Animal Modeling of Earthquakes and Prediction Markets

By

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Abstract

Prediction markets have been shown to generate fairly accurate odds of various events occurring in the future. The forthcoming possibility of natural disasters provides, on occasion, an opportunity for a bet, yet no wide scale and accepted prediction market has arisen despite its obvious importance, probably due in part to its 'politically incorrect' nature, but more importantly to the fact that we have yet to develop accurate forecasting models. Animals, however, have been forced through natural selection to develop elaborate anticipatory mechanisms to predict possible upcoming calamites. Recent studies suggest that animals can, days and sometimes weeks in advance, predict the occurrence of earthquakes. A wealth of recent observations and laboratory studies corroborate this. Natural disasters have lead to the development of 'risk taking' behaviors when the 'odds' of an upcoming disaster outweigh the benefits of maintaining territory, mating, and other basic behaviors. For various historical reasons discussed in this review, this field has had trouble coming of age, with little funding and support from the scientific community, particularly in the US. Due to the great odds at stake and the tremendous economic impact of earthquakes we wish to raise the awareness of this vital topic to the wider scientific community. We present a review of such animal predictive behavior and propose that an early "reading" of such models might lead to the development of a predictions market by humans.

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"For five days before Helike disappeared all the mice and martens and snakes and centipedes and beetles and every other creature of that kind in the town left in a body by the road that leads to Keryneia. And the people of Helike seeing this happening were filled with amazement, but were unable to guess the reason. But after the aforesaid creatures had departed, an earthquake occurred in the night; the town collapsed; an immense wave poured over it, and Helike disappeared..."

- Aelian (373 BC)

Introduction

The recent catastrophic events in Japan and New Zealand speak for themselves. Among the various natural disasters that effect life on earth, earthquakes are probably the most awe inspiring, and for good reason. The massive loss of life and damage caused by earthquakes have been the basis for many legends and myths. It is not only the sheer force and destructive nature of earthquakes that has brought on these "stories", but perhaps one of their most unique characteristics – the element of surprise. Beside modern preventative building measures there is nothing we can do to mitigate the damage from an earthquake once it has occurred and there is no way we can prevent an earthquake. Yet, if we knew when and where one will strike many lives could be saved, and the financial damage minimized.

Since at least 2000 BCE, Babylonians, Hebrews, Greeks, Romans, Chinese, Japanese, Indonesians and other Pacific islanders, natives of the Americas, residents of Southern Europe and the Mediterranean Basin, and a myriad of other groups have been telling stories about uncontrollable and unpredictable earthshaking events (Bluestone, 2010). Despite their relatively common occurrence and "antiquity", it was only during the 1960's that we began to understand what causes earthquakes in the first place (Wyss, 2001). The theory of plate tectonics, whereby the outermost part of the earth is comprised of puzzle-like pieces called plates that float atop a more fluid interior space, took time to be widely accepted (Bluestone, 2010). Most of the pioneering work in the field of seismology was naturally concentrated on understanding the basics; actually predicting earthquakes was not dealt with until later (Wyss, 2001). However, earthquake prediction in the time frame of several months to less than an hour before the catastrophic event ("short term") has been a subject of extensive research and controversial debates both in academia and mass media over the past two decades (Geller, 1997; Geller et al., 1997; Wyss et al., 1997; Wyss, 2001; Uyeda et al., 2009; Cicerone et al., 2009; Ryabinin et al., 2011). A wide range of precursory signals precede earthquakes. The term *earthquake precursor* is used to describe a wide variety of physical phenomena that reportedly precede at least some earthquakes (Cicerone et al., 2009). Kirschvink (2000) mentions that in an attempt to systematically evaluate such observations, the International Association of Seismology and Physics of the Earth's Interior (IASPEI) organized a sub-commission on earthquake prediction with the task of evaluating these precursory events through a peer-review process and creating a preliminary "List of Significant Precursors" (Wyss, 1991; Wyss and Booth, 1997). Between 1989 and 1997, a total of about 40 nominations were made and evaluated by this subcommittee. The five cases placed on the preliminary List included foreshocks, preshocks, seismic quiescence before large aftershocks, radon decreases in ground water, and ground water level increases (Wyss, 1997). In the most recent and comprehensive review of the topic, Cicerone et al. (2009) present a list of these phenomena. Among them, electric and magnetic fields, groundwater level changes, gas emissions, temperature changes, surface deformations, and anomalous seismicity patterns are mentioned. Unusual (or anomalous) animal behavior as it is often referred to in the literature is deemed as "anecdotal" and does not make either list.

