Reconciling anthropogenic climate change and variability on decadal timescales: history and philosophy

Roger N Jones

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Date	1654	1687	1783	1809	1824	1850
Persons involved	Fermet and Pascal	Newton	Lavoisier	Gauss	Carnot and others (later)	Clausius, Rankin and others
Theoretical advance	Calculation of the odds	Law of Gravity	Calorific law (conservation of heat)	Statistical theory	Second Law of Thermodynamics	First Law of Thermodynamics
Methodological development	Mathematics of chance (risk)	The square of the distance between objects	Heat balance	Least squares analysis	Thermodynamic equilibrium	Conservation of heat (heat and work in 20th century)
Scientific value	Predictability	Balance and order, universality	Balance, measurement	Balance, order, management of uncertainty	Balance, irreversibility, harnessing of energy	Balance, order
	1654	1687	1783	1809	1824	1850

	1940s	1963	1970s	1979	1990	2013
	Many	Lorenz	Many	Hasselmann	Santer and others	Most climatologists
	Information theory	Chaos theory (deterministic non-periodic flow)	Detection of climate change	Temporal and spatial detection of climate change	Scalability of climate change signals over 3+ decadal time scales	Climate variables gradually respond to increasing greenhouse gases
	Signal-to-noise models	'Strange' attractors, butterfly effect, Lorenz equations	Signal-to-noise models used in past and present climate data	Signal-to-noise models used in climate model data	Pattern scaling	Pattern scaling, signal-to-noise, lines of best fit
	Separating useful information from noise	Non-linearity, chaos	Extraction of climate signal from 'noisy' data	Attribution, prediction of change	Predictability	Predictability – separate the signal from the noise
	1940s	1963	1970s	1979	1990	2013

Key words: paradigm, history and philosophy of science, climate change, uniformitarianism, nonlinear dynamics, hypothesis testing, scientific narrative, scientific values, scientific method

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Victoria Institute of Strategic Economic Studies
Victoria University
Po Box 14428 Melbourne
Victoria Australia 8001
Phone +613 9919 1340
Fax +613 9919 1350
vises@vu.edu.au

Abstract

How the climate changes on decadal timescales can be described by two alternative hypotheses: 1) externally forced climate change is gradual and linear within a background of random variability and 2) the two phenomena interact, producing a distinct nonlinear response. Current methods for analysing and communicating climate change self-select the linear hypothesis. This is characterised by linear trends applied within a signal to noise model and is communicated through a scientific narrative that describes climate change as being gradual. Theory and a growing set of observations support the nonlinear hypothesis, suggesting that decadal scale climate change is episodic, exhibiting nonlinear complex system behaviour. Scientific paradigms are a mix of methods, theory and scientific values that evolve at different rates. This paper examines how the gradualist paradigm arose, why nonlinear phenomena are treated as noise despite being a fundamental part of the climate system and why it has taken over 50 years since Lorenz' discovery of fundamentally nonlinear behaviour for the gradualist paradigm to be seriously challenged. Linear methods and their supporting cognitive values trace back to the scientific enlightenment. Uniformitarianism and gradualism began as cosmological values within the earth sciences, later evolving into cognitive values that underpinned the development of the signal-to-noise model. The recent attacks on climate science by political and vested interests have discouraged mainstream climate science from openly investigating theoretical alternatives to the status quo. While other areas of the physical and natural sciences have moved to explicitly represent complex system behaviour, climatology is the last branch of the earth sciences to do so.

Introduction

Scientific paradigms are powerful, complex and often misunderstood, especially with regard to how their social and theoretical components interact (Laudan et al., 1986). Scientific communities communicate paradigms through scientific narratives, between themselves and with the outside world. This paper addresses the paradigms and narratives describing how climate changes on decadal timescales. Its central theme is understanding the current imbalance between theory and practice and how it can be reconciled.

Kuhn (1996) described paradigms as “scientific achievements that, for a time, provide model problems and solutions for a community of practitioners”. The model problem is how to understand and forecast human-induced climate change over the coming decades. This problem is not only scientific but will affect the community at large. Scientific solutions will address model problems but can also make an essential contribution to managing these broader risks, so it is important that they are being addressed correctly.

The theory and practice associated with a changing climate can be summarised according to two hypotheses. These describe the interactions between climate change and variability, which make up the external and internal components of climate forcing (Corti et al., 1999;Hasselmann, 2002;Branstator and Selten, 2009):

1. Greenhouse gas-induced climate change and natural variability change independently of each other (*H1*), or
2. They interact in some way (*H2*).

