Teaching uncertainty: the case of climate change

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Abstract

The concept of uncertainty plays a significant role in higher education in the 21st century. However; the *pedagogy* of uncertainty tends to focus on ontology and the feelings of uncertainty experienced by teachers and students, as opposed to treating it as an epistemological concept. This research considers the epistemology of uncertainty in the context of climate change and investigates how it is conceptualised and taught by academics working in the subject area. The theoretical frameworks of troublesome knowledge and threshold concepts are employed to aid the characterisation of uncertainty as a concept in higher education.

Following a methodology based on grounded theory, interviews were undertaken with 10 academics involved in teaching climate change. The interview data was analysed and categorised according to the interview participants' conceptions of uncertainty and the implications for teaching uncertainty.

The research found that uncertainty in the context of climate change is a complex and multivariate concept and this was reflected in the interview data, with many of the participants holding several different conceptions of uncertainty simultaneously. In terms of teaching uncertainty, the concept also aligns with the theoretical frameworks, in that it is troublesome knowledge and a threshold concept in the context of climate change, with broader implications as an interdisciplinary threshold concept arising from the difficulty encountered when attempting to integrate diverse conceptions of uncertainty. Maturity and personal development were also found to play a role in teaching uncertainty. Several strategies and approaches to teaching uncertainty are discussed, and a critical reflection on the pedagogy of uncertainty is offered. The critical reflection proposes a pedagogy for teaching uncertainty whereby the concept is situated centrally in the higher education curriculum and taught explicitly through student-centred approaches that take into account issues of personal development and variation.

Declaration

I declare that the work in this thesis was carried out in accordance with the regulations of the University of Gloucestershire and is original except where indicated by specific reference in the text. No part of the thesis has been submitted as part of any other academic award. The thesis has not been presented to any other education institution in the United Kingdom or overseas.

Any views expressed in the thesis are those of the author and in no way represent those of the University.

Signed.. .... Date. 20/06/11.....

Acknowledgements

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Mick has also been the lead member in my supervisory team and has performed the role admirably, always encouraging and an excellent guide on my first steps into the realm of academia. My other supervisors have also assisted greatly in getting me to this point: Professor Ray Land; a remarkable intellect yet always humble and with a refined taste in public houses, Professor Frank Chambers; a genuine expert with an admirably sceptical streak and Dr John Hunt; responsible for inspiring my interest in uncertainty and who remained a valuable source of ideas and feedback even after serious illness. Thank you, all.

I am also grateful for the moral support of my colleagues at CeAL, without whom I probably would not have made it this far. Particularly Laura Lannin, Jo Lonsdale and Claire Hanson, who have always been on hand with kind words, sound advice and stimulating conversation.

Thanks must also go to my family – Mum; for her ceaseless encouragement and belief, Dad; for inspiring and challenging me, Lindsay; for further inspiration and laughter and Eilidh; for her timely cheerfulness (I've kept swimming!).

Finally, I must thank Sally, to whom this thesis is dedicated. You have made this possible through your love and support and I am so proud to be called yours. Let's get married.

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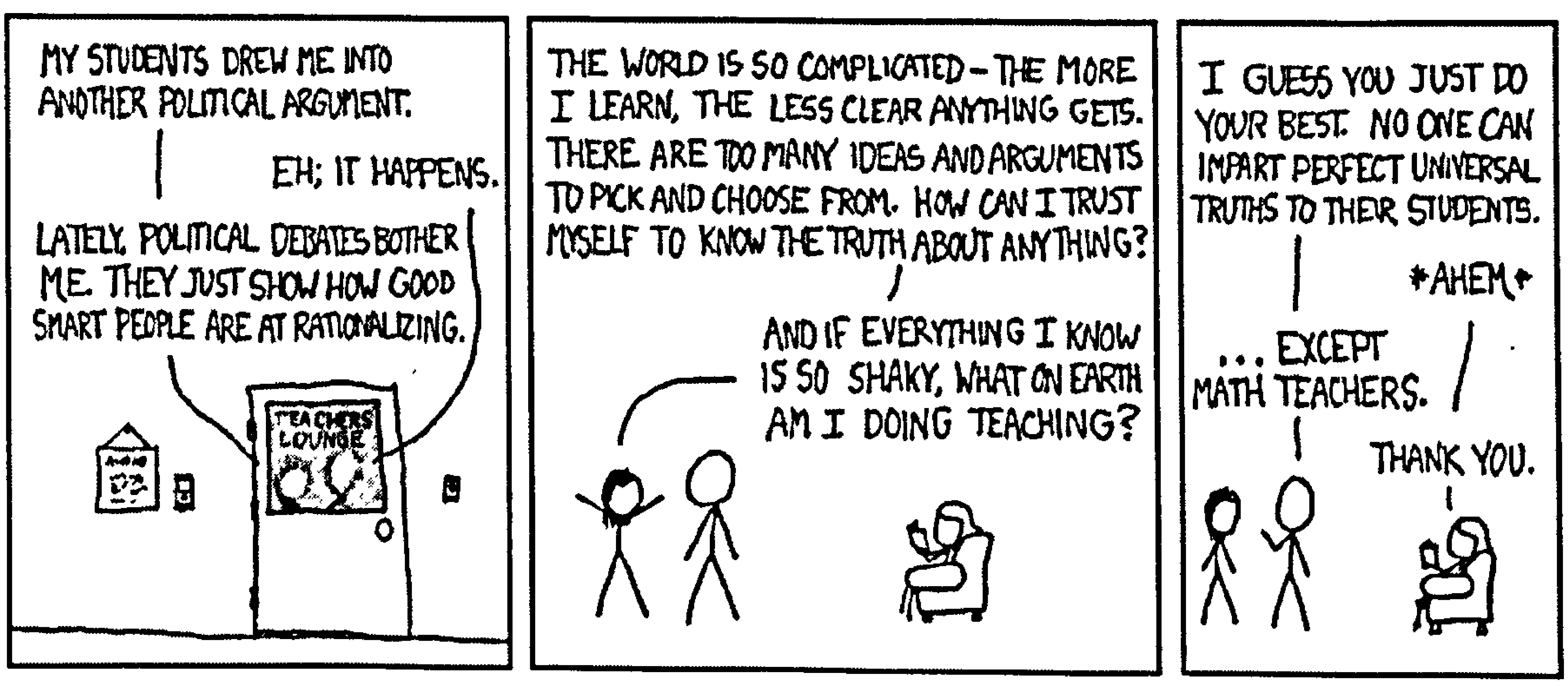
Contents – Tables and Figures

"The only certainty is uncertainty"

- Pliny the Elder (Roman scholar, AD 23 – 79) (cited in Katz 2001)

"As we know, there are known knowns. There are things we know we know. We also know there are known unknowns. That is to say we know there are some things we do not know. But there are also unknown unknowns, the ones we don't know we don't know."

- Donald Rumsfeld (US Secretary of Defence, 2002) (cited in Pittock 2009)



- Randall Monroe (xkcd.com, no. 263)

Chapter One

Introduction

Teaching uncertainty

This thesis is an investigation of teaching the concept of uncertainty at higher education level, situated within the context of climate change. Uncertainty has become a pressing concern for higher education in recent years as the need has been identified to prepare students for a 'supercomplex' world characterised as an "Age of Uncertainty" (Barnett 2007; 2000, Baumann 2007). In a supercomplex world, the complexity brought about by the accessibility and connectivity of knowledge and information is compounded by challenges to the frameworks that would normally be employed to synthesise and utilise such knowledge. This results in extreme difficulty orienting oneself to the world and even being able to describe it (Barnett 2000). A key component of understanding the supercomplex world is understanding the concept of uncertainty, allowing for the ability to learn and operate in a world where knowledge and values are contested (Barnett 2009). There appears to be merit, therefore, in investigating the concept in order to assess the potential implications of uncertainty in higher education and the potential for developing strategies and pedagogy for teaching uncertainty.

'Uncertainty' in this case refers principally to epistemological uncertainty, associated with the status of knowledge or knowing related to a given subject or phenomenon. Uncertainty relating to knowledge includes a range of possible interpretations including that which is unpredictable, as yet unknown or even unknowable. The concept of uncertainty referred to here may refer to any or all of these interpretations such that an understanding of uncertainty may include understanding that something is uncertain, why and how the uncertainty arises and what the implications of that uncertainty are. However, the concept of uncertainty can also be said to be ontological as well as epistemological in character; bringing about feelings of being uncertain as challenges and realisations relating to the status of knowledge are encountered (Barnet 2009).

Uncertainty is, therefore, not an easy concept to constrain or define and requires a context that offers some structure to its epistemology.

The case of climate change

Climate change is a subject area in which uncertainty plays a major role and, therefore, offers some context to the investigation of teaching uncertainty. The term climate change may be defined as: "a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use" (Intergovernmental Panel on Climate Change (IPCC) 2007). The "climate change subject area" refers to the context in which the concepts relating to climate change are taught and researched by academics working in universities. In the context of climate change the term uncertainty "can range in implication from a lack of absolute sureness to such vagueness as to preclude anything more than informed guesses or speculation. Sometimes uncertainty results from a lack of information and on other occasions it is caused by disagreement about what is known or even knowable" (Moss and Schneider 2000, p. 35). Teaching and learning about climate change "necessitates the ability to deal with uncertainty on several levels – not only uncertainty about the workings of the complex physical climate system, but also uncertainty with respect to social and cultural processes that mediate human response to changes within the system" (Rebich and Gautier 2005, p. 355). The subject area of climate change contains numerous examples of the epistemological uncertainty referred to earlier in a setting that reflects closely the supercomplex nature of the modern world. This makes climate change an excellent context in which to investigate the realities of teaching uncertainty in higher education. The major sources and manifestations of uncertainty in the context of climate change are discussed in depth in chapter two, which gives insight into the epistemological character of the concept in this subject area.

Theoretical frameworks

Investigating the teaching of uncertainty has necessitated the research and employment of theoretical frameworks of teaching and learning that relate to potentially troublesome, yet also transformational, concepts such as uncertainty. The theoretical frameworks selected in this instance are those of 'troublesome knowledge' (Perkins 1999, Meyer and Land 2003) and threshold concepts (Meyer and Land 2003; 2005). Troublesome knowledge centres on the idea that there are certain types of knowledge that students find particularly troublesome and that require adaptable and creative constructivist pedagogies in order to help students learn (Perkins 1999). Threshold concepts is a theoretical framework that posits that within certain disciplines there are key concepts that act as 'portals' or 'thresholds' towards a higher level of thinking about a subject. These threshold concepts are characterised by several criteria, all of which relate to their power to bring about a potentially significant shift in a learner's subjectivity or even world view (Meyer and Land 2003). Threshold concepts also provoke a state of ontological uncertainty, characterised as liminality, as a student makes the transition across the threshold – this allows the framework to capture the ontological as well as epistemological uncertainty relevant to this research. An in-depth analysis of these frameworks and their applicability to this study is given in chapter three.

Aims and research questions

The aims of this study are as follows:

- To explore the nature of uncertainty in the context of climate change

- To investigate uncertainty in the context of climate change in terms of how it is conceptualised and taught by academics working in the subject area

- To offer a critical reflection on the pedagogy of uncertainty

In order to achieve these aims, the study is centred around four key research questions relating to the teaching of uncertainty in the context of climate change, these are:

- Research question 1: **What is the nature of uncertainty in the context of climate change?**
- Research question 2: **Does uncertainty represent troublesome knowledge in the context of climate change?**
- Research question 3: **Can the concept of uncertainty be described as a threshold concept in the context of climate change?**
- Research question 4: **What strategies do teachers use to teach uncertainty in the context of climate change?**

The first research question aims to go some way towards understanding the epistemology of uncertainty in the context of climate change, in order to allow for a more in-depth appraisal of the implications this has for teaching uncertainty. The second and third research questions seek to ascertain whether uncertainty fits the definitional criteria provided by the theoretical frameworks used in the study and what the implications of this may be. The fourth research question aims to build on the preceding three and provide some insight into potential pedagogic approaches and strategies that may be suitable for teaching uncertainty at higher education level. Consideration is also given to themes that emerged over the course of the research and the implications that these may have. The conclusions of the study are summarised in relation to the research questions in chapter seven, which also includes a summary of the emergent themes of the work, suggestions of future research directions and a critical reflection on the pedagogy of uncertainty.

Research methods

The data for this study was collected through semi-structured interviews with 10 academics teaching about climate change on Geography degree programmes at universities in the UK and overseas. The research methodology employed was a flexible, inductive and open-ended approach based on grounded theory, where theory emerges from qualitative data through an iterative process of simultaneous data collection and analysis (Bryant and Charmaz 2007). The data was analysed by means of a series of close readings of the interview data through which analytical categories emerged relating to the participant's conceptions of uncertainty and implications for teaching uncertainty. The process and rationale behind developing the research methods and methodology are discussed in detail in chapter four. The analysis and discussion of the interview data may be found in chapters five and six.

Position statement – opening

The following statement offers an insight into the background and perspectives of the researcher as well as giving some context to the choice of research topic and the direction the research has taken:

I am a 27 year old white male from Edinburgh, Scotland, who has, for the last five years, been based at the Centre for Active Learning, University of Gloucestershire where I have held the post of Postgraduate Researcher and worked towards a PhD in Education. Prior to taking up this post I completed a Bachelor of Science Honours degree in Earth Science at the University of Glasgow where my chief interests lay in geomorphology, landscape evolution and quaternary geology. It was also in this setting that an interest in education first developed as I worked as an undergraduate demonstrator in the field, teaching Earth Science to younger undergraduates.

Taking up the role at the University of Gloucestershire afforded me the opportunity to pursue a part time postgraduate degree through pedagogic research and in this I was given a great degree of freedom in designing my research project. This did prove troublesome at the time however, owing to my perceived lack of knowledge and expertise in the field of pedagogic research. It was in discussion with colleagues that the difficulty of teaching 'scientific uncertainty' related to climate change was raised and it immediately piqued my interest as a potential research project. I had developed an interest in past climates and contemporary climate change through my Earth Science degree and, upon reflection, had also come to realise how much uncertainty was associated with studying the Earth and its complex physical systems. I therefore resolved that teaching uncertainty in the context of climate change would be the subject of my research as I endeavoured to complete my PhD part time while working at the Centre for Active Learning.

At this point I was still lacking in confidence in relation to pedagogic research, as the transition from a scientific disciplinary background to a social science setting was a major and quite uncomfortable change for me. I was, however, able to quickly build research capacity in this area through my day-to-day work with colleagues on educational development projects related to active learning and also the Centre for Active Learning reading group of which I was an active member. This was an activity that brought together new and more experienced researchers to discuss pedagogic research literature in an informal and supportive setting. Through the reading group I encountered many of the key pedagogic theories employed in this thesis, including threshold concepts and the implications of supercomplexity, as well as many different research methodologies; affording me the ability to tailor my methodology to the needs of my research and justify my choice of methods. Building my personal capacity for pedagogic research also led to me taking ownership of the PhD early on in the process and integrating my own ideas. This has led to the study evolving from where I initially had a strongly scientific conception of uncertainty to a much wider view of the concept in all its complexity. Researching climate change and the part that uncertainty plays in the issue, whilst challenging, has also taught me a lot about how science and society interact and the complex implications this has for decision making.

The research and writing of this thesis had a profound effect on me as both an academic and a person. Some personal reflections on the research and the concept of uncertainty are provided at the end of the thesis.

Chapter Two

Uncertainty in Context: The Case of Climate Change

This chapter examines many of the sources and manifestations of uncertainty in the context of climate change. This overview of the nature of uncertainty in climate change is a key research outcome of this study. The chapter also aims to go some way towards describing uncertainty epistemologically in this context or, in other words, how the concept of uncertainty appears in teaching and learning about climate change. The chapter is split into sections and sub-sections dealing with the various key areas in which uncertainty can be seen to have a significant presence and impact, these are:

- Uncertainty in climate change science
    - As a result of the complex and chaotic nature of the physical climate system
    - In the use of proxy data to understand and reconstruct past climates
    - In the design and construction of climate models
    - In scientific discourse;

- Uncertainty in future projections of human behaviour
    - In the construction of hypothetical scenarios
    - In the identification of strategies for adaptation and mitigation;

- Uncertainty in decision-making –
    - In characterising uncertainties for decision makers.
    - In the complexity of decision-making and frameworks such as post-normal science and the precautionary principle

This chapter will discuss each of the above groupings of uncertainty in turn, outlining the key points pertaining to each and some examples of how uncertainty appears and is understood. This will give a detailed picture of the multivariate and diverse nature of uncertainty in climate change.

Uncertainty in climate change science

Science is faced with much uncertainty in its attempts to understand the workings of climate and climate change. This uncertainty may stem from a variety of different sources including the complex and non-linear interactions of the vast number of components that make up the climate system, a lack of available data for a given component, disputes over the quality of the data and disagreements about what conclusions may be drawn from different datasets (IPCC 2007).

Complexity, chaos and surprise

According to Rind (1999) a complex system is "literally one in which there are multiple interactions between many different components" (p. 105). The climate system clearly meets this definition made up as it is of a vast number of intricately linked components (a representation of which is shown in Figure 2.1). The vast scale and complexity of the Earth's climate system makes it difficult to constrain, model and thereby fully understand all of the myriad components and their multiple interactions, for this reason the evident complexity of the climate system may be regarded as a source of uncertainty. This is exemplified by the use of climate models as tools for understanding climate and climate change, by their very nature they are simplified and reductionist and can never truly reflect the true complexity of physical reality (Ridley 2001, p. 58).

Additional complexity arises from the chaotic and non-linear behaviour of elements of the climate system. For example, it may be relatively straightforward to understand a given component of the system, say the transport of water molecules through the system (from evaporation/transpiration, through condensation, precipitation, run off etc.), as it behaves in a fairly predictable, linear fashion, however, when the whole system is taken together, with all the interactions between these sub-systems and sub-components, these interactions may produce behaviour which is not similarly predictable.

Essentially, these 'non-linearities' occur in complex systems where "steady inputs to the system cause unsteady outputs" (Pittock 2009, p. 44); in other words whilst factors affecting climate may remain constant the interaction of these factors can lead to an effectively infinite number of possible outcomes that remain inherently unknowable. Similarly, small changes to initial conditions in the system can lead to the system evolving in completely different ways, which are again unpredictable (Ridley 2001). This chaotic behaviour of the climate system makes predicting the precise effects of future climate change difficult, although not impossible (Pittock 2009). The apparent chaos of the climate system actually tends to produce relatively stable conditions over long time scales and large spatial scales, for example the mean global temperature has probably not varied by more than ±5% throughout the history of the Earth (Rind 1999). It is easier, therefore, to make a prediction of the effects of some change in forcing factors on the future climate at larger global scales, rather than smaller local or regional scales and over longer rather than shorter timescales.

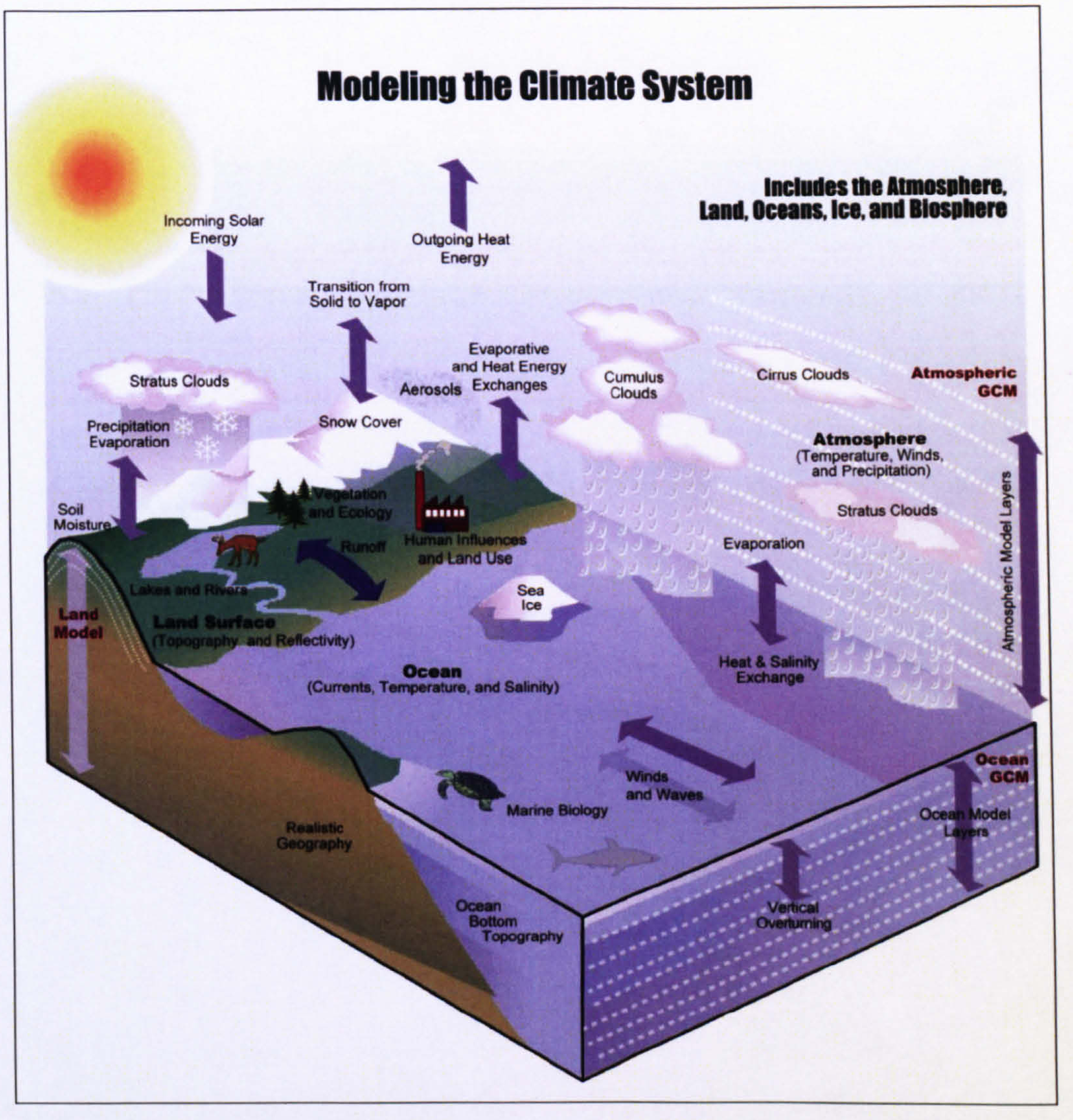


Figure 2.1: Components and interactions of the climate system, from Karl and Trenberth (2003).

This is evidenced by the possibility of abrupt non-linear responses of the climate, which may be termed "surprises" (Schneider 2003, IPCC 1995). These surprises are characterised as low-probability, but high consequence extreme events produced as a result of some change to forcing factors. For example changes to the Thermohaline Circulation in the Atlantic Ocean as a result of freshwater inputs due to melting of the Greenland ice sheet, which could have a profound effect on Western Europe (Schneider 2003). This 'surprise' is characterised as "very unlikely" by the IPCC (2007) (see Table 2.3), however, the potential consequences of such unlikely events mean they have to be included in any consideration of future climate change, adding another layer of uncertainty to the complex analysis of the impacts of climate change.

Furthermore, many of these surprises may be irreversible in that they represent a transition to a new equilibrium state that will exist even when the original forcing conditions are restored (Schneider 2003). This potential for irreversibility places these surprises alongside theoretical "tipping points" that may exist in the Earth system (Lenton *et al.* 2008). Tipping points are described as critical states that, once reached, may push components of the Earth system into "qualitatively different modes of operation, implying large-scale impacts on human and ecological systems" (Lenton *et al.* 2008, p. 1786). Indeed, abrupt climate changes as described above may be characterised as points where the thresholds that tipping points represent are crossed leading to rapid, 'run-away' changes where the nature of the new equilibrium state is extremely difficult to predict. Uncertainty exists in attempting to identify where tipping points exist, as they are largely theoretical, and the conditions that are required for them to be reached and initiated (IPCC 2007, Lenton *et al.* 2008).

Palaeoclimate and proxies – learning from the past

As mentioned above, the complex and often chaotic nature of the climate system makes understanding climate change and the reasons behind it difficult. This is compounded by the fact that changes to the climate often occur over very long spans of time, meaning that identifying current and potential future changes requires data that covers similar timescales. However, this data is not always readily available – indeed, the record of climate data directly observed and recorded by humans only extends back around 200 years, coinciding with the advent of precise analytical instruments such as thermometers, barometers and anemometers (Pittock 2009). In order to achieve full understanding of the climate it is necessary, therefore, to examine 'proxy' records of climatic conditions that allow scientists to evaluate what climatic changes have occurred over a longer time period and the possible forcing factors behind them.

Proxy climate records are, essentially, archives of past climate that give an indication of climatic conditions at the time through some indirect correlation (Pittock 2009). A summary of some of the available proxy indicators of climatic variation is given in Table 2.1. By their nature, many proxy records are beset by uncertainties arising from gaps in the proxy climate record, an inability to be precise about what proxy evidence may signify and the fact that some proxies are not directly coupled to climatic fluctuations. An example of this may be the use of fossilised plant and animal remains to reconstruct past climates. Any use of fossil evidence (such as pollen grains) requires certain assumptions about factors such as productivity, the ecological requirements of the organism in question and how it came to be deposited in the location in which it was discovered (Bunting and Middleton 2009). If the organism used in reconstruction is now extinct, uncertainties over fossil ecology and other factors tend to be resolved by comparison with contemporary organisms that share similar morphological characteristics. However this is not an exact process as differences may exist in the environmental parameters suited to the fossilised organism compared to its contemporary ancestor. Variations in the fossil record may also arise as a result of some other disturbance, rather than being entirely due to a fluctuating climate (Bradley 1999), meaning that fossil records alone are insufficient to fully reconstruct past climates.

Table 2.1: Some commonly used proxy indicators of climate variability and their associated uncertainties - adapted from Pittock (2009) with additional material from Bradley (1999), Chambers *et al.* (2010), Hall *et al.* (2006), Jones *et al.* (2001), Jordan *et al.* (2005), Mudelsee (2001) and Schiermeier (2010).

Indicator	Property Measured	Time Resolution	Time Span	Climate-related information obtained	Associated Uncertainties
Tree Rings	Width, density, isotopic ratios, trace elements	Annual	Centuries-Millennia	Temperature, rainfall, fire events, biomass and vegetation patterns, volcanic eruptions	Spatial limits of fire events, divergence, dating methods
Lake/bog Sediments	Deposition rates, fossil ecology (micro- and macro-fossils), charcoal	Annual	Millennia	Rainfall, atmospheric water balance, biomass and vegetation patterns, fire events, volcanic eruptions, storminess	Imprecise dating methods, fossil ecology
Ice Cores	Isotopes, fractional melting, annual layer thickness, gas bubbles	Annual	Millennia	Temperature, snow accumulation rates, gas concentrations, solar activity, biomass and vegetation patterns, volcanic eruptions	Possibility of contamination, dating methods, phase relations
Ocean Sediment Cores	Fossil ecology (pollen, shells etc.), deposition rates, isotopic ratios	Annual	Millennia	Sea temperature, salinity, acidity, ice volumes, sea level, aridity, terrestrial vegetation	Fossil ecology, dating methods
Old Groundwater	Isotopes, noble gases	Multi-decadal/ centuries	Millennia	Temperature	Dating methods
Glacial Moraines	Max. glacial length	Decadal	Decades	Temperature and precipitation	Dating methods
Coastal Landforms	Ledges, raised beaches, debris lines	Decadal	Decades-Millennia	Sea level, storm events	Dating methods
Documentary Evidence	Reports of extremes, harvests, dates of river/lake/sea ice break-up	Annual	Centuries-Millennia	Temperature, precipitation, vegetation and biomass patterns, volcanic eruptions, sea level	Reliability, accuracy

Indeed, most proxy climate records are limited either by indirect coupling, as described above, or spatially, in terms of the coverage that they provide geographically (Jones *et al.* 2001). For this reason proxy climate records are now most commonly used as part of 'multiproxy' studies that utilise a diverse range of proxy climate data across large spatial distributions and with varying temporal resolution (Mann *et al.* 1999, Frank *et al.* 2010, Moberg *et al.* 2005). Clearly the use of multiple datasets from many different sources somewhat increases the complexity of already complex reconstructions of past climate. The increased use of the multiproxy approach and the attendant increase in complexity is highlighted in Figure 2.2, which shows the changing ways in which the IPCC has graphically presented evidence for recent global warming (Frank *et al.* 2010). It is interesting to note the transition from a basic and seemingly arbitrary representation of historic global temperature in 1990 towards a much more complex representation in 2007. Also noteworthy is the apparent inversion of the period depicted as the 'Medieval Warm Period' in the 1990 graph compared to the later two graphs, where the same time period is shown as below the 1961-90 average. This may represent an improvement in the accuracy of palaeoclimate science or an increase in the amount of data available; either way there does appear to be a clear shift in the use and resolution of multiproxy climate studies the latest of which appears the most uncertain. Perhaps somewhat paradoxically, the use of a greater number of proxy records, which may be expected to reduce overall uncertainty, appears to have instead resulted in an increase in the level of uncertainty.

The complexity of the multiproxy approach presents further difficulties in terms of accommodating uncertainties from diverse sources and this is compounded by the fact that all proxy climate records require calibration with instrumental climate records in order to be used effectively (Esper *et al.* 2005, Frank 2010). Calibration is based on the period of overlap between the instrumental and proxy records and is carried out either through regression (Mann *et al.* 1999, von Storch *et al.* 2004), where proxy data values are assumed to correlate exactly to values recorded instrumentally, or through adjustment, where the mean value and variance of proxy data values are adjusted to agree with the instrumental record (Moberg *et al.* 2005). The assumptions and adjustments involved in the calibration process indicate that this is another source of uncertainty in the use of proxy climate data, and this is indeed the case (Frank *et al.* 2010). Uncertainties may be compounded by the inherent bias in the instrumental record in terms of spatial distribution; for example instrumental coverage is markedly poorer in the southern hemisphere compared to the northern hemisphere owing to patterns of human migration and differing rates of human development through history (Jones *et al.* 2001).

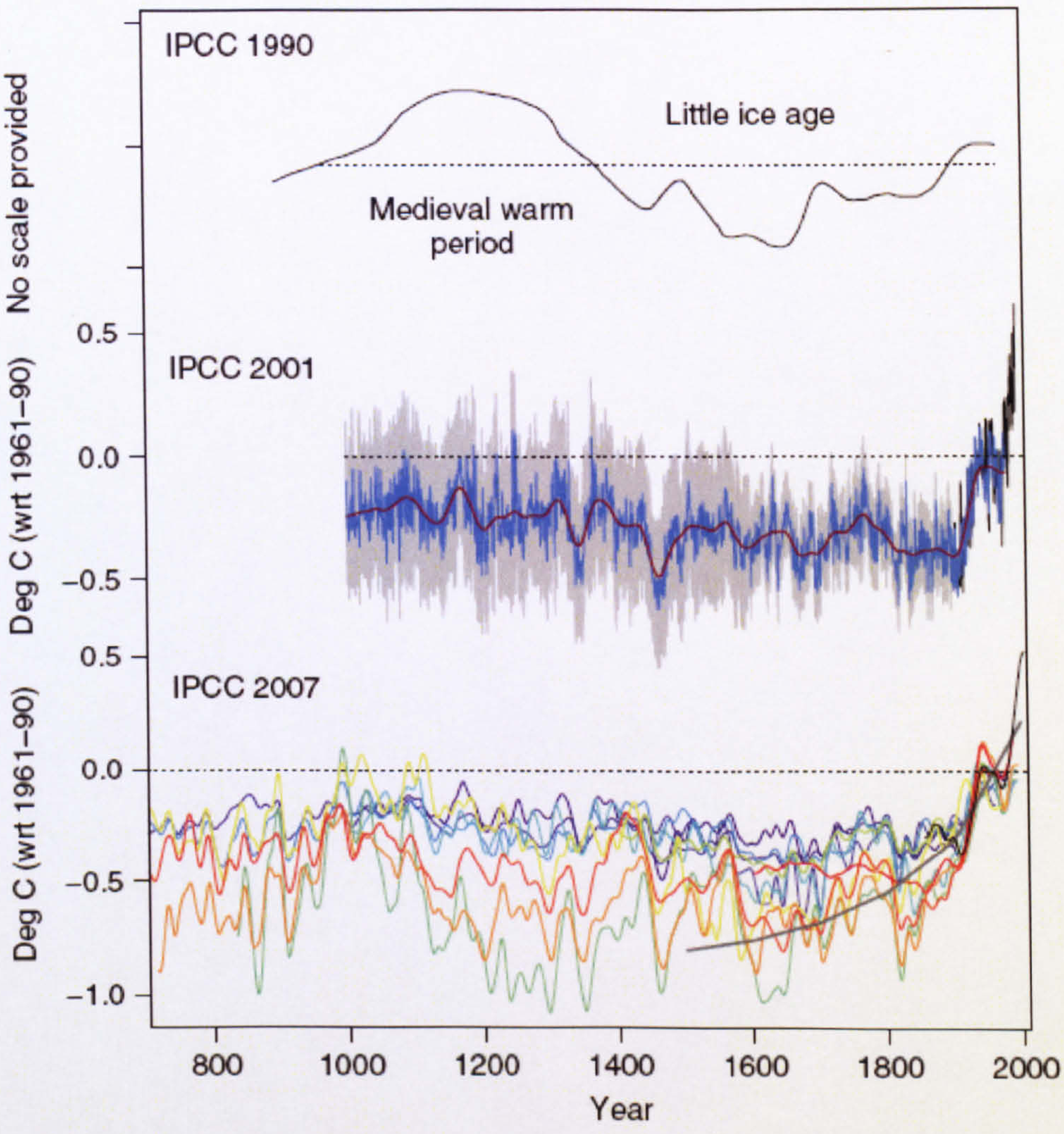


Figure 2.2: Changing icons used by the IPCC to demonstrate warming from pre-industrial to industrial times from Frank *et al.* (2010). This shows a transition from illustrative presentation of simplified averaged values towards a more quantified multi-proxy based presentation, which appears to signify a gradual increase in the overall uncertainty associated with global historic temperature.

Another calibration necessary for the use of proxy climate data is that of the temporal position of the record in question, or where it occurs in the climate record. This is of fundamental importance as without a reliable estimate of when events occurred it is impossible to investigate the rates at which past environmental changes happened or whether certain signals in the climate record are synchronous with one another and, therefore, whether a signal is relevant to understanding the causes behind climatic variation (Bradley 1999). However, dating of proxy climate records is rarely precise, relying on a range of radioisotopic, palaeomagnetic, chemical and biological methods (Figure 2.3) that contain varying levels of uncertainty (Table 2.1).

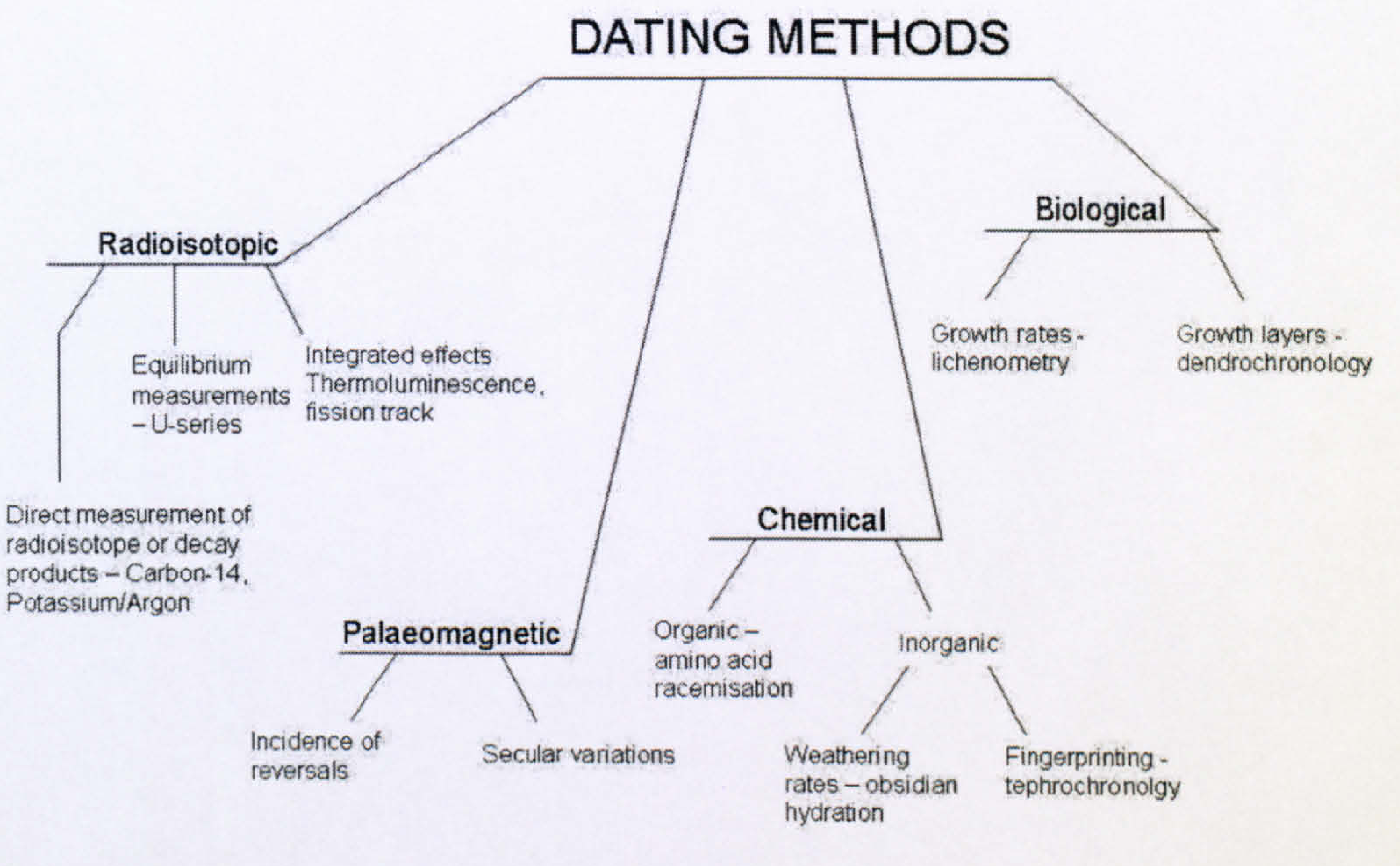


Figure 2.3: Dating methods used in palaeoclimate research - from Bradley (1999)

Biological dating methods tend to be among the most accurate, relying as they do on growth rates that are closely linked to environmental factors such as temperature and rainfall (Bradley 1999). Dendrochronology for example essentially involves 'counting back' the number of annual growth rings in a tree and is, therefore, an accurate means of determining the time of some environmental variation, recorded in the width of the growth rings themselves (Bradley 1999, Jordan *et al.* 2005). Other palaeoclimatic records, however, require other, less direct dating methods that may give less precise temporal information. A good example of this is radiocarbon dating, which uses the decline in the isotope Carbon-14 as a result of radioactive decay, as a means of estimating the age of organic remains (Bradley 1999). This decline begins at the point of death of the organism and is capable of resolving ages up to 62,000 years B.P. (Before Present) in samples with organic content (Plastino *et al.* 2001). However, radiocarbon dating cannot give a precise age for a sample and radiocarbon dates are instead statements of probability rather than absolute ages. This arises from uncertainties linked to the random nature of radioactive disintegration, as it is impossible to know for certain when a given atom of Carbon-14 will decay, but it is possible to assign an average value to the number of atoms that will decay in a given time (Bradley 1999). This uncertainty is resolved statistically with radiocarbon dates typically expressed in the form $x \pm y$, where x is the midpoint in a Poisson probability distribution for the sample and y is the standard deviation (Bradley 1999). This uncertainty is then accommodated in the assessment of the signal that is being examined. Other sources of error in radiocarbon dating may arise from problems with sample selection and contamination, which may lead to results being skewed by confusion with modern carbon measurements (Bradley 1999), or by bias produced by changes in the concentration of Carbon-14 in the upper ocean (Muscheler *et al.* 2008). Other methods for dating palaeoclimatic data sources may face similar levels of uncertainty, however; even with approximate age ranges the records remain highly useful for interpreting past changes to climate.

Multi-proxy climate reconstruction studies also frequently suffer from an inability to constrain precisely the amplitude of a given environmental signal and, therefore, the sensitivity of the climate to forcing factors (Hegerl *et al.* 2006, Frank *et al.* 2010, Esper *et al.* 2005). This is demonstrated in the 'IPCC 2007' graph in Figure 2.2, where the various proxy data sources largely agree on the timing of major shifts in global temperature, but with clear divergence on the amplitude of these changes. Typically these divergences are again resolved statistically; giving a 'best fit' or mean representation of the amplitude and sensitivity that marginalises the uncertainties (Hegerl *et al.* 2006). However, uncertainty over the amplitude of climatic signals in proxy climate records has profound implications for understanding the climate system and how it may respond to anthropogenic forcing (Esper at al. 2005). Constraining the climate sensitivity would therefore appear to be a key aim of multi-proxy palaeoclimate studies (Frank *et al.* 2010).

One final notable source of uncertainty in palaeoclimatic reconstruction and, perhaps more fundamentally, understanding the climate system is that of phase relations, or establishing the leads and lags in the interactions between forcing factors and climatic signals. This is particularly relevant in studies of 'fossilised' bubbles of atmospheric gas contained in ice cores, which record the concentrations of atmospheric gases at the time. Here, researchers measure the concentration of greenhouse gases such as carbon dioxide at certain time periods and link them directly to the other climatic signals contained in the ice (such as the thickness of the annual snow layer or evidence of fractional melting). Broadly, changing concentrations of greenhouse gases may be expected to 'lead' (or correlate very closely with) fluctuations in temperature, effectively directly causing increases in temperature as a result of increased concentrations and vice-versa (Petit *et al.* 1999, Kump 2002). However, this is not always apparent, particularly over shorter time scales, where the lead/lag relationships between greenhouse gases and temperature can become unclear or affected by 'noise' (Mudelsee 2001). This clearly has profound implications for understanding anthropogenic warming as whilst the link between greenhouse gases and temperature has been clearly demonstrated (Pittock 2009, IPCC 2007), there remains uncertainty over the complex positive and negative feedbacks that interact to produce the end climatic result on human timescales.

<u>Climate modelling – understanding the past, predicting the future</u>

Climate models are numerical constructs that are used to describe and understand the Earth's climate through equations that represent the laws of dynamics and thermodynamics, essentially calculating the transfer of energy and matter through the system (Vidale *et al.* 2003, Pittock 2009). A representation of some of the factors that are accommodated in climate models is shown in Figure 2.1 and a breakdown of some climate model types is shown in Table 2.2. They vary in complexity from fairly simple Energy Balance Models, which use the incoming and outgoing infra-red radiation to provide an estimate of the overall atmospheric temperature, through to highly complex Earth Systems Models, which attempt to capture all the major 'spheres' that combine to influence the climate (atmosphere, hydrosphere, lithosphere, pedosphere(soil), cryosphere (ice)), and the cycles within them, as well as human influences (Table 2.2). Climate models can be used to test the reliability of palaeoclimate data in reconstructing past climates (von Storch *et al.* 2004, Moberg *et al.* 2005, Zorita *et al.* 2003) and, similarly, models can be tested using palaeoclimate data, allowing for the uncertainties inherent therein, by recreating known examples of past environmental conditions such as the last glacial maximum or the warm mid-Holocene (IPCC 2007). However, where climate models are most often used is in the projection of future climate change, attempting to understand the potential outcomes of changes to forcing factors in the present and near future. In doing this climate modellers face considerable uncertainty owing to the limitations of the climate models they use.

Confidence in climate models can be drawn from the aforementioned ability to reconstruct past climates, as well as the capacity to replicate currently observed conditions and instrumental records (Figure 2.4) and, perhaps most fundamentally, in the fact that climate models are based on well established physical laws such as the conservation of mass, energy and momentum (IPCC 2007). These well understood and explicitly resolved physical laws coexist, however, with physical processes that are necessarily parameterised and with theoretical and computational limitations (Vidale *et al.* 2003). Parameterisation is a means of constraining variation in physical forcing factors across temporal and spatial scales, particularly where these scales are less than the resolution provided by the model (McGuffie and Henderson-Sellers 2001, IPCC 2007). For example, in both terrestrial and marine ecology different processes dominate at different spatial scales making it necessary to parameterise the processes by either choosing the most dominant one or averaging the effect of all processes (McGuffie and Henderson-Sellers 2001). Some parameters that are difficult to accommodate in climate models may simply be acknowledged and left out of the final construct altogether (McGuffie and Henderson-Sellers 2001).

Table 2.2: Types of climate models and some factors they may include - sources: Claussen *et al.* (2002), Friedlingstein *et al.* (2006), Karl and Trenberth (2003), McGuffie and Henderson-Sellers (2001), Nordhaus (1993), Nordhaus and Yang (1996), North and Stevens (2006), Pittock (2009), Vidale *et al.* (2003), Webster *et al.* (2002), Zorita *et al.* (2003). NB: GHG, Greenhouse Gas; ENSO, El Nino Southern Oscillation; NAO, North Atlantic Oscillation.