Recent scientific studies suggest that this unusual animal behavior is far from "anecdotal" (e.g. Ikeya et al., 2000; Kirschvink, 2000; Freund, 2003; Yokoi et al., 2003; Ikeya, 2004; Whitehead et al., 2004; Grant and Halliday, 2009; Li et al., 2009; Liu et al., 2010). Furthermore, recent advances in studies on animal behavior, particularly in the field of magnetoreception, provide much insight into the possible underlying mechanisms of this behavior (e.g. Ikeya, 2004; Moore and Riley, 2009; Nishimura et al., 2010; Southwood and Avens, 2010). Decades of research into the direct physical aspects of earthquake precursors has provided much insight, yet very little progress in actual predictions. Animals have been forced over the course of evolution to come up with solutions to life-threatening problems. The question thus naturally arises: why is there no prediction market for earthquakes? One might imagine that the market does not exist owing to inherent unpredictability.[2] In this paper, we show that there are solid grounds for the argument that plausible prediction models may be derivable via appropriate monitoring of animal behavior.

We do so by presenting a survey of the literature on unusual animal behavior preceding earthquakes and the current knowledge on possible mechanisms explaining these behaviors.

Earthquake prediction

For centuries humans have tried to predict earthquakes (Stothers, 2004; Ikeya, 2004; Bluestone, 2010). Predictions have been based on a variety of seismic and non-seismic phenomena, including animal behavior; water level, temperature and composition in wells and springs (ground water); electric and magnetic fields and radio waves on the ground and in the air; electrical resistivity of the ground and the air; cloud formations or other atmospheric phenomena; infrared radiation; pattern recognition; temporal clustering; and variations in the rate or pattern of seismicity (Luen and Stark, 2008). There is much debate on the extent to which we will ever be able to properly predict (with accuracy) future earthquakes. Some argue that the tectonic processes are to a large extent random (Geller, 1997; Geller et al., 1997) and thus fundamentally unpredictable. Others suggest it is more our lack of knowledge that impedes on this field of research (Wyss, 1997; Wyss, 2001; Luen and Stark,

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[2] In light of the recent revelation that a prediction market exists for no balls in Test cricket, this is perhaps no longer an important criterion. But then again no one has yet figured out how to rig earthquakes!

2008). Putting it econometrically, earthquake occurrence may be an inherently high variance phenomenon or the random errors in our prediction regression(s) contain many missing variables. Either way, these amount to nearly the same thing from a prediction point of view.[3] An example of the dominant approach in the USA can be found on the web page of the U.S. Geological Survey (USGS). They have an FAQ titled – "Can you predict earthquakes?", their answer is as follows –

> "No. Neither the USGS nor Caltech nor any other scientists have ever predicted a major earthquake. They do not know how, and they do not expect to know how any time in the foreseeable future. However based on scientific data, probabilities can be calculated for potential future earthquakes. For example, scientists estimate that over the next 30 years the probability of a major EQ occurring in the San Francisco Bay area is 67% and 60% in Southern California.
> The USGS focuses their efforts on the long-term mitigation of earthquake hazards by helping to improve the safety of structures, rather than by trying to accomplish short-term predictions."[4].

Consequently, there is no real program for earthquake prediction research in United States (Wyss, 1997). In contrast, China and Japan (far more afflicted by earthquakes) have serious, active programs.

The above USGS statement is not only astounding in its unambiguity but it's also untrue. The best known example of a major earthquake predicted was the 1975 Haicheng earthquake in China. In their extensive and quite critical study of the events surrounding the 1975 Haicheng Earthquake (M = 7.3), Wang et al. (2006) show that Chinese scientists, using a multitude of parameters, among them unusual animal behavior, indeed predicted the general time and location of the earthquake. Around 1,400 people died in the earthquake, yet it is estimated that over 100,000 people were saved (Bluestone, 2010). At the official level, the warnings given out were varying; this more to do with problematic communication protocols and bureaucracy. The Chinese earthquake prediction program suffered set backs after their failure to predict the devastating Tangshan earthquake (M = 7.8) in 1976, killing at least 250,000 people. Although later studies suggest that also in the case of the Tangshan earthquake there were various precursory signs, among them unusual animal behavior (Buskirk et al., 1981). Internal political changes and the association of Chairman Mao and the Cultural Revolution to the earthquake prediction program also contributed to difficulties in the efficient dissemination of early warnings at the local level (Wang et al., 2006). In addition to the Haicheng earthquake prediction, several other less well known earthquakes are claimed to have been successfully predicted (see Luen and Stark, 2008 for a review).