H1 is generally characterised as smooth lines of gradual change (the signal) surrounded by the random noise of climate variability. It is associated with analysis methods largely based on ordinary least squares trend analysis. Physically, this implies that the climatic response to external forcing is through trend-like gradual change. *H2* is associated with more complex interactions characterised by nonlinear change, such as relatively stable regimes punctuated by rapid shifts or step changes.

Efforts to determine whether *H1* or *H2* is more likely have so far proven inconclusive (Solomon et al., 2011;Christensen et al., 2013). For example, in defining internally and externally forced variability in near-term climate change in the IPCC Fifth Assessment Report, both are treated as linearly additive with the following caveat: *This separation of T, and other climate variables, into components is useful when analyzing climate* *behaviour but does not, of course, mean that the climate system is linear or that externally forced and internally generated components do not interact* (Kirtman et al., 2013). However, current methods based on trend analysis used to analyse, attribute, project and communicate climate change overwhelmingly self-select *H1* over *H2* (Jones et al., 2013;Jones, 2015b). This can lead to a general impression that the theory supporting *H1* is more solid. In that sense, the method becomes the theory.

The scientific narrative accompanying this description has been coined the gradualist narrative (Jones et al., 2013). When combined with the hypothesis *H1* of gradual change within a signal-noise construct, it can be referred to as the gradualist paradigm. The alternative hypothesis *H2*, is inherently nonlinear, but lacks an established set of scientific achievements that link model problems and solutions. *H2* therefore, does not currently qualify as a fully-fledged scientific paradigm, because there is no identifiable set of model problems and solutions for a community of practitioners.

Given that both *H1* and *H2* are considered theoretically plausible, the main justification for the gradualist paradigm is social, in that it is widely accepted by the scientific community and is methodologically successful. However, as Wallace (1996) said concerning climate variability, if preconceived notions as to its causes are wrong, research is likely to get on the wrong track.

Evidence for the climate signal being nonlinear over decadal timescales is mounting. Ji et al. (2014) use empirical mode decomposition to show that global warming rates were nonlinear over the 20th century. Sea surface temperature has undergone two major step changes in the 20th century according to Varotsos et al. (2014). Jones and Ricketts (2015b) show that step changes explain over half of the 20th century observed global mean warming and that steps dominate the signal compared to internal trends (trends between shifts) in climate model output (Jones and Ricketts, 2015a). At the local scale, no evidence of trends can be found for regional warming in south-eastern Australia, central England or Texas (Jones, 2012;Jones and Ricketts, 2015b), where most of the warming can be attributed to steps. Step changes have been identified in air temperature, sea surface temperature, rainfall, tide gauge data, fire danger index and daily extreme temperature at global, regional and local scales (Hare and Mantua, 2000;Overland et al., 2008;Meehl et al., 2009;Lo and Hsu, 2010;Fischer et al., 2012;Reid and Beaugrand, 2012;Jones et al., 2013;North et al., 2013;Belolipetsky, 2014;Menberg et al., 2014;Varotsos et al., 2014;Belolipetsky et al., 2015;Jones, 2015c;Reid et al., 2015). Some of these authors associate these changes with climate variability, while others suggest they may be a nonlinear response to external forcing. Warming and associated changes follow a step-like progression in the 20th century and an elevator-like process in the 21st century, where temperatures follow a step and trend pathway (Jones et al., 2013;Jones, 2015a, b, c). These latter findings are consistent with climate producing a complex trend over many decades, while demonstrating nonlinear behaviour over shorter timescales.

This paper examines how the gradualist paradigm arose, the nature of challenges gradualism in the earth sciences has faced over time, and why climatology is one of the last areas of the earth sciences to embrace nonlinear, complex system behaviour. The nature of paradigms originated by Kuhn (1970, 1977, 1996) and elaborated by Laudan (1984) is used to show how changing scientific methods and values have influenced how anthropogenic climate change is framed, analysed and communicated.

Styles, scientific values, paradigms and methods

Central to the gradualist narrative, are the scientific values that informed its origin and how they have evolved. This narrative and the statistical and analytic methods underpinning it resemble what Hacking (1992) called "models of relatively permanent, growing, self-modulating, revisable features of science." Hacking (2012) refers to these as styles of scientific thinking and doing and suggests that "the result of their persistence is a body of what is counted as objective ways of determining the truth, of settling belief, of understanding meanings, a body of nothing less than logic itself". This latter construction describes the foundation for many areas of science. Each discipline will utilise a variety of different styles and adapt these over time to changing science, technology that influences ways of doing science and values.

