is climate risks. If our perspective is an individual disaster event, such as an extreme hurricane, we could refer to it as a perfect storm, as our knowledge about the phenomena is relatively strong (although the event may be considered very unlikely to occur). However, when we are referring to compound climate risks, our perspective is different; we are talking about the confluence, of which our knowledge is significantly weaker. We have little or no reliable data and the phenomena is subject to large uncertainties. With such a perspective, compound climate risk events would be covered by the dragon king metaphor.

Based on the reflections above, we present our recommended definitions of the metaphors, in Table 6.

Although the perfect storm and dragon-king metaphors can be viewed as black swans, they are justified as independent metaphors. They draw attention to some specific types of situations, for which some aspects of the phenomena considered are well-understood, whereas others are subject to rather weak knowledge. The metaphors can help us identify and highlight areas where the risks related to potential surprises are highest and, thus, where focus on enhancing knowledge should be directed.

Knowledge is a key concept in the understanding of all metaphors. As stated in this paper, the knowledge concept is related to the predictability feature; the ability to predict is contingent on a specific foundation of knowledge. Because knowledge and predictability are dynamic features that develop across time, an event that is unpredictable at present (given the current knowledge) may be predictable at a later time (given a stronger knowledge foundation).

This line of reasoning has implications for risk management and decision-making; by acknowledging that there is a gap between the knowledge we have at some given time, and the knowledge that can be obtained, it opens up for the notion that analysts and decision-makers are responsible and accountable for taking the knowledge dimension into account when assessing and managing the risk of rare, surprising and extreme events. This does not mean of course that the occurrence of any extreme event is a result of poor risk management. At a specific point in time, the relevant knowledge could be weak for legitimate reasons, yet the message is clear: prudent risk management needs to take the surprise aspects of risk seriously and implement measures that can meet this risk. In this way, potential extreme events can be avoided.

Author statement

The work has been carried out by Ingrid Glette-Iversen and Terje Aven, based on close collaboration on all aspects of the paper and the research, with Ingrid Glette-Iversen as the first author writing most of the original text.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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