It is not within the scope of this paper to discuss all the examples but many recent studies provide a multitude of earthquake precursors that can be monitored for telltale signs of upcoming earthquakes. They are usual grouped into electromagnetic, hydrological/hydrochemical, gasgeochemical, geodetic and seismic (see Cicerone et al., 2009 and Ryabinin et al., 2011 for comprehensive reviews). Following are some examples with relevance to our story. Perturbations in the ionosphere, measured by very low frequency (VLF) and low frequency (LF) electromagnetic signals , have been observed in a time frame from 2-3 years to minutes before earthquakes (Chou et al., 2001; Muto et al., 2008; Cicerone et al., 2009; Hayakawa et al., 2010; Hayakawa

[3] Presuming that the missing variables are uncorrelated with the explanatory variables in the regression(s).

[4] http://earthquake.usgs.gov/learn/faq/?faqID=13.

et al., 2011). Changes in hydrological and hydrochemical factors - including ground water level and quality changes in the weeks, days and hours prior to a number of earthquakes have been measured. Groundwater temperature changes and variations in the concentration of some dissolved ions in the months and days before an earthquake (Cicerone et al., 2009; Ryabinin et al., 2011). Gasgeochemical signals are most often found in anomalous gas emission patterns, the majority of which are reported for the concentration of radon gas. Ryabinin et al. (2011) note that the are over 100 studies showing a change in radon exhalation from the earth's crust in the months, weeks and days before a number of earthquakes (see Cicerone et al., 2009 for further detail). Ground tilt, seismic foreshocks and extended nucleation, producing low frequency seismic noise, are further physical phenomena that have been observed in the months to days before numerous earthquakes (Bouchon et al., 2011; Ryabinin et al., 2011). Seismic electrical signals (SES), often referred to as VAN predictions (Dologlou, 2010), are claimed to be precursory in the days to minutes before many earthquakes. Yet as with other earthquake prediction methods, here too there is much controversy (Geller, 1997; Luen and Stark, 2008). Finally, there are reports that the compression of rocks on the earth's surface, among other yet unknown processes, preceding earthquakes release abnormal electric and electromagnetic pulses (Adams, 1990; Ikeya and Matsumoto, 1997; Ikeya et al., 2000; Freund, 2003; Freund, 2010). Interestingly, although not surprising from an evolutionary perspective, many of these geophysical "signs" can be sensed by different animals.

Earthquake prediction and Animal behavior - Background

Evidence supporting the anticipation of some earthquakes by animals is being accepted by a growing segment of the scientific community, but researchers do not seem inclined to do much about it (Kerr, 1980). Little has changed in the past three decades. The relatively small amount of financial support and consequently very few studies conducted have prevented this topic from coming of age. Either inspired or challenged by China's success in predicting the Haicheng earthquake, in 1978 the United States Geological Survey (USGS) funded Project Earthquake Watch, a study undertaken by the independent, nonprofit research institute, SRI International, which investigated the feasibility of using animal behavior to predict earthquakes. The project was halted after four years, however, and the subject has not been revisited since. The current official stance of the USGS is that while — "anecdotal evidence abounds of [creatures] exhibiting strange behavior anywhere from weeks to seconds before an earthquake [,] . . . consistent and reliable behavior prior to seismic events, and a mechanism explaining how it could work, still eludes us. Most, but not all, scientists pursuing this mystery are in China or Japan…" (Bluestone 2010).[5]
The ever-present notion that conducting experiments based on "anecdotal" evidence, particularly in the west, and the still relatively negative attitude of the scientific community toward this kind of research has further impeded it. Yet the sheer wealth of "anecdotal" evidence demands a closer look at what has been told in the past and what we know today.

[5] See also http://earthquake.usgs.gov/learn/topics/animal_eqs.php.

The earliest known account of unusual animal behavior preceding an earthquake is found in a manuscript by the roman writer Aelian. In his book *On animals* (as cited in Soter, 1999), he presents an extraordinary account of the Helike disaster of 373 BC:

For five days before Helike disappeared all the mice and martens and snakes and centipedes and beetles and every other creature of that kind in the town left in a body by the road that leads to Keryneia. And the people of Helike seeing this happening were filled with amazement, but were unable to guess the reason. But after the aforesaid creatures had departed, an earthquake occurred in the night; the town collapsed; an immense wave poured over it, and Helike disappeared, while ten Spartan vessels which happened to be at anchor close by were destroyed together with the city I speak of.