Styles are ways of scientific thinking or reasoning (Hacking, 1992;Crombie, 1994;Kwa, 2011;Hacking, 2012) and are the means by which cognitive values are applied. Scientific styles have influenced European thinking since ancient Greek times and guide how science is developed and validated. Crombie's six styles as articulated by Kwa (2011) are deductive, experimental, analytical-hypothetical, taxonomic, statistical, and evolutionary. Both Hacking (2012) and Kusch (2010) caution that this list is not exclusive and that both past but no longer active (e.g., hermeticism) and future styles could be added. Two important styles of the modern era are systemic reasoning and simulation. The first involves an understanding of system complexity, networks and self-adaptive behaviour while the second uses models to envision plausible futures and to illustrate theorised or speculative behaviour. Both have become central to climatology, although systemic reasoning is perhaps not being used enough.

Styles evolve relatively slowly compared to methods and paradigms. Winther (2012) proposes an interweaving framework of styles, paradigms and models with the former underpinning the latter. Each manifests on decreasing time scales, with the lifetime and rate of evolution being the longest/slowest for styles and shortest/fastest for models. These will interact with methods and scientific values. Interweaving with styles, cognitive values change more slowly, and often independently, of paradigms and methods.

Scientific values inform how science is conducted, influencing how commitments to factual claims and to value judgements co-evolve (Kitcher, 2011). Kitcher (2011) suggests three levels of values within a broad ethical framework:

1. The broad scheme of values that society holds;
2. The personal set of values that relates to an individual's knowledge goals;
3. A probative set of values: which problems are most important and which rules best validate/invalidate scientific conclusions?

The latter two bestow value to scientific knowledge, and are applied at the scales of the individual scientist and community of scientific practice, respectively. However, because the problem of climate change extends across both science and society, all three levels of value can be conflated with each other, especially if the social amplification of risk within society interacts with scientifically calculated risk (Kasperson, 1992;Rosa, 2003;Renn, 2011).

The cognitive values maintained by a particular scientific community will influence the heuristics that it uses. These often inform the methods that are viewed as being so basic and/or foundational to a discipline that they are taken for granted. They act as received wisdom and are rarely questioned. Trend analysis and its underlying values are foundational in both climatology and econometrics, for example. These values inform how styles are applied and combined. Each style contains a probative set of values that change over time. For example, early statistics would have accepted the line of best fit in a noisy sample as representing the 'correct' answer, whereas today a range of alternative approaches to significance testing can be used.

Kuhn (1977) lists five cognitive values that inform the whole of science: accuracy, consistency, scope, simplicity and fruitfulness. These values wax and wane but are not linked to any one particular style, and change quite independently of paradigms. They are necessary but collectively, are resistant to formalisation, illustrating why science does not have strict rules (Feyerabend, 1993;Laudan, 1996). Attempts to agree on such rules have always ended in failure and in any case, would stifle new science. Collectively, they protect against such things as cherry-picking and selective bias.

Many values influencing scientific world views relate to structure and change, and these in turn influence how frameworks and models are perceived. For the broad area of earth sciences including climatology, such values include balance/equilibrium, gradualism/uniformitarianism, chaos/complexity and prediction. Various styles are interpreted through such values, influencing both how paradigms are developed and the methods used to analyse and illustrate them. For example, the uniformitarianism developed as part of classical geology has had a formative influence on climatology, manifesting as gradualism. This is despite a growing appreciation of the Earth system as a nonlinear, complex system (Palmer, 1998;Corti et al., 1999;Stainforth et al., 2007).

Together, the cognitive values and styles influencing climatology form a kind of historical epistemology that describes how science addresses concepts such as knowledge, belief, evidence, good reason, objectivity and probability over time (Hacking, 1999;Feest and Sturm, 2011). How they are informed by scientific and broader world views can be illustrated by a number of historical examples, including Oreskes (1999) account of the how the acceptance of Wegener's theory of continental drift by the American geological community was delayed because it challenged their existing standards and practice of the time. Of particular interest here, is how the gradualist narrative has maintained its hold on the analysis, interpretation and communication of climate change science, even though the climate system itself is widely accepted as being a nonlinear, complex system.

Paradigm construction

Kuhn describes periods when science is operating within a particular paradigm as 'normal science' and activities within that as puzzle solving. Paradigm change, he interpreted as a scientific revolution (Kuhn, 1996), treating it in a holistic manner involving the wholesale over-turning of theory and practice. In the discussions following the release of *The Structure of Scientific Revolutions*, Masterman (1970) identified metaphysical, sociological and methodological aspects in paradigms, describing their sociological aspect as a "set of scientific habits".