Model Type	**Examples**	**Spatial resolution**	**Factors that may be included**	**Complexity**
Energy Balance Model	EBM	Global-latitudinal	Long wave radiation (LWR), shortwave radiation (SWR), sensitivity, albedo feedback, area, seasonal cycle	Lowest
Regional Climate Model	CHRM	Regional	EBM + temperature, precipitation, land surface (topography, soil processes), cloud cover	Low-High
Integrated Climate-Economy Model	DICE, RICE	Regional-Global	Optimal economic growth, GHG emissions, sensitivity, capital, labour, technology, GHG concentration, climate, cost	Low
Earth System Model of Intermediate Complexity	EMIC, IAP RAS, IMAGE 2	Global	EBM + moisture balance, biospheric carbon dynamics, inland ice, sea ice, atmosphere and ocean characteristics	Intermediate
General Circulation Model (A-atmosphere, O-ocean)	AGCM, OGCM	Regional-Global	AGCM – LWR, SWR, atmospheric structure (layers), evaporation, precipitation, aerosols, winds, greenhouse effect, cloud cover, albedo feedback, volcanic eruptions, 2D-ocean of given surface temp OGCM – ocean structure (layers), currents, salinity, fresh/saltwater flux	High
Coupled General Circulation Model	AOGCM, ECHO-G	Regional-Global	AGCM + OGCM + dynamic and interactive oceans, seasonal oscillations (e.g. ENSO, NAO), sea ice cover	Higher
Earth System Model	C^4MIP, IGSM	Global	AOGCM + Land model (realistic topography, reflectivity, land use, glaciers, ice sheets), biological components, human factors, carbon cycle	Highest

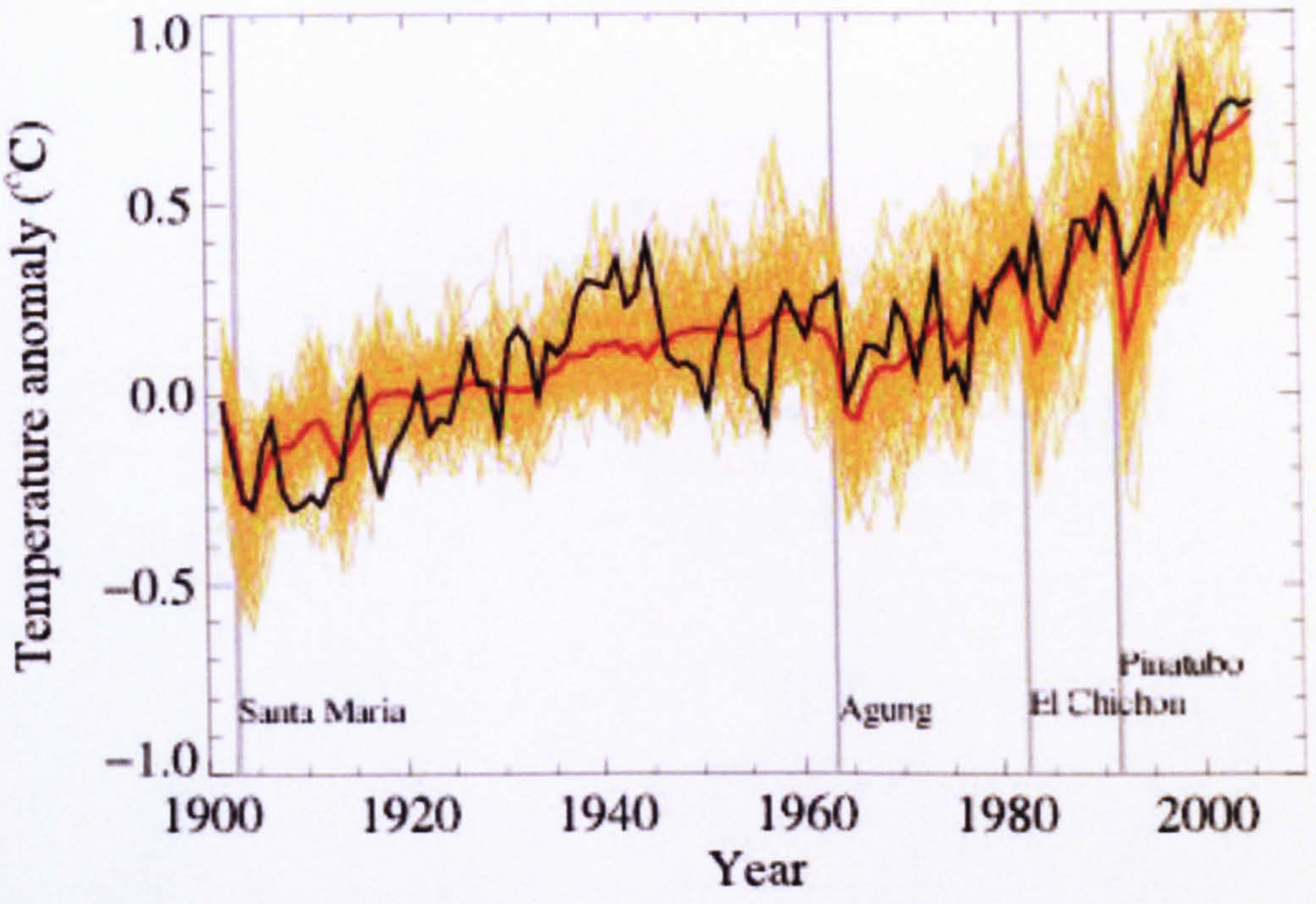


Figure 2.4: Global mean near-surface temperature in the 20th Century from observations (black) and as obtained from climate models (yellow, mean in red). The range of uncertainty generated by the models is evident but broad trends are clear. The vertical grey lines show incidences of major volcanic eruptions, also well represented by the models. From IPCC (2007)

Theoretical limitations affect the accuracy of climate models owing to the inherent difficulty in effectively modelling factors that are not well understood. This is particularly evident in the modelling of small-scale factors that have the potential to have large impacts on climate, such as the formation of clouds and the response of cloud formation to climate change (IPCC 2007). Owing to the lack of direct observations of the complex process of cloud formation, understanding of this process is not as comprehensive as that of some other factors included in climate models. Furthermore, cloud formation tends to be a relatively small-scale process, having a large effect on regional to local scales which are considerably harder to resolve in climate models (IPCC 2007). Processes such as these are, therefore, parameterised in terms of how they interact with larger scale processes leading to climate models presenting a large range of outcomes caused by varying interpretations of cloud physics and responses to other forcing factors such as increasing greenhouse gas emissions (IPCC 2007).

A further significant challenge that faces climate modellers is that of computational limitations, or the sheer impossibility of exactly replicating the complexity of the climate system using even the most advanced computers available (McGuffie and Henderson-Sellers 2001). As mentioned in the first sub-section on complexity, models are simplifications of reality designed to afford an insight into the workings of an almost limitlessly complex system, whilst they give valuable information it is not specific and is poorly resolved at smaller spatial scales. Complexity in this instance may refer to the detail of description and the number of processes included explicitly in the model (Claussen *et al.*. 2002) (see Table 2.2) or it may also refer to the representation of complex behaviour – chaos and the interaction of feedbacks within the system (McGuffie and Henderson-Sellers 2001). Ever-increasing computer power has led to the development of climate models that are capable of explicitly including a large number of factors that affect climate (Table 2.2); however, these models are limited principally by their inability to replicate fully the complex behaviour of the system and also by their resolution. Because a larger number of factors affect climate variability at smaller scales, that different processes dominate at different scales and that a far larger number of data points are required to construct the model, modelling at these resolutions is highly troublesome, though improving (Vidale *et al.* 2003, IPCC 2007). Regional climate models (Table 2.2) in particular face "uncertainty problems" owing to local topography for example, which can have a profound effect on climate over a relatively small geographical area (Schiermeier 2010, p. 285).

Complex behaviour may be captured in a model through running ensembles of models or 'coupling' distinct models with one another (McGuffie and Henderson-Sellers 2001). By running ensembles of climate models side by side several times a picture can be built up of the climate realisations that may result from changes in forcing factors and the estimated likelihood they have of occurring (Patt 2007). Furthermore, ensembles may be created where different forcing factors, such as greenhouse gas emissions, are added one by one to note the emergence of complex behaviour and allow the impact of the factors to be observed and understood (McGuffie and Henderson-Sellers 2001). The ensemble approach and the success it has in capturing likely outcomes and emergent behaviour has led to a recent shift away from striving for the development of evermore complex Earth System Models to the use of Earth System Models of Intermediate Complexity (EMICs), which have less detail of description than the more comprehensive models but a higher number of interacting components (Claussen *et al.* 2002). This integration allows for more effective simulation of feedbacks between components of the climate system (Claussen *et al.* 2002), the understanding of which is considered highly important in predicting the effects of future changes to forcing factors (McGuffie and Henderson-Sellers 2001, IPCC 2007).

Ultimately, the outcomes and usefulness of climate models are determined by the data that is input at the start (the initial conditions) and throughout the model run. Initial conditions are likely to be largely based on parameters and assumptions, either as a result of incomplete or inaccurate palaeoclimatic data or the inherent difficulty in capturing the true complex state of the climate at any one time (Vidale *et al.* 2003). Climate data is also subject to issues of quality, in that there may be errors present as a result of either technical or human failings or "noise" produced by biased or incomplete observations (Moss and Schneider 2000, Petersen 2000). Although these uncertainties can be accommodated to a degree through parameterisation similar to the other limitations described above, they are a fundamental and largely intractable source of uncertainty in climate modelling.

Scientific discourse – conflict and consensus

As well as the operational uncertainties contained in climate models (parameterisation, theoretical limitations, computational limitations, data issues – outlined above), uncertainty may also arise as a result of expert disagreement over the initial conditions applied to the model and the means of model evolution. This may be termed 'conflict-based' uncertainty and is largely overlooked by the IPCC and other assessment panels in favour of more quantifiable probability estimates (Patt 2007, Moss and Schneider 2000, Webster *et al.* 2002). Conflict-based uncertainty stems from experts, or groups of experts, reaching different conclusions as a result of earlier subjective judgements about the starting conditions and development of the system being modelled (Patt 2007). Although conflict-based uncertainty tends to be given less weight than model-based probabilities, Patt (2007) demonstrates that the two are logically equivalent in people's minds – indicating that conflict-based uncertainty may be just as important a consideration in decision-making.

This then raises the issue of how uncertainty in climate change science is communicated to the public or those who design policy related to human impacts on the climate. This has been a major consideration for scientists for some time and has been an explicit priority for the IPCC over the last decade (IPCC 2007, Moss and Schneider 2000). Previously, the reporting of uncertainty has been inconsistent and, as a result, steps have been taken to standardise how uncertainty is reported in climate change science (Moss and Schneider 2000). This has generated a range of terminology that seeks, to a degree, to quantify the qualitative and vice-versa through the expression of likelihood and confidence – this is shown in Table 2.3.

Table 2.3: Likelihood and confidence as characterised and quantified through expression of probabilistic percentages and odds. From Risbey and Kanlikar (2007).

Likelihood		**Confidence**	
Terminology	Likelihood of occurrence (%)	Terminology	'Odds' of being correct
Virtually certain	>99	Very high confidence	At least 9 in 10
Very likely	>90	High confidence	About 8 in 10
Likely	>66	Medium confidence	About 5 in 10
About as likely as not	33-66	Low confidence	About 2 in 10
Unlikely	<33	Very low confidence	Less than 1 in 10
Very unlikely	<10		
Exceptionally unlikely	<1		

However, even the standardised schemes shown in Table 2.3 may be insufficient to describe fully the complex uncertainties that exist in climate change science. As Risbey and Kanlikar (2007) note: "the combination of these two metrics to assess information may engender confusion when low confidence levels are matched with very high/low likelihoods that have implicit high confidence. Part of the difficulty is that the degree to which different quantities in the assessments are known varies tremendously" (p. 1). They propose adapting the scheme to focus on expressions of likelihood that include an acknowledgement of the level of understanding pertaining to the object in question and this has since been adopted by the IPCC (2007, Risbey and Kanlikar 2007). Probabilities, however, remain an important part of the scientific discourse of climate change, despite a greater emphasis on more qualitative reporting of uncertainty (Pittock *et al.* 2001). Methods of communicating uncertainties and the implications of uncertainty for decision-making will be discussed further in the section on uncertainty in decision-making.

It should also be noted that when phenomena related to such a complex and multifaceted area as climate change are studied an approach that integrates knowledge from a wide range of research disciplines is required (Moss and Schneider 2000). This requires scientists to integrate not only knowledge but also uncertainties from beyond their own immediate context, together with the different approaches and technical language that these entail. As Moss and Schneider (2000) note: "estimates and outcomes are therefore affected not only by uncertainties in their immediate substantive domain, but also by uncertainties in the scenarios or parameters generated in other areas of research" (p. 38). As mentioned, this is particularly prevalent in the development of scenarios for studying future climate change where scientific knowledge must be brought together with the work of the social and economic sciences and expert opinion to create plausible pictures of future worlds. This will be discussed further in the sub-section on emissions scenarios below.

A final consideration of scientific discourse within the subject area of climate change is that of consensus. There is clear and widespread consensus among scientists on the nature and causes of climate change – i.e. that observed warming since the end of the 19th century is likely to be attributable to increases in anthropogenic greenhouse gas concentrations (Oreskes 2004). This is despite all of the attendant uncertainties that have been outlined in the sections above. However, this consensus may in itself act to exacerbate uncertainties by discouraging their frank and open interrogation (Oppenheimer *et al.* 2007). The "drive for consensus" often results in the importance of key uncertainties being minimised, where processes and feedbacks are poorly understood or models share similar assumptions about certain factors (possibly in a bid to minimise conflict-based uncertainty) (Oppenheimer *et al.* 2007, p. 695). Furthermore, consensus may exclude or downplay the more extreme potential consequences of climate change, meaning that abrupt changes and 'surprises' may be overlooked (Schneider 2003, Oppenheimer *et al.* 2007). Chambers and Brain (2002) also identify a danger in consensus leading to the construction of a new 'paradigm' where scientists may be afraid to challenge the prevailing attitudes for fear of being branded 'sceptics'. However, they also note that paradigm shifts towards theories of anthropogenic global warming are based on long-established foundations of climate science and are, therefore, more likely a process of a natural evolution of scientific thought following Kuhn's model of "scientific revolutions" (Chambers and Brain 2002, Kuhn 1996).

The consensus view of climate science towards anthropogenic climate change came under intense scrutiny with the events of 'Climate-gate' in November 2009, during which correspondence between leading climate scientists at the University of East Anglia's Climatic Research Unit (CRU) was published in such a way as to apparently show that scientists had "fudged" data in order to overstate the effects of warming and used words such as "trick" and "hide" with reference to the presentation of data by climate modellers (Jasanoff 2010, p. 695). Furthermore, suggestions were made that scientists refused to make raw data available to known critics and that papers questioning the consensus view were suppressed and kept from being peer-reviewed (Jasanoff 2010). Although the scientists involved have since been fully exonerated of any scientific misconduct, recommendations have been made for closer statistical analysis (Science Assessment Panel Report 2010). The report points out that although climate scientists may be adept at using statistics pertinent to their own particular specialism within climate science, engagement with the wider statistics community will help ensure more rigorous treatment of data in the future (Science Assessment Panel Report 2010). Others have called for the events of climate-gate to act as a driver for the implementation of greater measures of accountability in climate science, with a particular emphasis on how science relates to the public (Jasanoff 2010).

Uncertainty in future projections of human behaviour

Given that much of the interest in future climatic directions is focussed on anthropogenic influences on climate, the human dimension of the climate system is of obvious importance for understanding potential outcomes and impacts (Figure 2.1). However, this is also an area of climate change research that faces considerable uncertainty. Human futures are uncertain both in terms of projections of anthropogenic influence (emissions scenarios) and also with respect to social, cultural and political responses to climate change that may mediate the eventual outcome (Rebich and Gautier 2005).

Emissions scenarios

Greenhouse gas emissions are a particularly troublesome commodity to factor in to future projections of climate as they are effectively a product of highly complex socio-economic and political drivers to human behaviour and development, such as population change, socio-economic development and technological change (Pittock 2009). Greenhouse gases are the product of human activities that are subject to a large number of internal and external factors that may act to increase or decrease them at some point in the future, identifying all of these factors and when they will act to influence human behaviour is virtually impossible. In order to estimate future emissions it is therefore necessary to develop scenarios; plausible pictures that give alternative views of what the future may look like, based on expert opinion, from a range of academic disciplines, in the present (Pittock 2009). The IPCC uses a range of scenarios developed from four 'storylines' of internally consistent development across a variety of driving forces and multiple modelling approaches (Pittock 2009). These storylines are as follows:

- "The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy [industry]. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).

- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.

- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels." (IPCC Special Report on Emissions Scenarios (SRES) 2000)

The above scenario storylines can be used to generate hypothetical data that can then be put into climate models to give likely outcomes of the fluctuations in emissions coupled to the predicted paths of human development. The models can then generate potential values of factors such as temperature and sea level that may be affected by the changing emissions; these are likely to be expressed as a best estimate and likely ranges as shown in Table 2.4.

Table 2.4: Projected global average surface warming and sea level rise at the end of the 21st century based on SRES scenarios (IPCC 2007).

Case	Temperature change (°C by 2090-2099 relative to 1980-1999)		Sea level rise (metres)
	Best estimate	Likely range	Model-based range
Constant year 2000 concentrations	0.6	0.3 – 0.9	Not available
B1 scenario	1.8	1.1 – 2.9	0.18 – 0.38
A1T scenario	2.4	1.4 – 3.8	0.20 – 0.45
B2 scenario	2.4	1.4 – 3.8	0.20 – 0.43
A1B scenario	2.8	1.7 – 4.4	0.21 – 0.48
A2 scenario	3.4	2.0 – 5.4	0.23 – 0.51
A1FI scenario	4.0	2.4 – 6.4	0.26 – 0.59

The projected effects of future emissions scenarios are uncertain in themselves, expressed as both a range of potential outcomes and in terms of likelihood (corresponding to the values in Table 2.3). However, this uncertainty is compounded by the fact that, ultimately, these scenarios may bear little or no relation to the eventual future that is realised (Pittock 2009). This uncertainty is insurmountable but this does not invalidate the use of emissions scenarios and projections of future human development. Testing of emissions scenarios and uncertainty analysis may be carried out to determine the usefulness of these tools and generate other useful scenarios that may be used in climate models. For example, Webster *et al.* (2002) test the IPCC SRES scenarios using the MIT Integrated Global System Model (IGSM) and found a range of temperatures similar to that of the IPCC (0.9 – 4.0 °C by 2100 compared to 1.3 – 3.6 °C) but also that the IPCC projections seemed slightly biased in favour of higher global mean temperature change as a result of "strongly optimistic assumptions about reductions in sulphur emissions" (Webster *et al.*. 2002, p. 3669). Some economists have also queried the technical aspects of the IPCC SRES scenarios, indicating that, as a result, the scenarios may be "wrong or at least highly unlikely" (Pittock 2009, p. 242). Again, there is a feeling that the higher range of estimated global temperatures at 2100 produced by the IPCC is too high (Pittock 2009).

The large range of uncertainties associated with projections of future human behaviour are clear, though they tend to be well accommodated in assessments of future climate change (IPCC 2007). Probabilistic assessment of these uncertainties is more difficult, however, as assigning likelihood to the future worlds detailed in the emissions scenarios is extremely difficult (Mastrandrea and Schneider 2004). This is down to the subjectivity of the expert opinion on which the scenarios are based which, as Nakicenovic and Grubler (2001, p. 15) note, may be dismissed as "spurious". Attempts may be made to model potential social and economic futures (Nordhaus 1993, Nordhaus and Yang 1996 – see Table 2.2) and thereby assign some numerical probability to the potential outcomes of human development. However, these models tend to be relatively simplistic with significant limitations (Mastrandrea and Schneider 2004).

<u>Human responses and mitigation</u>

Human responses to future climate change are factored in to scenarios such as the IPCC SRES scenarios outlined above, mainly in terms of social attitudes such as the degree of regional or international collaboration in adapting to or mitigating against a changing climate (IPCC 2000). However, these responses and their potential effect can never be known specifically, adding to the speculative nature of the scenarios and their inherent uncertainty. Technological change is one of the hardest factors to predict but may potentially have the biggest impact on emissions, as in the A1 scenario 'family' outlined above (IPCC 2000).

Similarly, technology may be employed in direct action to mitigate climate change by actively lowering the Earth-surface temperature through geo-engineering proposals that "aim to intervene in the climate system by deliberately modifying the Earth's energy balance to reduce increases of temperature and eventually stabilise temperature at a lower level than would otherwise be attained" (Royal Society 2009, p. 1). This would seem like a reasonable solution to the potentially problematic consequences of a changing climate, allowing the natural evolution of technology to intervene to mitigate the warming climate and make it more suitable for humans. However, as with all aspects of future human behaviour, geo-engineering possibilities are again beset with numerous uncertainties. Principally, there is the uncertainty that stems from theoretical limitations in understanding the workings of elements of the climate system. For example, if the earlier example of theoretical limitations in cloud physics and formation are taken, these same uncertainties impact on any geo-engineering practices that seek to harness the ability of clouds to affect climate (Royal Society 2009).

Further uncertainties arise because geo-engineering practices are not widely used at present and are largely a speculative measure. This means that although potential risks and problems may be identified initially, any that arise as a technology evolves may lead to undesirable effects that cannot be easily contained. These may include irreversible changes to the environment caused by geo-engineering technologies that are not anticipated but emerge due to the complex interactions between the technology and the Earth system (Royal Society 2009). Large-scale projects will also be subject to the vagaries of public opinion and political pressure, which tend to operate over relatively short timescales (Royal Society 2009). This has profound implications for any strategy for the mitigation of climate change and must be considered a source of considerable uncertainty. For example, a typical 'western' democratic system based on a four-or-five year tenure for the ruling political party makes long-term planning for climate change impacts difficult as agendas are subject to frequent change (Pittock 2009).

Uncertainty in decision-making

As has been alluded to several times in this chapter, the many uncertainties that have been outlined above remain largely academic until decisions on policy are required to be made. At this point the application of uncertain knowledge and the inherent inability to know precisely what the future holds may cause significant difficulties. This in turn has implications for how uncertainties are presented for best quality decision-making and also whether established means for making decisions and designing policy remain the best course of action.

Characterising uncertainties for decision-makers

How experts engage with policy makers in presenting scientific and socio-economic uncertainties in climate change has become a key area of debate within the IPCC (Lempert *et al.* 2004). Several different approaches to this are advocated for a number of different reasons; however, it is clear that uncertainties are compounded by the further uncertainties associated with how best to engage with decision makers in characterising and communicating uncertainty. Since the preparation of the IPCC's Third Assessment Report (TAR) (2001), the organisation has sought to unify how authors and contributors describe the level of certainty attached to their particular area of expertise within climate change, which, as mentioned earlier, had previously been widely varied according to the particular traditions of the disciplines involved or individual preference on the part of the contributor (Moss and Schneider 2000). This process has led to the production of a series of guidelines for assessing and presenting uncertainty that includes recommendations on how best to represent the 'state of knowledge', how to determine the appropriate level of precision and how to characterise the distribution of values that a parameter, variable or outcome may take (Moss and Schneider 2000).

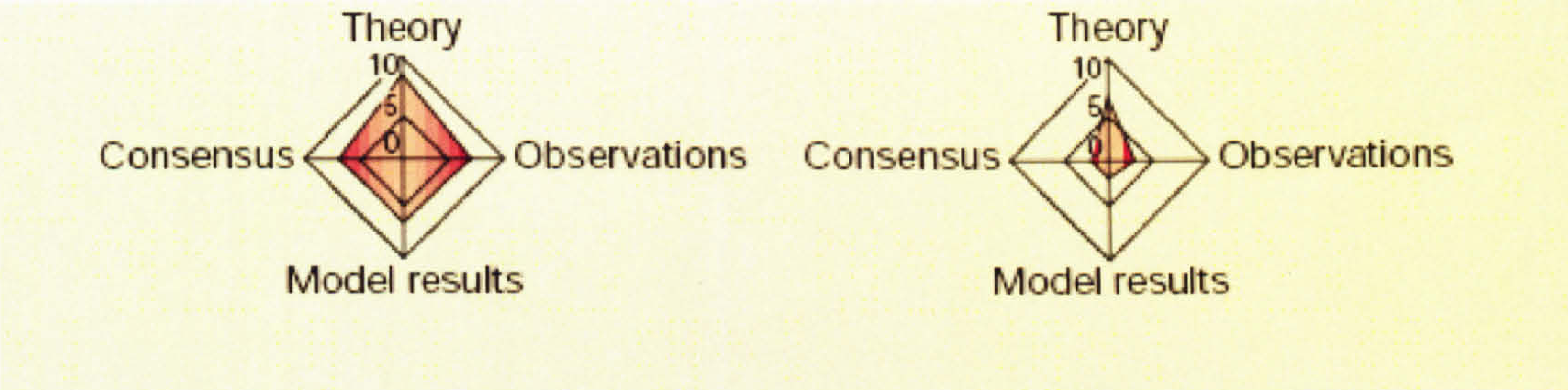


Figure 2.5: Graphical representation of confidence in probabilistic assessments of future temperature change (left) and flooding risk (right) due to climate change. The axes represent the degree of confidence in the theory, the observations, the models and the consensus within the field – the values on each axis are joined to create a shape, the area of which represents the overall degree of confidence in the result and where this confidence arises (from Giles 2002).

Ultimately, this process has led to an emphasis on probabilistic statements for the likelihood of future climate outcomes, as shown in Table 2.3, and graphical representations as shown in Figure 2.5. Probabilistic assessment of climate change is seen as essential by advocates of the approach as it encourages decision makers to evaluate potential outcomes more objectively. The inference is that "without explicit efforts to quantify the likelihood of future events, users of scientific results (including policy-makers) will undoubtedly make their own assumptions about the probability of different outcomes, possibly in ways that the original authors did not intend" (Mastrandrea and Schneider 2004, p. 571). The recommendations for probabilistic assessments of future events have also been extended beyond science, to encompass all spheres of knowledge that feed into the planning for future climate change, including the socio economic sciences. Pittock *et al.* (2001, p. 249) state that probability estimates are essential as without them "engineers and planners will be left needing to foster resilience and adaptive capacity, hedge their bets, delay their decisions, or else gamble on whether humanity will go down high or low emissions development pathways as they adapt design standards and zoning to climate change. It is far more sensible to establish cumulative probability distributions to allow optimal, focused adaptation plans".

Some of the limitations of this overtly quantitative approach have been pointed out as in the reference to Risbey and Kanlikar (2007) above. However, these can be addressed to a degree through the employment of methods such as that depicted in Figure 2.5, which shows how confidence is derived in probabilistic assessment and indicates the level of understanding that may be attached to a given outcome. A further limitation has been identified, however, in that the characterisation of uncertainties with probability distributions leads to a 'predict-then-act' approach which does not necessarily befit the complex decision-making frameworks necessary for climate change (Lempert *et al.* 2004). This is due to two main reasons: firstly that the policy problems relating to climate change are many and radically diverse in their contexts and, secondly, the uncertainties associated with the decision-making process are too deep (Lempert *et al.* 2004). Probabilities may, therefore, offer poor descriptions of the real world, meaning that decisions made on their basis may misallocate resources. It is also more likely that decision makers will find most credible those probability distributions that most closely align with their own beliefs or political motivations, thus rendering their apparent objectivity redundant (Lempert *et al.*. 2004). The emphasis on providing probability distributions may detract from research that could more usefully be employed in providing information for decision makers under the uncertain conditions that pervade climate change policy making. Uncertainties over how best to characterise uncertainties also, therefore, impacts the selection of the most effective frameworks for decision-making under these conditions.

Post-normal science

Post-normal science is a framework for decision-making that relates to the highly complex policy problems that exist in the modern world. The term 'post-normal' is used so as to distinguish the type of scientific enquiry required for solving these types of problems from the 'normal science' described by Thomas Kuhn in his work '*The Structure of Scientific Revolutions*' (1996). Normal science is chiefly concerned with three classes of problems. According to Kuhn (1996, p. 34) these are "determination of significant fact, matching of facts with theory and articulation of theory". Normal science represents a transition from "preparadigmatic" science, where a number of hypotheses compete and none is deemed more valid than any other, to a state in which one prevailing hypothesis or theory dictates the epistemic regime of the scientific discipline (Bray and von

Storch 1999, p. 440). Problems are conceptualised and approached using standardised methods defined by the prevailing paradigm and which may come to define the paradigm itself.

Post-normal science on the other hand is concerned with informing decision-making where systems uncertainties are high, decisions are required to be made urgently, high stakes are involved and a significant scientific component may be included (Funtowicz and Ravetz 1994, 2003) – see Figure 2.6. Where systems uncertainties and so-called 'decision stakes' are low normal or applied science is sufficient to provide consensus. When these two variables reach a medium level (see Figure 2.6) unresolved methodological debates come to the fore and solutions require new actors and skills to be brought to bear (Jasanoff and Wynne 1998). This medium level is characterised as being 'client-led', as in professional consultancy, and consensus is based on subjective expert judgement (Funtowicz and Ravetz 1994); this relates to the probabilistic assessment frameworks described in the section above. Post-normal science is an alternative strategy for issues where systems uncertainties and decision stakes are both high and although applied science and professional consultancy may be part of the overall activity they do not dominate the decision-making process (Funtowicz and Ravetz 1994). In post-normal issues it is the uncertainties, both epistemological and ethical, that dominate, necessitating new approaches that are not bound by the same structures and rules of the aforementioned strategies. Epistemological uncertainties may encompass insoluble questions of how models relate to the real world (owing to limitations of the kind discussed earlier), in a manner that may even be described as outright ignorance (Petersen 2000, Funtowicz and Ravetz 1994). Indeed, there may be a deeper epistemological uncertainty that constitutes "ignorance of ignorance" (Funtowicz and Ravetz 1994, p. 1884). These epistemological uncertainties will also extend to the epistemic regime normally dictated by the prevailing paradigm of normal science, as in the case of modellers calling into question the abilities and limitations of their tools. Where in applied science the approach to the problem is set according to the conventions of a paradigm, in post-normal science frameworks are beset with uncertainties that prevent these frameworks from operating, thus creating the need for new approaches.

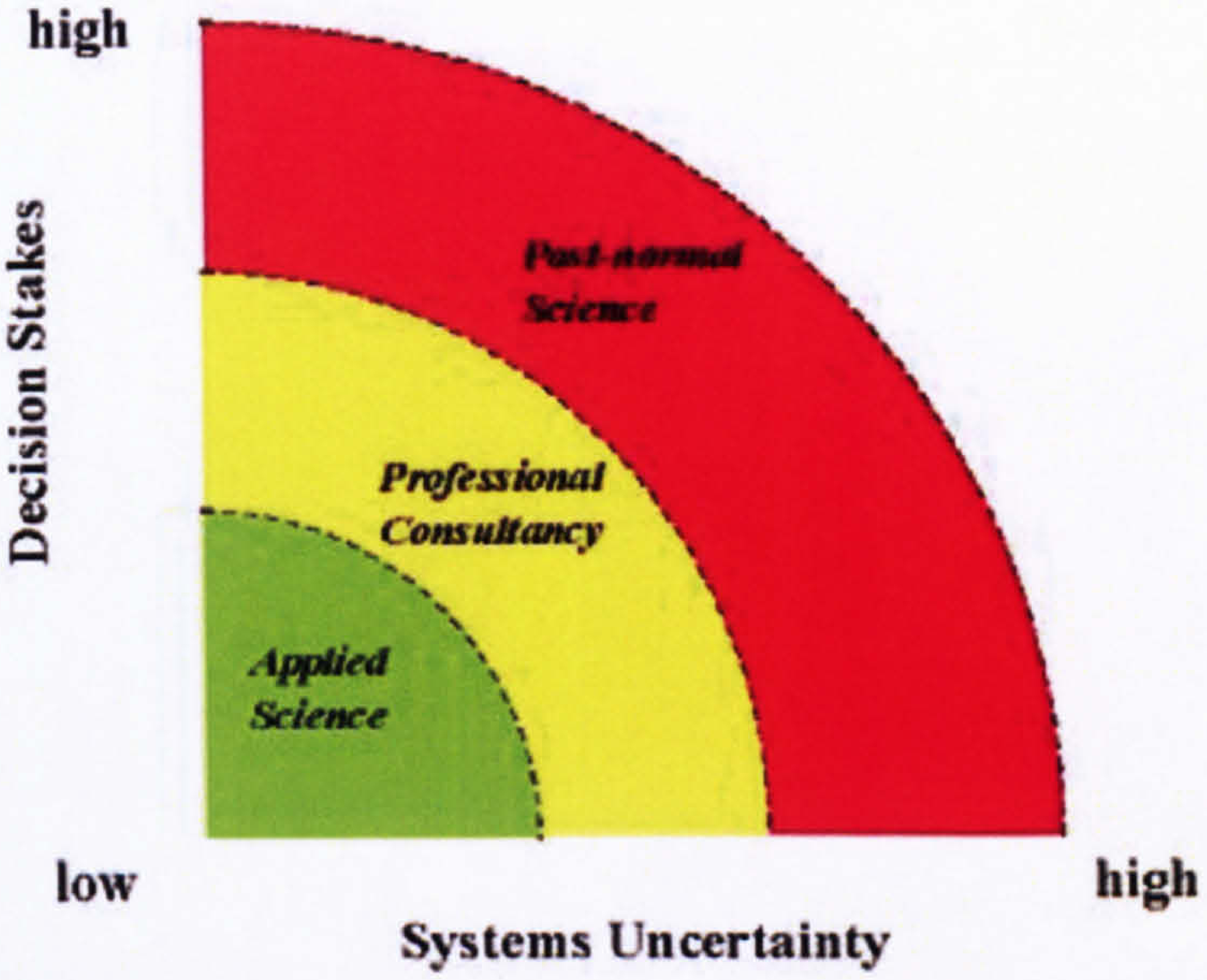


Figure 2.6: Three types of problem-solving strategy. From Funtowicz and Ravetz (1993).

Epistemological uncertainties of the magnitude described above lead to an inversion of the classic distinction between "hard facts" and "soft" value judgments (Funtowicz and Ravetz 2003, p. 2). Where applied science for problem-solving relies on objective and testable 'truth', post-normal issues frequently require more subjective value-based decisions as hard facts are simply unavailable and decisions must be made before any degree of certainty has been established, if it will ever be established at all. In this sense the uncertainties involved go beyond systems-based epistemology to encompass ethical uncertainties over the welfare of stakeholders and concepts of equity (Funtowicz and Ravetz 1994). Values in this sense are frequently disputed, as in the case of biodiversity loss as a result of human development where it is impossible to rationalise the rights of humans with the harm that may be inflicted upon the environment (Funtowicz and Ravetz 1994). Value conflicts and severe uncertainties in complex modern problems lead proponents of the post-normal science approach to call for a greater emphasis on quality in scientific enquiry and more open discourse between scientists and 'extended peer communities' of stakeholders and decision makers (Funtowicz and Ravetz 1994; 2003). In this framework issues are resolved through the inclusion of legitimate participants in the selection and establishment of credibility of experts and other aspects of quality assurance, all through open dialogue (Funtowicz and Ravetz 1994). This may even lead to direct solutions for problems being devised by stakeholders affected by the outcomes of the issue in question that would otherwise have evaded accredited experts (Funtowicz and Ravetz 2003).

It should be stated, however, that post-normal science in no way invalidates the work of Kuhn, who himself believed in the existence of "extraordinary problems" beyond the reach of normal science (1996, p. 34). As mentioned earlier, the solutions to post-normal issues will likely involve practices of applied science and professional consultancy as not all aspects of the problem will be subject to high stakes and severe uncertainties. Figure 2.6, therefore, represents not a static hierarchy but a dynamic approach to problem-solving where different aspects of the problem relate to different activities and this interaction leads to the issue evolving towards a solution (Funtowicz and Ravetz 1994). This is a complex approach that reflects the complexity of post-normal issues. Parallels may also be drawn between post-normal science and the "wicked problems" identified by Rittel and Webber (1973). This term is attributed more widely to problems of social policy (wicked) as opposed to typically scientific problems, which are described as "tame" (1973, p. 155). Part of what makes these problems "wicked" is the inability to define social equity objectively meaning that there can be no 'correct' answer to a given problem and any optimal solutions must be heavily qualified (Rittel and Webber 1973). Post-normal science attempts to reconcile value disputes such as these through engagement with the extended peer community, where open debate leads to solutions that stakeholders have had a part in designing, as opposed to having them imposed by experts.

Climate change as post-normal science

Funtowicz and Ravetz (1994; 2003) and Funtowicz *et al.* (1998) link much of their work on post-normal science to global environmental issues and 'science for sustainable development', which possess many of the epistemological and ethical uncertainties identified in the description of the framework. Here, the difficulties in mitigating against poorly understood and complex interactions of the Earth system and putting these difficulties into a social context is seen as exemplary of problems requiring the post-normal science approach. Climate change would certainly appear to fit these criteria, given the uncertainties that have been identified previously in both scientific and social contexts and the complexities of human behaviour and responses to the problem.

Climate change is considered problematic chiefly through the expression of the dangers and risks that may emerge as a result of anthropogenic forcing of the climate system. Indeed, much of the work of groups such as the IPCC and individual authors (e.g. Schneider 2003, Mastrandrea and Schneider 2004) is concerned with identifying the parameters that may represent a risk principally to humans but also to other species through changes in conditions. Dangerous climate change is defined mainly externally through risk analysis of system characteristics and vulnerability is generally expressed as thresholds in either physical or social terms, but also internally by those who experience said danger (Dessai *et al.* 2003). Physical vulnerability may be represented by a threshold such as the modification of the Thermohaline Circulation in the north Atlantic mentioned previously, whereas social vulnerability may be expressed in terms of the destabilisation of international order as a result of environmental refugees leading to conflict (Dessai *et al.* 2003). 'Surprises' such as these represent epistemological uncertainties owing to the extreme difficulties inherent in quantifying their likelihood or identifying where tipping points may exist (Schneider 2003, Saloranta 2001). The definition of these dangers is also likely to be subject to value conflicts as they will not be consistently dangerous for all people and the definition of danger itself is subjective (Saloranta 2001). One nation's danger may in fact represent an opportunity for others; for example, climate change may result in huge pressures on island based peoples in lower latitudes due to rising sea levels but may also represent an increase in viable agricultural land for more northerly nations.

It is also viable to identify the existence of the aforementioned "ignorance of ignorance" within climate change or, in other words, that we do not always "know what we don't know" (Petersen 2000, p. 269). Funtowicz and Ravetz (1994) assert that this is "a dangerous state for mankind" (p. 1884), a statement borne out by Sir Crispin Tickell who opines that "we are dangerously ignorant of our own ignorance" (p. xvi, in Lovelock 2007) with respect to global environmental issues such as climate change. This clearly pertains to deep epistemological uncertainty but also potentially raises ethical uncertainties about whether enough is known to countenance any mitigating action. The existence of profound epistemological and ethical uncertainties relating to climate change is clear. The apparent risks of climate change also indicate that any related decision-making is likely to be urgent and require engagement internally with those likely to experience the negative effects.

Climate change would, therefore, appear to be an excellent example of a post-normal issue and this is indeed the case. Saloranta (2001) identifies climate change as an example of post-normal science and points to the very existence of the IPCC as evidence. The IPCC process involves not only the contribution of lead authors but also formal review and revision by governments, non-governmental organisations and individual experts (Saloranta 2001). As Saloranta (2001, p. 400) notes: "In this description, one can easily recognize the essence of the 'Post-Normal' Extended Peer Community, where, under coordination of the [Working Group], diversing (*sic*) and different perspectives are welcomed into the dialogue and, at least seemingly, synthesized into a more or less balanced and quality assessed outcome, the [Second Assessment Report]. The extraordinary broadness and size of this Extended Peer Community arises evidently from the all-involving nature of the issue". Bray and von Storch (1999) also identify climate change as an example of post-normal science, describing it as an 'empirical example' following a questionnaire survey of 1000 scientists in Germany, the United States and Canada and a series of in-depth interviews. The conclusions reached from the data suggest that there was a degree of variation in the subjective assessment of urgency for action but that the status of knowledge was sufficient to justify abatement measures being initiated (Bray and von Storch 1999). Consensus extended to recognising the inability to specify explicitly the potentially harmful effects of climate change, leading the authors to suggest that climate change represents an area where advice is a product of both scientific knowledge and normative judgement and therefore requires a post-normal science approach (Bray and von Storch 1999). Climate change does not fit with the traditional scientific research questions of 'what?' and 'how?', which aim to limit uncertainty, but rather requires the asking of the 'what if?' questions related to potential risks where the full complexity of the issue is acknowledged and we are "expecting the unexpected" (Ravetz 1997, p. 537).

Real experimentation in the conventional sense is impossible where climate change is concerned as there is only "one Earth with one history", which precludes the conventions of reproducibility and control that constrain the methods of normal science (Petersen 2000, p. 265). Climate change is also not an "esoteric problem" in the Kuhnian sense (1996, p. 24), as Hulme and Turnpenny (2004) note: "understanding and responding to climate change covers issues of great complexity, involving many different organizations, many different spatial and time scales, and many different academic disciplines. It cannot be addressed by any one discipline" (p. 111-112).

Climate change and the precautionary principle

The precautionary principle is a guideline for environmental decision-making and may be characterised thus: "when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically" (Raffensperger and Tickner 1998, p. 1). Within this there are four key guiding principles, namely: "taking preventive action in the face of uncertainty; shifting the burden of proof to the proponents of an activity; exploring a wide range of alternatives to possibly harmful actions; and increasing public participation in decision-making" (Kriebel *et al.* 2001, p. 871). This clearly has strong resonance with post-normal science, and may be seen as effectively a statement that captures its key principles.

Kriebel *et al.* (2001) see the precautionary principle as a means of counteracting the limitations of conventional scientific enquiry, which tends to define uncertainty narrowly and is subject to distinct disciplinary divisions which limit enquiry into complex problems. This then creates a need for new scientific methods that support precautionary enquiry. This is echoed by Ravetz (1997), who views the style of 'what if?' post-normal science questions as an extension of the precautionary principle, in that they "protect scientists against a premature choice of research problems to be investigated, and a hasty closing down of exploration" (p. 537). Ravetz (2004) sees the 'mainstream' of normal scientific enquiry increasingly linked to industry, where the emphasis is placed on something being "safe until proven dangerous" (p. 348). The precautionary principle not only turns this around but also calls into question the motivations for inquiry through shifting the burden of proof to proponents of an activity, thus allowing for more open interrogation by an extended peer community and a more complex appraisal of uncertainty. The precautionary principle and post-normal science are intrinsically linked and both generate similar recommendations and implications. These are new forms of knowledge production that question whether the methods and tools, such as models, employed to address complex problems like climate change, require to be comprehensively questioned and reviewed in terms of their suitability for decision-making (Haag and Kaupenjohann 2001).

Conclusion

The uncertainties associated with climate change reflect the issue itself in that they are extremely complex, multifaceted and all-involving. Uncertainty in climate change extends from a lack of absolute sureness through such vagueness as to necessitate reliance on informed guesses and speculation and on to outright ignorance or 'ignorance of ignorance' (Moss and Schneider 2000). Ultimately, there is little or no certainty when dealing with future climate change as "there will be only one outcome, which cannot be measured now" (Pittock *et al.* 2001, p. 249). However, despite the high level of uncertainty, and its ubiquity, the knowledge and tools relating to understanding climate change remain useful. Overall, the academic community involved in assessing climate change appear to be well aware of the uncertainties that exist and the implications they have for understanding and decision making. Examples such as climate modelling or the development of emissions scenarios can be seen as to demonstrate this, where uncertainty is an inevitable component in their design and is acknowledged by designers and users alike.

This chapter has described many of the fundamental uncertainties associated with climate change and the implications that they may have, although it is not exhaustive. A summary of the sources of uncertainty identified in this chapter, with examples and key references from the literature is given in Table 2.5. This demonstrates the range of contexts in which uncertainty is encountered in the climate change subject area and provides a picture of the epistemology of uncertainty relating to climate change. This chapter has also demonstrated that uncertainty is a key concept within the subject area. This will carry forward into the next chapter which deals explicitly with teaching uncertainty and some frameworks that may be employed to aid in its characterisation.

Table 2.5: A summary of the sources of uncertainty identified in this chapter together with examples and key references from the literature

	Source of Uncertainty	**Example**	**Key references**
Climate Change Science	Climate System	Complexity, Chaos, Surprises	Rind (1999), Schneider (2003)
	Climate Reconstruction and Proxies	Multiproxy reconstructions, Dating (e.g. C^{14}), Leads and Lags	Bradley (1999), Frank et al. (2010)
	Climate Modelling	Parameterisation, Model Resolution & Complexity, Data Quality	Vidale et al. (2003), McGuffie and Henderson-Sellers (2001)
	Scientific Discourse	Conflict & Consensus, (e.g. 'Climategate')	Patt (2007), Oreskes (2004), Jasanoff (2010)
Human Behaviour	Emissions Scenarios	IPCC SRES 'Storylines'	Webster et al. (2002)
	Adaptation & Mitigation	Geo-engineering	Royal Society (2009)
Decision-Making	Characterising Uncertainties	Probabilistic vs. Qualitative descriptions	Moss and Schneider (2000)
	Decision-Making Frameworks	Post-normal Science, Precautionary Principle	Funtowicz and Ravetz (1993; 1994; 2003), Saloranta (2001), Bray and von Storch (1999), Ravetz (2004), Kriebel at al. (2001)

Chapter Three

Theoretical Frameworks: Troublesome Knowledge and Threshold Concepts

The main aim of this chapter is to introduce and describe the theoretical frameworks that have been used in this study, the reasons for their selection and their applicability in this case. The first section deals with a more general overview of the role of uncertainty in teaching at higher education level, before going on to discuss the specific pedagogic frameworks used in this study. The frameworks of troublesome knowledge (Perkins 1999, Meyer and Land 2003) and threshold concepts (Meyer and Land 2003; 2005) are employed to assist with the characterisation of uncertainty as a concept in the context of higher education and the potential implications for teaching uncertainty. These frameworks have also informed research design and themes for data analysis. This chapter will first describe the frameworks before going on to highlight why they have been chosen, how they have informed the research and how they may relate to the uncertainty in the context of climate change.