Despite their relative abundance, little is found in western literature with regard to earthquake accounts in general and animal behavior in particular, until the great Lisbon earthquake of 1755. Immanuel Kant, better known for his work in philosophy, wrote a comprehensive report on this major disaster that took place during his time[6]. This was probably the first attempt to explain the cause of earthquakes as a natural phenomenon, as against the predominant view at the time, that they were of supernatural origin. It must be said that most of Kant's theory has since been scientifically disproven. All the same, he provides yet another interesting empirical glimpse into animal behavior in the vicinity of earthquakes:

Eight days before the concussion the ground near Cadiz was covered by a multitude of worms that had crept out of the earth. Only the adduced cause drove them out. Of several other earthquakes, violent lightning in the air and the fear that one notices in animals have been the precursors.

In recent times numerous reports have been made worldwide of unusual animal behavior, usually domestic (dogs, cats and fish) and farm animals (sheep, cows and birds), at various time scales before earthquakes (for further details see Buskirk et al., 1981; Tributsch, 1982; Kirschvink, 2000; Ikeya, 2004). Some even suggest there is a connection between the number of reported missing pets in the weeks and days before an earthquake, and other unusual behavior (e.g. dogs barking, cats becoming violent, fish jumping out of aquaria, although once again there is much controversy surrounding this latter claim (Schaal, 1988; Whitehead et al., 2004)

In contrast, eastern literature, most notably in China and Japan, is full of earthquake accounts in general and related unusual animal behavior in particular (Ikeya, 2004). This is of no surprise considering that Asia was, and still is, far more active seismically than most other parts of the world. Also, the eastern approach to science is somewhat different from that in the west. The holistic view of the world, "interdisciplinary studies" in current western terms, and the fact that "anecdotes" are

[6] Available in English translation at http://www.hkbu.edu.hk/~ppp/fne/essay1.html and http://evans-experientialism.freewebspace.com/kant_earthquake01.htm .

given more weight has generated many more studies in this field that in the west (Ikeya, 2004; Bluestone, 2010).

In many cultures worldwide the legends surrounding the cause of earthquakes is quite often attributed to one animal or another. Buffalo in Bulgaria, Borneo, Malaya and the Lesser Sunda Islannds; Turtles in North America; The serpent in the Moluccas and Sumatra; and the crab in Persia (Bluestone, 2010). In each of their respective geographical locations these animals are the ones who bring on/cause earthquakes according to the local culture.

It is in some of the more detailed "anecdotes" that we can find some clues to perhaps explain “theories” of this nature. In Mongolia, the story of the earth-bearing frog is more nuanced than the other animal tales. The earth was said to quake whenever the animal moved. More specifically, the locals identified a correlation between a particular movement of the frog, such as shaking its head or stretching out one of its legs, with an earthquake in a certain region. The earthquake was said to happen in the place on the globe immediately above where the frog‘s individual body part moved (Bluestone, 2010). In Chinese mythology it is the serpent that is the cause for earthquakes (Ikeya, 2004), but frogs too have their place. The first known seismoscope was invented in China by the astronomer/magician Zhang Heng (132 AD). It was a large bronze vessel with eight dragons holding a small ball in their mouth facing downwards. Beneath the dragons, frogs with wide open mouths were situated. In the event of a shake from one of the eight wind directions, a ball would fall into the mouth of the corresponding frog. Probably the most well known creature held responsible for earthquakes is the catfish, or *namazu*, of Japan (Ikeya, 2004; Bluestone, 2010). The earliest known written record linking catfish to earthquakes is a letter from Toyotomi Hideyoshi (1536-98), the unifier of Japan. Near the end of his life, he decided to build a castle in Kyoto's Fushimi district, and of course he wanted it to withstand any earthquake. In a letter to the Kyoto official in charge of administering and policing, he wrote, "During the construction of Fushimi Castle, be sure to implement all catfish countermeasures." His choice of words indicates that at least as early as 1592, when the letter was written, a connection was being drawn between seismic activity and catfish (Kazuaki, 2005). The *namazu* became further culturally entrenched after the Ansei Earthquake of 1855, when earthquake stories about catfish were circulated along with *namazu-e*, color woodblocks of Earthquake Catfish Pictures (Smits, 2006; Bluestone, 2010). Most *namazu-e* depict a large catfish being held down by the Kashima deity with a stone or sword, and when he is away or the catfish overcomes him that earthquakes occur (depicted in Figure 1). For centuries, Japanese fishermen have reported that eels disappear from well established fishing grounds, and that catfish, normally showing little to know activity, act abnormally, swimming around in the days before an earthquake (Ikeya, 2004).