Paradigms that form part of normal science become part of the furniture of doing science, consisting of a range of methods and practice that are generally accepted by the scientific community and rarely questioned. They set up a set of simplified analogies that a community can accept as a series of core beliefs, while continuing to work on puzzles that concern areas of incomplete knowledge, alternative explanations or system uncertainty. As such, paradigms give rise to scientific narratives that tell the story of the model problems, solutions and achievements Kuhn refers to. Scientific narratives are very powerful in that they map out which values are most important, which problems and solutions are accepted and delineates core methods from those that are exploratory and developmental.

Laudan (1984) critiqued Kuhn's holistic vision of the revolutionary overturning of paradigms. Instead, he proposed a three-part reticulated structure for paradigms covering theory, methods and cognitive aims and values (consistent with Masterman's (1970) interpretation of Kuhn's paradigms), arguing that these elements do not all change at once but inform each other through a process of justification and harmonization. In this construct, any one of the three can change, but to have an internally consistent paradigm that involves all three aspects, the other elements will have to adjust in some way. This reflects the previous discussion on styles and cognitive values that evolve on different timescales to particular scientific paradigms.

Figure 1 shows this model with the methodological and theoretical narratives supporting H1 and H2. The methodological narrative is dominated by methods and cognitive values relating to a set of criteria such as explanatory power, simplicity and predictability. The theoretical narrative addresses hypotheses H1 and H2 and is informed by set of probative values relating to how hypotheses are validated by evidence (probative, or proof values). The two separate narratives shown in Figure 1 illustrate a conflict in how methodology and theory are being interpreted by the climatological community. These two narratives are often encountered within a single book, paper or chapter.

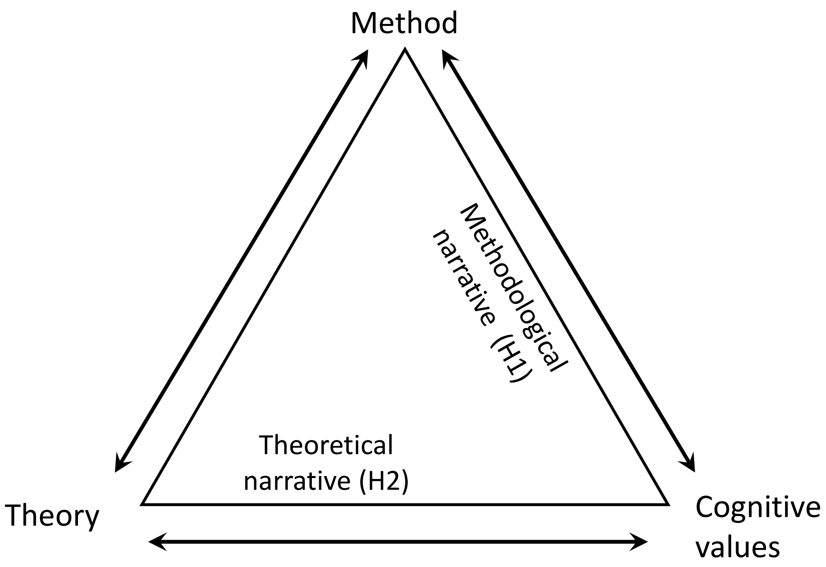

Figure 1. Theory, method and cognitive values within a scientific paradigm (Laudan, 1984) aligned with the methodological (*H1*) and theoretical (*H2*) narratives of how the climate changes.

To date, statistical methods have failed to clearly distinguish between these two hypotheses (Seidel and Lanzante, 2004;Jones, 2015b). One counterfactual to gradual atmospheric climate change is that abrupt change is widely recognised in palaeoclimatic reconstructions and regime changes at the decadal to millennial scale (Overpeck and Webb, 2000;Alley et al., 2003;Shuman, 2012). If the atmospheric-ocean system has often changed abruptly in the past, as is generally accepted, smooth atmospheric change would be an exception to this process. Greenhouse gases would need to produce gradual *in situ* warming in the atmosphere in a way not governed by ocean or ocean-atmosphere processes associated with climate variability, but that is influenced by them. If atmospheric variables change abruptly, then some other explanation is needed.

Historical influences on methods and values

If paradigm change is a reticulated structure as maintained by Laudan (1984), influenced by the different timescales of change within styles, values, theory and methods, then the history and evolution of climatological thought will reflect these varying influences, similar to the punctuated take-up of continental drift within the earth sciences (Oreskes, 1999). This section surveys the evolution of climatology since the scientific enlightenment, taking particular note as to how values such as balance, gradualism, uniformitarianism, prediction, chaos and complexity have been applied.