The pedagogy of uncertainty

Uncertainty appears to play many roles in teaching, indeed it is seen as an evident and inevitable aspect of teaching practice (Floden and Clark 1988). It may be characterised as troublesome or productive, depending on the nature of the uncertainty and the context in which it arises. This section details some of the literature surrounding the pedagogy of uncertainty and how it is viewed in the context of education. Lustick (2002, p. 13) describes it in terms of 'uncertainty of outcome' where teachers are unsure about "what, if any, learning will occur in response to specific actions, decisions or comments", how a teacher deals with this uncertainty is seen as a measure of how accomplished they are. The expectation is that accomplished teachers will see unexpected outcomes or unforeseen questions as opportunities for enriching teaching and learning rather than an obstacle to it (Lustick 2002). Indeed, a degree of uncertainty of outcome in the classroom is seen by many as a necessity rather than a threat to a teacher's authority or control over students (Lustick 2002). There is, however, an acknowledgement that uncertainty may make teaching an inherently stressful practice and that subjective choices and assumptions made in the face of uncertainty may escalate this stress (Clifton and Roberts 1993).

Campbell (2007, p. 1) makes a distinction between what may be perceived as the "certainties of teaching (the technical strategies and practical skills) and the uncertainties of teaching (the theoretical, ideological, philosophical, social and cultural foundations and enduring tensions)". These uncertainties are related to questions relating to how best to prepare student teachers for life in schools and classrooms, although they may be seen as a constant in teaching practice. Floden and Clark (1988) identify enduring sources of uncertainty that teachers are likely to encounter constantly throughout their career. For example, uncertainty may arise from questions of 'what is true?' from students, which may in turn lead to uncertainty on the part of the teacher in terms of how to respond. Uncertainty may also stem from a teacher's own lack of knowledge or skills, although this may be reduced through further training and gaining more experience of teaching (Floden and Clark 1988). "Imperfect subject-matter understandings", although understandable, may lead to teachers feeling uncertain about what concepts to cover in their teaching (Floden and Buchmann 1993, p. 375). Whilst teachers understanding may fall short of the best scholarship (owing to issues related to the range of content they must cover and the comparative brevity of teachers' content studies in some instances), the uncertainty that they feel is unlikely to be dissipated by further study – "in a sense, the better one's education the greater and more varied are one's uncertainties" (Floden and Buchmann, p. 376). Uncertainty would, therefore, appear to be a feeling that teachers should get used to or even embrace as an inherent part of their profession. Helsing (2007) describes case studies of two teachers with alternate views of uncertainty in teaching, one who is "oriented towards" and the other "away" from uncertainty. The teacher oriented towards uncertainty describes herself as being "addicted to feeling panicked and out of my element and uncertain", seemingly enjoying uncertainty of outcome and uncertainty over content knowledge as opportunities for creativity in designing approaches and openings for student-led enquiry (Helsing 2007, p. 47). The 'promise of uncertainty' may also be seen to operate at higher levels in education, for example, Atkinson (2000) sees uncertainty over conceptions of 'best practice' in teaching as an opportunity to challenge educational policy from a postmodernist position, challenging settled assumptions of knowledge and truth and the authority of educational models, language and identity.

The inherent uncertainty of the 'real world' is a theme in what Shulman (2005a) describes as "Pedagogies of Uncertainty". These are closely related to Shulman's conceptions of 'signature pedagogies': "the forms of instruction that leap to mind when we think about the preparation of members of particular professions" (2005b, p. 52). These pedagogies arise in disciplines such as law, medicine, and the like and obviously have a strong vocational dimension where Shulman notes, "it is insufficient to claim that the combination of theory, practice and ethics defines a professional's work; it is also characterised by conditions of inherent and unavoidable uncertainty" (2005a, p. 18). This is familiar in terms of Floden and Clark's (1988) assertions about teaching practice, as a profession it too is fraught with inherent uncertainty. In these instances of uncertainty in professional practice and education considerable learning through experience may be achieved in the face of uncertainty (Shulman 2005a). This is characterised by real world learning experiences, such as junior doctors doing 'rounds', where there is a very real element of anxiety and risk as a result of uncertainty, but where learning is maximised through the encounter with this uncertainty.

As Shulman alludes to above, the world is an inherently uncertain place and careful consideration should be made of how best to prepare students for this. Barnett (2000; 2009) notes that the modern world now exists in a state of "supercomplexity", a world where nothing may be taken for granted and everything (even the frameworks by which we orient ourselves to the world) is contested. This may also be characterised in terms of an 'Age of Uncertainty' (Baumann 2007, Barnett 2007). Preparing students for the supercomplex world has implications for the mode of education, where new emphasis may need to be placed on the assimilation of information and adaptability over traditional approaches to teaching and learning. Key to this is the concept of uncertainty, which Barnett (2009, p. 439) links to "problems of being", where realisations of an epistemological nature have a profound ontological effect upon a learner.

The examples above are some of the ways in which uncertainty may be considered to have an impact on teaching. However, many of them appear to be more concerned with ontological uncertainty (uncertainty about one's state of being) rather than epistemological uncertainty (uncertainty about the state of knowledge). Even where epistemological uncertainties do appear the concern is more to do with how it makes a person (teacher or student) *feel,* in other words returning to ontological uncertainty. This thesis is concerned principally with uncertainty as an epistemological concept, where uncertainty is *the object of teaching and learning itself* as opposed to *a condition under which teaching and learning occurs* or an ontological outcome of teaching and learning processes (although uncertainty as a concept may well manifest this). Particular theoretical approaches are therefore required to be able to conceptualise uncertainty in this way (i.e. as an epistemological concept with an ontological dimension) and appreciate the implications for teaching it.

Troublesome Knowledge

The term 'troublesome knowledge' refers to several distinct types of knowledge initially identified by Perkins (1999) and expanded upon by Meyer and Land (2003), that may be potentially troublesome in some way for a learner. These types of knowledge are associated with constructivist approaches to teaching, where teachers are encouraged to design particular approaches that respond to learner's difficulties (Perkins 1999). In other words, the types of troublesome knowledge that have been identified all have a distinctive character that has a bearing on the implications of these types of knowledge for teaching. The forms of troublesome knowledge identified by Perkins and Meyer and Land are detailed below:

<u>Ritual Knowledge</u>

This is knowledge that has a "routine and rather meaningless character" (Perkins 1999, p. 8). Ritual knowledge is that knowledge that is routinely called upon when asked a certain question or when seeking a particular result. Names and dates may be considered to be of this nature, so too may basic arithmetic.

Concepts that become 'ritualised' in this way may be troublesome as they lose relevance, context or meaning. Students may fail to make connections between related ideas as a result.

Inert Knowledge

This is knowledge that "sits in the minds attic, unpacked only when specifically called for by a quiz or a direct prompt" (Perkins 1999, p. 8). Simply put, inert knowledge is that which is learned but not used actively. Knowledge becomes inert in this way through students failing to make links between what they are learning in the classroom and their experiences of the real world. For example, students may learn scientific concepts in a fairly abstract or detached way without making connections to their experiences of the real world and thus gaining a deeper understanding of the concepts themselves. When knowledge becomes inert it becomes more difficult for students to access and apply, hence why it may be considered troublesome.

Conceptually Difficult Knowledge

This is knowledge that students find difficult to grasp and may arise as a result of a combination of factors such as misimpressions gained from everyday experiences, pre-existing misconceptions or expectations and the complexity of the concepts themselves. In other words, conceptually difficult knowledge is knowledge that is troublesome in the conventional sense of being 'hard' for students to understand. Often, the response to conceptually difficult knowledge is a form of mimicry using ritual knowledge where students learn responses to definitional questions but their intuitive beliefs remain unchanged, thus making it difficult to apply these concepts in the real world (Perkins 1999). Students, therefore, may be comfortable responding to quantitative problems, where ritual responses may be employed, but find that their intuitive beliefs and interpretations resurface when faced with more qualitative problems (Perkins 1999). This may be down to the fact that qualitative questions tend to be more contextualised and, therefore, more complex and conceptually difficult –

especially pertinent when knowledge is applied outside the classroom in real-world settings.

Foreign or Alien Knowledge

This is knowledge that "comes from a perspective that conflicts with our own" (Perkins 1999, p. 10). Students may struggle to engage with ideas that have arisen in social, cultural and historical contexts that are different or opposed to their own beliefs. This may be extended to include concepts that are seen to 'belong' to different disciplinary cultures to the one students see themselves as 'belonging' to. Students may find difficulty engaging with concepts that do not meet with their expectations of what learning within their own particular chosen discipline should look like. The knowledge may also be regarded as 'foreign' if it is in some way counter-intuitive, that is to say concepts that are contrary to students' own experiences or views of the world, there is some overlap with conceptually difficult knowledge in this instance where counter-intuitive concepts lead to misimpressions.

Tacit Knowledge

Identified by Meyer and Land (2003) when building on Perkins' work, and perhaps related to the idea of 'belonging' outlined above in relation to foreign or alien knowledge, is the concept of tacit knowledge. Tacit knowledge is that knowledge which exists implicitly either at a personal level (Polanyi 1958) or within a specific community of practice (Wenger 1998) or paradigm (Kuhn 1996). Tacit knowledge has implications both for conceptually-difficult knowledge, where implicit or intuitive beliefs emerge in response to qualitative problems, and foreign knowledge where concepts are seen as belonging to different disciplinary cultures to the student's own. Tacit knowledge may be described as forming the 'background' knowledge of a discipline or subject area, important for understanding (and potentially complex or counter-intuitive) but not dealt with explicitly by teachers (Hall 2006). Some students will, therefore, fail to recognise the significance of tacit knowledge, thus making broad understanding within their subject area, and the understanding of other troublesome concepts, more difficult. Owing to its nature, tacit knowledge may also evade teachers when designing curriculum, further compounding the troublesomeness of this type of knowledge. Tacit knowledge may be linked to what Perkins (1997) terms 'epistemic games' these will be discussed in more detail in the next section.

Implications of troublesome knowledge for teaching

Troublesome knowledge offers an opportunity for teachers to engage with learners' difficulties and respond in ways that will most benefit the learner in terms of achieving understanding. The variety of these different approaches reflects the variety of constructivism itself whilst simultaneously allowing a more strategic approach that helps to temper the complexity of the constructivist philosophy (Perkins 1999). Many of these approaches are based on learners being cast in 'roles' as *active learners* (where knowledge and understanding are actively acquired), *social learners* (where knowledge and understanding are socially constructed) and *creative learners* (where knowledge and understanding are created or recreated) (Phillips 1995).

Active participation by students in this regard would appear to be crucial, as Perkins (1999) notes, "constructivism generally casts learners in an active role" (p. 8). Ritual knowledge, for example, may be made more meaningful by engaging students in authentic problem-solving exercises that they can then relate to their own understanding of the world. Similarly inert knowledge, by its very nature, may be 'rescued from the mind's attic' through active use (Perkins 1999). Conceptually difficult knowledge may be overcome through confronting students with discrepancies in their misimpressions or posing more qualitative problems rather than quantitative ones that may invite ritual response. Alien or foreign knowledge offers opportunities to engage in active role-playing exercises where students attempt to "get inside mindsets different to their own" (Perkins 1999).

Another potential source of troublesomeness for the learner linked less to conceptual knowledge and more to ways of thinking and practicing are so called 'epistemic games' described by Perkins (1997) thus:

"What inquirers do to investigate something can be in part characterized as a somewhat regular pattern of action analyzable into forms, moves, goals, and rules. The pattern recurs across particular content within a domain -- and often across domains -- so people can be said to be following the same or a very similar pattern of action even when investigating different things." (p.51)

Epistemic games may be *explicit* (where patterns of inquiry are recognised and talked about explicitly by practitioners) or *tacit* (where these patterns are recognised implicitly) in nature (Perkins 1997), where the latter may be considered as potentially troublesome as any other form of tacit knowledge. These regular patterns of action are an intrinsic part of inquiry, indeed learning through inquiry would seem inseparable from them, guiding as they do the very process of inquiry (Perkins 1997). However, there is evidence that these epistemic games may constitute a source of further difficulty for learners (Perkins 1999). For example, the epistemic game of *justification* through statistical reasoning has been demonstrated to be troublesome, with learners struggling with misconceptions post-instruction and failing to apply understanding in instances removed from the typical instances of formal instruction (Nisbett 1993). This may be of particular interest in the context of teaching uncertainty, given that is frequently justified through the use of statistics; this is discussed in more detail below. As well as the epistemic game of justification there exist two further kinds of epistemic game, *characterisation* (efforts at description or representation) and *explanation* (efforts to account for something). These epistemic games vary from the generic to the specialised and the formal to the informal and are all intrinsically linked to inquiry, as Perkins (1997, p. 57) notes: "What would an inquiry be like with no concern to characterize target phenomena, offer explanations, or justify conclusions? There would be nothing left recognizable as inquiry."

Uncertainty as troublesome knowledge in the context of climate change

Climate change as a subject area is positively fraught with examples of knowledge that may be considered in some way troublesome. Anthropocentric notions of man-made climate change may be challenged by the potentially counter-intuitive idea of natural climate variability operating over conceptually difficult geological timescales. The Earth system itself and all the many facets that affect climate may present a barrier to understanding through its complexity and sheer scale. Also, owing to its multidisciplinary nature the subject area of climate change is likely to throw up many examples of 'alien' knowledge that are seen to belong to different disciplinary contexts, particularly where scientific conceptions are brought to bear on issues such as policy which have a distinctly 'human' dimension and vice versa (Hall 2010). The question to be considered here, however, is whether uncertainty constitutes troublesome knowledge in this context.

As demonstrated in chapter two, uncertainty is prevalent in almost all aspects of the climate change subject area from the complex physical climate system to human impacts and responses and the tools and knowledge used in understanding and providing solutions to climate change. The very concept of uncertainty may be considered counter-intuitive by some students, being seemingly at odds with their expectations of their being a definitive 'right' answer. Uncertainty itself may also be considered something of an abstract concept that students (and teachers) find conceptually difficult. Whilst students may find uncertainty reasonably straightforward to quantify using statistics and so forth (learning the ritual mechanisms for generating statistics without ever discovering their true meaning, in other words failing to recognise the significance of this particular epistemic game), they may struggle when asked to qualify uncertainty, what it means and its implications. Equally, however, students may be more comfortable with more qualitative conceptions of uncertainty but find more scientific conceptions troublesome, again this may be down to disciplinary culture and context having an effect. Given its prevalence, there is also a chance that uncertainty may become tacit or implicit in some instances. In other words, it is such an integral part of the climate change subject area that those practicing and teaching the subject may not recognising it explicitly as an important concept for understanding, instead they may focus on the more immediately recognisable troublesome concepts that constitute ritual or conceptually difficult knowledge (Hall 2006). The nature of uncertainty as troublesome knowledge will be explored in more depth through the research but at present it seems a reasonable candidate.

Threshold Concepts

Related to the framework of troublesome knowledge is that of threshold concepts. The basic principle of the threshold concept theory is that "within certain disciplines there are certain 'conceptual gateways' or 'portals' that lead to a previously inaccessible, and initially perhaps 'troublesome', way of thinking about something" (Meyer and Land 2005, p. 373). The idea of the threshold concept is that students' understanding, interpretation and way of viewing something is transformed and without this transformation there can be no progression in their understanding of the subject area. The comprehension of a threshold concept may occasion a shift in the students' internal view of the subject matter, or even the students' worldview. Threshold concepts, therefore, may be described as operating at a higher and more profound conceptual level than what may be termed 'core concepts' within disciplines – conceptual building blocks that progress understanding of a subject without necessarily leading to a qualitatively different view of the subject (Meyer and Land 2003). Some suggested threshold concepts from specific academic disciplines are listed in Table 3.1. In most cases, these concepts are examples almost unique to their disciplinary context, perhaps even going some way to define the discipline itself. This section will focus mainly on the generic characteristics of threshold concepts; the applicability of the framework to the context of climate change and issues of disciplinarity are discussed towards the end of the section.

Table 3.1: Examples of threshold concepts in academic disciplines, adapted from Stokes *et al.* (2007)

Discipline	Suggested Threshold Concept(s)	Reference
Economics	Opportunity cost; Elasticity	Reimann & Jackson (2006)
Pure Mathematics	Complex numbers; Limits	Meyer & Land (2003)
Computer Science	Object oriented programming; Pointers	Boustedt *et al.* (2007)
Biology	Process, e.g. energy transfer	Taylor (2006)
Geoscience	Geological time	Truscott *et al.* (2006), Cheek (2010)

Threshold concepts and troublesome knowledge

It should be noted that the 'troublesomeness' of a concept forms part of the criteria that define it as a threshold concept i.e. students should experience difficulty and discomfort when faced with the concept but they must overcome this as progress within their discipline will be all but impossible without an understanding of the concept (Meyer and Land 2003). Concepts that are alien, counter-intuitive or conceptually difficult are more likely to lead to new conceptualisations of a subject area on the part of the student. In this way threshold concepts build directly on theories of troublesome knowledge as the various types of troublesome knowledge imply approaches to teaching for understanding and may also, therefore, imply methods for 'approaching the threshold'. Troublesome knowledge can also, therefore, provide a useful starting point for identifying where threshold concepts exist within disciplines and curricula.

Meyer and Land (2003) also note the existence of troublesome language as a potential barrier to understanding and another dimension of troublesome knowledge. All language has this capacity to become troublesome, particularly where it is identified with and contextualised by a particular community of practice (Wenger 2000, cited in Meyer and Land 2003):

"Specific discourses have developed within disciplines to represent (and simultaneously privilege) particular understandings and ways of seeing and thinking. Such discourses distinguish individual communities of practice and are necessarily less familiar to new entrants to such discursive communities or those peripheral to them (Wenger, 2000). The discursive practices of a given community may render previously 'familiar' concepts strange and subsequently conceptually difficult." (Meyer and Land 2003, p. 11)

Whilst language may then manifest itself as another kind of troublesome knowledge it is also linked to disciplinary identities, practices and knowledge. It may, therefore, be as important an element in crossing the threshold as any of the other aspects of the threshold concept; this will be expanded upon later.

Other characteristics of threshold concepts

As well as their troublesome nature threshold concepts are also defined according to a number of other criteria. As touched upon above, threshold concepts are considered to be *transformative*, that is, once understood they lead to a significant shift in the learners' perception of a subject. This in turn leads to a shift in the feelings or attitude of the learner towards their subject and may also lead to a repositioning of subjectivity or even an altered worldview (Meyer and Land 2003). Secondly, threshold concepts should be *irreversible*, in that the aforementioned change in perception is unlikely to be forgotten or will only be 'unlearned' through considerable effort (Meyer and Land 2005). In this way threshold concept theory differs from theories of Conceptual Change Learning, a constructivist framework commonly employed in science education based on learners moving up through a series of conceptual 'steps' towards a better understanding of a subject. Authors on Conceptual Change Learning assert that unless the learner's momentum is preserved a process of conceptual decay may occur whereby the learner regresses to a previously held conception (i.e. a lower 'step') (Georghiades 2000). According to Meyer and Land however, learners will not regress to previously held conceptions, once they have grasped a threshold concept, without considerable effort. This is what is meant in terms of a threshold concept occasioning a significant shift in subjectivity, so significant in fact as to become more or less permanent. It may be said that Conceptual Change Learning pertains more to core concepts within disciplines as opposed to threshold concepts. Irreversibility may, however, be a difficult criterion to measure in relation to learning as there is no telling whether a student will regress in the future and this may only be ascertained through prolonged longitudinal research.

Thirdly, a threshold concept should be *integrative* or, in other words, should "expose the previously hidden interrelatedness of something" (Meyer and Land 2005, p. 373). In simple terms, understanding of a threshold concept allows the learner to make connections between concepts that were previously hidden to them (Cousin 2006). The threshold concept should give shape and structure to the subject from the point of view of the expert, however this presents problems for the learner owing to the fact that they must first acquire pieces of knowledge that can only be integrated later (Davies 2003). It is advisable that teachers should, therefore ensure that the threshold concept is not introduced too early as to be inaccessible to the students and should also ensure that once the concept is grasped steps are taken to reveal the integrative power of the concept to the students (Davies 2003). In their first paper on threshold concepts (2003) Meyer and Land also note that a threshold concept may often be '*bounded*' in that "any conceptual space will have terminal frontiers bordering with thresholds into new conceptual areas" (p. 6). However, in their second paper on the subject (2005) they note that this raises complicated questions relating to the identification of such boundaries and power relations with and between discipline areas.

Changes in language and identity

Another key aspect linked to threshold concepts and the associated repositioning of subjectivity is that of language – another characteristic of threshold concepts is that they have a *discursive* element. A shift in perspective on the part of the student will, inevitably, be accompanied by an extension of their use of language. This language may be generated by the student or may be part of the prevailing discourse within an academic community or community of practice and will lead to the student being identified (and identifying with) the particular community he or she is working within (Meyer and Land 2005). However, Meyer and Land also note that the shift in perspective mentioned above may be occasioned through a change in a students' use of language. They observe that: "through this elaboration of discourse new thinking is brought into being, expressed, reflected upon and communicated" (2005, p. 374). In other words the externalisation of a student's ideas can help them organise their thinking and generate new thoughts, thus leading to better understanding of the subject. As noted above it may also be the troublesome nature of the language itself that is the stimulus for students crossing a particular threshold to a new way of thinking about something, bringing with it as it does new ways of thinking linked to disciplinary identities. In some ways the student may be said to have crossed the threshold once this new discourse is adopted and new language is brought to bear on problems that are encountered.

Linked to this discursive shift (and, as noted above, perhaps signalled by it) is a shift in the learner's identity as a result of crossing a particular threshold. Threshold concepts may possess a *reconstitutive* effect on the part of the learner, causing them to redefine their sense of self and how their beliefs relate to the world (Meyer and Land 2005). This is a transformation not just of how the learner views their subject but a "repositioning of the self" (Meyer and Land 2005, p. 374). In other words, threshold concepts may be said to possess not simply an epistemological dimension, in terms of a progression of a learner's knowledge or way of thinking about something, but also an *ontological* dimension, in that there is a transformation in the learner's way of *being*. This reconstitutive effect may be said to combine many of the other elements of threshold concepts to the extent that it may be viewed almost as the 'end point' of the journey through the threshold: it is clearly deeply transformative; it is integrative as it allows learners to relate their knowledge to other concepts within and beyond their discipline; it may well be irreversible, given the significance of the identity shift that may have occurred; in the same way that it may be integrative it may also allow the learner to see the boundaries of the conceptual terrain of their discipline; there is the aforementioned discursive element to changes in both thinking and identity and, finally, the reconstitution of the learner's identity is likely to be in some way troublesome. Whilst this may be considered as the 'end point' to the journey through a portal, the journey itself should be explored through other means.

Liminality

In their second paper on threshold concepts Meyer and Land explore the nature of the conceptual spaces entered by students as they cross thresholds in terms of states of 'liminality'. The concept of liminality comes from ethnographic studies of central social rituals such as rites of passage (van Gennep 1960; Turner 1969) and is used to describe the transitional space and time within which the ritual occurs (liminality from Latin *limen*, 'boundary or threshold). For example the wedding ritual in Western culture involves the wedding ceremony as a 'threshold' followed by a liminal honeymoon period (Trubshaw 2003). The comparison with liminality is favoured for many reasons. Firstly the process is transformative and usually involves an individual being altered from one state to another and secondly the rituals often involve the participants acquiring new knowledge and therefore gaining a new identity and status within the group (Meyer and Land 2003). Secondly, this transition is, however, often troubling for the participants as it involves a period of being stripped of identity somewhere between the two states where they are neither one nor the other, they are "naked of self" (Goethe 2003 cited in Meyer and Land 2005). This is similar to educational settings where students frequently feel anxious or apprehensive when their understanding of a concept is not complete, but when the concept is grasped fully they are able to move on with confidence. Thirdly, the transformation can be protracted and involve oscillations between states before the new identity or status is achieved, however, once passed there can be no ultimate return to the pre-liminal state (Meyer and Land 2003). This liminal space can shed new light on areas where students feel 'stuck' in their progress to understanding and has implications for course design in terms of helping students past problem areas (Meyer and Land 2003).

It would appear, therefore, that thresholds in academic disciplines cannot be viewed as simple 'portals' through which a learner passes on their way to better understanding. Rather, the learner must traverse liminal space in order to move past the threshold and towards the shift in perspective this will bring. However, this presents great difficulty in an educational context owing to the fact that liminal space is abstract and is personally constructed by the learner. In order to try and overcome this educators may take a student-centred approach where the teaching is designed to take into account and accommodate for the individual needs of the learner and the *variation* in the experiences of learners. In this way students can be helped through their own personal liminal space in order to overcome barriers to their understanding and allow them to grasp threshold concepts. This in turn, however, raises more practical issues of time constraints and meeting the needs of all students at an individual level (Meyer and Land 2005).

Liminality, variation and implications for teaching

Attempts to take a broader and more traditional approach to introducing threshold concepts to students may result in the creation of more barriers to understanding. It has been noted that in cases where a simplified version of a threshold concept has been introduced to ease students into the process of understanding it has been this simplified version that has been carried forward by the student. It seems that first impressions matter most in these instances and that student will carry forward simplified concepts as ritualised knowledge, which will create more barriers to understanding the more complex aspects of the concept (Meyer and Shanahan 2003 cited in Meyer and Land 2005). Students may also adopt a kind of mimicry, regurgitating verbatim information relevant to understanding the concept without actually grasping the concept itself. This is similar to the ritual responses that students may adopt when faced with conceptually difficult knowledge (Perkins 1999). However, mimicry may itself be an approach that students adopt in a serious attempt to understand the concept in question and should not be discounted out of hand (Meyer and Land 2005). The student-centred approach mentioned above should also take into account the variation in students' tacit understandings of a concept. Meyer and Land (2005, p. 384) identify this in terms of "*pre-liminal variation*" and indicate that it may give valuable insights into the possible reasons why some students "will productively navigate liminal space and others find difficulty in doing so". This pre-liminal variation may, therefore, be a useful starting point for introducing students to threshold concepts and deciding how to proceed in terms of their teaching.

Teaching and assessment methods built on considerations of individual variation in how students perceive concepts and where they encounter conceptual difficulty are a helpful way of understanding how the portal initially comes into view, is negotiated and where the students ends up (Meyer and Land 2008). This may be considered in terms of the aforementioned pre-liminal variation (the starting point, as stated above), *liminal variation* (how the portal is entered, negotiated, passed through or not) and *post-liminal variation* ("the point and state of exit from the liminal state") (Meyer and Land 2008, p. 3). Post-liminal variation has clear implications not only for the future direction of a student's learning but also the expectations of future teachers for what that student knows already (Meyer and Land 2008). Furthermore, there may be variation at a more tacit level through students' knowledge of the 'underlying game' or 'way of knowing' within their discipline (Meyer and Land 2008). This is linked to the epistemic games mentioned in the section on troublesome knowledge above but exists at a level below these more practical facets of inquiry, a subliminal level. Where epistemic games represent ways of thinking, underlying epistemes represent ways of *knowing* a subject, "systems of ideas and ways of understanding that allow us to establish knowledge" (Perkins 2006, p. 42). Variation in how students perceive and utilise these underlying games may be termed *subliminal* variation, difficult to 'get at' but potentially crucial in determining progression through liminal space and onward (Meyer and Land 2008).

Implications for curriculum design

Threshold concepts also have clear implications for curriculum design in that they offer a structure whereby curricula are designed around reconstitutive experiences or concepts and considerations of 'stuckness' and liminality. Some recommendations on how to re-evaluate curricula to include a greater focus on thresholds include considerations of:

"a) The sequence of content.

b) The processes through which learners are made ready for, approach, recognise, and internalise threshold concepts. We would argue that this process of the student's learning, their encounter with threshold concepts in a given subject, might be considered as akin to a journey or excursion. Such an excursive account of the learning experience would see these processes as a framework of engagements, designed to assist students to cope with threshold concepts.

c) The ways in which learners and teachers recognise when threshold concepts have been internalised – in effect what would constitute appropriate assessment for the attainment of threshold concepts."
(Land *et al.* 2005, p. 56-57)

Points b and c in the quote above are related to the notions of variation described in the section above and the kind of assessment methods that best take into account this variation. Cousin (2006) describes a 'less is more' approach to curriculum design dictated by threshold concept theory, striving to avoid 'stuffing' the curriculum with too much content and allowing students to explore the complexities of their subject area for themselves. Further to this, Land *et al.* (2005, p. 59) advocate students taking a recursive approach to threshold concepts "attempting different 'takes' on the conceptual material until the necessary integration and connection…begins to take place". This student-centred, exploratory approach echoes the constructivist methods relating to troublesome knowledge above and has found favour amongst educators from a wide range of disciplines.

Uncertainty as a threshold concept in the context of climate change

Having described the major characteristics of threshold concepts and some of the potential implications for teaching and curriculum design it is now time to consider whether uncertainty may be considered a threshold concept in the context of climate change. The first consideration is whether uncertainty as a concept in this context fits the criteria of a threshold concept, as described above. The section on troublesome knowledge above suggests some ways in which uncertainty may be considered troublesome, the other criteria will be discussed in turn.

It is reasonable to assume that an understanding of uncertainty may have a transformative effect upon a learner. Uncertainty challenges conceptions of truth and the existence of definitive answers, it also reveals the complexity of knowledge and how we rationalise our understanding of the world – likely to be an eye-opening experience for any learner. In this particular context it not only reveals the complexity of the climate change subject area but it also has the potential to redefine how we think about just about any facet of climate change. In this sense it is also integrative, uncertainty is prevalent across the board in terms of understanding the climate and how humans relate to it. It is, therefore, one of few commonalities shared by the diverse range of concepts and discipline-situated knowledge that make up the climate change subject area and, therefore, it has the power to link understanding of all these concepts and by extension the subject as a whole. Irreversibility is more difficult to assess, however it is not unreasonable when one considers the profound nature of uncertainty as a concept that it would be unlikely to be 'unlearned'. (Hall 2006) It is also difficult to think of uncertainty in terms of being bounded, given its ubiquity and somewhat abstract nature. It does, however, open up new avenues for inquiry and may be considered bounded in this sense.

Uncertainty in climate change has a language all of its own that is likely to have an effect on how students think and talk about the subject. Terms such as 'confidence', 'probability' and 'risk' have a distinctive meaning in this context and they all imply uncertainty. It is likely that an understanding of uncertainty will be accompanied by an extension of a student's language through using these terms, so uncertainty may be said to have a discursive impact. As alluded to above, it is also probable that the transformation associated with gaining an understanding of uncertainty is likely to be of a profound nature. Whether it is fully reconstitutive in the effect it has on a student's sense of self is more difficult to ascertain, but once again it is not unreasonable to assume. Given that threshold concepts also provoke a state of liminality it should also be considered whether the concept uncertainty has this same ability. Liminality is associated with feelings of discomfort and powerlessness, given the challenging, abstract and conceptually difficult nature of uncertainty it would seem an excellent candidate for a concept that provokes this state in a learner. The fact that liminality is itself defined as a kind of state of uncertainty (Land *et al.* 2005) indicates that it may provide a useful means for analysing not just the conceptual nature of uncertainty but also the deeper, more ontological notion of uncertainty – the condition of uncertainty. Just as threshold concepts may be described as having both an epistemological and an ontological character (in terms of liminality), so too uncertainty. As Barnett (2009, p. 439) notes: "The concept of 'uncertainty'...looks in two directions. It is epistemological in character (pointing to limitations in our knowledge) and it is ontological (pointing to moments of insecurity or even anxiety as being is dislocated)". This again indicates that threshold concepts is a useful framework for analysing uncertainty as it can accommodate both the epistemological and ontological characteristics of the concept.

Uncertainty would, therefore appear to be a good candidate in terms of being defined as a threshold concept and threshold concept theory would appear to present a useful framework for analysing uncertainty. However, there is one potential flaw that may appear – up until this point discussion has been centred on threshold concepts which appear within specifically defined *disciplines* (Table 3.1). This is only natural given that learning is socially-situated and the acquisition of new ways of understanding leads to social re-positioning on the part of the learner. This social re-positioning naturally leads to the creation of communities made up of like-minded individuals; this may inhibit or facilitate learners in their approach to thresholds (Meyer *et al.* 2006). Whilst climate change is a subject area of large and growing interest it is, by its very nature, multidisciplinary. This may first appear to invalidate the use of threshold concepts as a theoretical framework in this context; however, there are suggestions that interdisciplinary threshold concepts may exist, indicated by similarities between threshold concepts and theories of integrative learning (Higgs and Hall 2008). Recognising these thresholds may help learners to integrate concepts from diverse disciplines. Interdisciplinary is also a growing area of interest in the higher education community related to threshold concepts and some examples of interdisciplinary thresholds have been identified. Brooks and Ryan (2008, p. 12), for example, posit that the concept of sustainability may be a "permanently shifting threshold concept [where] both disciplinary and interdisciplinary understandings of it will...be useful". In other words, a degree of multidisciplinary thinking may be necessary in order to analyse certain threshold concepts.

Although being studied in depth in the particular context of climate change, the concept of uncertainty may have profound implications across any number of disciplines, perhaps forming an interdisciplinary threshold or remaining open to local interpretation with the same profound implications for learning.

Conclusion

The theoretical frameworks outlined in this chapter would appear to represent useful tools for the characterisation and analysis of uncertainty as a concept and the implications for teaching uncertainty. Consideration has also been given to uncertainty in climate change and how the epistemology of the concept in this context may fit with the theoretical frameworks. This will be explored in more detail in chapter six, which provides analysis and discussion of the theoretical frameworks in relation to the epistemology of uncertainty in the context of climate change as discussed with the interview participants. The methodology and methods used in collecting and analysing the interview data for this study are discussed in the following chapter.

Chapter Four

Methodology and Methods

This chapter outlines the key stages in the development and design of the research methodology and methods used to collect and analyse the data used in this study. The chapter begins with a discussion of the process of developing the methodology including frameworks and methods that were explored and subsequently not utilised as part of this process. The second section is concerned with the development and design of the semi-structured interviews used for data collection and the selection of participants for the study.

Developing the methodology

The development of the methodology employed in this study was a lengthy process that involved the exploration of a number of methodological frameworks and techniques before the final methodology was settled upon. This section outlines the key stages of this process, including consideration of the reasoning behind the final choice.

Stage 1: The questionnaire

The first excursion into developing a methodology for the study included the design of a questionnaire intended to be circulated among U.K.-based academics involved in teaching or researching climate change or some aspect of the subject. The questionnaire (see Appendix 1) was based on 9 questions designed to yield easily quantifiable data concerning academic's perceptions of the climate change subject area as well as some basic qualitative data concerning potentially troublesome concepts.

The intended purpose of the questionnaire was fourfold: firstly, to give a picture of what the subject area of climate change looked like in the context of U.K. higher education (i.e. what concepts and ideas were taught at what stages); secondly, to tentatively identify examples of troublesome knowledge and whether uncertainty was among them (i.e. whether it emerged despite not being explicitly mentioned on the questionnaire); thirdly, to give a profile of the people involved in teaching and researching climate change in terms of their academic background, research and teaching interests; and fourthly, to determine whether academics were receptive to the prospect of participating in in-depth interviews and to provide a means to select academics for interview based on their responses to the questionnaire.

The selection of the interview candidates was to be based on their responses in terms of generating a certain amount of pre-determined variation in both the attitudes of the respondents to either uncertainty or climate change and their own personal context. For example, the intended sample for interview would contain a range of individuals from different academic backgrounds, with varying research interests and varying levels of teaching experience. Candidates would also be invited for interview on the basis of whether or not they had mentioned uncertainty on the questionnaire, particularly in the section on troublesome concepts.

The questionnaire was never employed; however, as it was felt that it was more suited to a general exploration of the nature of climate change research and teaching in U.K. higher education rather than a tool for the specific research of teaching uncertainty. Whilst this data would no doubt have been of significant interest it did not contribute much towards the central aim of the research, namely the investigation of uncertainty and how it is perceived and taught in the context of climate change. The complexity of this subject precludes the inclusion of extraneous and potentially distracting data which the questionnaire may have generated. However, the development of questions for the questionnaire did assist in the development of interview questions detailed in the relevant section below.

Stage 2: A phenomenographic approach

Concordant with the development of the questionnaire was the exploration of methodologies pertaining to the next phase of the data collection, namely the interviews conducted with academics identified through their questionnaire responses. At this stage the methodology considered best suited to the aims of the research was phenomenography, a research methodology commonly used in higher education research (Ashworth and Lucas 2000) that is chiefly concerned with measuring variation in the different ways that phenomena are perceived. Phenomenography may be defined as: "the empirical study of the limited number of qualitatively different ways in which we experience, conceptualise, understand, perceive, apprehend etc., various phenomena in and aspects of the world around us" (Trigwell 2001, p. 3). The methodology is typified by individual interviews carried out in a dialogical manner where the interviewee is encouraged to reflect on various aspects of the phenomenon in question (Trigwell 2001). The data is then analysed and assigned to 'categories of description' that capture the limited number of different ways that the phenomenon in question is perceived by the interviewees (Dortins 2002). These categories are hierarchical and, therefore, measure the variation that exists in perceptions of the phenomenon in question (Trigwell 2001). This process requires a rigorous approach that requires the researcher to enter as far as possible into the participant's "life world" in order to generate outcomes that are defensible and valid (Dortins 2002, Ashworth and Lucas 2000). Phenomenographic research may also prescribe the number of participants in a study, with 15-20 candidates viewed as sufficient to fully capture the range of variation in how a given phenomenon is perceived (Trigwell 2006).

At first, this methodology appeared to be ideally suited to the study, given its prevalence in higher education research and the fact that it has already been used as a means of investigating academics' experiences of understanding both their subject matter and their teaching (Prosser and Trigwell 1999, Prosser *et al.* 2005). However, there are some significant limitations to the methodology that precluded its use in the research. Foremost among these is the focus on describing key aspects of the variation in how a phenomenon is experienced at the expense of capturing "the richness of personal experiences" (Trigwell 2001, p. 3). The phenomenographic approach does not permit the researcher to examine the personal context of the participant and the influence this has on their perceptions; as Haggis (2006, p. 1) notes: "though phenomenography is concerned with context, its focus tends to be limited to the context of the institution or to context in the sense of the development of conceptual understanding in specific disciplinary areas". The emphasis on identifying cognitive structures that can be generalised beyond the individual, limits the ability of the methodology to capture complex perceptions of complex phenomena that are grounded in personal context (Haggis 2006). Given the complexity of the phenomenon in question in this study (i.e. uncertainty in climate change) this was a clear limitation of the methodology.

Furthermore, the aforementioned studies that have employed exclusively phenomenographic approaches to research academics' experiences of teaching have tended to further limit complexity by seemingly rejecting variation through emphasising the diametrically opposed furthest ends of the hierarchical scale of categories (Meyer and Eley 2006). For example, the 'Approaches to Teaching Inventory' (ATI) developed by Prosser and Trigwell (1999, above) was based on phenomenographic research into the experiences of and approaches to teaching adopted by academics. The research initially identified a phenomenographic scale of conceptions of teaching ranging from teacher-centred, information transmission based approaches through to student-centred, conceptual change based approaches, with a number of different conceptions in between. However, the eventual outcome of the research (the ATI – developed as a tool to assist teachers in conceptualising their approach to teaching practice) removes these other conceptions in favour of focussing on the two extreme ends of the spectrum and, therefore, "manifestly does not reflect a functionally useful range of 'approaches to teaching'" (Meyer and Eley 2006, p. 633).

It would appear that there is a further clear limitation inherent within this methodology, in that the full range of perceptions may be brushed over in favour of an emphasis on extreme differences in perception. This is compounded by the hierarchical nature of the phenomenographic categories, which tend to express perceptions in terms of their 'sophistication' relative to others. There was a danger that the identification of participants from their interview responses would predispose the study towards concentrating solely on the outlying perceptions rather than the full range of complex responses. This was particularly relevant given that the selection of candidates for interview was to be predicated on whether or not they had included or omitted a certain term on their questionnaire response – i.e. uncertainty. It became apparent, therefore, that an alternative methodology was required, one that allows for deep interrogation rather than the shallow investigation encouraged by phenomenography and that emphasises the description of 'different' perceptions as opposed to 'better' ones.

Stage 3: Using grounded theory

The decision not to use the phenomenographic approach outlined above led to a shift away from methodologies that prescribe research methods in favour of a more open ended approach founded on the principles of grounded theory. This approach contrasts to phenomenography in the sense that it is inductive as opposed to deductive. Grounded theory is a methodology developed by two sociologists, Barney Glaser and Anselm Strauss (1967), who desired methodological tools that were better able to capture the richness and dynamics of complex social and interpersonal situations than those more commonly used for social research at the time (Shank 2006). Grounded theory is an approach whereby "the researcher begins with an area of study and allows the theory to emerge from the data" (Strauss and Corbin 1998, p. 12). Theory is 'discovered' through the process of carrying out research as analysis begins when data is collected and proceeds simultaneously throughout the data collection process and beyond; researchers are encouraged to engage in "persistent interaction with their data" as they move iteratively between raw empirical data and the emerging analysis (Bryant and Charmaz 2007, p. 1). Theories in this instance may be considered "organised meaning claims" that makes sense of a given phenomenon, the practice of constructing theories from the ground up is, therefore, an exercise in "making meaning" (Shank 2006, p. 129). This approach has clear benefits in researching something as complex and multifaceted as uncertainty in climate change as it allows the researcher to be open minded in order to explore fully the many different perspectives that are bound to emerge. This emergent, inductive methodology has an innate strength over the previously explored methods and methodologies in that it allows and encourages the collection and analysis of rich, personally-situated qualitative data as opposed to a broader, shallower analysis that is more concerned with variation. This 'openness' inherent in grounded theory extends to the scale of a qualitative study, where the amount of data collected is subject to the judgement of the researcher. Researchers using grounded theory proceed with data collection until such time as they feel that 'saturation' has been achieved, that is to say that they have learned sufficiently from what they have already seen and heard and additional data collection appears counter productive (Strauss and Corbin 1998).

It should be noted, however, that mainstream grounded theory still possesses a number of standardised 'rules' for conducting research in this mode. This includes a systematic set of procedures designed for the collection and analysis of data in order to derive grounded theory inductively (Strauss and Corbin 1990). The procedures are largely analytical and are based on generating categories of data, coding these categories and then linking them through consideration of the structure of the theory and the process by which it is derived (Shank 2006 after Strauss and Corbin 1998). The procedures may be viewed as a means of standardising the approach in order to make the emergent theories more generalised and widely applicable. Within the framework there is, however, room for creativity on the part of the researcher, particularly in terms of the identification and nomenclature of categories in imaginative ways (Strauss and Corbin 1990). Researchers using grounded theory are also encouraged to use strategies and structures flexibly in their own way and innovation is seen as central to the development of both the theory and the researcher (Charmaz 2006).

The development of the methodology used in this case was based on many of the key tenets of grounded theory but did not subscribe fully to the procedures and rules for the collection and analysis of data, chiefly defined by Strauss and Corbin (1990, 1998). The methodology was more akin to the philosophies of Glaser (1978), who deviated from the original model devised with Strauss (Glaser and Strauss 1967) towards a more open ended approach. The rules for data gathering and manipulation are rejected in favour of a looser framework that keeps the researcher open and aware of new possibilities of meaning within the emerging data record (Shank 2006). The methodology used in this case, therefore, contains many important grounded theory components, chiefly the emergent and inductive nature of the approach, but also the focus on collecting rich data, persistent interaction with data, the creation and linking of categories, the creative development of research methods and the principle of saturation. The inherent flexibility of qualitative research compared to quantitative research means that researchers can add new pieces to the 'puzzle' while the puzzle is still emerging (Charmaz 2006). This allows for constant review and enhancement of research methods and the pursuit of leads that emerge from the process of data collection, particularly powerful when using an inductive approach such as this. In the case of the methods employed here, the methodology allowed for subtly different approaches to be employed throughout, invaluable given the complexity of the research and the concept of uncertainty.

Developing the research methods

This section outlines how the methods employed in the collection and analysis of data for the study were developed, including the formulation of questions used in semi-structured interviews and the selection of candidates for participation in the interviews.

Developing questions and techniques for semi-structured interviews

Following the decision not to use the questionnaire and the development of a methodology that focussed on collecting rich qualitative data it was decided that the most effective means of data collection would be through semi-structured interviews with academic candidates who fitted certain loose criteria. The selection process is discussed in more detail in the following subsection. The development of the interview questions drew from three main sources, these were: guidelines for developing and conducting semi-structured interviews, from the literature on research methods; the questions developed as part of the questionnaire; and the theoretical frameworks used in the study, namely threshold concepts and troublesome knowledge.

Semi-structured interviews are a useful means for collecting qualitative data in that they have a degree of structure that is balanced by an inherent flexibility, which means they are an efficient means of collecting rich data (Gillham 2005). The key elements of the semi-structured interview technique may be considered as follows:

- The same questions are asked of those involved

- Questions go through a period of development to ensure topic focus
- Interviewees are prompted using supplementary questions if they have not spontaneously covered the area of interest
- Approximately equivalent time is allowed for each interview (Gillham 2005)

Within the structure of the interview there are also a further two key elements that assist in the gathering of rich data, these are:

- The use of open questions that encourage interviewees to expand their answers; thus offering a wealth of additional data that may not otherwise be forthcoming. For example, *how long have you been teaching?* may be considered a closed question as it invites only the statement of a number of years; *can you describe your 'academic journey' to this point?* offers the interviewee an opportunity to add much more to the response in terms of interesting information concerning their personal context.
- Probes may be used by the interviewer when they judge that there may be more to be disclosed at a particular point or there is an interesting development beyond the structure of the interview that merits exploration – similar to the concept of new 'puzzle pieces' or the following of leads described by Charmaz (2006) in the section above (Gillham 2005)

This method has many strengths over both survey-based methods and completely open ended interview techniques where no structure is employed. Firstly, the structure allows the researcher to develop questions iteratively through a process of rigorous preparation (Gillham 2005). The interview can be piloted several times if required in order to establish the robustness of the questions and the technique of the interviewer, this also extends to continuous adjustment of the questions and interview structure as the research progresses. Secondly, a degree of comparability between participants may be achieved owing to the fact that they have all answered the same questions during the interview (Barriball and While 1994). This adds to the richness of the data collected and aids the researcher in data analysis and the identification of categories. There is also evidence to suggest that response rates for interview-based research are far higher than survey-based approaches as potential candidates are more motivated to participate in face to face rather than survey-based research (Barriball and White 1994). Response rates of 70-80% are not untypical, further enhancing the efficiency of the method (Kidder 1981).