Could it be that some, if not all, of these legends are based on some aspects of animal behavior noticed by the common man in the time before/during earthquakes? Curiously, many of the animals mentioned in folklore and their respective unusual behaviors, are ever-present in the current scientific literature.

Figure 1. Kashima is holding his sword over *Namatzu*.
Jinshin o-mamori – Protection against earthquakes.
(Figure 1 in Smits, 2006)

Earthquake prediction and Animal behavior – Scientific findings

Perhaps the largest problem in studies concerning unusual animal behavior preceding earthquakes is that the latter are relatively rare and unpredictable events. Thus designing experiments in this field has always been problematic, most often the studies being conducted *posteriori*. Furthermore, the inherent variability in the behavior of animals, and the fact that much of the unusual behavior seen before earthquakes is also seen in other contexts, makes things all the more difficult (Grant and Halliday, 2009). Kirschvink (2000) suggests that it is precisely these "normal" behaviors often observed, such as flight from a potential predator or fire (the latter is instinctive in all land animals), that have been harnessed through natural selection into an anticipatory/predictive programming many animals have evolved. He shows theoretically that the coupling of anti predatory response (panic and flight) to externally sensed cues preceding earthquakes could have easily evolved, even with the rarity of earthquakes in most locations. It is generally accepted that many animals sense an earthquake some minutes before humans do (Kirschvink, 2000). Most unusual animal behavior reported before earthquakes coincides with the arrival of P-waves, which travel faster than the damaging S-waves (2-4 km/sec faster). Depending on the distance from the epicenter, P-waves can be felt seconds to minutes before an earthquake. The response to P-waves isn’t a real predictive response, but rather an 'early warning system' (Kirschvink, 2000; Grant and Halliday, 2009). Only animals right at the epicenter wouldn’t have enough time to flee. Moderate to large earthquakes like the 1989 Loma Prieta earthquake (M = 6.9) can cause liquefaction at distances of 50 km (Pease and Orourke, 1997), and thus it is reasonable to infer that burrow collapse could be triggered in loose topsoil at greater distances. Hence, animals that live tens of kilometers from the epicenter have several seconds after detection of the P-wave to escape the effects of the energetic S-waves. Although anecdotal in nature, these observations support the hypothesis that a potential seismic-escape response is present in the behavioral repertoire of animals, and that it can be released at least by the sensory perception of low-frequency vibration (Kirschvink, 2000). Various animals, especially rodents (e.g. California kangaroo rats) use low frequency "footdumming" for communication and to notify predatory snakes that they are aware of their presence (Kirschvink, 2000). A great deal of anecdotes from Africa and South East Asia speak of elephants fleeing before earthquakes. Recent studies have shown that they too use foot tapping to communicate signals and their trunks to pick them up, at distances over 30 km (See review by Arnason et al., 2002). Despite these findings, to our knowledge, no controlled experiments have been conducted to simulate earthquake shaking and subsequent animal behavior. It should be emphasized that such controlled experiments are conducted in a wide range of animal behavior fields and much insight can be gained, even if the shaking isn't a real earthquake. Yet these seismic signals are only available in the very short period before an earthquake, thus are of much less interest (and controversy). However, one should keep in mind that modern day early warning missile launch systems are effective in a range of minutes and are certainly life-saving.