Order and overcoming uncertainty are central themes in climatology as they are in other areas of science. The act of obtaining balance from uncertainty (variability) and developing predictability through order are rarely questioned. These ideals were a feature of the scientific enlightenment, especially France during 1770–1810, and informed the development of the physical sciences and economics (Wise, 1993). Particularly influential was Newton's gravitational model (Newton, 1999). His distance squared model of gravitational force was adapted into the least squares model of curve fitting and the development of Gaussian statistics. This method has a long-standing status across science and economics (Stigler, 1986), and is fundamental to the measurement of climate.

The scientific reasoning of the time can be characterised as inductive inference based on a set of rational values (Gould, 1965;Baker, 1998). The world was viewed as rational and mechanistic, conforming to fixed principles. This is a normative view originally articulated by Newton that was later adapted and applied to a whole range of disciplines framed as "this is the way the world works." In that sense, science's role was to provide a logically valid explanation for a pre-existing cosmology instead of exploring what nature actually says

(Baker, 1998). The world, including human thought, was considered to conform to the laws of probability and logic (Chase et al., 1998) and science's role was to provide evidence in support of this. Cognitive values, including simplicity, actualism and gradualism, were imposed to ensure valid inductive reasoning (Baker, 1998).

Wise (1993) describes how technologies and methods developed by French scientists such as Lavoisier and Laplace were designed to achieve balance and overcome disequilibrium. Chief amongst these was the calorimeter, linking the domains of chemistry and physical astronomy, which balanced heat in the same way that a mass balance equilibrates objects. These ideas of balance were expanded into national accounts and balance sheets, particularly by Lavoisier (Holmes, 1987). As Wise (1993) says *Measurements are not self-justifying. They employ particular sorts of instruments constructed for the purpose of attaching quantitative values to valued things.*

The notion of balance as rationality was given coherence between different areas of knowledge bridging the sciences, economics and society. Balance and order were also a foundation of what became uniformitarianism in the earth sciences (Baker, 1998) – originally linked to geology but eventually expanding to whole areas of earth-system sciences. Through the calorimeter and similar developments, they also had a strong influence on the evolution of thermodynamics (Wise, 1993).

Two sets of methodologies developed during this period, one qualitative and the other quantitative, have had a lasting effect on the subsequent development of climatology. Uniformitarianism has influenced its descriptive (qualitative) aspect, whereas probability calculus in the form of least squares method of signal extraction dominates its analytic (quantitative) aspects. Both have gradualism at their core.

Qualitative methods: gradualism and uniformitarianism

Gradualism was introduced by Hutton as a cosmological approach to an ordered geological history of the earth, consistent with Newton's structure of the heavens (Baker, 1998;Palmer, 2003). Catastrophism, Biblical (earlier) and scientific (later) was, at that time, the dominant view of geological change. This cosmology applied value-based assumptions that portrayed God as an ordered regulator rather than as a catastrophic creator. Gradualism combined actualism – the view that present day processes were a guide to past events – with the assumption that change occurred at a constant rate (Palmer, 2003). These ideas were advanced by Lyell (1830), whose geological doctrine of gradual change, proposed partly in opposition to the alternative theory of catastrophism, became known as uniformitarianism (Baker, 1998). Lyell's insistence that rates of change did not divert from the observable, sidelined deductive speculation about the possibility of more extreme, or different events and processes that may have occurred in the past (LeGrand, 1988).

Gradualism, derived from Lyell's *Principles of Geology*, also underpinned Darwin's development of the theory of evolution (Mayr, 1991). Darwin argued that gradualism was essential to his view of evolutionary adaptation (Gould, 1982). This view survived into the 20th century, only being widely challenged through the work of Gould (1965, 1982), in addressing mass extinctions and evolutionary responses to these, and was eventually modified. Catastrophism survived throughout the 19th century, but was always subordinate to uniformitarianism. By linking it with religion, catastrophism's opponents politicised it in such a way that the public debate could be turned into a science versus non-science argument, rather than a debate as to whether geological processes were constant or shaped by specific, often catastrophic, events (Palmer, 2003).