The guidelines for semi-structured interviews outlined above informed the design of the interview questions and an interview in two parts was devised (see Appendix 2). The first part included general questions about the participant's development and teaching while the second part of the interview was more specifically focussed on the concept of uncertainty in climate change. The wording of many of the questions was developed from those originally conceived as part of the questionnaire, as the intent remained largely similar (see Appendix 1). Further influence on the wording of the interview questions was derived from the theoretical frameworks of threshold concepts and troublesome knowledge, with questions two and three (see Appendix 2) designed to elucidate academics' conceptions of concepts that may meet the criteria of these frameworks in the context of climate change. In the context of the interview these questions were left open-ended with no suggestion of concepts forthcoming from the interviewer. This was designed to see if uncertainty emerged as a candidate for a concept considered either as a threshold or an example of troublesome knowledge without intervention from the interviewer, as this had the potential to yield interesting insight into the status of the concept in this context. If the concept had not emerged in response to these questions part two of the interview was designed to explore uncertainty in the context of teaching climate change in more detail (see Appendix 2). The questions in part two were also designed so that they could be employed as 'probes' should uncertainty emerge in the discussion prompted by the questions in the first part of the interview. A final question was also appended to the interview in the case that there was sufficient time available to discuss figures that the interviewees particularly admired within the field of climate change research, in order to see whether this generated any additional interesting data pertaining to the participant's conceptions of either uncertainty or climate change.

Selecting participants for interviews

Initially the criteria for interview candidate selection were based on the teaching interests and situation of the candidates. That is to say that candidate selection was initially based on identifying academics teaching about climate change within Geography programmes at universities in England and Wales. The disciplinary context of Geography was chosen as climate change is likely to form a large part of any higher education Geography curriculum owing to its core principle of teaching and researching human interactions with the physical environment as well as a strong emphasis on systems-based thinking and an appreciation of scales and patterns of change (QAA 2007, Pointon 2008). The selection was achieved through researching the Royal Geographical Society-Institute of British Geographer's (RGS-IBG) list of Geography degree courses to see whether climate change formed part of the degree curriculum, followed by contacting staff members in order to identify suitable candidates for interview. This process led to the scheduling of nine interviews with academics based at universities in the South West of England and South Wales. Further to this process opportunities also arose to interview academics from international universities, through the 'visiting fellowship' scheme at the Centre for Active Learning, University of Gloucestershire where the researcher is based. This led to two further interviews being conducted with academics from universities in New Zealand and Australia respectively. A breakdown of the participants, their personal context in terms of time spent teaching and research interests, and where they are based can be found in Table 4.1.

Table 4.1: Participants in the study and their personal context, expressed in terms of teaching experience, first degree, research interests and the context in which uncertainty in climate change is taught (i.e. the module or degree course in which it emerges). NM, Not Mentioned

Participant/ Gender	Location	Years teaching (approx)	First degree	Research interests	Teaching context (+ level)
Participant 1 Male	England	13	Geography	Thermoluminescence dating, Quaternary Science	Quaternary Environments, Global Environmental Change (all levels)
Participant 2 Male	England	2	Geology	Climate Modelling	Climate Change (level 3)
Participant 3 Female	England	2	Physics	Climate Modelling	Climate Change (level 3)
Participant 4 Male	England	8	Geography	Palaeoclimate, Geo-chronology	NM
Participant 5 Female	England	5	Physics	Climate modelling, Thermoluminescence dating	Environmental Change (level 2)
Participant 6 Male	Wales	NM	Geography	Micro-palaeontology, Coastal Science, Pedagogy	Coastal Science, Climate Change (NM)
Participant 7 Female	England	6	Anthropology	Tourism Geography	Tourism/Tourism Geography (level 2)
Participant 8 Male	England	29	Geography	Historical Geography	Sustainable Energy (level 2)
Participant 9 Female	New Zealand	5	Geography	Pedagogy, micro-climates	Micro-climates, Geography (level 4)
Participant 10 Female	Australia	15	Geography	Climate change policy, Atmospheric Science	Climate policy (all levels – BSc and MSc)

Carrying out data collection and analysis

This section is concerned with the actual practice of the methodologies and methods outlined above as well as the subsequent analysis of the data collected.

Doing the research interviews

Following the development of the interview questions they were piloted by the researcher in an interview with an academic colleague; the interview was highly successful and the questions and technique were deemed suited to the research. The interview structure and questions were, therefore, carried forward into the rest of the interviews, however; owing to the open ended nature of the methodology and the inherent flexibility of the research method every interview was different in character and format to the last. This was to be expected given the approaches adopted by the researcher, the questions asked and the fact that all people are different. However, there were few significant departures from the core structure of the interview and all participants were asked more or less the same questions. The one significant change to the interview structure was the omission of the final question about researchers or practitioners that the participants particularly admired. This was abandoned after the fourth interview as it was a question that the participants felt uncomfortable answering and added little in terms of data enhancement. A total of nine further interviews were conducted after the pilot and, on reflection, the data from the pilot interview was considered to be suitable for inclusion with the other interviews, giving a total of ten completed research interviews. After ten interviews it was judged that enough data of sufficient detail had been collected to answer the research questions, however this does not necessarily indicate that true saturation, in the grounded theory definition, had taken place. At this point a subjective decision was taken by the researcher whereby it was felt that the research questions could be answered in a manner befitting the level of the research and that additional data may prove overwhelming. The interviews varied in length from around fifteen minutes to over an hour, depending on how quickly uncertainty emerged in the discussion and the engagement of the participants – the response to certain questions and probes varied considerably depending on the level of interest of the participant. The approximate time spent on each interview is indicated in Table 4.2 – it should be noted that all participants were *allowed* an equivalent amount of time and no interview was cut short by the researcher. All participants gave informed consent for participation in the study (see Appendix 3) and all were afforded anonymity in accordance with the University of Gloucestershire's code on research ethics.

Data analysis

The interview data was transcribed in full by the researcher before being edited slightly for ease of interpretation – pauses and stutters between statements, for example, were removed to make the reading of the interview transcripts smoother. Two full research interview transcripts are included in Appendix 4 as exemplars of the data collection and transcription process and to demonstrate the variation in how the discussions unfolded in terms of the relevance to teaching uncertainty. The analysis was based initially on several close-readings of the interviews by the researcher, akin to the 'micro-analysis' of grounded theory described by Strauss and Corbin (1998). This initial analysis led to the identification of two broad 'species' of category that in turn defined both the future course of the analysis and the writing of the thesis, namely categories of conceptions of uncertainty (outlined in chapter five) and categories relating to teaching uncertainty (outlined in chapter six). These broad categories then set the tone for two separate periods of micro-analysis designed to expand these categories and identify distinct sub-categories within them. The identification of categories and sub-categories was assisted by the use of the semi-structured interview method as the posing of similar questions naturally led to comparable responses. This was particularly evident in the case of instances where discussion of uncertainty overlapped with the criteria of threshold concepts and troublesome knowledge; with an additional level of interest emerging from whether these discussions developed without prompting from the researcher. Dedicated software packages for qualitative data analysis were considered for the analysis; however, these were not employed as the researcher favoured the process of iterative close-reading enhanced by the ongoing analysis that occurred through the conduct and transcription of the research interviews in accordance with the methodology.

The analysis is expressed in the structure of chapters five and six where the categories and sub-categories are discussed in turn with reference to relevant quotes from the interviews with the participants. A summary of how the presented data relates to the dataset as a whole is given in Table 4.2. The percentage of each interview transcript presented as quotes in the analysis and discussion chapters varies between 14 and 42%, with an average of 30% of the transcript used in the analysis. Overall, approximately 31% of the total data collected was used in the analysis; this total reflects the whole interview and includes instances where the interviewer was speaking. Clearly, some of the interview participants have had more individual quotes used than others – a reflection of the diversity of the participants, the varying levels of engagement and the proportion of discussion relevant to the research. This is also reflected in the varying length of time taken for each interview. A comparison between the two interview transcripts included in Appendix 4, together with the data from table 4.2, demonstrate the different levels of engagement of the participants and the differences in the data collected that have led to the variation in the amount of data presented from each participant. Participant 3 is in the top bracket in terms of the number of distinct quotes presented in chapters five and six (9) and the proportion of the interview transcript that is presented (42). A review of the transcript included in Appendix 4 demonstrates the high level of engagement of this participant and the concordantly large amount of discussion directly relevant to teaching uncertainty – hence the large number of quotes presented from this participant. Participant 7, on the other hand, whilst clearly engaged in what is an interesting discussion about climate change, does not offer much that is explicitly related to teaching uncertainty. This leads to only one quote being used in the analysis and discussion, although this is a significant passage that in itself represents 21% of the interview transcript. Table 4.2 and the interview transcripts in Appendix 4 are designed to offer transparency in terms of how the data was used; the findings that have emerged from the discussions are discussed in more detail in the analysis and discussion chapters where relevant quotes are attributed to the participants who supplied them.

Table 4.2: Summary of relationships between data presented in analysis and discussion chapters (chapters 5 and 6) and the total dataset

Participant	Interview duration (approx.)	% transcript used	Number distinct quotes used	% total data
1	34 minutes	36	8	4
2	16 minutes	14	2	1
3	26 minutes	42	9	5
4	30 minutes	24	6	2
5	20 minutes	27	7	2
6	17 minutes	32	4	2
7	28 minutes	21	1	2
8	25 minutes	30	9	2
9	21 minutes	31	5	3
10	58 minutes	38	18	8
		Average – 30%		Total used – 31%

Chapter Five

Analysis and Discussion Part 1: Conceptions of Uncertainty

This chapter analyses the data gathered from the interviews conducted with academics teaching climate change in terms of their *conceptions* of uncertainty in this particular context. The conceptions identified are presented in three main categories (scientific conceptions, qualitative conceptions and pragmatic conceptions), which are then further divided into sub-categories – discussed in more detail in the relevant sections. These were identified by in-depth analysis of the interview transcripts with a particular emphasis on the contexts in which uncertainty was encountered during the interviews and the descriptions of these contexts given by the participants. The categories of conception are illustrated by indicative quotes from the research interviews.

The conceptions of uncertainty, and the attendant categorisation, give vital information about how uncertainty is viewed by those that are teaching and researching climate change and this in turn gives a key insight into the nature of uncertainty in climate change (the exploration of which is a major research outcome of this study). The conceptions also build into the next chapter where the teaching of uncertainty is discussed, as there are suggestions that how a teacher understands a particular concept is likely to have a profound affect on their teaching – as Walshe (2007) notes, teachers conceptions of their subject area are "reflected in the experience students receive" (p. 117). The conceptions may also give some indication of the importance of the personal context of the participants in determining their conceptions of uncertainty and whether their conceptions are inextricably and exclusively linked to their own research and teaching interests, or the academics are able to integrate diverse conceptions of uncertainty and hold multiple conceptions simultaneously.

Scientific Conceptions

The conceptions grouped together in this category are comprised of those instances where the discussion of uncertainty was situated in what may be described as scientific contexts. These contexts include uncertainties in the construction and employment of climate models, the use of statistics in quantifying uncertainty in climate change or climate science, uncertainty that arises as a result of factors within the physical climate system and uncertainties inherent in the nature of climate science and science more generally.

Climate Modelling

Climate modelling was identified by a number of participants as an area of climate change where they recognised uncertainty or encountered it in their teaching. Models used to forecast future climate change (and model past climate) contain many uncertainties. These uncertainties include those arising from theoretical limitations (where elements of the system are not fully understood or entirely unknown), computational limitations (where current computing power is insufficient to accurately model the full complexity of every aspect of the system), data issues (where data may be missing, inaccurate, insufficiently detailed or not to a sufficiently high resolution – this data then has to be parameterised in order to be included in the model) and assumptions (where factors such as initial conditions or future emissions scenarios are included in the model in order to make it as accurate as possible, but must be estimated based on realistic projections and assumptions) (Vidale *et al.* 2003; IPCC 2007). Climate models are, therefore, fraught with 'gaps', parameterisations, assumptions and limitations, all of which contribute to the significant uncertainties inherent within them.

This view of the uncertainties inherent within climate models is borne out by the following response from participant 10:

> "I do talk a bit [in my teaching] about climate modelling and how that works because I think that's also important, not that they [students] will necessarily turn out to be modellers at all, but just that they understand what assumptions are being made in a model and where the parameterisations are and where the difficulties are with data input...you know, it's all about uncertainty, so it's understanding that when you see that number that's in all the models saying

it's going to be between x degrees and y degrees by 2100, where does that actually come from." (Participant 10)

An interesting point to note here is the view that climate modelling is "all about uncertainty" and that understanding this uncertainty is important for an understanding of how the results generated by models are arrived at and used in decision making. The emphasis here is not on how the inherent uncertainties might undermine the use of climate models, rather that a comprehension of the uncertainties enhances the understanding of the models themselves and, therefore, how and why they are useful in understanding climate change and in decision making. Also noteworthy is the point that climate models and their inherent uncertainties are worth learning about, even if students won't go on to become climate modellers in the future. This perhaps indicates that climate models are a useful way of introducing uncertainty when teaching climate change. The view that understanding the uncertainties associated with climate models does not undermine an appreciation of their usefulness was supported by participant 3:

"I might spend a lecture talking about...state of the art climate models and all the terrible problems they have in predicting things and yet how useful they are as a tool for predicting future climate change" (Participant 3)

Interestingly, in this case, this is a conception that has its origins in the particular research interests of the participant, as illustrated in this quote:

"I feel comfortable in the ways that we can explore the uncertainty...I'm working on the palaeoclimate modelling [in my research] so you can compare your model to lots of different eras and test it quite strongly I think, and although you know that it's got it's weaknesses it doesn't mean you don't know what those are, you know, you're not walking blind through a mist or something you know that it's particularly good at one thing and particularly less good let's say at another...so I think we're quite aware of the limitations...but if you go around saying well you know the model can't do this and the model can't do that and we're not sure about that it does sound quite negative when in fact we've got a reasonable handle on lots of these things" (Participant 3)

The above quote demonstrates that the participant has an awareness of the potential dangers of presenting uncertainty in this context (i.e. the potential negative impact associated with the idea that uncertainty may undermine people's perceptions of knowledge), but that she herself is comfortable with uncertainty and the procedures and methods used to explore and understand it in the context of climate modelling.

Uncertainties associated with limitations in computing power were identified as being potentially troublesome for students by participant 5:

"I mean they [students] have more issues with things like modelling, what really goes into a climate model what's really achievable given kind of current computing power...I mean, when you start talking to them first of all they kind of have an idea that you can shove everything into a climate model and you can have ice sheets and ecosystem processes and stuff, and then when you tell them what actually is [in] a climate model they kind of think, that's really quite simple and [laughs] does it really give you a good answer? You know that sort of thing, which is good that they're kind of questioning it." (Participant 5)

This may be linked to a difficulty, on the part of the students, in comprehending the complexity of the climate system and the need to simplify it significantly in order to model it. It may also be linked to beliefs regarding the ability of computers and technology to solve any problem, no matter how large. Interestingly, the participant notes that this questioning of the "answers" provided by climate models is a good thing – potentially linking back to an understanding of models being concordant with an understanding of their limitations and inherent uncertainties.

As alluded to in all the quotes above, climate models present a useful means of framing and contextualising uncertainty in the context of climate change. This is demonstrated further by the following quote from participant 9:

"I mean uncertainty came through probably, in some of the climate courses that I've been involved with, when we've been using climate models and looking at specific models and sensitivity and so forth...and realising that there were some feedback mechanisms that were really poorly understood and some huge assumptions." (Participant 9)

The above response resulted from a question about whether the participant was asking her students to consider uncertainty explicitly through her teaching. Interestingly, it was through teaching about and practically *using* climate models that she felt uncertainty was encountered by her students and realisations about uncertainty were achieved. The point that not just a theoretical understanding but also the practical application of models was useful in terms of understanding uncertainty in this context is an interesting one; this will be explored in more detail in chapter six.

Quantifying Uncertainty

Many of the participants conceptualised uncertainty in terms of how it is quantified in scientific contexts – in other words, this category is comprised of those instances where uncertainty was described in terms of statistics, confidence limits, probabilities and measures of reliability. Quantifying uncertainty was seen by many as a key method for framing uncertainty and thereby achieving understanding, however it was also noted by many that a quantitative approach was potentially troublesome for students, particularly in the context of Geography programmes and departments.

The perception that students perhaps find a quantitative approach to learning about uncertainty troublesome is highlighted in this quote from participant 8:

"One of the issues that I think my physical [geography] colleagues have grappled with more than probably us on the human side is the question of scientific uncertainty and the fact that students take a while to understand [say]...70% certainty...they [students] really have difficulty understanding probability and probabilistic forecasting and if you say to someone, oh tomorrow there's a 50% chance of rain it doesn't mean it'll rain or not." (Participant 8)

Aside form the issue of a quantitative approach proving troublesome for students, and perhaps staff (it is something that "colleagues have grappled with"); it is also interesting to note this particular participant's conception that this numerical means of presenting uncertainty is specifically related to what he calls "scientific uncertainty". This scientific uncertainty is seen as being external to the participant's own area of expertise (in human Geography) and defined in terms of percentage probabilities and probabilistic forecasting. The potential conclusions that may be drawn from this are two fold: firstly, that scientific uncertainty is distinct from other types of uncertainty and refers to those uncertainties that may be quantified in some way, and secondly, that perhaps this scientific approach is in some way troublesome for teachers and students alike, although the conceptualisation of scientific uncertainty appears to come easily.

The conception that a numerical or statistical approach to uncertainty is central to achieving understanding is highlighted in the following quote, from participant 3:

"I think part of the interesting thing about becoming a scientist and learning about doing real science is when you realise that nobody else has done it and nobody knows the answer so you really have to sort out your statistics to sort out how sure you are about it and I think things are changing...I've heard in Geography there's a lot more statistics taught than there used to be, I'm not really sure but I think that whole thing is really important to get across quite early on...statistics is kind of the point you know...dealing with the statistics properly is kind of the point of science and there's no point in doing any experiment unless you know how sure you are about the result...and that would link in with the uncertainty stuff you know because if you don't have a good feel for what a 2% uncertainty is compared to a 50% uncertainty and how you calculate those and how you assess those then that all feeds in...that would be more like the really quantitative stuff..." (Participant 3)

This quote highlights the importance, for this participant, in understanding how and why uncertainties are quantified – getting a "feel" for the differences between different uncertainties that have been assigned different numeric values. Interestingly, this participant also sees this understanding as being more widely useful, she talks in terms of "becoming a scientist" and "doing real science" and how an understanding of the use of statistics for tasks such as quantifying uncertainty is central to this. She also notes that there is a movement within the wider discipline of Geography to use these sorts of approaches, perhaps an indication that this is something that students struggle with despite its importance; this also echoes the conceptions of participant 8 above.

The emergence of quantitative conceptions of uncertainty and the realisation that numerical approaches may be a valuable means of introducing and understanding uncertainty are lent further significance when one considers just how uncertain a subject area such as a climate change is. This is emphasised by the following quote, again from participant 3:

> "The kind of models I was used to in Particle Physics were obviously relatively simple you could run them quite quickly, the equations in them were quite few and quite simple and they gave incredibly exact predictions for...I mean kind of statistical distributions not exact predictions but for things that you know...very quantifiable numbers of momentum of particles and mass of particles and things...and climate change is so much fuzzier than that, for example in Particle Physics you wouldn't announce a result unless you had the confidence limits of 99.9%, which is sort of 5-sigma or whatever...but in climate science people are incredibly happy with sort of 90% confidence limits or lower...you know 50 or 60 % confidence limits, so it's so much more fuzzy and the models are so incredibly complicated and no one person understands, for example, the whole of the Hadley centre model, people understand different bits of it...so it does feel...yeah, quite uncertain compared to my previous field..." (Participant 3)

Here, she refers to her previous field of academic research (Particle Physics) and compares it to her current research on climate models. There is an interesting contrast here between other branches of science and climate science and their respective approaches and attitudes towards uncertainty. There is also an allusion to the fact that the participant has struggled somewhat with the switch between fields and the change in her conceptions of uncertainty that this has required. However, it may be that it is this change that has led her to her current position on the importance of the use of statistics and other numerical methods and, by extension, the importance of understanding uncertainty through these methods.

A slightly different approach to quantifying uncertainty was highlighted by participant 1 and is demonstrated in the following quote:

> "Certainly in the kind of statistical sense we try and make them [students] appreciate uncertainty...so, certainly in laboratory methods we have a way in which we try to get them to appreciate reliability through assessing reliability of a technique, directly and indirectly. So, they [students] will take a standard sample of known concentration, a certain chemical or something, and then they'll see how well three techniques are able to recover that value and then they'll test it indirectly on unknown samples and they'll look at how comparable the data is from these three techniques...now these three techniques essentially measure the same thing but in very independent ways and if you're arriving at the same value at the end of it having gone through three different routes then you can be assured of the reliability...so they get that kind of quantitative sense of reliability..." (Participant 1)

The exercise described above is chiefly concerned with determining the reliability of various analytical techniques and may not a first be considered a direct approach to understanding uncertainty in a "statistical sense". However, the reliability of instruments and techniques, and the values they generate, is a key component in understanding sources of uncertainty, after all, one of the key sources of uncertainty described above in relation to climate models stems from issues with numerical data. It is interesting in itself that this participant has identified this exercise as being central to an understanding of what may be described as 'scientific uncertainty' and perhaps reveals a conception of uncertainty that is rooted in highly analytical and instrumental research. This may be a reflection of the participant's particular research interests in Geochronology.

Nature of the system

Some of the participants in the study identified the physical climate system itself as a key source of uncertainty, conceptualising this in terms of the complex nature of the system, the action of positive and negative feedbacks and the idea of randomness and chaos. These conceptions were again characterised by their potentially troublesome nature, as highlighted in this quote from participant 5:

> "They [students] struggle with ...trying to get a handle on uncertainties and things...the idea of randomness and chaos...which is quite difficult to explain." (Participant 5)

The troublesomeness of this conception of uncertainty is twofold with students struggling to "get a handle on uncertainties" and the complex ideas of randomness and chaos (the sources of uncertainty in this instance) and a further acknowledgement, from the teacher, that this is "difficult to explain". This inherent difficulty in communicating how the physical climate system works is echoed by participant 4:

> "I try to actually let students know how little we know about things and how you know we're after the leads and lags in the system but often it's too difficult to actually do that...but I let them [students] know where we're trying to get to." (Participant 4)

Here the uncertainty is framed in the context of "how little we know about things" and the difficulty this presents in establishing what the "leads and lags" (essentially, how factors affecting the climate system temporally and spatially 'phase' with their concordant effects) within the system are and how they relate to one another. The aim here is to "let them [students] know where we are trying to get to", this reveals not only the uncertain nature of our understanding of the climate system but also the idea that there may not be certain outcomes or definitive answers.

Perhaps linked to the seemingly random and chaotic nature of the physical climate system and the issue of leads and lags, is the complex action and interaction of positive and negative feedbacks, which characterise the conception of uncertainty in the following quote from participant 1:

"Something we do at level 3, and we're going to build it into level 1 with our new Geography course, is a kind of understanding of systems theory and the...effect of negative feedback and positive feedback, how positive feedback amplifies disturbance and negative feedback leads to diminutions in that disturbance...just coming up with these very basic systems diagrams to show interactions of various aspects and I think that's a very good way of getting them to appreciate the connections between things and how the uncertainty...the individual uncertainties associated with that aspect of the system can then propagate to a massive uncertainty once you accumulate...once you, um...sum them is the wrong word..."

Interviewer: "Because of the complexity of the system?"

"Yeah, exactly." (Participant 1)

The uncertainty in this case is defined in terms of the complex interaction of the components of the climate system through positive and negative feedback mechanisms and the propagation of the associated uncertainties that may result when the full complexity of these interactions is considered. This is an important conception in terms of understanding not only the uncertainties associated with our knowledge of components of the system and how they interact but also of the role of complexity as a source and potential multiplier of uncertainty. It is interesting to note that the strategy in this instance is to come up with "very basic systems diagrams to show interactions of various aspects", in other words eliminating some of the inherent complexity, before reintroducing this complexity from the perspective of the effect it may have on uncertainties associated with the components and their interaction.

Nature of Science

Many of the conceptions of uncertainty held by academics are rooted in those uncertainties that are inherent in the nature of the science of climate change and science more generally. The uncertainties included in this sub-category are comprised of the uncertainties arising from the provisionality of scientific knowledge and the practice of the scientific method, uncertainties in palaeo-climatological proxies, uncertainties emerging from incomplete knowledge of elements of the physical climate system and uncertainties compounded owing to the multi-disciplinary nature of climate change science. This is a fairly broad sub-category, however, all the conceptions grouped here are linked in that they are all defined in terms of what the participants do and think as teachers, researchers and scientists, whilst not necessarily being as contextualised as the conceptions described in the sections above.

The status of scientific knowledge as provisional and contestable is seen as a key source of uncertainty and one that students may find potentially difficult. Participant 8 identifies this through his students questioning the scientific consensus on anthropogenic climate change:

> "They [students] ask, well is science agreed that climate change is human induced or not? And you have to say well the evidence is pointing that way, more and more...but don't forget evolution is still a theory that hasn't been proved to everyone's satisfaction and that has been going round for over 100 years so." (Participant 8)

The participant in this case identifies the theoretical nature of science, the fact that although scientific frameworks may elegantly and comprehensively explain phenomena observed in reality (as in the case of evolution) they retain the status of theory as opposed to incontrovertible (in other words certain) truth. This is close to what Yore *et al.* (2006, p. 113) characterise as "The Nature of Contemporary Science" where scientific knowledge is described as:

"A set of temporary descriptions and explanations that best fits the existing evidence and current understanding of the real world within the limitations of people's sensory and intellectual abilities. Science knowledge develops epistemologically as a hypothesis and collected data is utilized to support or refute the hypothesis. Knowledge claims are not absolute, only supported or falsified; and the science community and broader public are expected to evaluate these claims critically".

There are parallels between this description and the concept of post-normal science described in chapter two and this "modern" definition also offers a contrast to the "traditional view" that scientific knowledge is developed solely through "observations, measurements and human reasoning" (Yore *et al.* 2006, p. 113). This is a fundamental source of uncertainty; however, it is also one that scientists recognise and deal with on a constant basis, content to operate in a mode in which knowledge is provisional and theories are constantly reviewed and refined. This is emphasised by the following quote from participant 2:

"Science, or what we find in science is changing all the time...like, when I teach something that is quite recent I find myself adding that, yeah probably in 5 years time it's going to be rubbish...it's going to be rubbish in the sense that...not that it's rubbish but its going to change and we'll think differently and we'll know other things and...I think this is a very good lesson...you learn or you study the up to date, what is going on, but I feel that I have to make sure that people are not clinging to it as...that's the truth, that's the ultimate truth...so this is something about science itself, that I think is important..." (Participant 2)

The above quote reveals that the participant not only recognises the dynamic nature of scientific knowledge but also that there are important lessons to be learned about the absence of "ultimate truth" and, therefore, the absence of true certainty in science. This conception is built upon by participant 3 (in direct response to the question of what she felt were the key concepts within the subject area of climate change) who links this conception of the uncertainty of knowledge to the scientific method and what may be termed a 'scientific mode of thinking' whereby scientists are able to hold many provisional and theoretical explanations at once and are prepared to alter them in the face of new evidence:

"I think the very top one for me...is certainty, uncertainty and certainty...because in various different conversations with non-scientists, not just about climate change, it's really hard to convey the scientific method to someone who is not familiar with it...and by that I mean mainly the way that scientists will say no we're absolutely sure about this because we have tested it and we've done lots of experiments and we've thought about it very hard and we've done lots of sums and we've looked at it from all angles...and yet I won't be surprised if next week we find out something new that puts it all completely, you know...the whole sort of Einstein over Newton type stuff...where it can all kind of go out the window, but we're very sure right now but tomorrow we might be saying something completely different and scientists can kind of hold all that stuff in there, they are quite used to that sort of process of yes we're very sure but we're completely open to being wrong." (Participant 3)

This openness to "being wrong", however, may not be as straightforward in all cases. This is alluded to by participant 1, who further contextualises uncertainty in the scientific method in terms of the testing of hypotheses, acknowledging that in complex subject areas such as climate change hypotheses do not always provide solutions that correspond to all available evidence:

"I can think of an example where we talk about Cenozoic cooling and how there are 4 hypotheses for Cenozoic cooling...actually, and I make no bones about it, the examples are taken from Ruddiman 2001 which is an excellent text in that he presents the hypotheses one by one and then tests them for specific periods of global cooling in the past and then...at the end of the lecture we have this kind of summary diagram which puts all 4 hypotheses together and looks at whether or not the timing of them are consistent with global cooling and...invariably that is the side where students see that there's a mass of uncertainty, that no one hypothesis explains every period of global cooling that the Earth has encountered so...they are aware that there's uncertainty and they are aware of the debates but I think they're probably in the same position as the scientific community are at the end of the day that they know that there's uncertainty and unless...you introduce one hypothesis you don't tend to stick to one particular hypothesis to explain something. (Participant 1)

Not only are the hypotheses themselves incomplete in their explanation for the observed phenomenon (in this case global cooling in the last 65 million years) but there is also considerable debate around which hypothesis fits best. The participant rationalises this through the idea that it is mainly the proponents of a given hypothesis who are likely to adhere to their particular interpretation of the evidence and compares students' awareness of this uncertainty to that of the scientific community itself. This is an interesting conception that brings in a human dimension to climate change science; this will be discussed further in the section on qualitative conceptions. The uncertainty inherent in palaeoclimate reconstruction work, such as attempts to explain Cenozoic cooling, forms part of this conception from participant 6:

"Where a quaternary [time period from circa 2 million years ago to the present] interest comes into modern climate change studies...which may be an attribute of my interest rather than the broader climate change debate...but in terms of practical work we do a lot of lab work on microfossils and how they can be used to hind-cast climate if you like, but the reason for doing that is perhaps to test the accuracy of your models to predict future climate...but of course that contributes to the uncertainty because you're uncertain about what the fossil ecology was, you have a good guess but there's uncertainty there which you can't really quantify...which then somehow has to get fed into the future prediction so...I think they start to get a good grasp of that sort of uncertainty through palaeo-climatology...and to some extent, you know this may be a personal opinion but...coming from a palaeo-climatological background I think they probably get a better idea about what potential for climate change impacts will be in the future if you know what similar environmental impacts had been in the past." (Participant 6)

In this case the uncertainty is centred on the largely unknowable factor of fossil ecology. Whilst attempts can be made based on observed ecologies of similar organisms in contemporary environments, scientists will never be able to say for certain how exactly ancient and now extinct organisms lived. This is a fundamental and accepted part of 'palaeo-science' however and, as the participant above alludes to, understanding this uncertainty may give an improved understanding of issues associated with debates around contemporary climate change. It is interesting to note that, once again, the participant links this conception of uncertainty to his own personal research interests and how he brings this into his teaching.

This question of research background and its importance in determining conceptions of uncertainty develops further when one considers the multi-disciplinary nature of climate change science and the concept of 'ownership' of uncertainties. This was a point raised by participant 4:

> "Each area within climate change considers themselves to be happy with the errors or whatever associated with their proxy or other...but it's now that their all trying to combine these things in the global earth system that you need to know about the uncertainty associated with somebody else's research...and it's not easy to map that uncertainty from somewhere else on to your own research area...so I know there are lots of efforts to do that and to come up with strategies to do that." (Participant 4)

The point is expanded upon together with some of the "strategies" mentioned above in the following quote:

> "You can have chronology people, you can have data people, you can have modelling people who all think they know what uncertainty is but they don't understand somebody else's type of uncertainty...for example, I know the models might be wrong, I don't know how wrong they are because often the only people who know that are people who work with them closely...and there is...I mean generally now all those different spheres are revealing more of themselves to other communities...not saying that each group was ever dishonest it's just that there's a sort of feeling that you've got to be more open

about it and...the reason it's easier for people to be more open about it is that there's funding associated with it [laughs]...those bodies that are awarding cash recognise that they've thrown so much money at collecting data that they should now be throwing money at the analysis and synthesis of that data and understanding rather than let's go and collect more...so there's a certain amount of retrospective operation...it's certainly something that has appeared over the last 5 years it feels like to me...first it was all about going out and collecting data now you have to put it somewhere so it's all about repositories, and I suppose that was so that the next generations can then re-analyse data, but also share it with other groups, so once you've got a repository set up it's ok I've got your data but I don't know what it means...I suppose it's also a response to community...you know scientific community practices often were individual, whereas now you just can't survive as a loner you have to be part of networks, consortia and by being part of those networks you branch out, you probably branch out into fields you're uncomfortable with and need to know more about their uncertainty." (Participant 4)

This conception is clearly one that is heavily grounded in the participant's own experience of climate change science research rather than teaching, but it is an interesting one nevertheless. The notion that there are unique and different types of uncertainty associated with different disciplinary areas within climate change science and that it is difficult to not only understand these 'foreign' uncertainties but also combine all of them in the complexity of the climate system has fairly profound implications for teaching uncertainty, particularly in relation to issues of tacit knowledge and the bounded nature of threshold concepts. These will be discussed in more detail in the following chapter.

In identifying what some of these diverse uncertainties may be and where they may originate participant 10 reveals that one of the fundamental aims of climate change science is reducing these uncertainties:

"And in climate change of course with the scientific uncertainty there is huge research going in to bringing those error bars down and so on, so disregarding the human element for a minute one can point to why it is that we are uncertain about the role of aerosols in radiative forcing for example, or the role of clouds…what do we understand, what don't we understand, why don't we, what work is going on to push that boundary and bring the uncertainty down." (Participant 10)

It is interesting to note here the reappearance of the term "scientific uncertainty", in this instance explicitly linked to "disregarding the human element". It would seem then that there are uncertainties associated with climate change that are viewed as the preserve of climate change science and that it is the job of science and scientists to reduce these uncertainties. The allusion to pushing a boundary may imply that this work is seen as being at the cutting edge of climate change science. The question of "what do we understand, what don't we understand, why don't we" forms part of the final scientific conception of uncertainty, described here by participant 9:

"[A former student from our department, now working in climate change science, came back and did a presentation]…he was actually putting parameters around, well this is the bit that scientists are fairly certain about…and here are the bits that we're still really in the dark about what might be happening, so it was a really interesting pitch I thought for people to get an understanding of…here's the science behind it, here are the bits that we're fairly confident about but here are the bits that we're really very uncertain about and unsure of and need more research and so forth so…some people make some assumptions about that and if those assumptions are right then this is the scenario but it could be wrong, something else might happen…so yeah, it was a kind of interesting pitch I thought – the students could appreciate that." (Participant 9)

Similarly to participant 10, this conception identifies reducing uncertainty as a key task within climate change science – "the bits that we're really very uncertain about and unsure of…need more research". It is interesting to note here that this approach highlighting parameters, assumptions and uncertainties explicitly was seen as interesting and perhaps novel and something that "students could appreciate".

Qualitative Conceptions

The conceptions presented in this category are those whose origins are more qualitative or 'human' in nature. That is to say, they pertain to uncertainties that arise from human behaviour, predicting future scenarios, social or political factors and conflict between experts. They do not possess the overly scientific attributes of the conceptions in the previous chapter and thus manifest themselves in slightly different ways.

Human Behaviour – Scenarios and Choices

Many of the participants identified scenarios of human behaviour and human responses used in predicting the impacts of climate change as a significant source of uncertainty. These scenarios are based on qualitative assessments of factors such as future emissions of carbon dioxide from human activities, future mitigation measures used to temper the effects of climate change, future patterns of population flux and future economic development. Given that these factors are essentially unknowable and are ultimately an expression of human behaviour (which may be unpredictable) they form a large part of the uncertainty associated with prediction for decision making on climate change. The assumptions that these scenarios are based on are highlighted in the following quote from participant 10:

> "I'm very keen for them [students] to understand how scenarios work...so I use the IPCC scenarios and we spend several lectures on understanding how those scenarios are derived, what they're based on and that they're not actually based on climate science, they're based on assumptions about how the world is going to be with population and economic development...which immediately brings in that this is not about some aspect of the bio-physical system, it's the interaction which is important." (Participant 10)

It is interesting to note here the clear distinction the participant makes between the derivation of these scenarios and climate science, highlighting the fact that they are based on qualitative assumptions and are, therefore, uncertain to a degree. However, it is also prevalent to point out that she goes on to note that this realisation in itself is an important outcome, highlighting the fact that humans play a key role in the climate system and in climate change and, as such, should be included in any assessment or prediction of the future. This interaction between the human and physical elements contributing to climate change is highlighted by participant 3 in the context of climate modelling:

> "A lot of people in climate science will predict future things based on business as usual scenarios but it's pretty likely that things aren't going to be business as usual compared to like say the 1990s onwards...things are already changing, emissions levels are changing by country...some are going up quite a few are going down...so we might predict all this stuff and then governments act on it and then it doesn't happen so will people think that scientists were all kind of doing a 'millennium bug' on it and we were wrong or is it the fact that governments actually did something that changed it." (Participant 3)

The "business as usual" scenarios included in climate models are another example of the parameterisations and assumptions that are included as a matter of course in these reductionist tools, reference to which can be found in the section on climate modelling above and in chapter two. As the participant points out, these scenarios become immediately obsolete once they are included, which in turn contributes to uncertainty in the predictions generated by the models. Key to this is the notion that qualitative information of this kind is perhaps not as easily resolved as quantitative or scientific data and, therefore, presents a different challenge in terms of the uncertainty it precipitates.

A further interesting point to emerge from the above quote is the effect this qualitative uncertainty may have in terms of outcomes linked to decisions taken and choices made in the face of this uncertainty. If given outcomes precipitate that were not predicted or outcomes that were predicted do not occur (as in the case of the 'millennium bug'), is this as a result of mitigating action or were the original predictions simply "wrong"? This issue of choice and how it relates to uncertainty is raised by participant 8 in a discussion around a sustainable energy module:

Interviewer: "In the sustainable energy course…you've got an idea there of…yes you've introduced uncertainty but decisions have to be made…"

"Yes, that's correct…that we have choices and I think that whole idea of the first year module is…you can't just forecast long term trends, you've got to think about all sorts of choices and that choices can take you down several different pathways…and that you're not tied slavishly to follow a groove into the future…" (Participant 8)

Choice would, therefore, seem to be a key feature of human behaviour to consider when contemplating uncertainty. This element of choice means that "you can't just forecast long term trends", essentially making far-future predictions affected by human behaviour (such as in climate change) impossible. This, combined with the potentially unpredictable nature of human behaviour makes this an important dimension of the uncertainty associate with climate change. This is a view that appears to be shared by participant 8 as he draws together the issue of choice with an analysis of qualitative scenarios for predicting the future:

"What if we take these scenarios that are going to take us into 4 different futures…and it's all a question of political choice and political conviction… there's obviously a strength in looking at scenarios over and above the superficially scientistic [sic] approach from existing data, which students see as strong because it looks more scientific, so I think there is some success in that…" (Participant 8)

This approach is seen as successful in that it not only reveals the importance of choice in this context but also causes students to query the effectiveness of an approach that only considers science and existing scientific data when making predictions.

Whilst acknowledging the effect of choice on uncertainty in climate change, it would also appear worthwhile to note the effect that uncertainty has on personal choice in relation to climate change. That is to say, the effect that uncertainty has on students' personal decision making when they consider their own responses and feelings towards the climate change issue. This is reflected in the following quote from participant 7, who teaches about climate change in the context of tourism Geography:

> Interviewer: "Would you say for example taking a kind of policy angle and linking it to things like tourism...are students very certain of the kind of...you know are they aware of the uncertainty that exists in climate change...you know, that we can demonstrate to a degree that we are responsible for changing the climate but there's uncertainty inherent in that, there's uncertainty in terms of the policy response and the social response...do you think they have a handle on that or is it very much that they include climate change as an issue within tourism say?"
>
> "I think they're aware that they differ in their perspectives on this and one example I'll give you is that early on in the semester when I raise...climate change comes up in a lot of contexts and when I write a lecture I have general information and material I want to get across but occasionally I might...spontaneously as you think on your feet, you might link an issue if something comes up or something topical on this issue comes up and you discuss it in class and I remember I've asked for several years now, and this is something I'm just quite interested in doing potentially more research on...and this kind of links to my research on Antarctic tourism and climate change which I'll get to later...but I'm interested in one aspect of this...how the public, and this includes my students, how they perceive all of these...this bombardment of messages about climate change, how they filter that, how they process that and how that may in some way influence them to change their travel buying habits or their own practice in terms of tourism and so I ask them a few questions in class and we get a very interesting discussion going...I said to them, ok given what you know about climate change right now whether you understand all the facts and figures, whether you agree it's happening to the extent that some people argue it is and whether you agree with people who say it's nothing to worry about as much as people are saying, wherever you are on the spectrum what I want to know is...raise your hand if

what you know is influencing the way that you're making your tourism choices and...so we get different people raising their hands, so I say so how is it influencing you and one student said, well I'm not sure it's really influencing my decisions because I'm really not sure what to make of all the information and I'm just carrying on as normal, so someone else said, wait a minute, I'm definitely intentionally not travelling as far or I've made decisions not to travel as much because of climate change because if we all don't do our bit then nothing is going to change, then I have another student in my class and she has two young children, she's a mature student, and she said, well I'm not changing my habits at all in fact I'm probably going to travel more because I want to see those places before they change. And I said to my class, well how about that, what was the chances of that, that the first three students are presenting those three places on the spectrum, that's exactly what...I couldn't have explained that more clearly than you've explained that to each other that on this spectrum, regardless of what the messages are, regardless of there clarity or accuracy you are all drawing your own conclusions and changing your behaviour or not based on the information you are getting in the media...so that's very powerful in tourism terms and there are people in tourism that are concerned that the messages are going to limit or detract or affect in a negative way the amount people travel and other people are concerned that they might be able to design new products around this concern and create better aircraft and better forms of transport and more you know lower emissions and all these other things that might connect so that the transport doesn't contribute so much to global warming and so it's really interesting that in my own classroom the spectrum is represented that way but I suspect that in a university and if you did research on this with the public you'd find a similar thing that there's no clear...measuring the impact a particular media message has is very difficult to pin down." (Participant 7)

The inference here is that the uncertainty surrounding climate change has very different qualitative outcomes in terms of how it affects the students in this case. The first student feels that they can not integrate the mass of information surrounding climate change and therefore will "carry on as normal", the uncertainty in this case is sufficient to preclude any action as the 'correct' action is unclear. The other two positions on the "spectrum" offered by students appear to be more 'certain' in their appraisal of climate change, however the responses differ considerably. One may be described as a fairly considerate, worldly position while the other seems more selfish at first, although it appears to be characterised by the participant as a view born of personal experience. Research into the role of personal beliefs in relation to decision making under uncertainty indicate that beliefs may actually be constructed in the act of making choices, as a result of limits to the amount of information-processing capacity possessed by humans (Payne *et al.* 1992). It may be that the choices expressed by the students represent the articulation of their understanding of uncertainty and that the beliefs express their subjective position in relation to the uncertain phenomena of climate change – this may indicate that a liminal shift has taken place on the part of the learners, or that a degree of liminal variation exists among the group. It is interesting to note that the latter two preferences offered by the students appear to demonstrate a fairly pragmatic take on what is a potentially troublesome concept. Conceptions of this kind are discussed in more detail in the section on 'pragmatic conceptions'. The point the participant makes about "the bombardment of messages" and the difficulty in measuring the impact of material in the media brings into focus the position of uncertainty and climate change in the wider social context, discussed in further detail in the next section.

<u>Society – Politics, Risk and the Media</u>

This sub-category is broad in its scope; however, all the conceptions grouped here share the characteristic that they are all essentially grounded in human society. They include conceptions of uncertainty linked to political factors, uncertainty over risk and vulnerability and uncertainty arising from media reporting on the climate change issue. The politics of climate change was touched upon above, where it forms a key part in qualitative assessments of future climate change and contributes significantly to uncertainties in scenarios and associated with choices. Another dimension of politics, however, is the effect it has on how uncertainty is presented; this was highlighted by participant 10:

"And then there's the whole political dimension of the IPCC process and the fact that it's a consensus document that we see coming out...so while it has a huge relevance and currency it is nevertheless the product of a highly political process in many ways." (Participant 10)

The fact that the IPCC represents a consensus document that is affected by political decision-making infers that the presentation of uncertainty will be affected. Some uncertainties may be glossed over or go entirely unmentioned whilst others may be highlighted in great detail depending on the stance of particular stakeholders. This has the potential to have an effect not only on how uncertainty is perceived but also on understanding uncertainty.

The concept of risk or vulnerability associated with climate change was identified by participant 10 as another that may bring out uncertainty:

"I do the impacts and then I talk about mitigation and adaptation...with the impacts there I am really talking about uncertainty and risk and vulnerability, so there's that whole what constitutes vulnerability, what is risk and how do we asses it, and what are the responses to risk, and I look at it from a sectoral point of view, so we have a lecture on health impacts of climate change, and then I am getting them to...although the lecture may not talk about risk I then will come in and say, well we've seen that one, what do you think about the risk element of this, how vulnerable here where we live in Canberra to the possibility of malaria for example, and expanding out of the tropics, or dengue fever or waterborne diseases associated with flooding, and compare that vulnerability and risk to what it might be like in Indonesia or Bangladesh or whatever..." (Participant 10)

The approach outlined here is twofold, firstly to establish what risk and vulnerability are and how they may be assessed and, secondly, to consider the uncertainty associated with risk and vulnerability. Here the emphasis is on the potential risks to human health posed by climate change; once again these factors possess the inherently unknowable characteristics associated with qualitative assessments of climate change impacts, similar to the dimensions of human behaviour discussed above. What these health impacts may be, how they will spread or be contained, what effect they will have on the population is impossible to know for certain; however, this uncertainty is a key factor in determining the level of risk these impacts may hold.