Yosef (1997) presents strong evidence that birds of various species can detect an impeding earthquake in the very short term. At the outset, it should be stated that from a behavioral point we wouldn't expect much evolutionary pressure on birds to develop such a predictory response since they can take flight the moment an earthquake hits and thus be in far less danger than ground dwelling animals. He observed a variety of bird species before, during and after a strong earthquake in Eilat, Israel (22/11/95; M=7.2 at 06.16 local time). Several flocks of birds began to behave unusually at 06:00, including several hundred gulls (*Larus spp.*) and several other species (e.g. the pied kingfisher *Ceryle rudis*, European kingfisher *Alcedo atthis*, and the cormorant *Phalacrocorax carbo*) which left the area and flew north. The size and direction of travel of the flock of gulls was unusual for the time of year. Also a flock of grey herons *Ardea cinerea*, took to the air at 06:08 in an easterly direction towards Jordan. However, other small avian species (chiffchaffs *Phylloscopus collybita*, bluethroats Alcedo atthis, redstarts *Phoenicurus phoenicurus,* Spanish sparrows *Passer hispaniolensis* and littlegreen bee-eaters *Merops orientalis*) did not take flight until the first foreshock at 06:15 h and they hovered above the bushes until 06.25 when the main shock was over. It is interesting that the birds showing a stronger response were those that migrate over longer distances. It is known that many birds use geomagnetic cues for accurate navigation, being able to sense the slightest change in the earth's magnetic field (see review by Wiltschko and Wiltscko, 2006; Denis et al., 2007). Yosef (1997) continued to study the flock of Herons on 10 subsequent days through 37 tremors. It was found that herons only responded (by showing signs of restlessness or by taking flight) to tremors larger than M=4.3, and at the same time were significantly more sensitive than humans. The Herons reactions to the tremors consistently occurred 30–60 seconds before their detection by humans. This suggests that herons' responses to smaller tremors is due to detection of P-waves or other stimuli that occur close to the event, rather than an anticipatory response. However gulls' and herons' responses to the main event occurred 20 and 12 min, respectively, before the shock, and may have been a genuine anticipatory response (as cited in

Grant and Halliday, 2009). Chen et al. (2000) present a review of animal behavior data gathered in China before the 1975 Haicheng (M=7.3), 1976 Tangshan (M=7.8) and Longling earthquakes (M=7.3). Birds (e.g. pigeons and chickens), mammals (e.g. weasels, dogs, cats, rats, cattle and oxen), Reptiles (Snakes) and fish all showed a varying degree of anticipatory responses to the impending earthquakes. Not surprisingly, the birds were only observed acting abnormally in the very short period before the earthquakes (minutes to hours). Burrowing animals such as weasels, rats and snakes showed far stronger anticipatory responses some days before the earthquakes hit. Anomalous fish behavior was also reported some days before the earthquakes. It is interesting to note that of the three Chinese earthquakes, the 1976 Haicheng earthquake was the only one in winter (February), when snakes usually hibernate. Many observations both on the "amateur" and official level reported a highly unusual amount of snake sightings even in the weeks prior to the earthquake (Chen et al., 2000; Wang et al., 2006). These sightings had a strong impact on the establishment and much research was probably conducted on abnormal snake behavior in China after the event. To our knowledge there are no published studies on this and all the information is probably classified (as is the case with other data; see Wang et al., 2006). Proof of this research can be found in the form of official stations with snakes monitored constantly for abnormal behavior associated with a forthcoming earthquake. [7] It is unlikely that such a program would have been established without some prior serious studies on the subject.
All the same, there are many more published studies presenting compelling evidence of animals that responded well before an earthquake, and provide proposed mechanisms which suggested that animals can sense and consequently predict seismic events in the longer term, prior to the destructive event. It is proposed that these animals can sense various physical earthquake precursors (as discussed above), which are coupled to their innate flight response. The most recent and perhaps convincing example was observed before the 2009 L'aquila earthquake in Italy (M = 6.3). Grant and Halliday (2009) observed a decline of 96% in the number of male toads active around a known and well studied breeding site 5 days before the earthquake. Despite the being 74 km from the epicenter of the earthquake, the toads shifted their usually punctual mating time to some days after the full moon (after the earthquake). Although it is unclear what environmental stimuli caused the toads to postpone their mating and leave the breeding site, a significant correlation was found between pre-sesimic perturbations in the ionosphere (detected by very low frequency radio sounding) and the toad's movements prior to the earthquake.
Further examples of long term predictory responses can be found in studies on mice, another animal often mentioned in conjunction with earthquakes in folklore. The circadian rhythms of mice were monitored every 30 minutes for over a month before, during and after an earthquake in Kobe, Japan (17/1/95, M=7.3). A strong and significant disruption of their behavior (increased locomotor activity) was observed 1 day before the earthquake hit (Yokoi et al., 2003). One of the authors (Dr. Katsuya Nagai), noted that except before the Kobe earthquake, unusually disturbed circadian rhythms without any apparent reason had not been observed in 15 years of research activities, which usually involve keeping ten mice at the Institute for Protein Research. That means the unusual behavior was observed with a probability of one per 55,000 days on the day before the earthquake. Apparently, mice perceived certain preseismic signals a day before the Kobe earthquake (Yokoi et al., 2003).

[7] http://news.bbc.co.uk/2/hi/6215991.stm.