During this time, catastrophism survived by being associated with the large changes occurring as part of ice ages, as argued by Agassiz, who was more concerned with interpreting nature than imposing the idea of "this is how the world works" (Baker, 1998). Palaeoclimatology therefore, accepted the idea of rapid change more readily than other areas of earth science, especially after Milankovitch developed his theory of orbital cycles and their impact on climate (Milankovitch, 1920). That earth systems exhibit rapid responses to gradual change in orbital forcing eventually became widely accepted (Imbrie et al., 1992;Clark et al., 2002).

Instrument-based climatology has not taken up these ideas so readily, relegating the acceptance of abrupt change to phenomena such as basin-wide changes in ocean circulation, catastrophic ice-sheet break up, massive greenhouse gas out-gassing from permafrost or marine clathrates or nuclear/asteroid strike (Alley et al., 2003;Valdes, 2011). Abrupt change is generally not considered part of ordinary climate change involved coupled ocean-atmosphere interactions (Valdes, 2011), even though such changes are widely recognised as being a normal part of climate variability.

Gradualism remains an active cognitive value within the earth sciences but has waned significantly. Actualism or presentism, where the present is used as a guide as to how processes worked in the past (Oreskes, 2013), now dominates earth science methodologies (Marriner et al., 2010). In other disciplines that can be traced back to the French enlightenment, economics continues to combine gradualism with Newtonian cosmology (Solo, 1991;Rothschild, 2004;Nelson and Winter, 2009), whereas physics has moved well beyond it. All large physical and social earth systems exhibit complex behaviour, and some disciplines (e.g., physics, chemistry, biology, geography) have responded to this more rapidly and comprehensively than others (climatology, economics).

Quantitative methods: statistics

The co-evolution of values and quantitative methods has also resulted in gradualism dominating how future climates are analysed and communicated. The development and application of probability calculus by Laplace, Lagrange and others during the French enlightenment represented the balance of errors (Wise, 1993). The ordinary least-squares method of extracting signal from noise, published by Gauss in 1809, has been greatly enriched in the two centuries since, but the basic approach is largely unchanged since that time (Sorenson, 1970). Both probability calculus and least squares analysis are central to climate modelling and analysis today. Lagrange introduced techniques of variational calculus that were later developed into the Lagrangian mechanics of climate models. Gaussian statistics remain a staple method for understanding climate and climate change, although stochastic probability analysis methods, based on those developed by Lagrange, are becoming more widely used, especially for exploring nonlinear behaviour (Ghil, 2012).

A further major development was the signal-to-noise concept. Radio research utilised Gaussian statistics in the 1920s and 1930s, extending to radar in the 1940s. Electronic signals were valuable information whereas electronic noise needed to be removed. This value-based way of sorting information into useful and useless has spread into science communication and pedagogy, where valued information is now referred to as the signal and poor information as noise (Pierce, 1980;Ziman, 1991;Norton and Suppe, 2001). This has accentuated the value-laden aspect of the signal with respect to noise, with one being good and the other bad (Koutsoyiannis, 2010).

Climatology adopted the signal-to-noise model in the 1970s, assessing a variety of potential forcing mechanisms and their respective climate responses for past and present climates (e.g., Chervin et al., 1974;Chervin and Schneider, 1976;Hasselmann, 1976). For radiative forcing, the signal to noise (Gaussian) model linearises forcing and response, representing the first law of thermodynamics. For example, global temperature is linearised with forcing using the formula $\delta T = \lambda \delta F$, where T is temperature, F is forcing and λ is a constant related to atmospheric feedback processes (Ramaswamy et al., 2001). This relationship forms the core of a small set of simple climate models that have been the mainstay of uncertainty management and projections provided by the Intergovernmental Panel on Climate Change (IPCC) over most of its history (Houghton et al., 1997). It provides one aspect of predictability described by Lorenz (1975) where initial conditions are fixed but boundary conditions vary according to external forcing. Simple trends are a valid representation of this relationship, but do not represent the whole change process incorporating the other aspect of predictability, initial conditions uncertainty, which is more appropriately represented by complex trends.

Another contributing factor is the evolution of climate models. The earliest versions were relatively simple, so a smooth signal was the only meaningful output. Since then, models have become more complex in their representation of processes and resolution, simulating a wide range of realistic climate variability (Weart, 2008). Despite this, most analytic methods within statistical climatology retain the Gaussian model at their core. Methods have evolved through the incremental development of linear statistical methods rather than introducing and testing new methods that explicitly deal with nonlinearity. Over that time however, climate theory has evolved from linear, additive conceptual models to complex, nonlinear conceptual models (Lorenz, 1975;Hasselmann, 1976;Schneider, 2004). Climate models themselves contain steplike changes in both temperature and rainfall (Jones et al., 2013;Jones and Ricketts, 2015a).