The potential risk associated with climate change form a large part of the media reporting of the issue. In some cases this risk may even be overstated as a means of generating interest in a story, this is certainly the view of participant 6:

> Interviewer: "So if we can kind of follow on form that and maybe think a little bit more specifically about certain concepts this idea of complexity and also uncertainty...things like that, do you address that in your teaching?"
>
> "Yes...the uncertainty one in particular...because many students are aware of what media hype are saying about sea level rise and about temperature rise and so on and the unfortunate thing is that the media quite often will give you the maximum rate of the uncertainty to sell newspapers or whatever." (Participant 6)

This treatment of uncertainty in climate change by the media is clearly important to this participant's conceptions of uncertainty as a whole, identifying it as a key context in which his students encounter uncertainty. It is interesting to note that the participant feels it is important to bring this manipulation of uncertainty, as he perceives it, to the student's attention. This may partly be a reaction to the "unfortunate" nature of this practice but also a means of making students aware that uncertainty is prevalent in climate change and thereby bringing them closer to understanding the concept. This approach is taken slightly further by participant 9, who views the presentation of climate change in the media as a valuable means of engaging students with uncertainty:

> "I'm not sure about the role of the media in all this, certainly around the whole climate change debate, there's been a lot of uncertainty...there's a very strong lobby group who are sceptics in New Zealand and they have had a lot of media time in recent years...so I'm sure that helps in adding to students sort of understanding of this isn't a straightforward matter, whereas in some other topics they may not see that other side of it, but certainly it's got them to

question a bit more about what is going on, who is telling the truth, if they think there is a truth...which I suspect some of them do early on but as they sort of mature they should start to let go of that." (Participant 9)

The exposure of climate change "sceptics" in the media brings to student's attention the contestation of knowledge surrounding climate change, and climate change science in particular, as well as some of the qualitative factors such as political agendas associated with the issue. The participant sees this as a useful means for encouraging students to ask questions and explore not only what certainties and uncertainties existed but even whether "a truth" exists at all.

Conflict-based Uncertainty

Uncertainty arising from disagreement among experts has already been touched upon in the section above on the nature of science and in the reflection on the political nature of the IPCC process. This may also be presented in a slightly different way in the context of decision making where different 'experts', or groups of experts, present different conclusions about future outcomes owing to "subjective judgements and starting conditions and development of the system they are modelling" (Patt 2007, p. 38). The uncertainty that this creates is termed 'conflict-based uncertainty' (Patt 2007), as discussed in chapter two. The acknowledgement from participant 1 in the nature of science section above that it tends to be only the proponents of a given hypothesis who use it exclusively to explain something may be an expression of this, the researcher's subjective feelings causing them to hold fast to one particular conclusion and creating conflict based uncertainty with other experts. Participant 1 also conflates an understanding of uncertainty with the balancing of evidence, potentially a conception that is grounded in conflict based uncertainty:

"Well at level two they can begin to appreciate uncertainty, by level 3 they have to be critical about uncertainty and try and weigh up the balance of evidence... they are certainly aware that there's debate and that's something that we try to get them to at least acknowledge, the different areas of debate, but in terms of trying to get them to balance up evidence they don't tend to do that voluntarily at level 2." (Participant 1)

It is interesting to note that balancing evidence is seen in this case as "being critical about uncertainty", implying a deep level of thinking about uncertainty. This would seem to be supported by the fact that the participant sees this as an outcome of learning later in a student's university career, potentially linked to maturation – a subject that will be discussed in more detail in the following chapter.

Pragmatic Conceptions

The final category of conceptions of uncertainty comprises those conceptions that are related to dealing with uncertainty pragmatically. These conceptions pertain not only to understanding uncertainty but also to the impact it has on decision making and how it is 'dealt with' in life generally. All of the conceptions identified here come from participant 10, possibly as a result of the fact that much of her teaching about climate change is situated on a course specifically designed for climate change policy and decision making. This pragmatic approach to uncertainty is revealed in the following quote:

> "It [uncertainty] is such a fundamental in everything, particularly in this area of climate change, but it's ubiquitous, so coming to grips with uncertainty and how you deal with it, how you convey it, describe it, work with it, and how you move on despite it and make decisions despite uncertainty I think is a really key thing for me." (Participant 10)

Reference to the ubiquity of uncertainty, even beyond the area of climate change, would appear to indicate that understanding uncertainty may be an important outcome not only for an understanding of climate change but also in other educational contexts. In saying that, however, it is interesting to note the participant in this case using terms such as "coming to grips with uncertainty" as opposed to an emphasis on gaining an understanding of the concept. This reveals a pragmatic conception more concerned with moving on despite uncertainty, not allowing it to interfere too much with decision making. Parallels may be drawn between this 'moving on' and the tourism choices identified by the students discussed in the above quote from participant 7. One way in which this pragmatism manifests itself is in the precautionary principle, as outlined by participant 10 here:

> "One of the discussions that I often end up having with students, and it comes from them not from me, but it generally comes up, is, in the end if you're faced with a situation where you cannot be definite, you don't have a yes or no answer to give, then it comes down to the precautionary principle...and for me that is the guiding principle, or some variant on it, but if you make a decision make that decision in such a way that you do the least possible future damage, and the intergenerational equity and all those other things come in as well...but to me that's it, if you've got a choice to make you make the choice that is going to do the least harm given your understanding of the situation." (Participant 10)

Here the participant identifies the precautionary principle as a direct response to uncertainty, a practical solution to the potential problems it may cause. The precautionary principle not only offers a practical means of dealing with uncertainty but also a potentially valuable means of conceptualising it; encouraging an approach that makes uncertainty an explicit part of thinking about climate change and understanding uncertainty an important element in decision making so as to cause the least future harm. The need to make uncertainty explicit is seen as an important part of participant 10's pragmatic conceptions:

> "A few years back I might not have been so explicit about uncertainty, not trying to hide it but just not really putting it in front and centre, but now I am because suddenly people are really aware of it, they know that it's there and if you don't talk about it then there's an assumption that there's something that you're not addressing...so I've got to put it out there and say that here is the uncertainty, despite that uncertainty this is what we see occurring in the world, this is what we understand, this is what we measure...and then for the future

> these are our best guess scenarios for what the future is going to look like, if we continue doing what we are doing, so here's the choice...do you say, well we don't really know and the scientists are uncertain and they're still disagreeing, so we do nothing? Or, [do we use the] precautionary principle? But for me, the personal journey has been the maturity in myself I suppose, self confidence I suppose to be able to feel that I can do that" (Participant 10)

The above quote draws together both scientific ("this is what we measure") and qualitative ("these are our best guess scenarios for what the future is going to look like") conceptions and places them in a pragmatic context, where the explicit presentation of the uncertainty in climate change feeds directly into the use of the precautionary principle. Uncertainty does not undermine action in this case; rather it may be used to help to define the best course of action. It is interesting to note here the participant's feeling that personal maturity on her part makes her feel more comfortable in addressing uncertainty in this manner. This will be discussed in more detail in the next chapter.

Characterising conceptions of uncertainty

This chapter has been an attempt to categorise and describe the multitude of conceptions of uncertainty held by the participants in this study. These conceptions appear to represent a range of different ways of looking at uncertainty in this context, which may in turn offer a means of characterising the conceptions themselves. Broadly, the conceptions have ranged from the scientific to the qualitative and from the philosophical (as in the uncertainty inherent in the nature of science and implying a deep level of thinking about the concept) to the practical (as in the statistical quantification of uncertainties in scientific data and implying a more ritualised treatment of uncertainty). This may be presented diagrammatically as in Figure 5.1, where selected conceptions are plotted according to the aforementioned factors that may be utilised in their characterisation. Conceptions of fundamental scientific uncertainty and conflict based-uncertainty share a degree of overlap as they both raise fundamental questions about the nature of knowledge, its establishment, evolution and use. Furthermore, qualitative conflict over ideas is a part of science and a source of uncertainty within science, hence the overlap of the two spheres and the slight incursion of uncertainty in the nature of science into the qualitative side of the quadrant. Quantification of uncertainty may be seen as a very practical and highly scientific conception as it allows for scientific data to be made 'useful' through the statistical accommodation of uncertainty. Equally, projections of future human behaviour may be viewed as highly practical as they are a requirement for forward planning although with high levels of uncertainty attached. Nevertheless, they are constructed due to their practical usefulness in decision making. Decision making is also a significant driving force in the formation of pragmatic conceptions of uncertainty, which can be said to incorporate all the elements of the categorisation. Pragmatic conceptions combine not only the qualitative and the scientific (as in the final quote from participant 10 above) but also the practical, where decisions have to be made despite uncertainty, and the philosophical, through conceptual frameworks such as the precautionary principle.

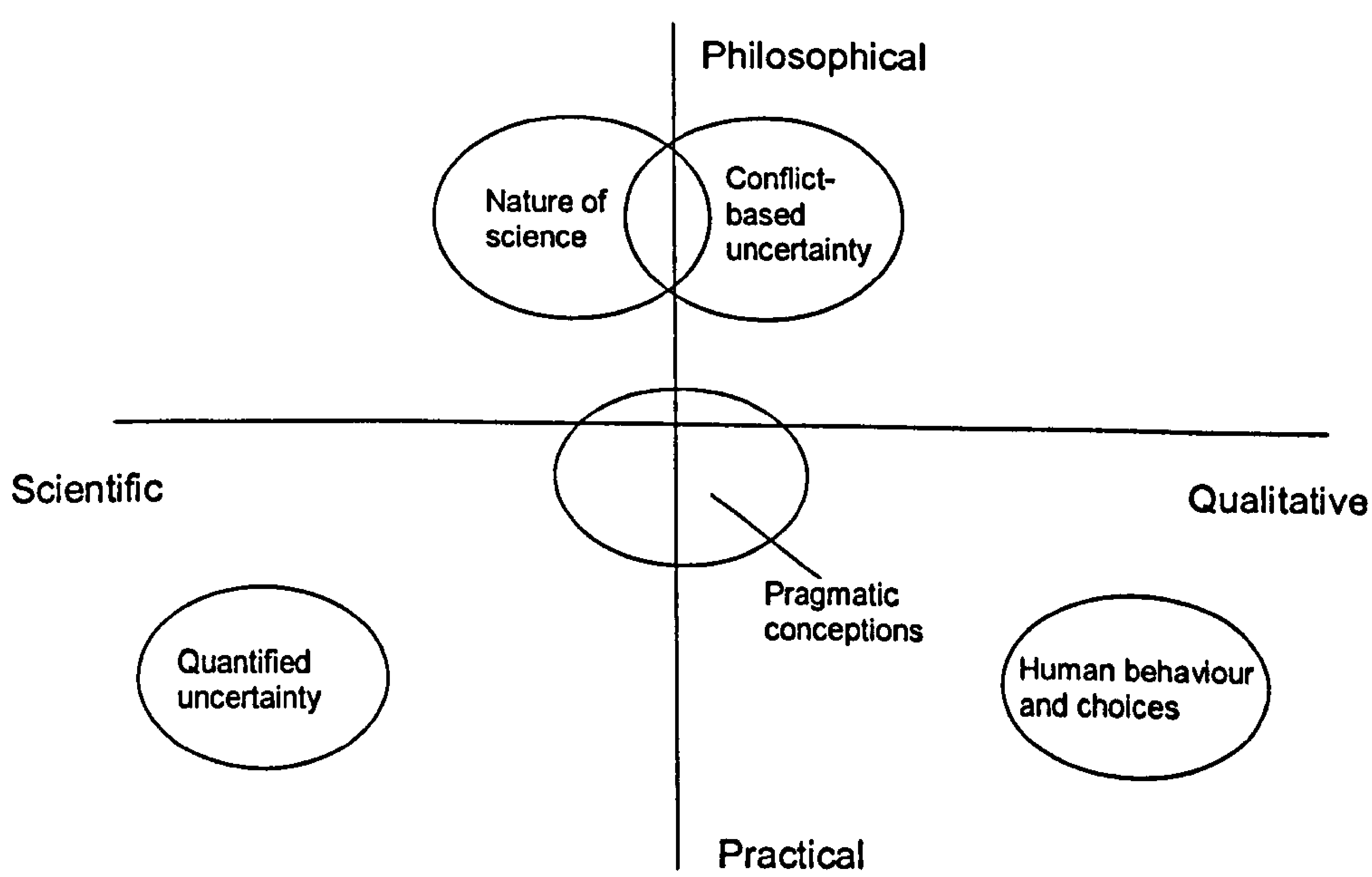


Figure 5.1: Characterising selected conceptions of uncertainty relative to their scientific/qualitative or philosophical/practical nature. Pragmatic conceptions can be said to accommodate all four factors.

It is interesting to note that in many cases the conceptions identified were directly linked to the participants' own research interests or teaching contexts, such as in the case of participant 6's interest in the uncertainty of fossil ecology or participant 10's pragmatic treatment of uncertainty in the context of a course on climate change policy. However, the conceptions of uncertainty were not limited by these research and teaching interests, participant 8, for example, recognises students' difficulty with quantifying uncertainty despite not being involved in teaching this himself. Indeed, many of the participants seem to hold conceptions from every category simultaneously, such as participant 3, who conceptualises uncertainty in very scientific terms, relating it to quantitative measures, climate modelling and the nature of science and the scientific method, while also conceptualising uncertainty through the difficulties of scenario-based assessments of "business as usual". This is partly a result of the categories themselves representing qualitative decision making on the part of the researcher but it may also signify a broad understanding of uncertainty in climate change on the part of the participants as well as an ability to conceptualise uncertainty in diverse and complex ways that reflect the nature of the subject area. One area where these multiple conceptions may be characterised explicitly is in the area of climate modelling (Figure 5.2), where practical considerations, including limitations in computing power, must be accommodated alongside more philosophical questions pertaining to the limits of scientific knowledge. The assumptions necessarily included in climate models contain an element of all of the different factors as an assumption may contain any one of the characteristics involved.

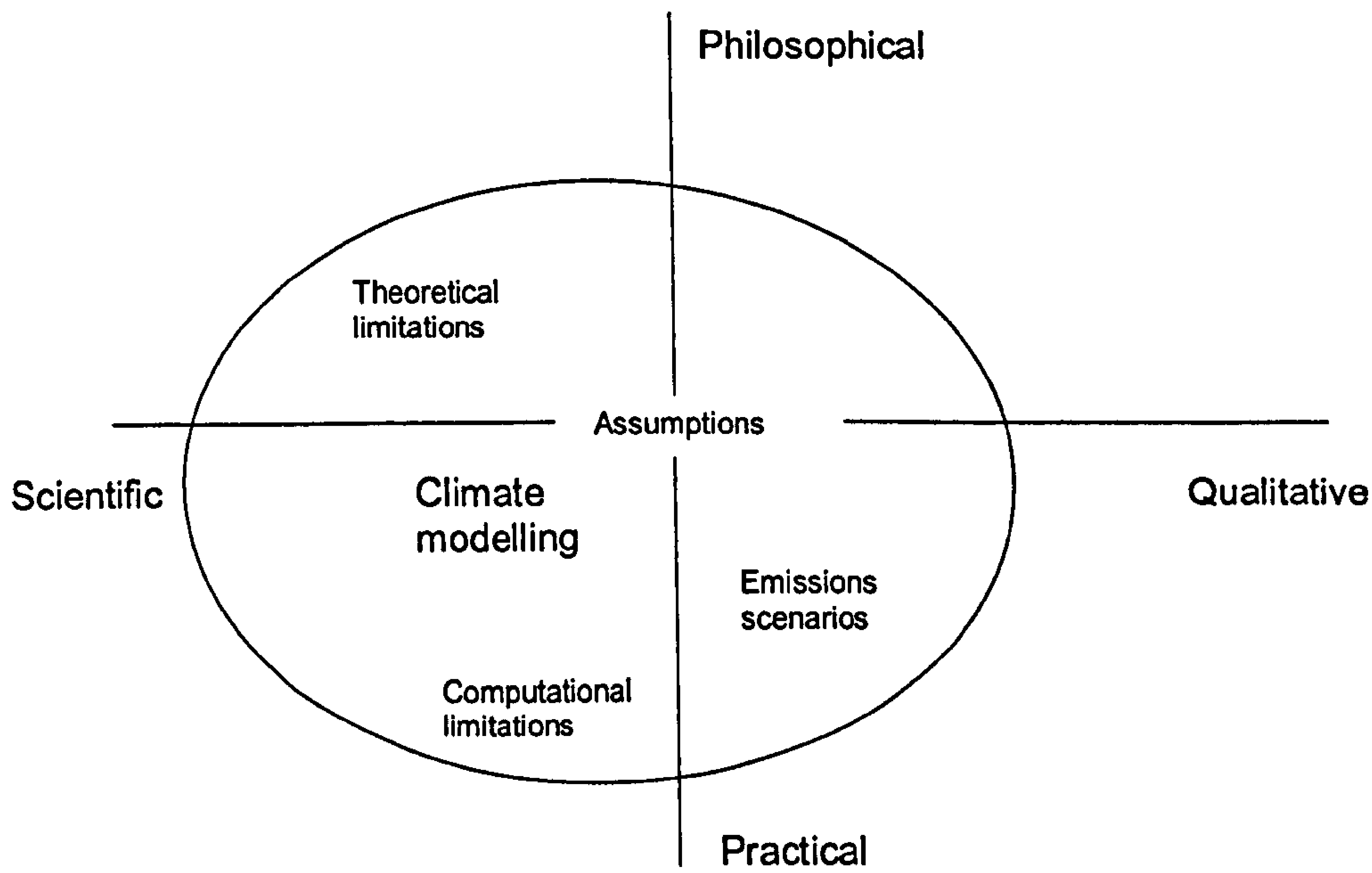


Figure 5.2: Climate modelling expressed in terms of the characteristics of the uncertainties involved. This demonstrates how academics may hold multiple conceptions of uncertainty and also why this appears to be the norm.

Climate modelling is an example of a significant area of study within climate change in which multiple conceptions of uncertainty are encountered and need to be accommodated. Examples such as this demonstrate how many of the participants in this study appear to demonstrate an ability to conceptualise the full complexity of uncertainty in climate change – the reality of uncertainty in climate change is that it is highly complex and this is unavoidable when one considers constructs such as climate models, among the best and most useful tools for understanding and predicting climate change yet still fraught with uncertainty. Whilst many of the conceptions can be linked to the academics' own specific interest, the ability to integrate other conceptions of uncertainty from diverse sources may be more valuable.

Chapter Six

Analysis and Discussion Part 2: Teaching Uncertainty

This second results and analysis chapter analyses the interview data from the perspective of implications for *teaching* uncertainty. This includes instances where uncertainty is identified as potentially troublesome knowledge or when uncertainty appears to fit the criteria of a threshold concept in this context. This chapter also includes discussion of potential strategies for teaching uncertainty, as identified by the interview participants, and consideration of other issues such as the impact of maturity on a learner's understanding of uncertainty. Owing to the nature of the interviews and, therefore, the data collected, there is a degree of overlap between the data presented here and that presented in the previous chapter on conceptions of uncertainty. The treatment of the data in this chapter will reflect the greater emphasis on teaching though links with the participant's conceptions of uncertainty will be explored where appropriate.

The chapter is divided into sections that address in turn the various implications for teaching uncertainty that have emerged from the data. The first two sections relate to the theoretical frameworks and consider whether uncertainty may be described as troublesome knowledge and a threshold concept in this context. This is then followed by discussion of the theme of maturity and personal development that has emerged from the research process and, finally, a section that details some of the strategies and approaches that have been identified by the participants for teaching uncertainty. Clearly this chapter is an important element of the thesis in that it reveals the actuality of teaching uncertainty as experienced by the participants. The identification of strategies for teaching uncertainty and consideration of how uncertainty fits into key theoretical frameworks of teaching and learning is a key outcome of this study that may have implications beyond the context of climate change in a broader pedagogy of climate change.

Uncertainty as troublesome knowledge

This section addresses whether or not uncertainty may be described as troublesome knowledge in the context of teaching climate change, based on the responses given by the participants. The section will be split into subcategories aiming to identify the specific types of troublesome knowledge identified by Perkins (1999) and Meyer and Land (2003), namely: conceptually difficult knowledge, foreign knowledge and tacit knowledge.

Conceptually Difficult Knowledge

Uncertainty was identified as conceptually difficult knowledge by several of the participants and is illustrated by a quote from participant 5, used in the previous chapter to identify a conception linked to the nature of the climate system but in this case used to identify the complex and troublesome nature of uncertainty as a concept itself:

> Interviewer: "Are there any kind of ideas when you're teaching climate change...that you find that students, maybe really struggle with? In your experience?"
>
> "Struggle with...they struggle with concepts of, I think, trying to get a handle on uncertainties and things...the idea of randomness and chaos...which is quite difficult to explain, I find" (Participant 5)

It is interesting to note that uncertainty is the very first concept to be identified by the participant in response to a question relating to troublesome knowledge and that the conceptually difficult nature of the concept extends to its teaching – being "difficult to explain". It is also worthwhile to note the use of the word "uncertainties" rather than the singular uncertainty. This acknowledges the multivariate and complex nature of uncertainty in climate change, as identified in the previous chapter, and perhaps gives an indication of why it is considered conceptually difficult. Uncertainty being complex, ubiquitous and diverse in the ways it is presented and contextualised indicates that it will not be constrained by a simple explanation, thus elevating it to the status of troublesome knowledge.

The conceptually difficult nature of uncertainty is also recognised by participant 3, who again puts it in terms of how difficult it is to teach:

> Interviewer: "So addressing it [uncertainty] explicitly is the way to deal with it?"
>
> "Yeah definitely...yeah...but it's really hard honestly if you're trying to get it across quickly...to someone who's not...say, someone who's quite sceptical about science in general, like...sometimes people have a kind of...they don't like authority or they don't like believing things that they're told automatically and they'll want to question everything...in a way that's obviously quite scientific to question everything, but in a way scientists also accept everything...you know you have to accept a certain amount of what's gone before, you can't question every single thing from first principles...so I think if you're trying to quickly explain to someone about this stuff it's quite hard, especially if they're already quite sceptical about scientists, suspicious of the ethics of science or that it's elitist or that it's pointless or that it's out of touch or all those sort of different things where people can have a bit of a mindset against science to start with it's quite hard...but I think talking to people who are quite open to learning about it it's fine...you can just say well you know we're sure about this we're not sure about this and that's why and they'll go, oh right yeah, you know, no-one's ever said that to me, and it's fine. I think it's just harder if people are obviously less willing to learn, just the same as anything..." (Participant 3)

There are frequent references in the above quote to teaching uncertainty being "hard" as a result of the conceptual difficulty learners may have with the concept. This is further qualified, however, by the recognition that it is difficult to teach complex and troublesome knowledge "quickly", perhaps an allusion to the necessity to return to concepts such as this frequently and recursively in teaching, or to take a structured approach where courses and curricula are designed centrally around concepts such as these as in the threshold concepts framework (Meyer and Land 2003, 2005). Also mentioned above is the impact of the attitude of the learner in addressing uncertainty, particularly in relation to familiarity with scientific modes of thinking and enquiry, or attitudes to science itself, some of which may be "sceptical", or believing that science is in some way "elitist" or even "pointless". The implicit difficulty here is that in teaching uncertainty in scientific contexts such as those seen in climate change, the uncertainty may be seen as undermining the science, thereby making teaching about other aspects of climate change potentially more troublesome. This may be an example of pre-liminal variation in relation to the concept of uncertainty, a subjective state that reinforces a previously held conception rather than leading to a repositioning of subjectivity. Liminal space is not entered in this case, rather, the introduction of the concept of uncertainty may actually lead to the learner adopting a more certain position in relation to climate change. A more "open" and "willing" approach to learning would appear to make integration of troublesome concepts such as uncertainty easier – accepting the entry to liminal space and the attendant shift in subjectivity once it has been traversed. This may align with the "will to learn" identified by Barnett (2007) as a key element in engaging students with learning in an uncertain world – which may extend to students learning about uncertainty itself. The issue of familiarity with uncertainty and the effect this has may allude to uncertainty representing foreign or alien knowledge; this will be discussed in more detail in the next section.

Foreign and Alien Knowledge

Troublesome knowledge of this kind was again identified by a number of the participants who recognised the difficulty that students had with reconciling the concept of uncertainty either in the wider context of their learning or in relation to their conceptions of science. The perhaps troublesome relationship between science and uncertainty was alluded to by participant 3 above and this was echoed by participant 8:

> "I think they [students] think that science is completely cut and dried when they come into it and I think if anything the relationship between science and society is that we are having a bit more a nuanced understanding of science

now and that's good because you do tend to have some rather naïve notions about *fact* [italics for emphasis] and so on...but I think my physical [Geography] colleagues have borne the brunt of that...and we've had a series of people dealing with this issue [of uncertainty] and everyone has their own way of dealing with it..." (Participant 8)

The foreign nature of uncertainty in this instance is twofold, firstly there is the aforementioned conflict that uncertainty may bring about in students' conceptions of science – science being "completely cut and dried" along with "naïve notions of fact" – and secondly there is the acknowledgement by the participant (who describes himself as a human geographer) that it is the physical geographers in the department that 'bear the brunt' of teaching uncertainty. Uncertainty would appear to be seen as 'belonging' to science and, by extension, the more overtly scientific branch of Geography. This view is seemingly borne out by the prevalence of scientific conceptions identified in the previous chapter; however, it is important to also acknowledge the more qualitative conceptions that have emerged and the potentially alien nature of these depending on the individual's own background or specialisation. Whether knowledge is classed as foreign, and therefore troublesome, would appear to depend largely on how the teacher or learner identifies themselves, as is suggested in the quote below, again from participant 8:

"I can't say it's a largely discreet area of study...I haven't sort of taken an hour or two hours with students and said let's look at uncertainty as a philosophical conundrum or as a problem to be solved, but I'd say it's implicit in a lot of stuff we do..."

Interviewer: "Well, it can be a very difficult thing to tackle head on..."

"Yeah...you don't want students saying I'm doing Geography, not Philosophy..." (Participant 8)

In this case uncertainty is seen as a concept that, if dealt with explicitly, students see as being the preserve of philosophers, having little bearing on Geography and, in this context, climate change. This clearly presents significant challenges in terms of teaching uncertainty as students may struggle to recognise concepts that they see as not belonging to their discipline, therefore making understanding almost impossible to achieve. The impact of a teacher's self-identification is demonstrated in the following quote from participant 5:

> "It [teaching uncertainty] is especially difficult given that they're Geography students, they're not maths students or Physics students, in which case it could be more quantitative...to get to grips with it [uncertainty] without having the kind of basics can be quite tricky...explaining it to them in...well, I've been here quite a while, I'm getting used to the idea of explaining things in that sort of qualitative, very descriptive way" (Participant 5)

The above quote again makes reference to the difficulties inherent in teaching troublesome knowledge, but goes further in identifying the context of the students as the source of this troublesomeness. Here, the participant struggles to get across the nature of uncertainty as she cannot express it wholly in terms that she is comfortable with in the respect of her own background and specialisation (in Physics and climate modelling). She acknowledges that she has had to spend time "getting used to the idea of explaining things in that sort of qualitative, very descriptive way", in order to minimise the 'alien-ness' of uncertainty when it is presented to the students, she has had to conquer her own conceptions of alien knowledge and learn to accept new ways of describing uncertainty.

Tacit Knowledge

Uncertainty emerged as tacit knowledge in most of the interviews conducted with academics in this study. The quote from participant 8 above makes reference to uncertainty being "implicit in a lot of stuff we do" and this was a view echoed by many of the other participants, as illustrated by the following quote from participant 4:

> "So while...as I've said the theme of uncertainty might crop up, but it's not taught in a formal way... (Participant 4)

Whilst uncertainty is recognised as being an important concept when teaching climate change it is not always addressed "formally" in teaching. The above quote from participant 4 was preceded by the following which highlights this in more detail:

> Interviewer: "When you're dealing with climate change, be it past climate change or what's going to happen in the future...how important do you think things like uncertainty are?"
>
> "Well we know them to be very important...and it's...it's an interesting question as to how much do we teach of that...I don't think...I think it's a good point that we don't...whilst we happily declare that there's lots we don't know about climate change we don't tend to formalise that" (Participant 4)

The fact that uncertainty remains tacit and implicit would, therefore, appear to be down to two main reasons – firstly, that it is troublesome in the conventional sense of being complex, conceptually difficult or in some way foreign, alien or counterintuitive and as a result is not explicitly articulated so as to avoid the potential consequences of such troublesome knowledge for teacher and student alike and, secondly, that it is an intrinsic part of the discourse within the disparate climate change community such that it is not formalised – it is an 'underlying game' (Perkins 2006). This second view is borne out by the following quote from participant 10:

> "One of the things I struggle with is that so much of this [climate science/system] is obvious to me and to my peers, but it's not obvious to the students necessarily"
>
> Interviewer: "One thing I've noticed is that uncertainty can be implicit because it's so much a part of the discipline and everyone who practices is operating with uncertainty at the heart of what they do..."

"We just live with it and don't think about it, which is why I guess I was struggling to articulate how I approach it myself because you just do...you just deal with it" (Participant 10)

The above quote reveals the nature of uncertainty as being simply one of many factors that is "obvious" to practitioners and researchers within the subject area and echoes the 'pragmatic conceptions' identified in the previous chapter. Owing to its obvious nature the concept becomes more difficult to articulate and thereby teach and, as a result, may be 'lost in translation'. Participant 10 goes on to further elaborate on the troublesomeness of this tacit understanding of uncertainty in terms of communities of practice:

"Within communities of practice there's an accepted use of language as well as an accepted understanding of fundamental principles or the degree of uncertainty that we're all operating with or whatever...and it's not articulated, and then when you work multidisciplinary it becomes really problematic, or can do..." (Participant 10)

The above quote goes back to the conceptions of uncertainty that relate to the nature of climate change science in that the acceptance and understanding of different levels of uncertainty are seen as problematic when working in the necessarily multidisciplinary area of climate change. This may also present yet another obstacle to students in understanding uncertainty as not only is the uncertainty not articulated, it varies considerably depending on the context in which it is encountered. It is highly interesting to note that the above revelations from participant 10 came about as a result of extensive discussion and towards the end of the interview after she had earlier identified uncertainty as a concept that was explicitly dealt with in her teaching:

"I'm quite explicit that that's [uncertainty] one of the things that I deal with, but it's also both explicitly and implicitly there in everything that I'm doing in the course" (Participant 10)

It would appear that the tacit nature of uncertainty in this context can be troublesome even for those that feel that they recognise and teach uncertainty in an explicit fashion. The tacit troublesomeness of uncertainty also has implications for assessing whether students have understood the concept or even whether it has been 'taught' at all, this is demonstrated in the following quote from participant 2:

> "The advance of science, or where we are now, is something more subtle, it's something more hidden, something that...since I believe in it I think I convey it and I talk about it and I just mention it...and then either it clicks or not, I think it depends on the student, but I think since I believe in it it's probably something that I deliver and say well that's what we know...that's a consensus or not a consensus, some people will go against it and definitely it's going to change in a few years time so...we don't know much..." (Participant 2)

This participant feels that the inherent uncertainty within science is "subtle" or even "hidden" and, as such, he is unsure whether he gets it across to students. He then goes further to infer that it is then dependent on the individual student as to whether understanding is achieved. Clearly, this points to uncertainty presenting a highly troublesome concept in this context with major implications for teaching learning and assessment. Indeed, the design of assessment for teaching uncertainty is seen as highly troublesome, not least owing to the concept's tacit nature:

> "I think the way we sort of assess that is very...it's kind of in there somewhere but it's never something that we really...it's not explicit, it's like you might have an essay title and within that they have to kind of weave in some idea about uncertainty...in modelling where there are limits...but it's never really kind of set...but maybe it's something I need to think about, I mean it's definitely an important concept and I don't think I really have been aware how much they really get that so maybe it's something I should think about..." (Participant 5)

The above quote from participant 5 encapsulates many of the difficulties that uncertainty presents together with an admission that it is not something she has really considered before, perhaps because the underlying game at play here also remains tacit to the teacher. Particular strategies and approaches for teaching uncertainty will be discussed in more detail later but it is interesting to note at this point the implications of the troublesome nature of the concept of uncertainty.

Uncertainty as a threshold concept

Many of the quotes in the above section and the previous chapter have included mention of uncertainty as an "important concept" in climate change. Often, this was in response to a direct question as to whether the participants felt uncertainty was an important concept in this context, rather than the indirect question asking participants to identify key concepts in climate change. The latter question was designed to give some insight into whether uncertainty constitutes a threshold concept in this context. Whilst not a direct query into the potential status of uncertainty as a threshold concept it was nonetheless interesting to note that only 2 of the 10 participants identified uncertainty as a key concept unprompted by the interviewer. This is illustrated by two quotes form participants 3 and 10, which will, at least in part, be familiar from the previous chapter:

> Interviewer: "So if we can talk about climate and the discipline and it needn't necessarily refer to your experience of teaching it could just refer to kind of what you know and what you've learned in the last couple of years...what do you think are the kind of key concepts within the discipline that people should understand..?"
>
> "I think the very top one for me...is certainty, uncertainty and certainty...because in various different conversations with non-scientists, not just about climate change, it's really hard to convey the scientific method to someone who is not familiar with it...and by that I mean mainly the way that scientists will say no we're absolutely sure about this because we have tested

it and we've done lots of experiments and we've thought about it very hard and we've done lots of sums and we've looked at it from all angles...and yet I won't be surprised if next week we find out something new that puts it all completely, you know...the whole sort of Einstein over Newton type stuff...where it can all kind of go out the window, but we're very sure right now but tomorrow we might be saying something completely different and scientists can kind of hold all that stuff in there, they are quite used to that sort of process of, yes we're very sure but we're completely open to being wrong...and I think that's quite hard because obviously the public and people really want to know, especially, you know, future climate change is such a globally impacting thing, economically, socially and everything...people really want certainty don't they?...and it's just very hard to convey how certain you are, you know setting aside the fact that we don't find it easy to quantify numerically different probabilities and uncertainties, it is even harder to then communicate how sure we are to the public so that's like the main thing" (Participant 3)

Interviewer: "Are there key concepts that you think students should understand?"

"Yes...very basically they have to understand atmospheric composition and structure and...this is from a scientific point of view to start off with...and how radiative forcing works, so what I'm particularly interested in them understanding is that there is a natural greenhouse effect without which we wouldn't be here, that there is an enhanced greenhouse effect and what radiative forcing is, how it works and what contributes to it and that immediately brings in uncertainty, which is another absolutely critical concept...to me this is one of the key things because I find that most students are uncomfortable with uncertainty, particularly at the lower levels, but it's such a fundamental in everything, particularly in this area of climate change, but it's ubiquitous, so coming to grips with uncertainty and how you deal with it, how you convey it, describe it, work with it, and how you move on despite it and make decisions despite uncertainty I think is a really key thing for me" (Participant 10)

Clearly the two participants quoted above feel that uncertainty is one of, if not *the*, most important concepts that students learning about climate change should have an understanding of. The fact that they were the only two participants to identify the concept of uncertainty in response to this question would seem to add weight to the suggestion that uncertainty constitutes tacit knowledge for many of those teaching in the subject area.

The first quote from participant 3 characterises the importance of uncertainty in terms of troublesome knowledge – how "hard" uncertainty is to convey and, therefore, why it is so fundamental to have a good grasp of uncertainty in order to be able to communicate it. She also states that "people really want certainty" implying that not only is uncertainty troublesome in how it is conveyed but also that people, including students, are likely to be resistant to uncertainty when the concept is introduced. Participant 10 talks more of uncertainty in terms of its ubiquity and centrality within climate change. Even starting with what may be considered "very basic" concepts such as what the atmosphere is made up of and how it is constructed, or how radiative forcing works, uncertainty is present and must be addressed. This would suggest that uncertainty is truly integrative in the sense that it links every element of the climate change subject area, even from the most basic and fundamental principles. This is a view supported by the following quote from participant 1:

> Interviewer: "How important do you think it is? Like, if you talk about a philosophical understanding, how important do you think it is for progress within the discipline, to understanding climates changing, how important is it to have an understanding of uncertainty?"
>
> "I think it's incredibly important…there's I suppose a number of…all kinds of people working in the area of climate change, in our little niches, and to a certain extent there are global programmes which try to draw together the information and look at it holistically…get an overview and look at interactions…certainly in the modelling community they are moving away from global climate models to Earth system modelling…recognising that the interaction of ocean and climate is one aspect but that terrain, vegetation have

a key feedback so...I think it is important and one really good way of emphasising that to them is to...something we do at level 3 and we're going to build into level 1 with our new Geography course is a kind of understanding of systems theory" (Participant 1)

The above quote is an interesting response to the question of how important an understanding of uncertainty is because whilst the participant immediately states that "it's incredibly important" and goes on to talk about interactions, in what seems to be a statement in parallel with participant 4's conception of how difficult it is to integrate uncertainties from distinct research groups, he never explicitly mentions uncertainty. Again, this would seem to suggest that uncertainty remains tacit, due either to its troublesome nature or its inherence within the subject area.

Having demonstrated examples of how uncertainty may be considered troublesome, and how this leads to the concept being viewed as important, and how uncertainty appears to be integrative it is worth now considering another of the key facets of a threshold concept: its transformative ability. The quotes above demonstrate how an understanding of uncertainty may change a learner in giving them the ability to convey uncertainty, work with it and integrate it with other concepts they are learning. A more explicit example of how an understanding of uncertainty may alter a learner at a personal level is provided by participant 9:

Interviewer: "Uncertainty does operate on several levels...and you have that idea of...knowledge not being a fixed thing and at the same time you have much more specific things like sensitivity and parameterisation...structural uncertainties that are part of the day to day practice of something like climate science...do you think it's important to understand those things?

"Absolutely! Yeah, I'd say it's fundamental for anyone graduating, I would hope...and that's why I don't like to see it left until 4th year, I think graduates should come out with that realisation that knowledge is uncertain and that...they've developed an enquiring mind to actually question the evidence and make their own judgements about how well founded in the literature or in current perceptions this, whatever it is, is...you know climate change...so yeah I think they should come out with a grasp of that...whether they do or not is another matter [laughs]..." (Participant 9)

Here the participant identifies an understanding of uncertainty as "fundamental for anyone graduating", not just those studying climate change but all graduates from higher education. Understanding uncertainty is seen as going hand in hand with developing an "enquiring mind", clearly a fundamental change on the part of the student, which may also indicate that the change is irreversible. The fact that the participant does not like seeing the teaching of uncertainty "left until 4th year" (honours year in the New Zealand higher education system) implies that introducing the concept at an earlier stage, or employing a recursive approach, will enhance students' understanding of the concept. The view that uncertainty represents a "fundamental" concept for graduates of higher education indicates that it may be considered a key 'graduate attribute', even beyond the context of climate change. Graduate attributes may be defined as:

> *"The qualities, skills and understandings a university community agrees its students should develop during their time with the institution. These attributes include but go beyond the disciplinary expertise or technical knowledge that has traditionally formed the core of most university courses. They are qualities that also prepare graduates as agents of social good in an unknown future" (Barrie 2007, p. 440).*

As an attribute, an understanding of uncertainty would appear to fit this scheme well as uncertainty is applicable in a wide range of contexts, beyond disciplinary definitions. The reference to an "unknown future" also points to uncertainty being highly important in this regard. However, the participant also notes that there is considerable variation among students in attaining this attribute, raising the issue that not all students will cross the threshold and achieve understanding. This is a view shared by many of the participants and may indicate the existence of considerable pre- and post-liminal variation among students in their approach to uncertainty and subsequent repositioning. For instance, when asked whether uncertainty was something her students ever became truly "comfortable with", participant 5 gave the following response:

> "Some of them [students] do...yeah some of them take to it, really it's just the same as anything..." (Participant 5)

The acknowledgement that some students "take to it" implies, firstly, that others do not and, secondly, that this may be down to variation in how the students apprehend the concept of uncertainty. Equally, however, the variation in the response of students to uncertainty may be down to other issues arising as a result of the troublesome nature of uncertainty. Scheja (2006) reports that problematic learning experiences may cause students to feel that they are 'out of phase' with their studies, typically expressed as a 'lag' in understanding course material. It may be that students who at first appear not to have achieved understanding of a concept such as uncertainty may actually move beyond the threshold on their own time, away from the classroom and after having sufficient time to reflect (Scheja 2006). It is with some caution therefore that the variation in understanding is attributed to variation among the students themselves, although this is expanded upon through the following quote from participant 6:

> Interviewer: "How do you feel that your students understand or, kind of, cope with uncertainty?
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> "They...some of them cope very well...others tend to regurgitate what the media say and what their parents say and what they learnt in school...they're less likely to take on board what...they don't like it...students tend not to like uncertainty they tend to like hard and fast figures so...so a good student in an exam will put the range...you know if they're putting down where will sea level be in 2100 they will put the range from whatever it is, 8cm up to 61cm according to one of the IPCC reports but other students would put 61 you know and not qualify that...that that's the maximum range...yes different students take it on in different ways...it's not as easy as it should be, because

they should just think of it as the range rather than as a single figure" (Participant 6)

This quote indicates that whilst some students "cope very well" with uncertainty others may tend to respond with a kind of mimicry – regurgitating "what the media say and what their parents say and what they learnt in school" – as a result of being uncomfortable with uncertainty. Furthermore, a "good student" is defined as one that will put the range of possible outcomes in response to a question, demonstrating that there is considerable uncertainty in predicting the consequences of future climate change and using language and ways of presenting data consistent with the discursive shift that may occur when the threshold of understanding uncertainty has been crossed. However, it is worth considering that this approach in itself may represent a kind of 'epistemic game', an attempt to rationalise the uncertainty through qualification. It may be extremely difficult to separate this subliminal variation into those students who have attained a deep understanding of uncertainty and those who are utilising some kind of epistemic apparatus. This may be characterised as a 'strategic' approach to learning where responses to assessment requirements are predicated towards achieving the highest possible grades through organised study methods and strategies, although deep understanding may arise from engagement with other aspects of the academic content distinct from assessment (Entwistle 2000). The apparently tacit nature of uncertainty and the fact that it may represent an underlying game for teachers also points to the existence of subliminal variation amongst teachers in their understanding of uncertainty. It may be that subliminal variation is the most significant mode of liminal variation in terms of the implications for teaching uncertainty.

Further to the illustrations of the transformative ability of uncertainty and the existence of liminal variation among learners it is also worth considering another aspect of liminality, the ontological expression of uncertainty. The uncertain condition that may be initiated by a conceptual encounter with uncertainty is demonstrated by the following quote from participant 1:

Interviewer: "Do you feel in a sense that it [uncertainty] creates tension for the students and almost undermines…even though it's central to the kind of fabric, the very essence of the science that you're teaching...do you think that it undermines it in any way?"

"To a certain extent...I think you get a sense that some students exit some sessions with a complete bewilderment [laughs]...but I think it's important to emphasise that this is how science progresses...and you can't essentially, I suppose, lose hope in what you are studying...you've got to accept that you can't know everything and that you're contributing to an advance and on reflection of your degree, hopefully after three years if not perhaps even just at the end of your dissertation you realise that you have advanced the discipline, even in a small way, you've contributed. So, I think that's important you know...the progress can be fast it can be slow but nonetheless it is progress... (Participant 1)

The above quote makes reference to several ways in which ontological uncertainty may manifest itself when a learner encounters the concept of uncertainty. Learners may feel that, "to a certain extent", this uncertainty undermines what they are studying, thus leading them to a state of "complete bewilderment" about who or what to believe in. These, together with the 'loss of hope' described by the participant, are indicative of the profound feelings of uncertainty that may be experienced by a learner as they engage with a threshold concept. However, this participant notes, as have others, that this is a necessary process. The acceptance that "you can't know everything" is a fundamental not only to learning but to the advancement of knowledge itself. Interestingly, this participant also links this to the student achieving a feeling of having contributed in some way through the completion of a university degree. The reflection of the student may be a key element in this, allowing them to perceive the transition they have made across the threshold of uncertainty towards a greater understanding of the progress of their subject area and the integral role that uncertainty plays in that process.

There is much to consider then when asking whether uncertainty constitutes a threshold concept in this context, a problem perhaps compounded by liminal variation among teachers and learners. However, several of the defining criteria of threshold concepts appear to have been referred to at least implicitly by the participants. The language of uncertainty is obvious and prevalent throughout all of the responses form participants, suggesting that the understanding of uncertainty would indeed lead to a discursive shift on the part of the learner. This also suggests that the concept of uncertainty may be bounded in some way in this context, a notion supported by the apparent difficulties that exist when attempting to integrate uncertainties from different spheres within the subject area. This 'internal bounded-ness' could perhaps indicate that uncertainty may form a kind of interdisciplinary threshold in the context of climate change, rather than the conventional bounded-ness attributed to threshold concepts which may be seen to define a discipline. In the context of climate change uncertainty is an integrating and unifying concept that connects several diverse disciplines and integrating uncertainties from elsewhere may be a powerful means of making connections and crossing thresholds into new disciplinary territory.

According to the responses of the participants in this study, uncertainty would appear to be a good candidate for a threshold concept in the context of climate change. A final quote from the interview with participant 10 lends weight to the suggestion that uncertainty is indeed a threshold concept, elevated to a level above the more conventional conceptual fabric of climate change:

Interviewer: "Uncertainty comes up a lot as a key and troublesome concept but it has this fuzziness around it...does it constitute a concept in its own right? Well, it does but it's on a different level to something like understanding how radiative forcing works or understanding the role of clouds..."

"Absolutely...yes"

Interviewer: "Understanding uncertainty and that it is all pervading and has implications for everything we do is an entirely different thing..."