Li et al. (2009) conducted a similar study of mouse circadian rhythms before, during and after the great Sichuan earthquake in China (12/5/2008, M=8). Mice held under constant conditions showed a dramatic and significant change in their behavior (decreased locomotor behavior) 3 days before the earthquake. They found a significant correlation between geomagnetic intensity levels and the time the mice began to act abnormally. The difference in behavior between the Kobe and Sichuan mice, increased and decreased locomotor activity respectively, may be due in part to the differing physical cues present before earthquakes at different geographic locations.

As discussed in the above examples, beside direct seismic cues, geomagnetic anomalies may also be a possible cause, particularly in animals that already have a well-developed magnetoreception system for circadian or navigational purposes (Kirschvink, 2000). Alternatively animals could be detecting raised radon gas levels; as mentioned above there have been many reports of radon anomalies in groundwater before earthquakes, although as with other precursors, they do not always occur (Cicerone et al., 2009; Grant and Halliday, 2009). Yet it is the field of magnetoreception we wish to emphasize as the one which appears to be most promising in terms of the longer term predictions (as against direct seismic cues). Recent studies suggest that most of the aforementioned animals have very sensitive magnetoreceptive capabilities, especially with regard to circadian rhythms (time keeping) and navigation.

Japanese people traditionally believe that catfish and eel have the ability to sense earthquakes before they occur. Japanese fishermen often report that eels disappear from known fishing grounds days before earthquakes, and catfish, usually very docile animals, behave erratically (Chen et al., 2000; Ikeya, 2004). Both fish are known to be highly sensitive to electrical currents, but recent studies suggest that highly developed magnetic reception also exists (Walker et al., 2003; Moore and Riley, 2009) primarily used for navigation, shedding some light on a possible explanation for this unusual pre earthquake behavior.

Ruminates, also mentioned often in the anecdotal literature and to some extent in documentation of Chinese earthquakes (Chen et al., 2000) have been found to be very sensitive to the electromagnetic fields emitted by high voltage power lines. Significant changes in the herds orientation can be seen between sites near and far from high voltage power lines (Burda et al., 2009). Although this study was not earthquake related it gives some insight into possible research directions to further understand why livestock are often reported to behave abnormally before earthquakes.

Inspired by local folklore and amateur reports prior to the Kobe earthquake, Ikeya et al. (1998) studied the alignment of Silkworms under varying electromagnetic fields in the laboratory. They recorded electrophysiological responses in the Silkworms to the stimuli of seismic electrical signals (SES). They present an electromagnetic model which may be detected by Silkworms and other animals (primarily aquatic) leading to the observed abnormal behavior. The intensity of magnetic anomalies recorded prior to large earthquakes corresponds to the electric field changes which induced responses in the animals tested in the laboratory (Ikeya et al., 1998). By compressing granite rocks, as would happen in a real earthquake, they were able to provide an approximation of the electromagnetic effect they produce. Magnetic anomalies of 100 nT before a large earthquake would correspond to the electric field of 30 V/m corresponding to the magnetic field of EM waves. It must be noted that an electric field of 2 V/m, i.e., the magnetic field of 6.7 nT during the rock compression in their

work is for pulses with the width much less than 0.1 ms using digital storage oscilloscopes. This intensity is sufficiently high to surprise sensitive animals (Ikeya, 1998). It is known that aquatic animals like sharks and catfish with electrosensory organs can detect 10^{-5} V/m to capture prey and communicate with each other. Sensitive animals like budgerigar and crocodiles showed unusual behavior by producing a field of 0.3 V/m (magnetic field of 1 nT) for the persistence of 0.1 ms. (Ikeya et al., 2000).
In this respect it is interesting that the Israeli Water Management Authority is reputed to make us of Elephant Nose Fish (*Gnathonemus petersii*) to monitor water quality, primarily with regard to possible contaminations (e.g. caused by terrorists). The minutest change in water chemistry can be detected by the fish, consequently altering the frequency of their tail movement, a sign which can be quantified.[8] As with the Chinese snake monitoring, there is no published scientific literature supporting this program. And as with all the above cases, only through clever experimental planning (see Kirschvink et al., 2011), using both classical behavioral methodology and modern technological tools can we make progress in this field.