Simplicity (Ockham's razor), familiarity and ease of use are other values attached to the use of trend analysis and related methods, giving them preference over methods of nonlinear analysis. The signal-to-noise concept that treats externally forced and internally generated change independently, continues to dominate climate change research. This includes detection and attribution studies, and the projection of long-term change for a range of variables using time-slice methods and pattern scaling (IPCC-TGICA, 1999, 2007).

Quantitative methods: forecasting

Forecasting and prediction carry high scientific values (Lakatos, 1978;Douglas and Magnus, 2013). Scientific prediction is necessary for assessing model performance, so is an important cognitive value. However, scientific values and the value of forecasts themselves can become conflated in the minds of scientists and the general public if not examined closely. Successful methods within one field are often transferred to a related field if they share similar values and/or methods, however care needs to be taken to ensure the transfer can be justified.

Seamless links between weather and climate forecasting over a range of timescales are a key scientific target (Palmer et al., 2008;Hoskins, 2013). The Global Framework for Climate Services (World Meteorological Organization, 2011), reflects this: *Weather and climate research are closely intertwined; progress in our understanding of climate processes and their numerical representation is common to both. Seamless prediction (on timescales from a few hours to centuries) needs to be further developed and extended to aspects across multiple disciplines relevant to climate processes* (World Meteorological Organization, 2010). The goal of seamless prediction needs to be methodologically and theoretically consistent, which is difficult to achieve. This is partly because of the intersection of initial and boundary conditions issues, which influence the predictability of weather and climate via internal and external conditions (Lorenz, 1975) and are greatest over decadal timescales (Deser et al., 2012).

Solomon et al. (2011) state that *"Long experience in weather and climate forecasting has shown that forecasts are of little utility without a priori assessment of forecast skill and reliability"*. Although there is ample evidence that this assumption is appropriate for weather forecasting and for climate forecasting one season ahead (Kirtman et al., 2013), for multi-year climate forecasts there is little evidence such utility. Missing from this statement, is that although skill and reliability can be calculated from models, the success of multi-year forecasts can only be measured by assessing how useful they have been in reality. The modelling of rational decision making is not sufficiently strong in itself because of the substantial evidence that many other factors affect such decisions (Jones et al., 2014). Rationality cannot be taken as the benchmark of success, as desirable as it may be (Lindblom, 1959).

The available evidence of such success is contradictory, with stories of both success and failure in the limited number of cases where projections have been used and subsequent events have allowed some form of review (Power et al., 2005;Hulme et al., 2009;Jones, 2010). For example, the Melbourne Water Climate Change Study (Howe et al., 2005), produced numerical estimates of linear change and qualitative estimates of nonlinear change. A step change in climate meant that conditions projected for 2050 were encountered by the mid-2000s with conditions approaching crisis levels in 2006. The initial adaptation responses had been based on numerical estimates for 2020 and 2050 and were shown by this change to be inadequate (Jones, 2010). Hulme et al. (2009) argued this as a failure of prediction, however, in hindsight, the qualitative prognosis was more accurate and relevant (Jones, 2010). Feedback from decision makers was that the qualitative estimates were extremely useful and informed subsequent ‘worst case’ scenarios used to update actions after conditions worsened. Both linear and nonlinear projections were provided by the research and the warning that conditions could shift substantially, proved useful in designing a rapid response that (Rae Moran, pers. comm.). The Water Minister at the time when the initial research was presented, John Thwaites, has since told me he would have welcomed the full briefing, rather than the simpler ‘policy maker’ briefing he received.

Alternatively, for south-west Western Australia, early indications from the relatively simple climate models of the time projected regional drying (Pearman, 1988). Given the region was experiencing a prolonged dry period initiated in the late 1960s, major adaptations were put in place that turned out to be highly beneficial (Hennessy et al., 2007). Subsequent analyses shows that the observed rainfall change was step-like and permanent (Li et al., 2005;Power et al., 2005;Vivès and Jones, 2005), so the success was as much due to those who championed that information and encouraged action, as to the information the supported those decisions (Power et al., 2005). The local narrative was supported by observations of a shift or step change, and models have confirmed the direction of change, but not necessarily its abrupt nature (IOCI (Indian Ocean Climate Initiative), 2002). It is now widely accepted as a step change (Hope et al., 2010;Verdon-Kidd and Kiem, 2010;Reisinger et al., 2014).