"Yes." (Participant 10)

Maturity and development

Several of the participants, in this chapter and the previous one, have alluded to the importance of personal maturity and development in how a learner perceives and understands (or not) uncertainty. Whether it is the assertion that uncertainty should not be 'left too late' in terms of where it is introduced in the curriculum, as in the quote from participant 6 above, or whether it comes later in the form of reflection on degree and dissertation, as identified by participant 1, the particular 'stage' at which uncertainty is encountered does appear to have a bearing on the outcome. Indeed participant 1 talked fairly extensively on this subject during interview, putting the comprehension of uncertainty in very structured terms linked to the standard model of a student's progress through a university degree, such as in this quote – an expansion of a quote used in the earlier conceptions chapter:

> "Interviewer: Can I just ask how they [students] handle things like uncertainty, like when you're dealing with those?
>
> "Of course...well at level 2 they can begin to appreciate uncertainty by level 3 they have to be critical about uncertainty and try and weigh up the balance of evidence... you do see that progression amongst some students but some...I don't think there's a general awareness amongst students that there is an increasing demand for academic rigour between level 1 and 3, they just think it's a change of topic which gets more detailed but it's not really about that, and the level descriptors at the university are about moving from a kind of, not really moving on from A-levels, making sure everyone's on a kind of sound foundation, to one of being highly critical and looking at the balance of evidence come level 3...I don't think many of them grasp that...they just, all they see is the module...and the assessment criteria which should reflect the level of demand, but they don't really get to grips at level 2. But they are certainly aware that there's debate and that's something that we try to get them to at least acknowledge, the different areas of debate, but in terms of trying to get them to balance up evidence they don't tend to do that voluntarily at level 2" (Participant 1)

Here, the ability of students to "grasp" uncertainty is described not just in conceptual terms but also whether students understand exactly what is being asked and expected of them as they progress at university. This perhaps links to the potential status of uncertainty as a threshold concept, that it is not merely the content of the degree that changes (becoming "more detailed"), but that learners themselves are expected to change as a result of understanding concepts such as uncertainty – leading to them becoming "highly critical". However, the development of an 'appreciation' of uncertainty leading to an understanding of the concept is still seen as occurring in tandem with a student's advancement – implying that older students are effectively more capable of understanding uncertainty. This implication is perhaps supported by the following quote from participant 8, who identifies similar links between 'stage' and the encouragement of criticality:

> "I mean we try and get them to be critical starting in the second year, to get them to be critical of received knowledge...and ideas" (Participant 8)

This highly practical approach to identifying how uncertainty is taught may actually be a means of making explicit the troublesome and tacit knowledge of uncertainty, putting it in structured terms that allow rationalisation of how the concept is addressed through teaching. The practical considerations of undertaking a degree also feature in the next quote, again from participant 1, who acknowledges that the strategic approaches adopted by some students have a large bearing on their understanding, no matter when troublesome concepts are first encountered:

> Interviewer: "We've talked about level 1, level 2 and level 3 and we've talked about dissertations do you feel that there are like key levels where these things should be addressed or are there key levels where students understanding...clicks, or they reach a level of maturity?"

> "I think it's a balance between our expectations of progression between level one and three and...what a student considers important for their class of

degree that they're going to get at the end of the day...they are fully aware that they need to pass level 1, they are fully aware that level 2 doesn't necessarily have to count towards their final degree classification so...as much as we would hope that they'd progress in terms of their academic thinking between level 1 and 3 the majority will not knuckle down until it gets towards the end of their second year and they have to start thinking about their dissertations...the minute they start thinking about their dissertations and you give them that independence and that responsibility...and the thought of entering level 3 and marks counting towards final class of degree...that's when they start to knuckle down...and that's when things begin to click...so there is that kind of trade off between what we would hope how they would progress between level 1 and 3 and ultimately...they'll probably fit all of their progression into level 3 as it were...because for the majority of them it's level 3 that counts..." (Participant 1)

The above quote brings into fairly stark focus the realities for many students in higher education and, by extension, their teachers. Engagement with troublesome or threshold concepts happens as a matter of practical necessity as students reach the end of their degree programme. In this case it may not be that maturity is a factor in itself but that the 'real life' pressures of completing a degree and the attendant assessments propel students into engagement with concepts such as uncertainty. In an exercise such as an honours-year dissertation there is more scrutiny from assessors and, therefore, less of a chance that a learner will successfully mimic understanding or that a ritualised response will be accepted. It may be this realisation that eventually causes the learner to actually enter the liminal state provoked by uncertainty as opposed to avoiding it or employing some epistemic game to subvert it. This aligns with the findings of Kuh (2003, 2008) who describes 'capstone' activities such as final year dissertations and theses as "high impact educational practices" that have the capability to "positively influence student engagement, persistence, and satisfaction" (2008, p. 2).

Another example of how strategic approaches to learning and existing curriculum structures may impinge on a learner's understanding was identified by participant 8, again in relation to criticality as an expression of uncertainty:

> "I wish they [students] were more critical...they kind of just take it at face value very often...I mean in first year they don't look into these issues [such as uncertainty] very closely...it's just a case of taking different world views one after the other...and there's always this sort of tendency with students that what I studied last is going to be better than what we studied first because there's this kind of evolutionary...if you study concept A, concept B, concept C, concept C is going to be the best because it came last [laughs]..." (Participant 8)

This ritualised approach by learners which places concepts in a hierarchy according to their 'order' in the sequence of a curriculum would appear to echo many of the points of participant 1 above. The consideration of "different world views one after the other" suggests that there is no liminal shift occurring and that while a teacher may encourage exploration of different worldviews learners do not engage with them sufficiently to allow it to significantly affect their own. A further interesting point to note is that the concepts encountered later may be viewed as intrinsically 'better' than those that have preceded it. This point echoes the earlier point of participant 1 that indicated a lack of appreciation of increasing academic rigour on the part of students, although here it is expressed in terms of attitudes to the concepts themselves rather than the perceived "level of detail".

It would appear then that there is a case for consideration of some temporal framework related to teaching uncertainty, although this may be largely put in fairly structured, practical terms. Other participants were, however, more explicit in their appraisal of the importance of maturity in this context. Particularly participant 10, who brought her own experience to bear on the question of whether older students have a better understanding of uncertainty:

> "I think I could say reasonably...now, being a scientist I want to be precise [laughs]...that the more mature students with more life experience I suspect find it easier to deal with the idea of uncertainty, whereas the younger students who come straight through the school system and into university I think for them it's more challenging, because I think although...this is not a critique of

what they get at school or the early years of university, I think they come to their education when they're young with a sense that there are absolute truths and that they're going to receive these absolute truths and learn them and know about them and understand them and that that is going to explain the world to them, and of course there are some things that we understand to be true, in Physics and Chemistry and so on, but...as soon as you enter into the realms of complex systems, and particularly working where behaviour is involved, there aren't any absolutes and that I think is very confronting for them." (Participant 10)

The above quote summarises many of the troublesome aspects that uncertainty may present to those learning about climate change, and it is an interesting conclusion that older students with more "life experience" may deal with this troublesomeness better than those who are younger. It may be that the inherent uncertainty of human existence may give those who have experienced more of it a greater appreciation of the conceptual uncertainties associated with climate change. It is perhaps best, however, not to make generalisations in this regard, as acknowledged by the participant herself with her 'scientific' desire for precision. There is, however, a school of thought that links the development of students with an ability to understand and work with uncertainty, typified by the 'Scheme of Intellectual and Ethical Development' formulated by Perry (1970). Perry's model is based on an "ongoing qualitative reorganisation of the making of meaning" (Hofer and Pintrich 1997, p. 91) as a learner matures and develops. The model is based on four sequential categories, namely – *dualism*, *multiplicity*, *relativism* and *commitment within relativism* (Hofer and Pintrich 1997). The four categories are characterised as follows:

- Dualism – characterised by a dualistic, absolutist, right-and-wrong view of the world where authorities (i.e. teachers) are expected to know the truth and convey this to the learner.
- Multiplicity – the beginnings of recognition of diversity and uncertainty in knowledge, however, this is largely based on the conception that authorities who disagree simply have not yet found the right answer.

- Relativism – the learner begins to realise that knowledge is relative, contextual and contingent and recognise their own self as an active maker of meaning.
- Commitment within relativism – the learner is more focused on responsibility and engagement; individuals make and affirm commitments within relativism to values, relationships and personal identity (Hofer and Pintrich 1997).

Although largely theoretical, this scheme offers a general view of student development and the part that uncertainty may play within it. There is a sequential progression from an absolutist view where uncertainty is disregarded to a position where uncertainty is understood and integrated into the way the learner views their world and their place in it – in the act of making their own meaning. This is perhaps analogous to the profound shift in subjectivity associated with the theory of threshold concepts. Models such as Perry's seek to holistically theorise the development of the whole student, not just in terms of their learning (as with most theoretical pedagogic models) but also as a person. Baxter Magolda (2009) describes this holistic perspective in terms of 'self-authorship', where learners develop the means to deal internally with challenges to their identity and values. Learning about uncertainty may be seen as challenging in this sense, meaning that an understanding of uncertainty may again be viewed as being linked to development. Indeed, the development of this capacity is linked to a growing awareness of uncertainty (Taylor and Haynes 2008) and is potentially a troubling experience for the individual involved (Pizzolato 2004 in Baxter Magolda 2009). It may also be worth noting a similarity with these holistic perspectives and the idea of graduate attributes described earlier. 'Self authorship' and 'commitment within relativism' may be seen as analogous with the graduate attribute of understanding uncertainty, learning about uncertainty in the context of climate change may allow students to apply their understanding in different contexts and become "agents...in an unknown future" (Barrie 2007, p. 440).

Further to the above quote another interesting insight is provided by participant 10 in relation to maturity, this time on her own personal level and once again in alignment with the work of Perry and others:

Interviewer: "Do you think the consensus element [in the construction of IPCC reports] is partly an implicit attempt to limit the uncertainties? You constrain them by saying this is what we all kind of agree on...you focus on the common ground where the commonalities are then you ignore the kind of extremities where perhaps things are much more uncertain, and you also kind of ignore the cutting edge..."

"Yes you do, and I think that's a real limitation of doing it that way...but I was just thinking about what I would say to the students...so you know you're talking about uncertainty and they might challenge you and say well what can you tell us? What do you know? And so you go back to the middle...always...I'm willing to say but I believe that, this and this, but it's a belief rather than saying I know that's a fact..."

Interviewer: "I think you may be unusual in that sense, from a climate science perspective, although it's increasingly common that you see people pin their colours to the mast, those who are operating within the science, they're engaging in that discourse but at a personal level, saying well this is what I believe..."

"And that's another interesting question I think for me, ten years ago I wouldn't have done it, I wouldn't have been prepared to do it, now I am."

Interviewer: "So...you mentioned maturity on the part of the students...is that part of the journey that you yourself have been on?"

"Yes, definitely"

Interviewer: "Interesting, because it can be something that people never engage with and that extends to those who teach as well..."

"I think there's an important element in here which we have to be careful of and that is that there's potentially a very fine line between...what can I call it?

There's a difference between presenting a perspective on things which is scientifically based but within which you express a personal view, and advocacy." (Participant 10)

The above quote is interesting for a number of reasons, not least to acknowledge the realisation by the participant that she has herself matured in her understanding of and attitude towards her chosen subject area. This is expressed in terms of her willingness to now discuss the climate change issue in terms of "beliefs" as well as "facts". This perhaps demonstrates a more nuanced appreciation of uncertainty that allows the inclusion of subjective opinion as well as objective fact in discussing issues such as climate change. In so doing the participant sees herself freed from the "limitations" of consensus in her teaching, all as a result of the "journey" that she has been on. This would appear to resonate strongly with Perry's idea of 'commitment within relativism' and Baxter Magolda's notion of 'self authorship', the participant linking her development to the capacity to construct and commit to her own meanings relating to climate change.

This maturity on the part of participant 10 would also appear to extend to the concept of 'negative capability' described by the poet John Keats as a state in which a person is: "is capable of being in uncertainties, Mysteries, doubts, without any irritable reaching after fact & reason" (Simpson *et al.* 2002, p. 1209). This is a quality seen as important in leadership and teaching alike (Simpson *et al.* 2002). It would appear, therefore, that learning does not stop and that an understanding of uncertainty is always susceptible to change as one develops as a person. One final interesting point to note is that the participant feels she has to be "careful of" advocacy, perhaps an acknowledgement that advocacy largely results in the removal of uncertainty from any discourse as people seek to put across a view grounded in personal or political beliefs to the exclusion of other perspectives.

Strategies for teaching uncertainty

Emerging from much of the discussion of teaching uncertainty are suggestions of potential strategies, approaches and pedagogies that may assist students in grasping this potentially troublesome concept or crossing the conceptual threshold that uncertainty represents. Many of these strategic examples also encompass other elements of the analysis and discussion – the conceptions of uncertainty identified previously and the theoretical aspects of teaching uncertainty outlined above. Indeed, the question of where and when to introduce uncertainty arose many times in the interview and not just from the perspective of the maturity of the learner but also in the context of individual university courses and modules. This is highlighted by the following quote from participant 4:

> "What happens is I add layers and layers and layers on, by the time I get to lectures ten and eleven there is actually a quote I use...by Stephen Hawking, it was written at the end of the 20th century, and it says that the 21st century is going to be one of complexity...[laughs] I have to present the complexity kind of at the end to give them confidence that the more you know the less you know, so that is partly my theme...I do actually start off with...the first slide I give is, it's amazing what we don't know about climate change, because that also runs through as a theme, that's because there are always surprises and that's the thing that makes me...that's why I find it quite exciting really [laughs]...it's that around the corner someone will tell you that what you thought was quite simple doesn't work that way" (Participant 4)

Presenting the full complexity of the climate system and the climate change issue towards the end of the course is seen as being less daunting for the students, giving them more "confidence" that even though they may have become much more familiar with the workings of climate change the uncertainties remain as large as ever. This perhaps reinforces the very first assertion about the levels of uncertainty in climate change ("the first slide I give is, it's amazing what we don't know about climate change"), and allows students, upon reflection, to develop a true understanding of uncertainty in this context. This quote also highlights the fact that, for many of the participants, their teaching of climate change was but a small part of their overall work. Often climate change was confined to a single module within a Geography degree programme, or as a topic that was revisited in different contexts – such as in modules focussing on atmospheric science, quaternary science, global change, development, tourism or energy. The practical constraints that this places upon teaching and learning raise the question of whether a highly complex and uncertain subject area such as climate change can truly be addressed in full in this way. Along with the troublesome, tacit nature of uncertainty as a concept, together with the difficulties in crossing the conceptual threshold that it represents and issues of liminal variation, the question may be raised as to whether this can all be accommodated as part of a Geography degree, as in the context of this study.

Many of the participants actually felt that the context of Geography offered a more effective way of teaching uncertainty than in other subject areas. For example, participant 6 felt that the multi-disciplinary nature of Geography made it the ideal discipline in which to teach the many and varied aspects of climate change and the attendant uncertainty:

Interviewer: "Uncertainty is something that interests me because...it's obviously something that is multifaceted, there is the kind of methodological and statistical uncertainties that you're talking about but there's another level when you consider what you came back to earlier on in terms of our quite selfish view of climate change that that adds another level of complexity and uncertainty to it...do you address that at all? I mean I'm talking about kind of human factors and you know the unpredictability of those perhaps and the other level that they add"

"Well that's grown actually and that human factor within my teaching has grown in sort of tandem with its use by the IPCC and other authors in talking about climate change...in the 2001 IPCC report they brought in for the first time these very complex socio-economic factors...which relate to population and family size and all different...all adding up to emissions and at that point...it's quite good as a geographer to be talking about this because you then start to bring in...well as a physical geographer you then start to bring in the more human Geography aspects of it...and indeed bring human Geography colleagues on board to teach in what was hitherto seen as a physical Geography type area...and indeed now at [participant 6's previous institution] we've actually made...human Geography is now actually going to be teaching a third of the global environmental change, global environmental issues module whereas hitherto it's all been by physical geographers, so that appreciation that climate change is driven by socio-economic factors as well as the physical...cleaner emissions totals and so on is actually making a difference and making climate change more of a integrated geographical topic than it was before..." (Participant 6)

Utilising the different specialisations of colleagues may in this case allow for a deeper exploration of some of the uncertainties involved in climate change. Whereas previously physical Geography lecturers may have marginalised social and human factors through the use of 'business as usual' scenarios, thus rendering them more 'certain', now students can explore the complexities of these different areas with more engaged and knowledgeable teachers. This will perhaps give a better overall understanding of uncertainty in climate change. A further 'vocation' of human geographers is seen by participant 8 in terms of questioning science and issues that may exist within it:

"I think....lots of them [students] see themselves as scientists, you know the physical geographers or the environmental scientists...and they're coming in with a fairly kind of set view of what science is...I think it's part of human Geography's vocation, if it has one, to correct that and to introduce uncertainty, to introduce issues about science, science's method and science's difficulties with reflection...you know its philosophy. In a way human Geography has gone completely the other way and has become almost psychopathically self regarding [laughs]...to the extent that there's almost no empiricism in human Geography anymore...which is striking compared to the abundance of empiricism in physical Geography, which is almost defined by method...physical geographers are what they do, human geographers are not what they think because they've thought about something else! [Laughs]...I can't keep up with all the philosophers who are coming into it...so I think students find that quite disturbing [laughs] that the subject can still encompass so feverishly separate approach to the knowledge..." (Participant 8)

The differences that exist between the two 'branches' of Geography may be viewed as "disturbing" by students (perhaps down to issues with foreign knowledge and identity as alluded to at the start of the quote); however it may also be turned to positive use. Allowing students an environment where they can question science and scientific thinking may open their minds to the inherent uncertainty that exists in knowledge and, thus, attempt to cross the threshold of understanding uncertainty. In effect, the 'disturbance' felt by the students in this context may indicate the provocation of a liminal state prior to the crossing of the threshold.

A further strength of the discipline of Geography is described by participant 9, who views the traditions of fieldwork prevalent in Geography as a useful starting point in encouraging students to question theoretical explanations of reality:

Interviewer: "Were there any other examples of bits of...even the sort of broader climate stuff that they found tricky in your experience?"

"I'm just trying to think...certainly the sort of theory versus reality...that in a textbook they would read about these nice mountain/valley [microclimates] or something but when they went out to actually measure them [laughs] and interpreting their data and realising it was much more messy than in reality, so...so that's a huge thing overcoming the theory versus reality, but I think that's where Geography does really well through the fieldwork that you do, because that's the guide and I think once you've been on a Geography fieldtrip it transforms your thinking about the landscape and...and also about questioning textbooks and so forth, articles..."

Interviewer: "So that was one of the attitudes that you were trying to engender? That, kind of, questioning...not taking theory as fact?"

"Absolutely...that's right and I think that was played out mainly through the fieldwork part in second year particularly and third year as well...and then the other really important exercise I think in terms of questioning journal articles would be to have the group critique one article, and we would all do it together so that they would sort of learn that...and that was a real eye-opener for them I think, and I wish they'd done that earlier, that tended to happen in the third year...but then when thy realised they could actually be quite critical of you know...research methods that might be dodgy, and I tended to pick on a paper that had some rather interesting elements [laughs]...and suddenly they realised that some of the stuff that's in print is absolute garbage! [Laughs]"

Interviewer: "There's a feeling that it's for a higher level and the more able students...

"Yes...and certainly, traditionally in my department that used to carry on at honours year but we actually brought it forward a into third year research methods course and...you definitely see student making a transition there and I would say that it can happen earlier as well, I'm sure that the earlier they realise that the better..." (Participant 9)

This understanding of uncertainty begins in the field, where students experience how "messy" reality is compared to theoretical explanations, and continues in the classroom where students are encouraged to question the ideas and conclusions they may encounter in academic reading – again highlighting the inherent uncertainty of knowledge. This also encourages students to construct their own meaning, which may be a useful tool in addressing troublesome concepts. A 'hands-on' approach was viewed by many participants as a useful means of engaging students with uncertainty, allowing them to see uncertainties emerging for themselves and thus recognise the role that these uncertainties play:

Interviewer: "Do you have any kind of strategies for helping people through those sticky patches?"

"I think...the more hands-on they can be with things like that, looking at the data themselves...or what we get them to do here which is...well they get their hands on different kinds of climate models, so in the second year they...they build their own, but that's like a zero degree climate model, so it's just like a point thing, but they just do it in Excel, and they can add all the different processes to things, so they can see how, how complicated it is, because they are doing their own different climate model so they all end up with slightly different results at the end and it's like...ooh, right you know, and then they compare that to the IPCC climate models, so you can see that they get very similar kind of patterns and what the uncertainties are there and in the way that you build your climate model, time-stepping, you know what different components you include and how they feedback on each other...and then actually getting there hands on some proper climate model simulations as well that...kind of...helps them see...see their way through the kind of uncertainty and limitations towards that sort of thing. Yeah" (Participant 5)

In contrast to exploring "messy" reality, the exercise above uses a similar principle to explore the uncertainties and limitations of climate models. Even a relatively simple model exposes the complexity of the climate system, the uncertainties that this generates and the difficulties inherent in modelling this complexity.

The question of how to assess an understanding of uncertainty was rather more difficult for participants to answer. For some this may have been down to the tacit nature of the concept whilst for others, such as participant 3, it may have been down to a lack of familiarity with assessment methods:

Interviewer: "What I'm interested in is uncertainty and the kind of complexity of the system and how we teach it basically...how do you get it across to students and it's interesting what you say about existing in a climate, pardon the analogy, of being familiar with science and the practice of science and the evolution of scientific thought...and if they exist within that framework already they're already tuned into it and they can be quite comfortable with it...trouble comes when you come to assess it and things, it's quite difficult because at the end of the day you're assessing what is, in effect, the absence of understanding..."

"Assessing whether people have understood what you've said about the uncertainty?"

"Yeah, understanding uncertainty is really, really difficult...But I don't expect you've had any experience of that yet have you?"

"Well yeah...ask me after I've seen whether anyone's answered my questions on the course and I've marked their essays...I mean that in itself is quite weird for me because as a physicist my whole degree was numerical really and so the fact that I've kind of set exam questions that were essay questions and will be marking those, that's quite uncertain to me (laughs) you know and how to assess how well they've understood something how much they've either parroted something they've remembered from my slides or gone away and thought about it and looked it up and how to judge how much of either of those things they should have done, because probably Physics was based quite a lot on memory or at lease remembering how to derive things from first principles at least...so that's...no, I'm quite interested in that question myself, I'd quite like to know..." (Participant 3)

The difficulties with the particular assessment methods notwithstanding (clearly related to this participant's personal context and background), the difficulties inherent in assessing an understanding of uncertainty begin to become apparent. The difficulty not only lies in assessing the extent to which a student has learned the content of lectures but also in assessing how much the student has "thought about it". A potential means of assessing this level of thought is a consideration of how much the student has integrated an understanding of uncertainty into their answer, although, as has been demonstrated elsewhere, this is not an easy task in itself.

Some of the complexities involved in assessing an understanding of uncertainty are highlighted in the following quote from participant 10:

Interviewer: "How would you assess student's understanding of uncertainty?"

"Interesting...I suppose I'm not actually explicitly assessing it...but then the way I assess the course, I've got three components of assessment, I've got...a series of tests which are more...they're multiple choice which I construct very carefully, so they're partly designed from a factual standpoint, they [students] have got the terminology and they understand what it means...part of it is problem solving and application as well...so that's one element, then I've got the very practical campus-based sustainability assignment where...I'm looking there for capacity to scope a research question around a problem to handle data assimilation and collection and then to site that within whatever available literature there might be, in order to produce essentially a consultancy report, rather than an essay type article...so that's very much...we've got a real world problem where we're bringing an academic lens to it but with a practical focus and what recommendations can we make on the basis of whatever background literature and the analysis of the information...the final one is the simulation of the international processes and I suppose that's where the uncertainty comes in, but I'm not explicitly assessing their understanding of uncertainty, I'm looking at their ability to integrate a range of perspectives and information relevant to their particular country that they are representing, so relevant to the countries perspective on the issue of climate change, and negotiating points to go forward, they have to come up with three negotiating points for the debate and they have to motivate those, so they have to give me...fundamentally what the essay is about is motivating their three points, why have they come up with those? Why is it in their countries interest? Why do they think it would work or wouldn't work in the negotiations? Who would the allies be and why? You know those kind of things, and that's not really about uncertainty, that's about operating...understanding another cultural perspective, bringing together a range of information and understandings from the science, economics, governments, whatever it might be...social perspectives...and then putting that all into the context of how that all plays out when you're negotiating with people of other interests, but it doesn't actually deal with uncertainty, so I'm not explicitly assessing uncertainty, so I don't know...do you have any ideas? I've said that it's key, and it is for me, but I don't assess it explicitly...I can't think how I would..." (Participant 10)

The "simulation of the international processes" described above is an exercise that simulates a United Nations climate summit, where groups of students take on the identity of nation states and attempt to negotiate climate change related concessions with other groups. Gautier and Rebich (2005, p. 13) describe a similar pedagogy for engaging students with climate change and note that it "effectively provides learners with motivation and opportunity to prepare themselves for participation in and understanding of this complex area of scientific inquiry". However, whilst the exercise described by participant 10 is clearly a powerful one in terms of giving students an insight into the complex nature of climate change and human interactions within and around the issue, an understanding of uncertainty is not explicitly addressed. The exercise again reveals the pragmatic conception of participant 10 in that it is more about "operating" than achieving deep understanding. This emerges again from this quote, which follows immediately from the one above:

Interviewer: "One suggestion is a sort of viva, where you perhaps base it on a piece of research the student has done and try and tease out how they understand it…or just have a chat about it…"

"Now…I do that with the postgraduate students, but I run a separate tutorial for them and we do address it in that sort of way, we talk about it…and most of them are professionals who either are currently working in some sort of area related to climate policy or have worked in that area…so that works…with the undergraduates it's more difficult, they've got a class of 60 odd so…there are practical constraints to what you can do, and I suppose if I really think about it, do I want them to come out of it with a deep understanding of uncertainty and it's role in all of this, or is it more that they just recognise that it's there and that they're aware of it, and that as they mature and go on and apply all the things that they've learned, not just in my courses…that it's there as part of that mix, and I think maybe that's more what's important to me than that they can explicitly say…this is uncertainty and this is how it affects you know what I'm doing in my work and so on"

Interviewer: "So is it almost a skill that they're gaining?

"Yes, maybe it is...the ability to recognise uncertainty perhaps or something like that"

Interviewer: "Or the ability to work with uncertainty and..."

"Not be paralysed by it...yes" (Participant 10)

This is clearly a highly pragmatic take on uncertainty, stating that an ability to deal with uncertainty is a useful skill that perhaps precludes the need for a deep understanding of the concept itself. Whilst this may be down to practical constraints (class sizes, maturity etc.) it certainly appears to fit with this participant's particular take on uncertainty, as discussed previously. This raises fundamental questions about the motivations for teaching uncertainty and how this may be conducted in a manner most beneficial to students. A final quote from participant 10 puts this point into focus:

Interviewer: "I think there is a deeply philosophical way of thinking about uncertainty and it can be an extremely difficult thing...that is maybe not really appropriate for undergraduates...do you want them to have a deep understanding of uncertainty or do you want them to be people who can work in an uncertain world?"

"That's more important, definitely, definitely...which is why as I said at the beginning it is both explicit and implicit and the explicit part is a tiny part of what we actually talk about in class, there's an element of one lecture where we highlight uncertainty and we talk about sources of uncertainty and different types of uncertainty in science and so on...but then it just keeps cropping up naturally as the course moves along...I think that's right, I think it's more about wanting it to be there in the mix as one of the skills and then making it explicit at all and recognising that there are different uncertainties, but then making the point that we have to...the world is uncertain, everything is uncertain, stepping out of your front door in the morning puts you into a state of uncertainty and exposure to risk and so on...so how do we operate like that, and just for one thing, just to be aware that we are making these decisions unconsciously all the time...and not explicitly thinking about it, but we are operating in an uncertain world and this is just another dimension of that that is more explicitly out there, but that we shouldn't be paralysed by it...I suppose maybe that's fundamentally the thing for me...that's interesting...and that's really helped me to think through what I'm doing...that's fascinating, it's always good to talk" (Participant 10)

The above quote captures much that has been covered in this and the previous chapter. There is the pragmatic approach to uncertainty that typifies this participant's responses, however the need to make uncertainty explicit in teaching to some degree is still acknowledged. However, and perhaps most interesting of all, the participant seems to want to encourage her students to go through life without "explicitly thinking about" uncertainty. This appears to put uncertainty back in the bracket of tacit knowledge, which, given its place in communities of practice as an expression of identity, may indicate that this is a powerful learning outcome in itself.

Chapter Seven

Summary and Conclusions

This chapter summarises the preceding discussion and makes conclusions based on the analysis of the data and the wider context provided by earlier chapters. Before summarising the conclusions of the thesis there is a brief synopsis of the rationale behind the study, the theoretical frameworks and context of the study, the aims, and the methodology used. The summary points are structured under the four research questions examined in this thesis:

1. **What is the nature of uncertainty in the context of climate change?**

2. **Does uncertainty represent troublesome knowledge in the context of climate change?**

3. **Can the concept of uncertainty be described as a threshold concept in the context of climate change?**

4. **What strategies do teachers use to teach uncertainty in the context of climate change?**

Each section deals with the findings pertaining to each of the research questions in turn, with a further section outlining the themes that have emerged from the research and the implications of the work. There then follows an appraisal of the findings of this thesis in the context of formulating the pedagogy of uncertainty. The chapter ends with a discussion of where future research may build on the findings of this thesis and a closing position statement from the researcher.

Synopsis

The rationale behind the study was to investigate the teaching of the concept of uncertainty in higher education, which has become a pressing concern for teachers owing to the necessity of preparing students for a supercomplex and uncertain world (Barnett 2007, 2009). Pedagogic theory and research, however, tend to focus on ontological uncertainty – feelings of uncertainty experienced by students and teachers or the ontological consequences of encounters with epistemological uncertainty, or uncertain knowledge. It is epistemological uncertainty that is of most interest in this study, specifically in terms of how it is taught at higher education level. In order to contextualise the concept of uncertainty and describe its epistemological characteristics, the context of climate change was used – a subject area in which uncertainty plays a central role. The theoretical frameworks used for the analysis of uncertainty as a concept in higher education were troublesome knowledge (Perkins 1999; Meyer and Land 2003) and threshold concepts (Meyer and Land 2003, 2005). These theoretical frameworks contain several criteria useful for analysing uncertainty and suggesting potential implications the concept may have in teaching. The aims of the research were:

- To explore the nature of uncertainty in the context of climate change

- To investigate uncertainty in the context of climate change in terms of how it is conceptualised and taught by academics working in the subject area

- To offer a critical reflection on the pedagogy of uncertainty

The data collection for the study was based on ten semi-structured interviews with academics teaching about climate change on Geography degree programmes, the design of which was grounded in the theoretical frameworks and many of the principles of grounded theory (Bryant and Charmaz 2007). The analysis of the interview data also followed the inductive and open-ended approach advocated by the methodology of grounded theory and was based on placing the responses of the participants into categories relating to their conceptions of uncertainty and the implications for teaching uncertainty.

Research question 1: What is the nature of uncertainty in the context of climate change?

The nature of uncertainty in the context of climate change has been explored most specifically in chapters two and five. These chapters have revealed the nature of uncertainty, firstly, in the broader context of climate change, and, secondly, as it is conceptualised by the participants in the study. Fundamentally, the uncertainty found in understanding and predicting climate change reflects the nature of the subject itself; it is highly complex and diverse in character, open to many different interpretations and with a massive range of implications. This is reflected in both the literature covered in chapter two and the conceptions of uncertainty identified through the analysis of the data gathered from the interviews with the academic participants. The conceptions offered by the participants cover much of the uncertainty described in chapter two, with a similar range of sources and manifestations of uncertainty being discussed. This is shown in Table 7.1, a revised version of Table 2.5 where the key references from the climate change literature have been replaced with the contexts in which various sources of uncertainty were discussed by the participants in the research interviews. The contexts are drawn from the headings and sub-headings used to group conceptions identified through data-analysis and appear to show a considerable overlap with the sources of uncertainty discussed in chapter two. The participants identify uncertainty arising from the complexity and chaos of the climate system, in constructing and using climate models and also in terms of quantifying uncertainty for scientific purposes all of which pertain to the uncertainties that exist in the science of climate change described in chapter two. The participants also identify more qualitative conceptions of uncertainty pertaining to social components of the climate change issue and human interactions with the climate system. These correspond to many of the uncertainties related to human behaviour and decision making outlined in chapter two. Whilst specific examples may not have been discussed there is broad agreement between the sources of uncertainty discussed in chapter two and those identified through the research interviews. This demonstrates once again that uncertainty is a key concept in the climate change subject area, whilst also showing that the interview participants have a broad understanding of the many and varied sources of uncertainty relating to climate change indicating that the results hold further validity in this respect.

Table 7.1: A comparison between sources of uncertainty and examples identified from the climate change literature and the conceptions of the participants. All of the sources and examples of uncertainty identified in chapter two were discussed in some form in the research interviews although there is a degree of variation in the context in which these dscussions arose.

	Source of Uncertainty	Example	Context in which discussed by participants
Climate Change Science	Climate System	Complexity, Chaos, Surprises	**Scientific Conceptions:** Nature of the System
	Climate Reconstruction and Proxies	Multiproxy reconstructions, Dating (e.g. C^{14}), Leads and Lags	**Scientific Conceptions:** Nature of the System; **Scientific Conceptions:** Nature of Science
	Climate Modelling	Parameterisation, Model Resolution & Complexity, Data Quality	**Scientific Conceptions:** Climate Modelling
	Scientific Discourse	Conflict & Consensus, (e.g. 'Climategate')	**Scientific Conceptions:** Nature of Science; **Qualitative Conceptions:** Society – Politics, Risk and the Media; **Qualitative Conceptions:** Conflict-based Uncertainty
Human Behaviour	Emissions Scenarios	IPCC SRES 'Storylines'	**Qualitative Conceptions:** Human Behaviour – Scenarios and Choices;
	Adaptation & Mitigation	Geo-engineering	**Qualitative Conceptions:** Society – Politics, Risk and the Media
Decision-Making	Characterising Uncertainties	Probabilistic vs. Qualitative descriptions	**Scientific Conceptions:** Quantifying Uncertainty; **Qualitative Conceptions:** Human Behaviour – Scenarios and Choices
	Decision-Making Frameworks	Post-normal Science, Precautionary Principle	**Pragmatic Conceptions**

The conceptions of the participants, however, also offer a deeper insight into the nature of uncertainty by describing it in terms of how it is conceptualised and experienced by those teaching and researching within the subject area. The conceptions of the participants seem weighted in favour of characterising much of the uncertainty in climate change as "scientific uncertainty". At first, this may appear to be as a result of the backgrounds of the participants, most of whom were trained as scientists or physical geographers (see Table 4.1). However, those participants from 'less scientific' backgrounds also often chose to associate uncertainty with something that more scientifically-minded colleagues "dealt with". It may be that scientific uncertainty is actually a more recognisable form of uncertainty and, therefore, more straightforward to accommodate, contextualise and conceptualise. As chapter two and the first section of chapter five demonstrate, a large part of the work of scientists researching climate change is concerned with reducing uncertainty and quantifying it statistically or probabilistically and this in turn offers a context in which uncertainty may be resolved numerically. This is seen as more straightforward by some participants, for example participant 5, who views a quantitative approach to characterising uncertainty as being more straightforward than a qualitative or descriptive approach.

Other uncertainties associated with climate change, which may be described as more qualitative or human in nature, appear to be somewhat more difficult to characterise as factors such as choice and unforeseen social responses to climate change affect human futures to such a degree as to make them almost entirely unpredictable. This is demonstrated by the development and use of emissions scenarios based on future human behaviour and social interaction, which are highly uncertain in both the range of future outcomes they predict and the fact that these ranges are unlikely to reflect the eventual reality that transpires (Pittock 2009). It is perhaps easier to conceptualise these uncertainties in terms of the risks posed to society by climate change, as in the case of participant 10 who conceptualises uncertainty as a factor within the analysis of the risks to human health as a result of future climate change. Risk is a familiar form of uncertainty and may, therefore, be more straightforward to rationalise, although it does not cover the full range of social and qualitative uncertainty related to climate change.

It may also be argued, however, that the science of climate change offers a promising context for engagement with uncertainty, and is recognised by the participants more readily, as a result of the uncertainty inherent in the nature of science and scientific knowledge. Although not specific to the context of climate change, this was viewed as a significant source of uncertainty by almost all of the participants. The provisional nature of scientific explanations and theories and the dynamism of scientific knowledge are a source of fundamental uncertainty in all science and are revealed extensively in the science of climate change. Teaching about climate change necessitates the resolution of this uncertainty on the part of both teacher and student and it appears that climate change in turn offers an excellent context for the exploration of profound uncertainties relating to knowledge and the nature of science. Earth Science in general is characterised by Kastens (1995) as a discipline offering a "special opportunity" for exploring boundaries between the "known and unknown" and this would appear to be supported by the findings here relating to climate change, where there is considerable overlap with the subject area and the broader discipline of Earth Science. Indeed, many of the participants view the science of climate change as being more uncertain than other branches of science, for example participant 3 compares her experiences of climate change modelling with those of Particle Physics where a much greater degree of certainty is expected.

The uncertainties expressed in both the literature and the conceptions of the participants lend themselves to characterisation based on how qualitative or scientific and practical or philosophical they appear to be, as shown in Figures 5.1 and 5.2. This in turn lends weight to the characterisation of climate change science as post-normal science, encompassing a large range of epistemological uncertainties across scientific and social spheres of knowledge and with a strongly practical dimension related to decision making and the minimisation of risk. Just as in the context of post-normal science the uncertainties encountered in climate change operate across a range of different levels, prompting different approaches and conceptions depending on their character. Integrating the whole range of uncertainty may be highly troublesome or even impossible; this is inferred by participants 1 and 4 who identify different uncertainties as 'belonging' to different areas of research specialisation within the diverse multidisciplinary area of climate change and the problems caused by attempts to integrate them. However, the different characterisations of uncertainty may be accommodated in certain areas such as approaches to climate modelling (as shown in Figure 5.2), which offer a context in which a diverse range of uncertainties may be seen to interact.

Ultimately though, much of the uncertainty associated with climate change may be intractable and insurmountable. This is down to the considerations mentioned earlier, concerning the nature of scientific knowledge or the inherent unpredictability of human behaviour, and also the fact that there will be only one future reality, the nature of which it is impossible to predict precisely (Pittock *et al.* 2001). Whilst the uncertainties in climate change may be characterised to a degree it remains a concept that is difficult to constrain and, thereby, teach. Nevertheless, there appears to be much that may be gained from engagement with uncertainty in the context of climate change, not least the opportunity to explore the nature of knowledge and the interaction of society and complex systems. It should be noted, however, that the epistemological uncertainty associated with climate change does not invalidate progress towards understanding the complex whole. This thesis contains numerous examples, provided by both the participants and the literature, of instances where knowledge and tools for understanding remain useful in the face of even profound and fundamental uncertainty – such as in climate modelling or the development of emissions scenarios. Uncertainty is ubiquitous and all pervading in climate change and it gives rise to both challenges and opportunities in the context of teaching.

Research question 2: Does uncertainty represent troublesome knowledge in the context of climate change?

There is much evidence presented in the thesis, though particularly in chapter six, to suggest that uncertainty does indeed represent troublesome knowledge in the context of climate change. Chiefly the troublesome knowledge identified by the participants is in the form of conceptually difficult, foreign and tacit knowledge. However, forms of inert and ritual knowledge may also be inferred in the responses of students as a result of the troublesome nature of uncertainty described by the participants. Uncertainty is considered conceptually difficult in this instance primarily owing to its complexity. This is supported by the above assertions about the nature of uncertainty in this context and appears to present a challenge to both teachers and learners alike. This might be down to difficulties in explaining uncertainty, which were identified by participant 5 in terms of the randomness and chaos that exists in the climate system, or as a result of the attitude towards uncertainty adopted by the learner. Participant 3 describes this in terms of familiarity with the concept, implying that it is very difficult to teach uncertainty where the learner has not already encountered the concept through, for example, the scientific method. In this case uncertainty may be seen to act as a kind of negative reinforcement – confirming beliefs about science held by the learner and thus making them more 'certain' in their outlook and less likely to engage with uncertainty.

The issue of familiarity with uncertainty extends to the characterisation of uncertainty as foreign knowledge. Uncertainty may be considered foreign or alien by students either through a lack of familiarity, as described above, or due to the fact that it conflicts with their beliefs about science and scientific knowledge. Participant 8 describes students who have "naïve notions of fact" relating to scientific truth and who are unwilling to engage with the provisionality of scientific knowledge. Views such as this that conflict with a student's own epistemological beliefs are likely to be highly troublesome. Even if students do understand the implications of uncertainty in scientific terms, however, they may yet encounter troublesomeness in the context of climate change brought about by the post-normal nature of the science in this instance. The science of climate change does not fit with normal science paradigms and therefore challenges 'normal' approaches to uncertainties, which are not necessarily the same as the high systems uncertainties described by post-normal science. This in turn raises the issue of personal identity on the part of the learner or teacher and the part this plays in construing concepts as foreign. In this regard it was interesting to note the comments again of participant 8, who identified a potential conflict in teaching uncertainty explicitly to Geography students as he felt they were likely to see the concept as belonging more to Philosophy than Geography. A teacher's self-identification is also seen as troublesome in this regard; participant 5 outlines her own difficulties in teaching uncertainty in a more qualitative way as opposed to the strongly quantitative methods she was used to using. Furthermore, even accomplished researchers and teachers, who felt themselves familiar with uncertainty in climate change, acknowledged the difficulties presented by attempting to integrate diverse uncertainties from different areas of climate change research into the complex whole of the subject area. This is another reason for the characterisation of uncertainty as foreign knowledge and appears to be linked to the conceptual difficulty raised by the complexity of uncertainty in climate change mentioned earlier.

The question of identity and the part it plays in according uncertainty the status of troublesome knowledge in this context is brought into further focus through the identification of uncertainty as tacit knowledge. This was a factor that emerged frequently from the research (it is identified in both discussion chapters) and would appear to be the most significant typology of troublesome knowledge in terms of teaching uncertainty. In this instance uncertainty may be described as tacit knowledge for a number of reasons. Many of the participants, whilst acknowledging that uncertainty was "very important" in the context of teaching about climate change, also admitted that it was not a concept that tended to be "formalised" in teaching. Uncertainty is referred to as "implicit" on several occasions, either as a result of the other troublesome facets of the concept (i.e. conceptually difficult and foreign knowledge) making it difficult to teach and a concept to be avoided or internalised, or owing to its centrality, ubiquity and inherence within the multidisciplinary subject area of climate change.

This centrality appears to lead to uncertainty not being articulated as it is "just something climate researchers do" and would also appear to suggest that uncertainty is tacit knowledge, as described by Polanyi (1958) and Wenger (1998), in that it is something that is learned through practice rather than formal teaching. That uncertainty is tacit in the nature of climate change also seems to lead to further troublesomeness in terms of assessment. Participants describe it as being "hidden" and something that either "clicks or not" and that it is extremely difficult to assess explicitly; it is said to be "in there somewhere". Even those participants who assert that they do teach and assess an understanding of uncertainty explicitly are forced to admit that they do not, that it remains hidden in almost everything they teach. This was certainly the case for participant 10, who began her research interview with discussion of how uncertainty was "explicitly and implicitly there in everything I do" before coming to the realisation that the explicit teaching of uncertainty formed only a very minor element of the course in question. Following on from this, there is also much evidence from across the analysis and discussion of the interview data that many of the participants had not considered uncertainty explicitly in their teaching prior to the interview. It appears that as a result of questioning they have come to appreciate the tacit knowledge of uncertainty themselves and, therefore, indicating that there is a strong case to suggest that much of the troublesome nature of uncertainty in the context of climate change arises from its tacitness.

Research question 3: Can the concept of uncertainty be described as a threshold concept in the context of climate change?

As acknowledged in chapter six, evidence gathered from the research interviews suggests that uncertainty is a threshold concept in the context of climate change. It is clearly troublesome and the tacit nature of uncertainty is reinforced by the fact that only two out of the ten participants identified it as a key concept unprompted. Of the other participants, almost all felt that uncertainty was an extremely important concept for students learning about climate change to understand. The other criteria that define a threshold concept were, in some cases, more difficult to identify, partly as a result of there not being a direct question about threshold concepts in the research interviews and also due to the complexity of the concept itself.

The ability of uncertainty to transform a learner was alluded to by several of the participants where an understanding of uncertainty was linked to "becoming scientist", "realisations" about the uncertain nature of knowledge, developing an enquiring mind and developing criticality and skills of critical thinking. This transformation was also seen as "fundamental" for graduates, in a capacity that may be comparable to the notion of graduate attributes, particularly when one considers the stated desire to produce "agents for an unknown future" (Barrie 2004; 2007). This transformation also seems to lead to a discursive shift, evident in the discourse of the research interviews and alluded to by participant 6, who described assessment criteria that look for students using the "full range" of statistical uncertainty in their answers to questions about future climate change. This reveals some of the complexity of uncertainty in this context as it raises the question of whether discursive elaboration of uncertainty on the part of a student signifies genuine understanding or whether it constitutes an epistemic game or strategy that mimics understanding. In the same passage the participant mentions examples of mimicry employed by students who fail to cope with or understand uncertainty and it is worth considering, given the complexity of the subject area and uncertainty as a concept, that seemingly "good answers" may be more complex strategies that simulate understanding.

Whether epistemic games are at play or not, the resistance to learning uncertainty in this context is clearly demonstrated. Students are frequently characterised as not liking uncertainty, preferring "hard and fast figures" and avoiding the complex and troublesome concept of uncertainty, which may challenge their whole world-view and way of knowing. The casting of students as 'defended learners' (Land 2009) in this way indicates the existence of a liminal dimension linked to an understanding of uncertainty. This is borne out by the description of the profound ontological uncertainty experienced by students as they come into contact with the epistemological uncertainty inherent within climate change. This is expressed in terms of "bewilderment" and a "loss of hope" but also linked to progression, an essential and unavoidable waypoint on the path to becoming a scientist. This liminal aspect supports the selection of threshold concepts as a theoretical framework for this study as it encompasses both the epistemological and ontological uncertainty that may be encountered when teaching climate change.