It is noteworthy that earthquakes are not the only potential natural disasters preceded by unusual animal behavior. Heupel et al. (2003) report that hours before tropical storm Gabrielle hit the shore, all the juvenile blacktip sharks they were monitoring (N=13) fled their preferred habitat for deeper water, only returning days after the storm. They left well before the wind levels rose to abnormal levels or the rain started. A significant correlation was found between a minute change in barometric pressure and their time of departure. The authors concluded that the synchronicity of departures, similar behaviour of monitored blacktip sharks, and their young age (3–4 months) suggest that the blacktip sharks’ departure before these storms arrived was an innate response. Sea snakes have been shown to flee their usual habitat over a day before a strong typhoon. Here too a fall in barometric pressure is implicated as the precursory signal sensed by the animals for the upcoming storm (Liu et al., 2010). These examples provide further support for the notion that animals can, and do detect and anticipate future events which may have serious implications on their livelihood, whether they have or have not experienced such events in their lifetime. Figuratively speaking, it is the experience of their forefathers that is embedded in their DNA that gives them the ability to sense a precursory signal and act upon it, just as one instinctively flees when there are telltale signs of a predator nearby (Kirschvink, 2000). Due to the great progress made in the past two decades in molecular and cellular biology, more and more fields of animal behavior are gaining further support at the molecular level. The ability to study at high resolution what transpires at the cellular and sub-cellular level, genome sequencing and other numerous genetic tools provide us with the ability to verify what was often hard to understand behavior as it is seen "on the surface". This provides a better mechanistic view of the sometimes peculiar behaviors observed.

Conclusions

It is clear that there is much more to the observed unusual animal behavior before earthquakes than just "anecdotes". Its acceptance as a real factor in Chinese and

[8] http://www.haaretz.co.il/hasite/spages/713878.html.

Japanese prediction programs, and the wealth of current scientific data suggest much more should be done to study and invest in earthquake prediction in general and related unusual animal behavior in particular. It has often been asked why the 1975 Haicheng earthquake prediction hasn't been repeated. What is perhaps most interesting about that prediction is that the preceding anomaly monitoring on an amateur and scientific level – under direction from the highest political level - was perhaps the largest and most motivated "experiment" in earthquake prediction ever conducted. Clearly the unique political climate, facilitating at it did mass mobilization, coupled with the clear motivation to make progress brought on the successful prediction. If there is anything to learn from this event, luck aside, it is that earthquake prediction, properly funded and conducted, using a multidisciplinary approach, is indeed possible.

In this era of massive data compilation, storage and processing, we see more and more studies indicating that there is a wealth of physical phenomena preceding many, but not all, of the past few decades' earthquakes. Clearly, the ultimate goal in earthquake prediction is to find a specific and accurate measurement(s) indicating an upcoming event at a certain place and time. As with other technological advances, especially in the medical field, nature many times provides us with clues, often through the observation of animal behavior, to finding solutions to our problems. Our current inability to predict earthquakes and thus conduct *a priori* animal behavior studies in this field is over-exaggerated. Laboratory experiments in the field of animal behavior are conducted regularly, using well devised manipulations (in our case "table shaking" and magnetic/electrical field manipulations, for example) to elucidate the factors that promote various behaviors. Our anthropocentric nature has always undermined the acceptance of studies attributing to animals intelligence, emotions and perhaps most annoying of all – abilities we humans don't possess. Recent advances in molecular biology, our ability to measure changes in the expression of specific genes as a function of the conditions an animal is kept in and its associated behavior provide us with better means than in the past to elucidate the mechanisms underlying behavior. For instance, it was only during the second half of the 20th century that the concept of endogenous biological clocks was accepted. Clearly, there is a strong selective advantage in knowing today what will happen tomorrow. The understanding that animals do not respond only to the rising and setting of the sun or the ebb and flow of the tide, as direct cues elucidating a response, rather that natural selection has clearly played a part in the evolution of anticipatory mechanisms that gain benefit and ultimately viability. It should be clear that burrowing, slow moving, hibernating and many other types of animals would have developed a wide suite of predictive mechanisms based on sensing what we are gradually understanding as a wide range of physical phenomenon that precede earthquakes. The scientific studies which were lucky to be monitoring animal behavior before, during and after earthquakes, certainly support this view. Furthermore, recent advances in sensory biology, magneto and electrical reception in particular, point in this direction.
Knowing what we do about certain animals' unusual behavior before earthquakes, and those animals' sensory capabilities, there are a surprisingly large number of experiments, almost begging to be conducted, that have hitherto not been performed. What is required is a heightened awareness to the topic, greater financial investment (immeasurable in comparison to the possible gains) and above all an understanding that the evidence suggests it's possible, with odds far better than chance, for us to predict earthquakes. Animals already do it.

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