The resistance to learning uncertainty may also be viewed in terms of liminal variation on the part of learners, the assertion that some "take to it", whilst others do not, although this may be a result of delayed understanding requiring reflection on the part of the learner. Other examples of liminal variation include pre-liminal variation in terms of how students view the subject they are studying and the positive or negative reinforcement that learning uncertainty may precipitate – this is contextualised by participant 3 in relation to students reinforcing "sceptical" beliefs about science through the realisation that science cannot provide definitive answers. Whilst this may be seen as a shift in subjectivity it does not appear to involve the traversal of liminal space, there is no challenge to the previously held ideas of the student and no discomfort involved as a result. Instead, the previously held conception is reinforced and may actually lead to a more certain worldview with no component of ontological uncertainty experienced by the learner. Pre-liminal variation, which allows for the crossing of the threshold of understanding uncertainty, is characterised in terms of "openness" and "willingness" to accept the concept and its implications. This may be analogous to the "will to learn" identified by Barnett (2007) as essential for students learning in an uncertain world. Post-liminal variation may be identified in the exercise described by participant 7 in chapter five, which asked students to discuss their personal decision making relating to tourism as a consequence of what they had learned about climate change. In this instance a range of qualitatively different responses was described, all of which appeared to have integrated uncertainty to some extent. Given the link between personal choice and beliefs in uncertain conditions (Payne *et al.* 1992), it may be that the different subjective takes on tourism behaviour represent some post-liminal variation in how the students have integrated an understanding of uncertainty.

It is sub-liminal variation, however, that perhaps has the most significant implications for the threshold concept of uncertainty, although this is also the most troublesome and complex species of variation to identify and describe. It is again in the tacitness of uncertainty in this context that much of this difficulty is encountered and it is expressed in terms of the epistemic games described above and in the subtle distinctions between the conceptions of uncertainty identified among the participants, which may represent an underlying game (Meyer and Land 2008, Perkins 2006). Although many of the participants appear able to hold multiple diverse conceptions of uncertainty simultaneously, the integration of diverse uncertainties is seen as troublesome (as noted in the above section). It may be that the conceptions of uncertainty themselves represent sub-liminal variation among those teaching uncertainty, where they tacitly view uncertainty in a certain way, depending on their own personal identity or research specialism and, therefore, experience difficulty when integrating uncertainties from other areas within climate change. The understanding of uncertainty may be highly personal, making this sub-liminal variation difficult to recognise and accordingly giving rise to difficulty in teaching or learning the concept. This sub-liminal variation and diversity in the types of uncertainty encountered in climate change may also represent a kind of internal bounded-ness that separates uncertainty from other examples of more esoteric threshold concepts such as opportunity cost in Economics (Reimann & Jackson 2006) or geological time in the Earth Sciences (Truscott *et al.* 2006). Whilst uncertainty may be seen as integrative in the context of climate change, as it is ubiquitous and a "fundamental in everything" from the most basic to the most fundamental principles of the subject area, this integration may not be easy to come by. As a result, uncertainty may represent a kind of interdisciplinary threshold, a commonality between diverse disciplines in a complex subject area that is a troublesome concept, but with a strongly transformational dimension linked to discursive shifts and ways of expressing uncertainty. Uncertainty may be bounded internally with respect to the many disciplines that have a place in the climate change subject area; externally, however, uncertainty cannot be bounded or constrained in this way. Understanding uncertainty may lead to profound realisations about the nature of knowledge or new subjective positioning with respect to personal choice, but what it also offers is a new way of thinking about a complex subject area that is not constrained by boundaries of disciplinary knowledge and identity as it is a common feature to all people in all disciplines.

Research question 4: What strategies do teachers use to teach uncertainty in the context of climate change?

Examples of different approaches to teaching uncertainty are encountered frequently in the analysis of the interview data and are both explicit and implicit in the responses of the participants. This summary deals with those suggestions of strategy and why they may have been viewed as effective by the participants. Where they are implicit it is not a case of them being tacit in the same sense as troublesome knowledge or threshold concepts, but rather that they emerge naturally as a result of uncertainty being discussed in the context of teaching. Questioning the nature and status of the concept of uncertainty in the context of climate change in the interviews naturally led to discussions of situations in which uncertainty is encountered and the strategies that may exist for teaching it. One of the main suggested strategies that may be identified is, however, linked to the tacit nature of uncertainty in that there is value seen in making the concept explicit in teaching.

Knowledge that is troublesome in the tacit sense is difficult for students and teachers alike to engage with, making concepts such as this explicit is one way of ensuring that the concept is apprehended by students so that the process of crossing the threshold of understanding may begin. However, as has already been noted, this is likely to be difficult for student and teacher alike owing to the other troublesome aspects of the concept, namely that it is extremely complex and may be seen by some as counter-intuitive or alien in some way. It would appear; therefore, that making uncertainty explicit may not be sufficient on its own to overcoming the troublesomeness of the concept. In this instance the explicit teaching of uncertainty may be usefully supported by a degree of preparation on the part of the teacher as a well as a recursive approach where uncertainty is revisited frequently in teaching. This was mentioned by participant 3 in terms of allowing students to become familiar with the process of scientific enquiry and thereby engendering an openness and willingness to accommodate uncertainty. Married to this is the notion that understanding in this case cannot be achieved quickly and that the concept of uncertainty may require to be revisited frequently in order to keep it at the forefront of students' minds as they traverse liminal space towards an understanding of uncertainty. Some of the participants also stated that introducing students to the full complexity of the uncertainty associated with climate change may be best left until later in a course so as to not overwhelm students.

Ways of engaging students with uncertainty in diverse ways that reflect the nature of the concept were also identified by the participants. The example of fossil ecology was identified by participant 6, who viewed this as a way of introducing students to uncertainty in an aspect of climate change science that can then be extrapolated more widely to other areas of the subject (perhaps acting as an 'interdisciplinary threshold' as described in the above section). The reporting of climate change in the media was viewed similarly by participant 9 as a potential challenge to students' understanding of uncertainty, but also as an opportunity in which to engage students with the uncertain nature of knowledge relating to climate change. There is clearly a danger in this that students may choose to reinforce previously held conceptions as a result of these contextualised discussions of uncertainty or lose hope as a result of the ontological uncertainty it may bring about. However, this is a necessary process if a teacher wishes to make uncertainty explicit and allow students to achieve understanding.

In this respect, Geography was seen as a sound disciplinary context and community within which to explore and understand uncertainty in climate change. Whilst this is partly down to the context in which the research was carried out (i.e. with academics teaching on Geography degree programmes), it was also qualified by several of the participants in terms of what the discipline of Geography offers in terms of content and pedagogy. Firstly, the multidisciplinarity of Geography allows students to experience uncertainty in a variety of contexts, as in the use of fossil ecology and the media to contextualise uncertainty in diverse ways. This multidisciplinarity also allows students to experience different perspectives on uncertainty through interaction with a diverse range of academic specialists, which may help to break down some of the sub-liminal variation associated with the concept and ease the liminal transition for students. The field- and laboratory-based approaches inherent to Geography were also seen as a means of allowing students to experience the 'messiness' of reality and the uncertainties inherent in theories and models. Students are able to see for themselves the ways in which theories break down in relation to reality and, in designing and using simple climate models, how tools for understanding complex systems contain significant limitations and uncertainties. Indeed, climate modelling would appear to offer a powerful means of introducing much of the uncertainty relating to climate change in that, as Figure 2 (chapter 6) shows, the uncertainties encountered in climate modelling cover almost the full range that characterises uncertainty in this context. Gautier and Solomon (2005) identify enquiry-based climate modelling experiments as a useful means of introducing students to the potentially large differences in qualitative outcomes produced by small changes to initial quantitative inputs as a result of the complexity and uncertainty within the climate system.

Further to allowing students to engage with uncertainty in reality through field and laboratory work is the suggestion of problem-based activities that draw students into the complexity of climate change and allow them to experience the ambiguity and uncertainty inherent to the subject area. The example given by participant 10 of a mock climate summit would appear to be a useful strategy in this instance and this view is borne out by the literature on teaching climate change science (Rebich and Gautier 2005; Gautier and Rebich 2005). This pedagogy is seen as affording students an *insight into the uncertainty* experienced when making decisions around climate change, particularly with relation to ill-defined problems where the most suitable approach for problem solving is unclear and post-normal approaches that students have not yet considered may be required. Similarly, debates amongst students about issues such as climate change are seen as a strong approach as they encourage students to engage with uncertainty in terms of assessing the evidence used to support knowledge claims (Schweizer and Kelly 2005). Engaging students in research was also seen by many of the participants as a key strategy in helping them achieve an understanding of uncertainty. Participant 1 talks of the "independence" and "responsibility" that research encourages on the part of students as a crucial factor in their coming to comprehend troublesome knowledge and this may be a significant factor in a student coming to understand uncertainty either as a result of the earlier factors concerning the assessment of evidence for knowledge claims or their own experiences of attempting to produce certain answers amidst the inherent uncertainty of reality. Student-centred, problem-, research- and enquiry-based approaches would, therefore, all appear to be among the most fruitful for teaching uncertainty in the context of climate change and this echoes the constructivist pedagogies suggested by Perkins (1999) as the best methods for teaching troublesome concepts (Hall 2010).

Assessing an understanding of uncertainty was seen by many of the participants as one of the most troublesome aspects of teaching uncertainty. This is largely down to its tacit nature with several participants acknowledging that although it was a highly important concept they had not, up until the point of interview, previously considered how to assess their students' understanding of it. The main difficulty appears to be that the tacit nature of the concept means that the assessment of understanding uncertainty is also tacit. It is described as being "in there somewhere" in terms of assessing responses to essay questions about climate change but there appears to be no formal process or scheme for assessing an understanding of uncertainty. The suggestion emerged through discussion between participant 10 and the researcher that an oral exam or *viva voce* may afford the teacher an insight into a student's understanding of uncertainty, although this itself would represent a subjective appraisal of the tacit knowledge of uncertainty held by the students. The difficulties with assessing an understanding of uncertainty appear to be at odds with the assertions offered by many of the participants that, despite a degree of variation, at least some of their students achieve an understanding of uncertainty. This perhaps implies that tacitly recognising uncertainty is, for students and teachers alike, the chief means by which they understand the concept.

Emergent themes

Throughout the analysis of the data there have emerged several highly interesting themes pertaining to teaching uncertainty that were not an intended focus of the original research design. This has been facilitated by the open-ended nature of the research methodology, which has allowed for the exploration of these emergent themes in the course of both the data collection and analysis. A major emergent theme in the research has been the relationship between personal development or maturity and the teaching and learning of uncertainty. This was viewed by many of the participants as a crucial element in the ability of students to be able to understand fully the concept of uncertainty, either as a result of practical considerations (such as when uncertainty is encountered 'late' in the curriculum or through capstone activities) or through students making meaning (as in the schemes of Perry (1970) and Baxter Magolda 2009)). Capstone activities may be aligned to the strategies described above in that these are the instances in higher education where students undertake their own research and engage most deeply with a subject (Kuh 2003, 2008). In schemes of personal and intellectual development, such as those proposed by Perry and Baxter Magolda, an understanding of uncertainty is seen as crucial in allowing students to develop not only intellectually, but also as people. Given the responses of the participants in relation to when uncertainty is introduced (i.e. later in the curriculum) it would appear that they believe a degree of personal and intellectual development is also required in order to understand uncertainty. This suggests that a synergistic relationship exists between personal and intellectual development and uncertainty, where an understanding of uncertainty is necessary for development and constructing meaning, in the process of which a deeper understanding of uncertainty may be achieved. This was borne out by the reflections of participant 10, who felt that her own personal development as a person and researcher had made her much more able to accommodate and communicate uncertainty.

Participant 10 was also the main source of what were described as 'pragmatic conceptions' of uncertainty, which may be considered another significant emergent theme of the research. The focus of a pragmatic conception is characterised by "dealing with" or "coping with" with uncertainty as opposed to attempting to understand the concept in a deep way. Pragmatic conceptions are able to integrate diverse epistemological uncertainties (from the qualitative to the scientific, the philosophical to the practical) as well as ontological uncertainties in such a way that the uncertainties do not become "paralysing" for students. These conceptions are linked to tacit knowledge, where a tacit understanding of uncertainty may be seen as the most desirable learning outcome for students, and appear to be more practical than conceptual. Indeed, a pragmatic conception of uncertainty may be characterised in terms of attaining the 'skill' of dealing with uncertainty, rather than a deep understanding. In this sense the pragmatic conceptions align with Keats' (Simpson *et al.* 2002) idea of 'negative capability', where dealing with uncertainty is a desirable attribute or skill. This in turn aligns the pragmatic conceptions with graduate attributes where the emphasis is on 'acting' and the ability to make judgements and form meaning in uncertainty described by Perry and Baxter Magolda at the acme of their particular hierarchies. In essence, pragmatic approaches to uncertainty appear to be at odds with the status of uncertainty as a threshold concept in that the ontological uncertainty of liminal space appears to be avoided in favour of adopting strategies and learning skills to deal with uncertainty rather than engaging with the troublesome reality of teaching and learning uncertainty. It is not to say that one approach or characterisation is more valid that the other, however, and it is worth noting that the pragmatic conceptions have emerged largely from the responses of one participant and may not be as widely applicable as the approaches informed by threshold concepts, troublesome knowledge and the other aspects of the research.

Another theme that can be recognised as emergent in this thesis is that of variation. Liminal variation in how students encounter, recognise and come to understand uncertainty is discussed extensively in relation to the theoretical framework of threshold concepts and several other species of variation can be recognised as running through the discussion and conclusions above. For example, there is clear and wide-ranging variation in how the interview participants conceptualise uncertainty in the context of climate change and also in their approaches to teaching the concept. This may suggest that variation is a key factor in developing successful pedagogies for teaching uncertainty and that consideration of educational frameworks that emphasise variation may be valid. The 'variation theory of learning' is based on the premise that learning cannot occur unless students experience variation in their learning (Oliver and Trigwell 2005). Through variation students are able to experience difference, allowing them to discern what they are learning against a backdrop of previous experience of "something more or less different" (Oliver and Trigwell 2005, p. 22). This discernment leads to learning where critical aspects of variation in the object of learning are recognised by the student (Oliver and Trigwell 2005). The variation recognised as an emergent theme in the context of this research may offer a means of identifying the critical aspects or critical features of uncertainty as a concept and thus bringing the variation theory of learning into focus as another potential tool in the development of pedagogy for teaching uncertainty.

The varying conceptions of uncertainty held by the participants, for example, indicate that there exist a range of critical features of uncertainty that may be presented to students as a means of them coming to recognise the complex nature of the concept and understand its many facets. Figures 5.1 and 5.2 may be said to indicate how this variation can be characterised and, therefore, what may be gained from introducing students to different conceptions of uncertainty to allow them to understand the complex whole. There is also a wide range of epistemic positions in relation to uncertainty that can be recognised in this thesis which provide a further source of variation that may be utilised in teaching. Tacit understanding of uncertainty is one such position, pragmatic conceptions may be described as another. If these epistemic positions are recognised explicitly by teachers they may offer a further source of variation that could be harnessed to provide a diverse learning experience for students and allow them to better understand the concept. A range of epistemic positions could potentially be analysed by teachers in order to recognise their critical features and thereby discover the best means of introducing them to students in order for them to discern the variation for themselves. Further research where the variation theory of learning in relation to uncertainty is the focus may potentially yield promising insights into how the variation identified here may be utilised.

A final theme that has emerged strongly from this work is that the uncertainty encountered in climate change appears to be much the same as the uncertainty that is encountered ubiquitously throughout life in the modern world (Baumann 2007; Barnett 2007). In this sense the context of climate change has not constrained the definition or description of uncertainty but has revealed it to be merely another dimension of a supercomplex world in which humans interact in irreducibly complex ways with each other and the physical systems of the planet. Through this research, therefore, it may be possible to apply the findings more widely to many other areas of higher education, not confined to the teaching of climate change, but rather offering suggestions for teaching wherever epistemological and ontological uncertainty may be encountered. Equally, teaching and learning uncertainty in climate change would appear to allow an understanding of uncertainty to be more widely applicable, indicating that this may offer a useful context for students to engage with uncertainty.

A critical reflection on the pedagogy of uncertainty

The summarised conclusions related to the research questions above, together with the emergent themes, give some suggestions as to the realities of teaching uncertainty in higher education. Drawing these conclusions together and linking them with relevant literature and the reflections of the researcher allows for an appraisal of what an effective pedagogy of uncertainty may look like. Research questions 1 and 4 appear at first to be most specific to the context of climate change with questions 2 and 3 and the emergent themes offering more promise in terms of the wider applicability of the research in a pedagogic sense. However, given the realisations on the applicability and transferability of the concept of uncertainty beyond the context of climate change and the alignment of the teaching strategies used by the participants with the literature, all of the findings summarised above may be brought to bear.

As mentioned above, many of the specific pedagogies that arose from discussion with the participants echo the constructivist philosophies of teaching advocated by Perkins (1999) as approaches for dealing with troublesome knowledge. This is given further credence by the characterisation of uncertainty as troublesome knowledge as a result of this research. Constructivist approaches to teaching aim to cast students in the role of active, social or creative learners and although strategies may be recommended (as above), they are not prescribed. A strong emphasis is placed on *creativity* and *flexibility*, doing "whatever works" to assist students in understanding troublesome knowledge (Perkins 1999, p. 11). This creativity and flexibility in approach is inherently *student-centred*, focussing the teacher on how a student appears to be coping in trying to understand a concept and offering time and space for *reflection*. A student-centred pedagogy is also recommended when a concept comes to be recognised as a threshold concept (as above), as the implication of variation among learners is that different approaches may be required to allow them to pass the threshold (Meyer and Land 2005; 2008). In a sense a student-centred approach may be seen as an approach that embraces uncertainty, allowing for the full range of variation in how students apprehend, deal with and come to understand the concept and reacting accordingly to the needs of the student on an individual basis. This reflects Barnett's thesis that uncertainty in education calls for *uncertain* pedagogies and that "students count not *en masse* ... but as individuals" (2009, p. 170).

Given the apparent synergy between an understanding of uncertainty and personal and intellectual development, then the pedagogy of uncertainty should also, therefore, be *holistic* in nature. One means of doing this is by making uncertainty *explicit* at the core of the higher education curriculum, both to avoid to a degree the pitfalls of tacit knowledge and to avoid 'stuffing' the curriculum – as in the case of threshold concepts (Cousin 2006). It is likely that this will also allow uncertainty to be taught *recursively*, as it is not something that is easy to teach quickly or in an isolated setting. A holistic approach to teaching uncertainty will also allow teachers to take account of the *ontological* uncertainty that is likely to follow students learning about *epistemological* uncertainty. A full understanding of uncertainty may, in fact, be signified by an ability to integrate, and be comfortable with, both ontological uncertainty and epistemological uncertainty – either in the sense of having subjectively repositioned oneself or having fully developed the capacity for making meaning.

Although approaches for teaching uncertainty may not be prescribed, there appears to be promise in using methods based on student-led *enquiry* or problem solving. Undergraduate research is an activity advocated for a place at the "centre of the undergraduate experience" in order to help students understand and cope with uncertainty (Healey and Jenkins 2009, p.124). Enquiry of this kind should also be situated in *authentic* settings where students van experience the 'messiness of reality' described by the participants. The evident usefulness of the *multidisciplinary* context of climate change for investigating the concept of uncertainty also suggests that allowing students to encounter uncertainty in a variety of disciplinary settings may have some benefit. Furthermore, it appears that the principle of *variation* in teaching and learning about uncertainty may be central to an understanding of uncertainty and that teachers should be encouraged to recognise the range of epistemic positions that exist (including their own) as well as the critical features of the concept. The most effective pedagogy for teaching uncertainty would appear to be one that is itself uncertain, though grounded in fundamental principles of student-centredness, creativity, flexibility and variation. In this pedagogy, uncertainty should be made explicit and form a key threshold concept at the centre of the higher education curriculum where it can be taught recursively and holistically through undergraduate research or similar authentic enquiry in a variety of disciplinary settings.

The emergent theme of a pragmatic conception of uncertainty offers some contrast to the pedagogy outlined above, in that it emphasises developing skills and strategies for dealing with uncertainty as opposed to achieving an understanding of the concept. However, the apparent alignment between the pragmatic conceptions and theories of graduate attributes and personal development indicates that this may be another facet of the pedagogy of climate change as opposed to an alternative. This is an area that merits further research in order to appraise fully the potential to develop the pedagogy of uncertainty. The development of the pedagogy of uncertainty may provide teachers with a means to address what is clearly a problematic yet seemingly crucial concept in higher education. Given the tacit nature of uncertainty discovered through this research, it may even provide a solution to a problem that teachers are not aware that they have.

Instructional principles from the pedagogy of uncertainty

The pedagogy above offers what may be considered a broad set of principles that can be utilised to teach uncertainty effectively. It is worthwhile, however, to move slightly beyond this level and explore the possibility of more practical advice for teaching practitioners, what may be described as instructional principles. These principles could be offered in settings such as educational development workshops or teacher-training seminars as a framework that teachers may be able to take away and apply in their own particular teaching contexts. Whilst this is yet another important outcome of this research it should, once again, not be viewed as definitive – instructional principles such as these may be widely applicable; however, it is often more beneficial to use them as a point of initial discussion, allowing teachers to relate them to their own knowledge and experience and, in so-doing, develop the principles further each time they are discussed and applied.

The first key principle to note, and possibly the most important given its prevalence throughout this thesis, is the need to recognise uncertainty explicitly. For a teacher this is likely to begin with recognising where the concept of uncertainty may be relevant in their particular discipline or subject and reflecting on the dynamics between this epistemological uncertainty and ontological uncertainty – either their own feelings of uncertainty or those of their students. This reflection can then form the basis of the next important step: an explicit appraisal of the teacher's own conceptions of uncertainty in their disciplinary context and, upon further consideration, what potential range of other conceptions may exist. This process will begin to give a picture of the conceptual structure of uncertainty in relation to a subject and, therefore, a range of contexts in which it may be introduced to students. This does not imply that there is a finite range of conceptions of uncertainty that need to be addressed in the curriculum, it may be better to think of these different ways of understanding and interpreting uncertainty in relation to a subject as epistemic positions and acknowledging that there is variation among them. Variation allows for discernment, which may be a valuable means of teaching for understanding; this is a principle that can then be applied again when it comes to the time for teaching the concept.

The above principles are likely to occur as part of a planning phase, when a teacher is developing strategies and content in advance of a class or the commencement of a course. Having established their own position on uncertainty and given some consideration of the variation that may exist in conceptions and epistemic positions relating to uncertainty, it is now the time for the teacher to introduce the concept to students. Once again, the recommendation is to do this explicitly – acknowledge that uncertainty exists and encourage students to discuss and reflect on uncertainty, their understanding of the concept and how it makes them feel. This then also offers a valuable opportunity to capture students' conceptions of uncertainty and the variation among them. As noted above, this variation can then allow for discernment and may potentially allow students to grasp the complex nature of uncertainty rapidly and understand many of the different facets of the concept. The process of using variation among students' own conceptions of uncertainty as well as others established through the teacher's own reflection allows students to learn about uncertainty in a way that is relevant to both the subject and their own experiences. Conducting this process recursively may also allow students to comprehensively discern the critical features of uncertainty and, thereby, gain a deeper understanding of the concept. Beyond this, many of the principles described in the pedagogy outlined in the section above can be used with elements such as student-centredness, creativity and flexibility being crucial.

The instructional principles applied from this research may be summarised in the following key points and questions for consideration:

1. Recognise uncertainty explicitly – What uncertainty exists in this context? Where can it be recognised? How does it make me feel? How may it make my students feel?
2. Reflect on personal conceptions of uncertainty and identify variation – What is my understanding of uncertainty in this context? What other conceptions

of uncertainty may exist? Can these be translated to varying epistemic positions related to ways of understanding uncertainty?

3. Introduce uncertainty explicitly to students and encourage them to reflect on and discuss their own conceptions – What understanding do my students have of uncertainty? How do they feel about uncertainty?
4. Capture the variation among students' conceptions of uncertainty – How do my students conceptions relate to the variation I have already identified? How can I apply this in my teaching?
5. Teach uncertainty through the application of the pedagogy described in the section above and principles 1-4. Explore the concept recursively and utilise discernment through variation to assist students in achieving understanding.

The above principles, together, with the pedagogy of uncertainty that is described in the above section could potentially be applied in a range of teaching contexts. With further discussion and development among teaching practitioners this may lead to further refinement building upon the guidance that is offered here. Given the complex and troublesome nature of the concept of uncertainty this has the potential to be an extremely valuable tool for educators and must be considered as a key future research direction emerging from this work.

Key conclusions

This section concludes the above summaries and offers a succinct synopsis of the key findings of this research.

- Uncertainty in climate change is ubiquitous, complex and may be conceptualised and characterised in a wide variety of ways.
- The interdisciplinary nature of the climate change subject area leads to academics holding numerous conceptions of diverse uncertainties simultaneously, although integrating these conceptions may be troublesome.
- Uncertainty can be characterised as troublesome knowledge with seemingly the most troublesome aspect being the tacit nature of the concept in the context of climate change.

- Uncertainty is a threshold concept across the climate change subject area and possibly more widely in the context of higher education; it may form a kind of interdisciplinary threshold owing to its ubiquity, tacitness and lack of esotericism.
- Uncertainty would appear to be linked closely, and synergistically, to personal and intellectual development in that it is necessary to understand uncertainty in order to develop and also necessary to develop in order to understand uncertainty.
- Pragmatic conceptions of, and approaches to, uncertainty appear to offer a different means of teaching the concept where the emphasis is on adopting strategies and learning skills in order to cope or deal with uncertainty.
- An understanding of uncertainty in climate change may be more widely applicable indicating both that the findings of this study may be extended to other areas of higher education and that the context of climate change may be a valuable one for the teaching of uncertainty.
- The most effective pedagogy for teaching uncertainty would appear to be one that is itself uncertain, though grounded in fundamental principles of student-centredness, creativity, flexibility and variation. In this pedagogy, uncertainty should be made explicit and form a key threshold concept at the centre of the higher education curriculum where it can be taught recursively and holistically through undergraduate research or similar authentic enquiry in a variety of disciplinary settings.
- Some key instructional principles for applying the pedagogy of uncertainty have been identified with the following key stages:
  1. Recognise uncertainty explicitly
  2. Reflect on personal conceptions of uncertainty and identify variation
  3. Introduce uncertainty explicitly to students and encourage them to reflect on and discuss their own conceptions
  4. Capture the variation among students' conceptions of uncertainty
  5. Teach uncertainty through the recursive application of the pedagogy described in the section above and principles 1-4.

Further work

This research has examined the understanding of uncertainty principally from the perspective of teachers in higher education; using this understanding to elucidate the implications for teaching uncertainty. An obvious future direction of this work is the investigation of learning uncertainty, through interviews with students learning about climate change in a similar context to that employed in this thesis. This could take the form of research interviews with a range of students studying climate change in different contexts. This research could also be designed and built around the frameworks of threshold concepts and troublesome knowledge, which have been found so useful in this study, further developing the characterisation of uncertainty as an example of each.

Another obvious future research direction is the further development of pedagogic principles for teaching uncertainty and the potential to offer applied instructional content to teachers who may identify uncertainty in their subject area or discipline. The above research on students learning uncertainty has obvious implications in this area, another facet of which is likely to be the discussion and development of principles with teaching practitioners.

A related research topic is the development of the 'pedagogy of climate change' through research into key concepts and approaches to teaching, which has begun to an extent with this study (preliminary work can be found in Hall 2010). This may also include the investigation of Geography as a discipline for teaching climate change and other complex subjects and issues of multidisciplinarity and the integration of diverse teaching and research methods.

Building on the emergent themes of this research would allow more detailed explorations of variation and the implications for learning, pragmatic approaches to uncertainty and the links between uncertainty, development and negative capability to be investigated. There is some suggestion implicit in this work that an understanding of uncertainty may be in some way innate or something that develops as a personality trait or even skill. This is a fascinating future research direction that would involve the investigation of uncertainty in a variety of education contexts and disciplines and that has implications for the more complete development of the pedagogy of uncertainty.

Position statement – closing

The following statement offers some closing remarks from the researcher in terms of reflection on the research and the concept of uncertainty.

The completion of this thesis represents the culmination of a significant, and at times difficult, journey for me as both an academic and a person. In pursuing an interest in uncertainty I have grappled with a concept that is conceptually difficult and often deeply troubling at a personal level. I recognise in my own understanding the troublesome nature of uncertainty and the ability the concept has to transform one's view of the world. In many ways the PhD has represented a prolonged state of liminality for me where I have sought to achieve a deep understanding of other's conceptions of uncertainty whilst constantly re-evaluating my own understanding of the concept and the ontological uncertainty that I have had to deal with on a daily basis.

That is not to say that the experience has been a negative one, however, as I have thoroughly enjoyed overcoming the difficulties and rising to the challenges that I have faced. To have been afforded the time and means to explore deeply such a fascinating research topic as I have has been a true privilege. If anything, the understanding of uncertainty that I have gained through this research has shown me the promise and potential of this concept as an explicit goal of teaching in higher education. In this sense, I hope the thesis will represent a liminal transition – from research student to fully-fledged academic researcher and possibly teacher – so that I may continue to investigate the portals that this research has opened. In reflecting on teaching uncertainty and the journey I have undertaken I am reminded of the following quote from Martina Horner, a fitting end to the thesis:

"What is important is to keep learning, to enjoy challenge, and to tolerate ambiguity. In the end there are no certain answers".

- Martina Horner (President, Radcliffe College, 1972-1989)

References

Ashworth, P., Lucas, U. (2000) 'Achieving empathy and engagement: a practical approach to the design, conduct and reporting of phenomenographic research'. *Studies in Higher Education,* 25(3), pp. 295 – 308

Atkinson, E. (2000) 'The promise of uncertainty: education, postmodernism and the politics of possibility'. *International Studies in Sociology of Education,* 10(1), pp. 81-96

Barriball, K.L., While, A. (1994) 'Collecting data using a semi-structured interview: a discussion paper'. *Journal of Advanced Nursing,* 19, pp. 328 – 335

Barnett, R. (2000) 'Supercomplexity and the curriculum'. *Studies in Higher Education,* 25(3), pp. 255 – 265

Barnett, R. (2007) *A will to learn: being a student in an age of uncertainty.* (Maidenhead: Open University Press)

Barnett, R. (2009) 'Knowing and becoming in the higher education curriculum'. *Studies in Higher Education,* 34(4), pp. 429 – 440

Barrie, S.C. (2004) 'A research based approach to generic graduate attributes policy'. *Higher Education Research and Development,* 23(3), pp. 261 – 275

Barrie, S.C. (2007) 'A conceptual framework for the teaching and learning of generic graduate attributes'. *Studies in Higher Education,* 32(4), pp. 439 – 458

Baumann, Z. (2007) *Liquid times: living in an age of uncertainty* (Cambridge: Polity Press)

Baxter Magolda, M.B. (2009) 'The Activity of Meaning Making: A Holistic Perspective on College Student Development'. *Journal of College Student Development,* 50(6), pp. 621 – 639

Boustedt, J., Eckerdal, A., McCartney, R., Mostrom, J.E., Ratcliffe, M., Sanders, K., Zander, C. (2007) 'Threshold concepts in computer science: do they exist and are they useful?'. *ACM SIGCSE Bulletin,* 39, pp. 504 – 508

Bradley, R.S. (1999) *Paleoclimatology: reconstructing climates of the quaternary* (San Diego: Academic Press)

Bray, D., von Storch, H. (1999) 'Climate science: an empirical example of post-normal science'. *Bulletin of the American Meteorological Society,* 80(3), pp. 439 – 455

Brooks, C., Ryan, A. (2008) *Education for sustainable development interdisciplinary discussion series report* From: http://www.heacademy.ac.uk/assets/York/documents/ourwork/sustainability/interdisc_discuss_series2008.pdf (Accessed 25/8/10)

Bryant, A., Charmaz, K. (2007) 'Grounded theory research: methods and practices' in *The Sage Handbook of Grounded Theory*, Bryant, A., Charmaz, K. (Eds.) pp. 1 – 28

Bunting, M. J., Middleton, R. (2009) 'Equifinality and uncertainty in the interpretation of pollen data: the multiple scenario approach to reconstruction of past vegetation mosaics'. *The Holocene*, 19(5), pp. 799 – 803

Campbell, E. (2007) 'Glimpses of uncertainty in teaching'. *Curriculum Inquiry*, 37(1), pp. 1 – 8

Chambers, F.M., Brain, S. A. (2002) 'Paradigm shifts in late-Holocene climatology?'. *The Holocene*, 12(2), pp. 239 – 249

Chambers, F.M., Daniell, J.R.G., ACCROTELM members (2010) 'Peatland archives of late-Holocene climate change in northern Europe'. *PAGES News*, 18(1), pp. 4 – 6

Charmaz, K. (2006) *Constructing grounded theory: a practical guide through qualitative analysis* (London: Sage Publications)

Cheek, K.A. (2010) 'Why is Geologic Time Troublesome Knowledge?' in *Threshold Concepts and Transformational Learning*, Land, R., Meyer, J.H.F. and Baillie, C., (Eds.) (Rotterdam: Sense) pp. 117–129

Claussen, M., Mysak, L.A., Weaver, A.J., Crucifix, M., Fichefet, T., Loutre, M-F., Weber, S.L., Alcamo, J., Alexeev, V.A., Berger, A., Calov, R., Ganopolski, A., Goosse, H., Lohman, G., Lunkeit, F., Mokhov, I.I., Petoukov, V., Stone, P., Wang, Z. (2002) 'Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models'. *Climate Dynamics*, 18, pp. 579 – 586

Clifton, R.A., Roberts, L.W. (1993) *Authority in classrooms* (Scarborough: Prentice-Hall Canada)

Cousin, G. (2006) 'An introduction to threshold concepts'. *Planet*, pp.17, 4-5

Davies, P. (2003) 'Threshold concepts: how can we recognise them?'. *Paper presented at EARLI conference, Padova, Italy* August 2003. From: http://web.staffs.ac.uk/schools/business/iepr/etc/WorkingPapers/etcworkingpaper1.pdf (Accessed: 25/8/10)

Dessai, S., Asger, W., N., Hulme, M., Koehler, J., Turnpenny, J., Warren, R. (2003) 'Defining and experiencing dangerous climate change'. *Tyndall Centre for Climate Change Research – Working Report 28.* From: http://www.tyndall.ac.uk/sites/default/files/wp28.pdf (Accessed: 24/8/10)

Dortins, E. (2002) 'Reflections on phenomenographic process: interview, transcription and analysis'. *HERDSA 2002*, pp. 207 – 213

Entwistle, N. (2000) 'Promoting deep learning through teaching and assessment: conceptual frameworks and educational contexts'. *Paper presented at the TLRP Conference, Leicester*, November 2000

Esper, J., Wilson, R.J.S., Frank, D.C., Moberg, A., Wanner, H., Luterbacher, J. (2005) 'Climate: past ranges and future changes'. *Quaternary Science Reviews*, pp. 2164 – 2166

Floden, R.E., Buchmann, M. (1993) 'Between routines and anarchy: preparing teachers for uncertainty'. *Oxford Review of Education*, 19(3), pp. 373 – 382

Floden, R.E., Clark, C.M. (1988) 'Preparing teachers for uncertainty'. From: http://ncrtl.msu.edu/http/ipapers/html/pdf/ip874.pdf (Accessed: 25/8/10)

Frank, D., Esper, J., Zorita, E., Wilson, R. (2010) 'A noodle, hockey stick, and spaghetti plate: a perspective on high-resolution palaeoclimatology'. *Wiley Interdisciplinary Reviews: Climate Change*, 1(4), pp. 507 – 516

Friedlingstein, P., Cox, P., Betts, R., Bopp, L., von Bloh, W., Brovkin, V., Cadule, P., Doney, S., Eby, M., Fung, I., Bala, G., John, J., Jones, C., Joos, F., Kato, T., Kawamiya, M., Knorr, W., Lindsay, K., Matthews, H.D., Raddatz, T., Rayner, P., Reick, C., Roeckner, E., Schitzler, K-G., Schnur, R., Strassman, K., Weaver, A.J., Yoshikawa, C., Zeng, N. (2006) 'Climate-carbon cycle feedback analysis: results from the C4MIP model intercomparison'. *Journal of Climate*, 19, pp. 3337 – 3353

Funtowicz S., Ravetz, J. (1993) 'Science for the post-normal age'. *Futures*, 25(7), pp. 739 – 755

Funtowicz S., Ravetz, J. (1994) 'Uncertainty, complexity and post-normal science'. *Environmental Toxicology and Chemistry*, 13(12), pp. 1881 – 1885

Funtowicz S., Ravetz, J. (2003). 'Post-normal science' in *Internet Encyclopaedia of Ecological Economics*, From: http://www.ecoeco.org/pdf/pstnormsc.pdf (Accessed: 28/4/10)

Funtowicz S., Ravetz, J., O'Connor, M. (1998) 'Challenges in the use of science for sustainable development'. *International Journal of Sustainable Development*, 1(1), pp. 99 – 107

Gautier, C., Rebich, S. (2005) 'The use of a mock environment summit to support learning about global climate change'. *Journal of Geoscience Education*, 53(1), pp. 5-16

Gautier, C., Solomon, R. (2005) 'A preliminary study of students asking quantitative scientific questions for inquiry-based climate model experiments'. *Journal of Geoscience Education*, 53(4), pp. 432 – 433

Georghiades, P. (2000) 'Beyond conceptual change learning in science education: focusing on transfer, durability and metacognition'. *Educational Research,* 42(2), pp.119-139

Giles, J. (2002) 'Scientific uncertainty: when doubt is a sure thing'. *Nature*, 418, pp. 476 – 478

Gillham, B. (2005) *Research Interviewing: the range of techniques* (Maidenhead: Open University Press)

Glaser, B., Strauss, A. (1967) *The discovery of grounded theory: strategies for qualitative research* (London: Wiedenfeld and Nicholson)

Glaser, B. (1978) *Theoretical sensitivity* (Mill Valley: The Sociology Press)

Goethe, R. (2003) *Ritual and Liminality (NCSS Theme: Culture) - Purpose, Background, and Context* (web-link no longer available)

Haag, D., Kaupenjohann, M. (2001) 'Parameters, prediction, post-normal science and the precautionary principle – a roadmap for modelling for decision-making'. *Ecological Modelling*, 144, pp. 45 – 60

Hall, A.M., Hansom, J.D., Williams, D.M., Jarvis, J. (2006) 'Distribution, geomorphology and lithofacies of cliff-top storm deposits: examples from high-energy coasts of Scotland and Ireland'. *Marine Geology*, 232, pp. 131 – 155

Hall, B. (2006) 'Teaching and learning uncertainty in science: the case of climate change'. *Planet,* 17, pp. 48-49

Hall, B. (2010) 'Threshold concepts and troublesome knowledge: towards a pedagogy of climate change?' in *The Pedagogy of Climate Change – GEES Special Publication*, Haslett, S., France, D., Gedye, S. (Eds.) (Plymouth: GEES) IN PRESS

Haggis, T. (2006) 'Problems and paradoxes in fine-grained qualitative research: an exploration of 'context' from the perspective of complexity and dynamic systems theory'. *Paper presented at Higher Education Close Up 3, University of Lancaster,* July 2006. From: http://www.lancs.ac.uk/fss/events/hecu3/documents/tamsin_haggis.doc (Accessed: 24/8/10)

Healey, M., Jenkins, A. (2009) *Developing undergraduate research and inquiry* From: http://www.heacademy.ac.uk/assets/import%20assets%20here/documents/ourwork/research/DevelopingUndergraduateResearchandInquiry.pdf (Accessed 26/8/10)

Hegerl, G.C., Crowley, T.J., Hyde, W.T., Frame, D.J. (2006) 'Climate sensitivity constrained by temperature reconstructions over the past seven centuries'. *Nature*, 440, pp. 1029 – 1032

Helsing, D. (2007) 'Styles of knowing regarding uncertainties'. *Curriculum Inquiry*, 37(1), pp. 33 – 70

Higgs, B., Hall, B. (2008) 'Integrating concepts of integrative learning' in *Emerging Issues II, The Changing Roles and Identities of Teachers and Learners in Higher Education*, Higgs, B., McCarthy, M. (Eds.) (Cork: NAIRTL) pp. 63 – 74

Hofer, B.K., Pintrich, P.R. (1997) 'The development of epistemological theories: beliefs about knowledge and knowing in relation to learning'. *Review of Educational Research*, 67(1), pp. 88 – 140

Hulme, M., Turnpenny, J. (2004) 'Understanding and managing climate change: the UK experience'. *The Geographical Journal*, 170(2), pp. 105 – 115

Intergovernmental Panel on Climate Change (1995) *IPCC Second Assessment Report: Climate Change 1995 (SAR)*. From: http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1 (Accessed: 24/8/10)

Intergovernmental Panel on Climate Change (2000) *Emissions Scenarios*. From: http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#2 (Accessed: 24/8/10)

Intergovernmental Panel on Climate Change (2001) *IPCC Third Assessment Report: Climate Change 2001 (TAR)*. From: http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm#1 (Accessed: 24/8/10)

Intergovernmental Panel on Climate Change (2007) *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*. From: http://www.ipcc.ch/ (Accessed: 24/8/10)

Jasanoff, S. (2010) 'Testing time for climate science'. *Science*, 328, pp. 695 – 696

Jasanoff, S., Wynne, B. (1998) 'Science and decision making' in *Human Choice and Climate Change*, Rayner, S., Malone, E. (Eds.) (Columbus: Battelle Press)

Jones, P.D., Osborn, T.J., Briffa, K.R. (2001) 'The evolution of climate over the last millennium'. *Science*, 292, pp. 662 – 666

Jordan, G.J., Fortin, M-J., Lertzman, K.P. (2005) 'Assessing spatial uncertainty associated with forest fire boundary delineation'. *Landscape Ecology*, 20, pp. 719 – 731

Karl, T.R., Trenberth, K.E. (2003) 'Modern global climate change'. *Science*, 302, pp. 1719 – 1723

Kastens, K.A. (1995) 'Earth science as a vehicle for illuminating the boundary between the known and the unknown'. *Journal of Geological Education*, 43, pp. 138 – 140

Katz, R.W. (2001) *Techniques for estimating uncertainty in climate change scenarios and impact studies* (Boulder: National Centre for Atmospheric Research)

Kidder, L. (1981) *Sellitz, Wrightsman and Cook's Research Methods in Social Relations* (New York: Holt, Rinehart and Winston)

Kriebel, D., Tickner, J., Epstein, P., Lemons, J., Levins, R., Loechler, E.L., Quinn, M., Rudel, R., Schettler, T., Stoto, M. (2001) 'The precautionary principle in environmental science'. *Environmental Health Perspectives*, 109(9), pp. 871 – 875

Kuh, G.D. (2003) 'What we're learning about student engagement from NSSE'. *Change*, 35(2), pp. 24 – 32

Kuh, G.D. (2008) 'Diagnosing why some students do not succeed'. *The Chronicle of Higher Education*, December 2008. From: http://cpe.ky.gov/NR/rdonlyres/A69162CD-CA37-4F32-936D-C429F982670E/0/Diagnosingwhysomestudentsdonotsucceed.pdf (Accessed: 26/8/10)

Kuhn, T.S. (1996) *The Structure of Scientific Revolutions.* (Chicago: University of Chicago Press)

Kump, L.R. (2002) 'Reducing uncertainty about carbon dioxide as a climate driver'. *Nature*, 419, pp. 188 – 190

Land, R., Cousin, G., Meyer, J.H.F., Davies, P. (2005) 'Threshold concepts and troublesome knowledge (3): implications for course design and evaluation' in *Improving Student Learning Diversity and Inclusivity,* Rust, C. (Ed) (Oxford: Oxford Centre for Staff and Learning Development) pp. 53 – 64

Land, R. (2009) 'Enhancing Quality in an Age of Uncertainty: implications for practitioners'. *Paper presented at 15th Danish Network for Educational Development in Higher Education Conference, Fredericia, Denmark*, May 2009

Lenton, T. M., Held, H., Kriegler, E., Hall, J.W., Lucht, W., Rahmstorf, F., Schnellnhuber, H.J. (2008) 'Tipping elements in the Earth's climate system'. *PNAS*, 105(6), pp. 1786 – 1793

Lempert, R., Nakicenovic, N., Sarewitz, D., Schlesinger, M. (2004) 'Characterising climate change uncertainties for decision makers'. *Climatic Change*, 65, pp. 1 – 9

Lovelock, J. (2007) *The Revenge of Gaia* (London: Penguin)

Lustick, D. (2002) 'A study that identifies a framework and findings of teachers learning to manage, complexity, uncertainty and community' From: http://eric.ed.gov/PDFS/ED465727.pdf (Accessed: 25/8/10)

Mann, M.E., Bradley, R.S., Hughes, M.K. (1999) 'Northern hemisphere temperatures during the past millennium inferences, uncertainties and limitations'. *Geophysical Research Letters*, 26(6), pp. 759 – 762

Mastrandrea, M.D., Schneider, S.H. (2004) 'Probabilistic integrated assessment of "dangerous" climate change'. *Science*, 304, pp. 571 – 575

McGuffie, K., Henderson-Sellers, A. (2001) 'Forty years of numerical climate modelling'. *International Journal of Climatology*, 21, pp. 1067 – 1109

Meyer, J.H.F., Eley, M.G. (2006) 'The approaches to teaching inventory: a critique of its development and applicability'. *British Journal of Educational Psychology*, 76, pp. 633 – 649

Meyer J. H. F., Land R. (2003) 'Threshold Concepts and Troublesome Knowledge 1 – Linkages to Ways of Thinking and Practising' in *Improving Student Learning – Ten Years On*, Rust, C. (Ed.), (OCSLD: Oxford)

Meyer, J. H. F., Land, R. (2005) 'Threshold concepts and troublesome knowledge (2): Epistemological considerations and a conceptual framework for teaching and learning'. *Higher Education*, 49, pp. 273-288

Meyer, J. H. F., Land, R. (2008) 'Threshold concepts and troublesome knowledge (5): dynamics of assessment' *Paper presented at 2nd International Conference on Threshold Concepts, Threshold Concepts: from theory to practice, Kingston, Canada,* June 2008. From: http://www3.imperial.ac.uk/pls/portallive/docs/1/56017698.DOC (Accessed: 25/8/10)

Meyer J. H. F., Land R, Davies, P. (2006) 'Threshold concepts and troublesome knowledge (4): issues of variation and variability' in *Threshold concepts within the disciplines.* (Sense: Rotterdam)

Meyer, J.H.F. and Shanahan, M. (2003) 'The troublesome nature of a threshold concept in economics' *Paper presented at EARLI conference, Padova, Italy* August 2003.

Moss, R. H., Schneider, S. H. (2000) 'Uncertainties in the IPCC TAR: Recommendations to lead authors for more consistent assessment and reporting' in *Guidance Papers on the Cross Cutting Issues of the Third Assessment Report of the IPCC*, Pachauri, R., Taniguci, T., Tanaka, K. (Eds.) (Geneva: World Meteorological Organisation) pp. 33 – 51

Moberg, A., Sonechkin, D.M., Homgren, K., Datsenko, N.M., Karlen, W. (2005) 'Highly variable Northern Hemisphere temperatures reconstructed from low- and high-resolution proxy data'. *Nature*, 433, pp. 613 – 617

Mudelsee, M. (2001) 'The phase relations among atmospheric CO_2 content, temperature and global ice volume over the last 420ka'. *Quaternary Science Reviews*, 20, pp. 583 – 589

Muscheler, R., Kromer, B., Bjorck, S., Svensson, A., Friedrich, M., Kaiser, K.F. (2008) 'Tree rings and ice cores reveal ^{14}C calibration uncertainties during the Younger Dryas'. *Nature Geoscience*, 1, pp. 263 – 267

Nakicenovic, N., Grubler, A. (2001) 'Identifying dangers in an uncertain climate'. *Nature*, 412, pp. 15

Nisbett, R.E. (Ed.) (1993) *Rules for Reasoning* (Hillsdale: Erlbaum)

Nordhaus, W.D. (1993) 'Rolling the 'DICE': an optimal transition path for controlling greenhouse gases'. *Resource and Energy Economics*, 15, pp. 27 – 50

Nordhaus, W.D., Yang, Z. (1996) 'A regional dynamic general-equilibrium model of alternative climate-change strategies'. *The American Economic Review*, 86(4), pp. 741 – 765

North, G.R., Stevens, M.J. (2006) 'Energy balance climate models' in *Frontiers of Climate Modelling*, Kiehl, J.T., Ramanathan, V. (Eds.) (Cambridge: Cambridge University Press) pp. 52 – 72

Oliver, M., Trigwell, K. (2005) Can 'blended learning' be redeemed? *E-Learning*, 2 (1), pp. 17-26

Oppenheimer, M., O'Neill, B.C., Webster, M., Agrawala, S. (2007) 'The limits of consensus'. *Science*, 317, pp. 1505 – 1506

Oreskes, N. (2004) 'The scientific consensus on climate change'. *Science*, 306(5702), pp. 1686

Patt, A. (2007) 'Assessing model-based and conflict-based uncertainty'. *Global Environmental Change*, 17, pp. 37 – 46

Payne, J.W., Bettman, J.R., Johnson, E.J. (1992) 'Behavioural decision research: a constructive processing perspective'. *Annual Review of Psychology*, 43, pp. 87 – 131

Perkins, D. (1997) 'Epistemic games'. *International Journal of Educational Research*, 27(1), pp. 49 – 61

Perkins, D. (1999) 'The many faces of constructivism'. *Educational Leadership*, 57(3), pp. 6-11

Perkins, D (2006) 'Constructivism and troublesome knowledge'. In *Overcoming barriers to student understanding: threshold concepts and troublesome knowledge* J.H.F. Meyer, and R. Land (Eds.) (Routledge: London and New York) pp.33 – 47

Perry, W.G. (1970) *Forms of intellectual and ethical development* (New York: Holt Paperbacks)

Petersen, A.C. (2000) 'Philosophy of climate science'. *Bulletin of the American Meteorological Society*, 81(2), pp. 265 – 272

Petit, J.R., Jouzel, J., Raynaud, D., Barkov, N.I., Barnola, J-M., Basile, I., Benders, M., Chapellaz, J., Davis, M., Delaaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V.Y., Lorius, C., Pepin, L., Ritz, C., Saltzman, E., Stievenard, M. (1999) 'Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica'. *Nature*, 399, 429 – 436

Phillips, D.C. (1995) 'The good, the bad and the ugly: the many faces of constructivism'. *Educational Researcher*, 24(7), pp. 5 – 12

Pittock, A. B. (2009) *Climate Change: The Science, Impacts and Solutions.* (London: Earthscan)

Pittock, A.B., Jones, R.N., Mitchel, C.D. (2001) 'Probabilities will help us plan for climate change'. *Nature*, 413, pp. 249

Pizzolato, J. E. (2004) 'Coping with conflict: Self-authorship, coping, and adaptation to college in first-year, high-risk students'. *Journal of College Student Development*, 45(4), pp. 425 – 442.

Plastino, W., Kaihola, L., Bartolemi, P., Bella, F. (2001) 'Cosmic background reduction in the radiocarbon measurements by liquid scintillation spectrometry at the underground laboratory of Gran Sasso'. *Radiocarbon*, 43(2A), pp. 157 – 161

Pointon, V. (2008) 'Changes in A-level Geography & their implications for H.E.'. *Planet*, 19, pp. 9 – 11

Polanyi, M. (1958) *Personal Knowledge.* (London: Routledge)

Prosser, M., Trigwell, K. (1999) *Understanding Teaching and Learning: The Experience in Higher Education* (Buckingham: Open University Press)

Prosser, M. Martin, E., Trigwell, K., Ramsden, P., Lueckenhausen, G, (2005) 'Academics' experiences of understanding of their subject matter and the relationship of this to their experiences of teaching and learning'. *Instructional Science*, 33, pp. 137 – 157

QAA (2007) *Subject Benchmarking Statements: Geography* From: http://www.qaa.ac.uk/academicinfrastructure/benchmark/statements/Geography.asp#subject (Accessed (25/8/10)

Raffensperger, C., Tickner, J. (1998) *The Precautionary Principle in Action: a Handbook* From: http://www.mindfully.org/Precaution/Precaution-In-Action-Handbook.pdf (Accessed: 28/4/10)

Ravetz, J.R. (1997) 'The science of 'what-if?'' *Futures*, 29(6), pp. 533 – 539

Ravetz, J.R. (2004) 'The post-normal science of precaution'. *Futures*, 36, 347 – 357

Rebich, S., Gautier, C. (2005) 'Concept mapping to reveal prior knowledge and conceptual change in a mock summit course on global climate change'. *Journal of Geoscience Education*, 53(4), pp. 355-365

Reimann, N., Jackson, I. (2006) 'Threshold concepts in economics' in *Overcoming Barriers to Student Learning: Threshold Concepts and Troublesome Knowledge*, Meyer, J.H.F., Land, R. (Eds.) (London: Routledge) pp. 115 – 133

Ridley, B.K. (2001) *On Science.* (London: Routledge)

Rind, D. (1999)' Complexity and Climate'. *Science*, 284, pp. 105-107

Risbey, J.S., Kanlikar, M. (2007) 'Expressions of likelihood and confidence in the IPCC uncertainty assessment process'. *Climatic Change*, 85, pp. 19 – 31

Rittel, H.W.J., Webber, M.M. (1973) 'Dilemmas in a general theory of planning'. *Policy Sciences*, 4, pp. 155 – 169

Royal Society (2009) *Geo-engineering the Climate.* (London: Royal Society)

Ruddiman, W.R. (2001) *Earth's climate: past and future* (New York: W.H. Freeman)

Saloranta, T.M. (2001) 'Post-normal science and the global climate change issue'. *Climatic Change,* 50, pp. 395–404

Scheja, M. (2006) 'Delayed understanding and staying in phase: students' perceptions of their study situation'. *Higher Education*, 52, pp. 421 – 445

Schweizer, D. M., Kelly, G. J. (2005) 'An investigation of student engagement in a global warming debate'. *Journal of Geoscience Education*, 53 (1), pp. 75-84

Schneider, S.H. (2003) 'Abrupt non-linear climate change, irreversibility and surprise'. From: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.130.1702&rep=rep1&type=pdf (Accessed: 24/8/10)

Schiermeier, Q. (2010) 'The real holes in climate science'. *Nature*, 463, pp. 284 – 287

Science Assessment Panel (2010) 'Report of the International Panel set up by the University of East Anglia to examine the research of the Climatic Research Unit'. From: http://www.uea.ac.uk/mac/comm/media/press/CRUstatements/SAP (Accessed: 24/8/10)

Shank, G.D. (2006) *Qualitative Research: A Personal Skills Approach* (Upper Saddle River: Pearson)

Shulman, L.S. (2005a) 'Pedagogies of uncertainty'. *Liberal Education*, Spring 2005, pp. 18 – 25

Shulman, L. S., (2005b) 'Signature pedagogies in the professions'. *Daedalus*, 134(3), pp. 52-59

Simpson, P., French, R., Harvey, C.E. (2002) 'Leadership and negative capability'. *Human Relations*, 55(10), pp. 1209 – 1226

Strauss, A., Corbin, J. (1990) *Basics of qualitative research: grounded theory procedures and techniques* (Newbury Park: Sage Publications)

Strauss, A., Corbin, J. (1998) *Basics of qualitative research: techniques and procedures for developing grounded theory.* (Thousand Oaks: Sage Publications)

Stokes, A., King, H., Libarkin, J.C. (2007) 'Research in education: threshold concepts'. *Journal of Geoscience Education*, 55(5), pp. 434 – 438

Taylor, C. (2006) 'Threshold concepts in biology: do they fit the definition?' in *Overcoming Barriers to Student Learning: Threshold Concepts and Troublesome Knowledge*, Meyer, J.H.F., Land, R. (Eds.) (London: Routledge) pp. 87 – 99

Taylor, K. Haynes, C. (2008) 'A framework for intentionally fostering student learning'. *About Campus*, Nov-Dec 2008, pp. 2 – 11

Trigwell, K. (2001) 'Phenomenography: Discernment and variation'. From: http://www.learning.ox.ac.uk/files/Phenom_ISL_paper.pdf (Accessed: 24/8/10)

Trigwell, K. (2006) *Presentation at CeAL/HEA Pedagogic Research Conference, Cheltenham, UK,* January 2006

Trubshaw, B. (2003) 'The metaphors and rituals of place and time - an introduction to liminality, or Why Christopher Robin wouldn't walk on the cracks' From: http://www.indigogroup.co.uk/edge/liminal.htm (Accessed 27/8/10)

Truscott, J.B., Boyle, A., Burkill, S., Libarkin, J., Lonsdale, J. (2006) 'The concept of time: can it be fully realised and taught?'. *Planet,* 17, pp. 21 – 23

Turner, V. (1969) *The Ritual Process: Structure and Anti-Structure* (London: Routledge)

Van Gennep, A. (1960) *The Rites of Passage* (London: Routledge)

Vidale, P.L., Luthi, D., Frei, C., Seneviratne, S.I., Schar, C. (2003) 'Predicatbility and uncertainty in a regional climate model'. *Journal of Geophysical Research,* 108(12), pp. 1 – 23

Von Storch, H., Zorita, E., Jones, J.M., Dmitriev, Y., Gonzalez-Ruoco, F., Tett, S.F.B. (2004) 'Reconstructing past climate from noisy data'. *Science,* 306, pp. 679 – 682

Walshe, N. (2007) 'Understanding teachers' conceptions of geography'. *International Rsearch in Geographical and Environmental Education,* 16(2), pp. 97 – 119

Webster, M.D., Babiker, M., Mayer, M., Reilly, J.M., Harnisch, J., Hyman, R., Sarofim, M.C., Wang, C. (2002) 'Uncertainty in emissions projections for climate models'. *Atmospheric Environment,* 36, pp. 3659 – 3670

Wenger, E. (1998; 2000) *Communities of Practice: Learning, Meaning and Identity.* (Cambridge: Cambridge University Press)

Yore, L.D., Florence, M.K., Pearson, T.W., Weaver, A.J. (2006) 'Written discourse in scientific communities: a conversation with two scientists about their views of science, use of language, role of writing in doing science and compatibility between their epistemic views and language'. *International Journal of Science Education,* 28(2-3), pp. 109 – 141

Zorita, E., Gonzalez-Ruoco, F., Legutke, S. (2003) 'Testing the Mann et al. (1998) approach to palaeoclimate reconstructions in the context of a 1000-yr control simularion with the ECHO-G coupled climate model'. *Journal of Climate,* 16, pp. 1378 – 1390

Appendices

Appendix 1 – Questionnaire

Climate Change Science Staff Questionnaire – Brendan Hall, doctoral research

Name: Gender: M/F Age:

Institution:

Teaching:

1. How long have you been involved in teaching Climate Change Science?

A: < 5 years
B: 5 – 10 years
C: 11 – 15 years
D: 16 – 20 years
E: 21 – 25 years
F: > 25 years

2. At what levels in Higher Education do you teach Climate Change Science?

A: 1st Year
B: 2nd Year
C: 3rd Year
D: Taught Masters

3. At what levels are students exposed to the following concepts within Climate Change Science, either through you or through colleagues within the department, as part of Geography and related degree programmes? (Leave blank if not part of course content)

	1	2	3	Masters
A: **Climate Models.** Through you:	☐	☐	☐	☐
Through colleagues	☐	☐	☐	☐
B: **Palaeoclimate/Proxy Evidence.** Through you:	☐	☐	☐	☐
Through colleagues:	☐	☐	☐	☐
C: **Contrarian Views/Alternative Hypotheses.** You:	☐	☐	☐	☐
Colleagues:	☐	☐	☐	☐
D: **Earth Systems.** Through you:	☐	☐	☐	☐
Through colleagues:	☐	☐	☐	☐
E: **Forecasting Climate Change.** Through you:	☐	☐	☐	☐
Through colleagues:	☐	☐	☐	☐
F: **Documentary records of past climate.** Through You:	☐	☐	☐	☐
Through Colleagues:	☐	☐	☐	☐
G: **Human adaptation to future climate change** You:	☐	☐	☐	☐
Colleagues:	☐	☐	☐	☐
H: **Human mitigation of anticipated climate change.** Through you:	☐	☐	☐	☐
Through colleagues:	☐	☐	☐	☐

4. Are there any concepts from those listed above or others that, in your experience, students find particularly challenging when learning Climate Change Science? Please give brief details below.

Research:

5. Are you involved in Climate Change Science Research?

Yes/No

6. If yes: how long have you been involved in Climate Change Science Research?

A: < 5 years
B: 5 – 10 years
C: 11 – 15 years
D: 16 – 20 years
E: 21 – 25 years
F: > 25 years

7. What area(s) within Climate Change Science are you particularly interested in?

A: Climate Modelling
B: Palaeoclimate
C: Biodiversity/Conservation
D: Phenology
E: Ocean-Atmosphere Interactions
F: Impacts on Human Population
G: Human Response/Policy/Mitigation
H: Solar Forcing
I: Other(s) (Please specify below

____

8. Within the field of Climate Change Science is there a practitioner or researcher you particularly admire? If so, who and why? Please give brief details below.

Disciplinary Background:

9. What subject was your first degree in?

A: Physical Geography
B: Human Geography
C: Geology/Earth Science/Environmental Science
D: Chemistry/Biochemistry
E: Physics
F: Biology/Ecology
G: Mathematics/Computing
H: Sociology
I: Politics
J: Economics
K: Other (please specify below)

____

Thank you for taking the time to complete this questionnaire. Your participation in this research is completely anonymous and confidential; participants are also free to withdraw their consent at any point in the future should they wish. Please indicate below whether you would be willing to participate in the next phase of this research, which will involve interviews designed to gain further insights into teaching and learning climate change science.

I am willing to be interviewed in the future:

Yes ☐ No ☐

Please return to:
Brendan Hall, Centre for Active Learning, University of Gloucestershire, Francis Close Hall, Swindon Road, Cheltenham, GL50 4AZ

bhall@glos.ac.uk

Appendix 2 – Semi-structured interview questions

Interview Questions:

Opening statement: Researching teaching and learning climate change etc.

Part 1

1. Please could you describe your academic/disciplinary back ground? Your 'journey' up to this point? *Supplementary: How did you get involved in teaching?*
2. (Briefly) When teaching climate change, what do you think are the key concepts that students should have an understanding of? *Supplementary: Level?*
3. When teaching climate change, what are the concepts/ideas that you feel students find troublesome (struggle with?). *Supplementary: Level?*
4. (Briefly) What strategies do you have for coping with these troublesome concepts in your teaching?

Part 2 – If no mention of uncertainty by this point

1. Do you address uncertainty in your teaching? *Supplementary: how explicit do you make them? Supplementary: Please give an example of how you do this. Supplementary: Level?*
2. What is your understanding of uncertainty in climate change? *Supplementary: Does this include socially situated elements or purely methodological etc.?*
3. What do you feel is your students' understanding of uncertainty?
4. How do you feel students cope with the concept of uncertainty?
5. Do you include students' understanding of uncertainty in assessing their work? *Supplementary: Can you give an example of how you do this?*

And finally...

Within the field of climate change is there a practitioner/researcher you particularly admire? *Supplementary: If so who and why?*

Appendix 3 – Academic participant consent form

UNIVERSITY OF GLOUCESTERSHIRE

Centre for Active Learning

A CENTRE FOR EXCELLENCE IN TEACHING AND LEARNING

Participation Consent Form for CeAL Research (Brendan Hall PhD research)

I understand that my agreement to participate in this study involves participation in interviews which will be recorded. I understand that these interviews will involve discussion of my academic background, teaching, attitudes and students' learning.

I understand that my participation in this study is entirely voluntary and that I can withdraw from the study at any time for any reason. I understand that I am free to ask questions at any time. If for any reason I experience discomfort in any way I am free to withdraw or discuss my concerns with the researcher in person or with Martin Jenkins, Centre for Active Learning Academic Manager (Contact details below).

I understand that the information provided by me will be held confidentially, such that only the interviewer (Brendan Hall) will hear the tapes or see the typed discussions before these are anonymised. Your comments will be held in an anonymised and confidential format so that no information can be traced back to you as an individual.

I understand that in accordance with the Data Protection Act this information may be held indefinitely. Finally, I understand that at the end of the study I can be provided with a copy of the research report if I request it.

I, (please print)..

consent to participate in the study.

Signed:

....

Date:

....

For further information please contact Martin Jenkins, Academic Manager CeAL at the Centre for Active Learning, FCH, University of Gloucestershire.
Telephone: (01242) 714689 Email: mjenkins@glos.ac.uk

Appendix 4 – Interview Transcripts (Exemplars)

Participant 3 Interview 21/4/08

INTERVIEWER: If I could just begin by asking you to describe your kind of journey up to his point academically, in terms of how you got into the discipline and your background and education..?

P3: Ok...I guess you can go quite far back with these things...so my background is physics, which is the same as quite a lot of the people in this group and...and I guess I did physics through reading A Brief History of Time and enjoying that and ended up doing physics at Manchester University for 4 years undergraduate...and the sort of environmental side I guess...as a kid you grow up being idealistic about environmental issues and that kind of stayed with me and I wanted to go into kind of green things and saving the planet from school...but I kind of didn't really think I could go into that sort of are when I was at school...I wasn't interested in doing a degree in environmental science because it didn't seem sort of challenging enough, I went into physics because it was hard and interesting...and then I ended up doing a PhD in particle physics, because again it was hard and interesting...and it was quite sort of computer-y which was not what I was intending to go into but that was sort of ok and then I found the physics really interesting and...and then I was kind of looking around for jobs, I had decided to leave science because I thought particle physics was a bit dry, a bit computer based, a lot of the people in the field were not great at sort of interacting socially and I kind of wanted to leave that side of things and explore things that were a bit more either worthy or a bit more creative...and just kind of balance things out a bit more, personality wise...and I was looking for things in the public sector and local councils and...bits and bobs, but wanting to stay in the south west so it was a bit limited because a lot of jobs like that are in London...and then I bumped into...well I met a friend in the pub whose brother came along, who's an astrophysicist and said, oh you know you're looking for a job why don't you do climate modelling because they don't mind if you don't know anything about climate change beforehand, any of the science, but the fact that you know how to use computers and analyse lots of data, the fact that you're a physicist is good enough for them and they can teach you the rest...and he told me about the sort of email list with all the jobs, metjobslist, and...amazingly like about a month later a whole load of postdoc jobs came up and several were at Bristol so I applied for those and got one...so it was almost sort of accidental because I never knew about climate modelling as a job, like all through doing physics and my PhD and everything I never knew it was an option...and so it's kind of a complete surprise that I could sort of mix the hard physics side of things with the sort of environmental sort of worthy side of things in the same job, so I was really happy and it feels like kind of my niche and stuff and I feel really happy now so...so it was a bit accidental at the last minute but...

INTERVIEWER: And then you came to be involved in teaching?

P3: Yeah…so that was how I got into climate science…so that was my…I'm still in that same postdoc position I started about a year and a half ago…and so I'm just getting to the stage where I feel kind of confident enough to be explaining things to other people and answering questions on sort of topics a bit more broadly, both in terms of palaeoclimates which is my research and also like, twentieth century and future climates which is obviously what the public usually want to know about…so I've been trying to both kind of give talks to the public, because I think it's important and I quite like doing it, I really like doing it…public, sort of adults and children…and then the teaching obviously kind of a natural part of career is trying to get some teaching experience so that…well, bluntly put you know it's better for the C.V. if you've got a bit of…a bit more experience when you're applying for more permanent positions later on, although that wouldn't be for a while because I'll maybe do one maybe two more postdocs at least anyway…so I've been kind of putting the word around that I'm interested in getting experience…you know within the department. I keep nearly lecturing but it hasn't quite worked out yet…but then this thing came up at Gloucester so I…that was my first teaching job, that was just two afternoons that I did there…so basically I'm interested in communicating science in general, like as I say to the public and to policy makers…and then the teaching to students, I'm interested too and also as a kind of career requisite as well.

INTERVIEWER: Ok…So if we can talk about climate and the discipline and it needn't necessarily refer to your experience of teaching it could just refer to kind of what you know and what you've learned in the last couple of years…what do you think are the kind of key concepts within the discipline that people should understand..?

P3: I think the very top one for me…is certainty, uncertainty and certainty…because in various different conversations with non-scientists, not just about climate change, it's really hard to convey the scientific method to someone who is very, very not familiar with it…and by that I mean mainly the way that scientists will say no we're absolutely sure about this because we have tested it and we've done lots of experiments and we've thought about it very hard and we've done lots of sums and we've looked at it from all angles…and yet I won't be surprised if next week we find out something new that puts it all completely you know…the whole sort of Einstein over Newton type stuff…where it can all kind of go out the window, but we're very sure right now but tomorrow we might be saying something completely different and scientists can kind of hold all that stuff in there, they are quite used to that sort of process of yes we're very sure but we're completely open to being wrong…and I think that's quite hard because obviously the public and people really want to know, especially you know future climate change is such a globally impacting thing economically, socially and everything…people really want certainty don't they?...and it's just very hard to convey how certain you are, you know setting aside the fact that we don't find it easy to quantify numerically different probabilities and uncertainties, it is even harder to then communicate how sure we are to the public so that's like the main thing…

INTERVIEWER: That's very interesting...do you think that...do you think it's a big stumbling block for people learning climate change potentially...is it something you either get or you don't or is it something that you can teach?

P3: I think it's something you can teach in that...I think if it's something you're used to...you know if you grow up in school kind of being interested in science and learning about how people find things out and the way that knowledge builds on previous knowledge...then you just kind of get used to it and I think science students and geography students are probably reasonably used to those kind of things...I might spend a lecture talking about...state of the art climate models and all the terrible problems they have in predicting things and yet how useful they are as a tool for predicting future climate change...and that kind of balance students don't seem to blink an eye at usually because they've heard about lots of other examples of that not just in climate change in other science or wherever...but I think if you gave up science as soon as you could and haven't done anything kind of vaguely related to it and you've completely...you know you're completely in a world of sort of...well you now not in that world, then I think it's quite hard...but it is just exposure I think it is just kind of being around people who can explain it to you and...being used to hearing those ideas a lot and understanding how scientific knowledge kind of builds up...

INTERVIEWER: So addressing it explicitly is the way to deal with it?

P3: Yeah definitely...yeah...but it's really hard honestly if you're trying to get it across quickly...to someone who's not...say someone who's quite sceptical about science in general, like people...sometimes people have a kind of...they don't like authority or they don't like believing things that they're told automatically and they'll want to question everything...in a way that's obviously quite scientific to question everything but in a way scientists also accept everything...you know you have to accept a certain amount of what's gone before, you can't question every single thing from first principles...so I think if you're trying to quickly explain to someone about this stuff it's quite hard and especially if they're already quite sceptical about scientists, suspicious of the ethics of science or that it's elitist or that it's pointless or that it's out of touch or all those sort of different things where people can like have a bit of a mindset against science to start with it's quite hard...but I think talking to people who are quite open to learning about it it's fine...you can just say well you know we're sure about this we're not sure about this and that's why and they'll go oh right yeah you know, no-one's ever said that to me and it's fine I think it's just harder if people are obviously less willing to learn just the same as anything...

INTERVIEWER: It's interesting given that you're kind of...that you work in modelling that...well it's interesting to me because I haven't got a lot of experience and, to be frank, understanding of models and the ins and outs of how they work, I appreciate what they're used for...but you know it's interesting that you start from a position of uncertainty, given that models are dealing with...you know they're reductionist and they're dealing with the business of prediction.

P3: Yeah...I guess...

INTERVIEWER: Do you think that's because you came late to it...in the sense of your academic career?

P3: Possibly, because the kind of models I was used to in particle physics were obviously relatively simple you could run them quite quickly the equations in them were quite few and quite simple and they gave incredibly exact predictions for...I mean kind of statistical distributions not exact predictions but for things that you know...very quantifiable numbers of sort of momentum of particles and mass of particles and things...and climate change is so much fuzzier than that...for example in particle physics you wouldn't announce a result unless you had the confidence limits of 99.9% which is sort of 5-sigma or whatever...but in climate science people are incredibly happy with sort of 90% confidence limits or lower...you know 50 or 60 % confidence limits, so it's so much more fuzzy and the models are so incredibly complicated and no one person understands for example the whole of the Hadley centre model, people understand different bits of it...so it does feel...yeah quite uncertain compared to my previous field...

INTERVIEWER: But you're happy with that?

P3: Well I haven't got much choice (laughs)...yeah, but I feel comfortable in the ways that we can you know explore the uncertainty and the way that...especially coming...because I'm working on the palaeoclimate modelling so you can compare your model to sort of lots of different eras and test it quite strongly I think, and although you know that it's got it's weaknesses it doesn't mean you don't know what those are you know you're not walking blind through a mist or something you know that it's particularly good at one thing and particularly less good let's say at another...so I think we're quite aware of the limitations...but if you go around saying well you know the model can't do this and the model can't do that and we're not sure about that it does sound quite negative when in fact we're actually reasonably...we've got a reasonable handle on lots of these things...

INTERVIEWER: Ok...we've actually rattled quite quickly through what I was wanting to talk about...what I'm interested in is uncertainty and the kind of complexity of the system and how we teach it basically...how do you get it across to students and it's interesting what you say about existing in a climate, pardon the analogy, of being familiar with science and the practice of science and the evolution of scientific thought...and if they exist within that framework already they're already tuned into it and they can be quite comfortable with it...trouble comes when you come to assess it and things it's quite difficult because at the end of the day assessing what is in effect the absence of understanding...

P3: Assessing whether people have understood what you've said about the uncertainty?

INTERVIEWER: Yeah, understanding uncertainty is really, really difficult...But I don't expect you've had any experience of that yet have you?

P3: Well yeah...ask me after I've seen whether anyone's answered my questions on the course and I've marked their essays...I mean that in itself is quite weird for me because as a physicist my whole degree was numerical really and so the fact that I've kind of set exam questions that were essay questions and will be marking those, that's quite uncertain to me (laughs) you know and how to assess how well they've understood something how much they've either parroted something they've remembered from my slides or gone away and thought about it and looked it up and how to judge how much of either of those things they should have done, because probably physics was based quite a lot on memory or at lease remembering how to derive things from first principles at least...so that's...no, I'm quite interested in that question myself, I'd quite like to know...

INTERVIEWER: But it's something you designed...it's something you thought about was it?

P3: The exam questions? Yeah...I did find it quite hard. I had to set two and I found it quite hard to know how far to go away from my lecture so I wrote them before I wrote the lectures...so I found it hard to know how much to put in my lecture that was in the exam question...and how far they were expected to go away and find out things for themselves...so that was quite hard...and you know how to mark an essay, it's quite a different skill from marking a mathematical derivation (laughs) and that whole thing makes me a bit uneasy just because I don't have that much experience in it and I don't feel so comfortable as people from other degrees would in giving what feels to me like quite a...not arbitrary but quite subjective mark...and I'm used to like a marking scheme, have they written this, this and this...tick, tick, tick, that's fine and...but the whole well you know I feel that this and I believe that they've understood this...you know that is tough, I'm sure that just comes from experience as well...that's a bit off topic I guess?

INTERVIEWER: Well no it's not because I think the whole issue of...summative and formative assessment to give them their rather stuffy and broad titles is...it's an interesting question because concepts like uncertainty, when you're teaching climate change, I mean...what are the methods that are best suited to assessing it and then it's like you say...there's obviously a degree of subjectivity on the part of the person who's answered that question and the person who's marking it...it's something that I'm exploring because there's potential to emerge from this as kind of strategy for addressing these concepts in your teaching...I'm talking to a wide range of people with different experience and some of them are working in very specific areas of the discipline, some are just teaching it as a broad subject in maybe one module so...what I'm hoping will feed out of that is how we might think about addressing these concepts, given that they can be difficult.

P3: Yeah...I think...again this is sort of reasonably related to this...I am kind of belatedly...I think it takes a long time as a student to realise the importance and interest in statistics...because everyone goes oh groan statistics...certainly on my course everyone really resisted learning anything about it hated it dreaded it...our lab experiments left it until the last minute, made some of it up you know all that stuff...and then I think part of the interesting thing about becoming a scientist and learning about doing real science is when you realise that nobody else has done it and nobody knows the answer so you really have to sort out your statistics to sort out how sure you are about it and I think...like I think things are changing...I've heard in geography there's a lot more statistics taught than there used to be, I'm not really sure but I think that whole thing is really important to get across quite early on...statistics is kind of the point you know...dealing with the statistics properly is kind of the point of science and there's no point in doing any experiment unless you know how sure you are about the result...and maybe that would be one concrete thing that could be sort of expanded to kind of try to understand...and that would link in with the uncertainty stuff you know because if you don't have a good feel for what a 2% uncertainty is compared to a 50% uncertainty and how you calculate those and how you assess those then that all feeds in...that would be more like the really quantitative stuff...

INTERVIEWER: Yeah, it kind of breaks it down to not being just black and white as a known and unknown... (P3: Exactly) You know, there are shades of grey where you can put yourself in that spectrum...

P3: Yeah, because there's obviously...like the IPCC report has these you know very likely, likely, not at all likely...and they're supposed to correspond to certain confidence limits...so if like the general public and students and stuff could really get a feel for that and about what a 5-sigma confidence level is compared to a 1-sigma and just because your answer is outside some confidence limit doesn't mean it's wrong...you know all that stuff. I guess that's one of the key things, like day to day.

INTERVIEWER: But then it can come back to...well what's going to happen to Bristol as a result of climate change...whether climate change is kind of anthropogenic and all that it's still up for debate and then you know what's going to happen here, and you say well you know you can talk about confidence intervals and so forth then but then...the reality may be something other than that...completely outwith your prediction...that I think is what some people find difficult.

P3: Exactly, you might be in the 5 percent outside your confidence limit or...also there's loads of things, there's...the fact that a lot of people in climate science will predict future things based on business as usual scenarios but it's pretty likely that things aren't going to be business as usual compared to like say the 1990s onwards...things are already changing, emissions levels are changing by country...some are going up quite a few are going down...so we might predict all this stuff and then governments act on it and then it doesn't happen so will people think that scientists were all kind of doing a millennium bug on it and we were wrong or is it the fact that governments actually did something that changed it...

INTERVIEWER: It's another level of complexity?

P3: Yeah...they might create a whole new wave of sort of scepticism in science if the actual...loads of money spent on reducing non-mitigating global warming then not much happens...if it's at the sort of lower limits of our estimates then will everyone go oh you know well done for the fact that we spent all that money doing it or will they say well it wasn't going to happen anyway...like that's decades down the line but it could be quite bad for scientists potentially...

INTERVIEWER: But you have experience of communicating science now...and that's just what it is...that's all you can do quite often and that's part of the reason...what makes this area so interesting I think...it's you know the number of stakeholders and then what that means for science and then what that means for the knock on effects for policy and all that...

P3: Yeah, and it's a relatively one-sided direction...you know everyone's got a stake in this, everyone's got a self interest and mostly it's in not doing anything. I mean you can do lots persuading people that it will save them money to save energy or that it will create jobs to create wind-farms or whatever but the general bias is against it you know...people's self interest is in not doing anything and not bothering to recycle you know that sort of stuff...so it's quite weird that unlike perhaps as company where people want things to change so they get more profit...you're sort of...you know Joe public doesn't want things to change because it's easier or because it might cost them money...

INTERVIEWER: Very interesting...Thank you for taking the time to talk to me today.

Participant 7 Interview 20/3/09

INTERVIEWER: I'd be interested to hear your academic journey up to this point, how did you arrive and where have you come from?

P7: Well, I'm American by birth and I went through the university system in America and I went on for postgraduate study at the university of Chicago and I studied international relations...so my first degree was a BSc in anthropology at Utah...and I had more of an international outward looking viewpoint as a young person and I always knew that I wanted to study something looking at the world rather than something really close and not interconnected in some way to other things...so then I got working for the US Antarctic programme so I worked overseas and I travelled to Asia for a year when I finished my contract with the USAP and while I was working in Antarctica I put together a doctorate proposal for Antarctic research, so I came over to the UK to study at a polar institute in Cambridge and I did an MPhil in polar studies and a PhD in Geography at Cambridge university through the Scott Polar institute specialising in Antarctic tourism and environmental policy...so I think my journey to get to climate change here at Bath Spa links to how climate change links to tourism really and...I started my academic career at Sheffield Hallam University in their tourism management programme and I was there for six years and I moved here in 2003...so this is my 6th year with Bath Spa and I have tried to drive climate change in the curriculum in our department...or at least I say that, because I've sent out messages to colleagues to ask is it possible to put together a climate change undergraduate degree...an undergraduate degree looking at climate change issues in geography

INTERVIEWER: Right...linking climate change to geography and all the different elements of geography..?

P7: Because there's sort of expertise within the university in different bits...you know my GIS colleagues do climate and the physical geographers have some of the background...I thought I could bring the policy side of it, the tourism side of it and kind of round it off...but I think because we have our established programmes already we haven't really driven that idea forward...but I think there's a real sense of goodwill about including climate change in the curriculum because it's so relevant and pertinent to everyone...I think one of the frustrations I have is...about climate change is, I would like to see a clear module...like a stand-alone module that incorporates different elements so that rather than bolting them into different modules that I teach...that's how I think and I recognise that I'm in a university and colleagues think differently so I accept that but if I had my choice I would like to perhaps develop a stand alone module or even develop it in a way that it could be named on a degree...I don't know if that's ever going to happen but that's what I would like to see...because I say to my students I want you to see how what you're learning links with climate change in every way and I want to give you the tools to allow you to see that, but whether they do I really haven't measured.

INTERVIEWER: So...if we can talk about your teaching...what areas of your teaching do you teach related to climate change?

P7: Well I guess I started a few years ago trying to embed more climate change ideas, issues and literature into my modules and one example is in the introduction to tourism we teach in level 1 and students are taking that module from many different degree routes so we have students from education, sociology, psychology, business management as well as geography, tourism management and so forth, so it's not just tourism management students taking the class and…for a long time we had sustainability as a key strand in the module and so what we have done is broaden it out to include climate change within the notion of sustainability, in other words if the tourism industry and tourists and destination areas aren't planning or creating policies that link to mitigating climate change then tourism is not sustainable in that sense, so…in the initial part of…for first year students in my introduction class one of the things I do, and it's later on in the module, I have to rig it with the nuts and bolts of tourism earlier on in the module, I'll ask a question to them as a class and I'll say how do you think climate change links to tourism and so we start a discussion and then they say well you know aircraft emissions or when people travel really far to see places that has an impact and…so I get them to see the different ways that climate change links to tourism and then I basically ensure that they know the difference between global warming and climate change because there's quite a lot of confusion over that, I find even at university level and even in the press some people use the terms interchangeably and they're distinct…one of the beliefs I have in education is I like students to see how news reports link to what they're studying…students tend to see things in little boxes because they're taking this class and this class and I try to help them see the linkages and I'm not really sure how successful I am but I'm always encouraging them to think about how what they're studying in another module might link to what we're talking about in my module and how the news headlines today links to everything…because I think we need people that have joined up thinking, that's what's really going to be really important in addressing climate change, that's going to make the difference…not that people see it sort of compartmentalised or as relevant or less relevant to them because they're not in a certain kind of job…so in the first year we introduce the concept in relation to tourism and then in the second year I teach a research methods class and one of the readings I give them and they have to…submit a critical review of an academic article, so the article relates to international tourism and climate change…so it builds a bit on what was done in first year and…they have a class I teach…because I'm in semester 1 I teach another first year class next semester, managing visitor attractions, and where it's relevant I might mention climate change or if it's in any interaction management material in a case study I may talk about…I do a case study of the Disney corporation and they are known for their environmental policy and I would make points to say that all their efforts to protect the environment are linked in many ways to climate change, because of their recycling, their use of electric vehicles on site and all kinds of policies that they have…so in year 2 in the critical review they do for the research method class, I selected the article Richard Tull and others, in Global Environmental Change I think…they wrote an article that shows some initial thinking about climate change and international tourism and I want students to get some of those fundamentals…so I know that they've read at least one journal article by the first semester of year 2 and they've critically attempted to assess the evidence as presented in the article and tried to develop their critical skills…so that's one thing that I do….and I guess in the tourism policy and planning class in the 2nd year the students look at specific planning documents for tourism and…I ask students do you see evidence of they're taking on board issues like climate change and sustainability and we actively have them look in the documentation to see if there's mention of them and how the planning documents incorporate these important issues.

INTERVIEWER: If I could just take you back a step...you mentioned that some of the students struggle with the distinction between global warming and climate change; do you think there are any other concepts around climate change that they find difficult?

P7: Well I don't much run the science behind the climate change and some of my physical geography colleagues do...so I don't assess their knowledge or their awareness of those concepts...but it is possible that we would have a question on the exam that might look at sustainability issues and some students may incorporate climate change into that and that would be a much stronger answer than one that didn't for example...so in terms of can I really say what other concepts the struggle with, I think my perception overall is that some students come to university...and they're apolitical, or they seem to be policy unaware and I think that's just typical and I think that's how generations of policy activists get educated and get switched on at university, because they're in an enriching, influential environment that discusses how the world can be changed or how what we're doing needs to be redirected and I think the seeds are sown there for future change...but that's a big question that you asked and I think it's a good question...nothing is really jumping out in terms of a specific definition or concept that they say they don't understand but my sense is that...they focus on different things at different levels, so the 1st year student might focus on different things...and a second year student and third year student are going to be noticing different things and be influenced by different things, so...

INTERVIEWER: Would you say for example taking a kind of policy angle and linking it to things like tourism...are students very certain of the kind of...you know are they aware of the uncertainty that exists in climate change...you know, that we can demonstrate to a degree that we are responsible for changing the climate but there's uncertainty inherent in that, there's uncertainty in terms of the policy response and the social response...do you think they have a handle on that or is it very much that they include climate change as an issue within tourism say?

P7: I think they're aware that they differ in their perspectives on this and one example I'll give you is that early on in the semester when I raise...climate change comes up in a lot of contexts and when I write a lecture I have general information and material I want to get across but occasionally I might...spontaneously as you think on your feet you might link an issue if something comes up or something topical on this issue comes up and you discuss it in class and I remember I've asked for several years now, and this is something I'm just quite interested in doing potentially more research on...and this kind of links to my research on Antarctic tourism and climate change which I'll get to later...but I'm interested in one aspect of this...how the public, and this includes my students, how they perceive all of these...this bombardment of messages about climate change, how they filter that, how they process that and how that may in some way influence them to change their travel buying habits or their own practice in terms of tourism and so I ask them a few questions I class and we get a very interesting going...I said to them, ok given what you know about climate change right now whether you understand all the facts and figures, whether you agree it's happening to the extent that some people argue it is and whether you agree with people who say it's nothing to worry about as much as people are saying, wherever you are on the spectrum what I want to know is...raise your hand if what you know is influencing the way that you're making your tourism choices and...so we get different people raising their hands, so I say so how is it influencing you and one student said, well I'm not sure it's really influencing my decisions because I'm really not sure what to make of all the information and I'm just carrying on as normal, so someone else said, wait a minute, I'm definitely intentionally not travelling as far or I've made decisions not to travel as much because of climate change because if we all don't do our bit then nothing is going to change, then I have another student in my class and she has two young children, she's a mature student, and she said, well I'm not changing my habits at all in fact I'm probably going to travel more because I want to see those places before they change and I said to my class, well how about that, what was the chances of that, that the first three students are presenting those three places on the spectrum, that's exactly what...I couldn't have explained that more clearly than you've explained that to each other that on this spectrum, regardless of what the messages are, regardless of there clarity or accuracy you are all drawing your own conclusions and changing your behaviour or not based on the information you are getting in the media...so that's very powerful in tourism terms and there are people in tourism that are concerned that the messages are going to limit or detract or affect in a negative way the amount people travel and other people are concerned that they might be able to design new products around this concern and create better aircraft and better forms of transport and more you know lower emissions and all these other things that might connect so that the transport doesn't contribute so much to global warming and so it's really interesting that in my own classroom the spectrum is represented that way but I suspect that in a university and if you did research on this with the public you'd find a similar thing that there's no clear...measuring the impact a particular media message has is very difficult to pin down but...I'm interested in that side of it so I want my students to be thinking about these issues when they're working in the tourism industry to see how it's a very live issue and how companies have to respond to these consumer demand for more green products or concerns that people may not want to buy their products because they don't want to contribute to the problem...there's such a tangled nest of issues in there it's really rich for academic discussion and understanding...but building that into the curriculum and setting up debates with the students and having them think about how other people see things you know really role-play things and...I suppose what it comes down to is people's...every person's opinion...regardless of what their learning in class....i don't have any real sense of when they leave here what they learned has on say tourism choices or how it impacts them in their jobs, but that would be interesting too....

INTERVIEWER: You kind of hinted at the tangled web of climate change as an issue and, in fact, there's kind of a wealth of information out there and that you encourage your students to make linkages there so do you think an understanding of that kind of level of complexity is important to them?

P7: Well...absolutely, I think what you train students to do in university is think in a bit more clearly and more focussed way and see the interconnectedness of things...climate change affects all of us clearly...but what sources of information do students have? They're all going to differ. How many of them listen to the news or what sources of news they read or whether they even read the news...I only guess what types of things influence their...I don't find that they read the broadsheets daily or anything like that or many of them do or the Economist or Science or Nature or anything on a regular basis but some of them might and...I mean they are not science students so I don't know if that's going to limit the amount of knowledge before they come to do the course so I don't...

INTERVIEWER: This is really interesting because I haven't actually spoken to any non-scientists yet, so what I really wanted today was different perspectives and it's really interesting to see where climate change fits in a discipline like tourism geography for example, which I don't know an awful lot about myself but you can clearly see where it is and where it's involved in your teaching...Could you just describe the research you were talking about?

P7: Well sorry if I didn't say but I'm a human geographer and in the discipline of geography people would argue that there's human and physical geography but in the US for example you might call yourself a political geographer and there's many different types of geography but I'm a human geographer I'm interested in the relationship that mankind has with the world they live in and the physical environment, social environment and so forth...my research that links to climate change is very recent it's been in the past couple of years I would say but my background looks at environmental policy in the Antarctic and the tourism industry there and whether or not it is being regulated effectively, so with that background I presented a paper at the SCAR conference...my paper was on Antarctic tourism and climate change and I was interested to look at...we know that the industry is growing and we know that previous researchers have established some preliminary figures for the footprint of Antarctic tourism because it mostly entails a long-haul flight, so if you take into account that the industry is growing and most people have to take a long haul flight to get to the port and they take a cruise ship with it's emissions basically there's no way Antarctic tourism can be considered a form of eco-tourism it's got one of the largest environmental footprints of any form of tourism and the way that they market some of the tours they lead you to believe that it's an environmentally friendly product but they don't talk about all the emissions that get you there and let you see this environment so...my paper was looking at the link between the media and Antarctic tourism so this question is it growing because more people want to see it before the ice caps melt and before it changes and even these environmentally aware and sensitive tourists want to get there before it changes and I find that really interesting because through the...a journalist from New Scientist called me and said I'm really interested in the paper...I think it's linking to me...I said it is! New Scientist is one of the lead publications and your articles have a massive effect, even though you're giving the facts, you don't know what effect that's having, you may be driving people to travel more because they want to see the places before they change because your argument is so compelling...he said I've never looked at it that way and I said...it is really interesting but you probably can't study it properly and never quantify it...but perhaps what's driving you is your passion for the environment but you may be having an opposite or neutral effect...I'm not picking on you personally because I think it's really important to have the facts and everything...I just think that's really interesting because when I ask my students in the class, they are the generation that has the most knowledge or they are raised in that awareness bubble that perhaps came a little bit later for older people and some of them are not being influenced at all or they don't know what to make of it, it's just too much and one says one thing and one says another thing and they don't know what to believe so it's easier to do nothing so...he said let me know when I'm doing more research but I have a full time job as well...it's really rich but where it goes from here I'm not sure...

INTERVIEWER: Thank you very much for taking the time to talk to me today.