Decadal forecasting strategies are currently focussed on trend analysis, with plans to assess average trends using climate model ensembles within single climate models and across different models (Collins et al., 2011;Solomon et al., 2011;Meehl et al., 2013). The climate research community is aware that longer term climate forecasts are both an initial conditions and a boundary issue, but has not fully investigated from the end user point of view, whether future trends or event-based forecasts are more useful. Here, theory is critical, because if end users believe that climate change is trend-like, they will ask for trends, if they believe it changes abruptly, they will ask for shifts. They will be guided by scientific advice as to which should be sought.

Historically, the most useful forecasts have been event-based. Less useful are forecasts of trends, which suffer the same issues as economic forecasts (Tilman et al., 2001); usually, they are so general, they fail to identify critical decision points. For example, paraphrasing Wack (2002), most scenarios merely quantify alternative outcomes of obvious uncertainties (for example, global mean warming in 2080 may be 2°C or 4°C). Such scenarios, while useful for bounding uncertainties, are not overly helpful to decision makers.

The ability of climate models to forecast decadal-scale trends with some skill is not in question, but the reasoning used to validate those efforts is circular. The output is valuable because it has skill and because it has skill, it is valuable. Model skill may not be what the user requires most. Ensemble averaging for instance, can estimate how much the climate may change, but not how it will change. If trends are not the main way that climate changes, forecasts may be misleading. Event-based scenarios of plausible shifts in climate would be more useful, and we have been applying these for several years with significant success (e.g., Young and Jones, 2013). Having advance knowledge of shifts, steps and regime changes would be much more useful and work is progressing on improving their predictability (O'Kane et al., 2014;Monselesan et al., 2015).

Delay: recent reinforcement of the trend model

These scientific legacies, however, do not explain why future climate change is still being analysed and communicated as a linear process when the theoretical position remains unresolved. This inertia is almost certainly linked to the defensive stance climate science has taken in response to the manufacture of doubt from contrarian sources (Oreskes and Conway, 2010;Ceccarelli, 2011;Dunlap and McCright, 2011). As stated earlier, by representing a changing climate with linear trends, the method (with its associated cognitive value of gradualism) becomes the (default) theory. The scientifically naïve response is then to expect a gradual atmospheric response to gradual forcing and if that is not the case, the theory is wrong (e.g., Carter, 2006).

This is a form of crude empiricism that demands gradual warming from gradual forcing and if warming is abrupt, it cannot be due to increasing greenhouse gases. On the opposing side, Cahill et al. (2015) and Foster and Abraham (2015) argue that nonlinear responses to gradual forcing are impossible, in order to justify fitting segmented trends to temperature data. By agreeing that radiative forcing cannot cause nonlinear change, the arguments from both sides appear to be mutually reinforcing in an adversarial sense.

Building on this latter point, the claim that because atmospheric warming has stopped trending since the late 1990s, greenhouse theory is falsified, has become a major platform from which to create uncertainty and doubt (Boykoff, 2014;Lewandowsky et al., 2015;Lewandowsky et al., 2016). The defence of long-term trend analysis – defend the trend – has been the main scientific response to this opposition. However, decadal-scale variations in atmospheric temperature cannot be used to falsify global warming theory. The amount of heat added to the atmosphere between 1955 and 2010 is about 3% of the heat added to the top 2,000 m of ocean (Quantities derived from Levitus et al. (2005);Levitus et al. (2012)). No matter what the atmosphere does on these timescales, the climate system is warming regardless (Trenberth and Fasullo, 2013). Trying to explain the full picture publicly becomes problematic, because of the tendency within the general media to reduce explanation to soundbites. Every point then becomes contestable, raising further (unjustified) doubt bringing to mind the aphorism: “I learned long ago, never wrestle with a pig. You get dirty and besides, the pig likes it” (attributed to George Bernard Shaw).

Several opposing claims are being made. One is to claim that anything that is not a trend (i.e., a step, shift or pause) is not global warming and the other is an appeal to reason through the false middle (*argumentum ad temperantium*) or false balance argument (the latter applied to media reporting (Boykoff and Boykoff, 2004)). The first is an argument of dogmatic empiricism – where a cause is supposed to produce a like response; the second, false middle argument concedes some warming, but below the IPCC’s stated range. The third, the false balance argument, allows such claims to be aired as newsworthy opposition to mainstream views, thus giving them more credibility than they warrant.

Efforts to defend the trend has strengthened *H1* as the orthodox scientific position defending climate theory. Most of the scientific argument so far that have been made, have all served to emphasise *H1*:

1. Efforts to detect a physical cause for lower trends, including sulphates from volcanism (Santer et al., 2014), anomalous conditions cooling sea surface temperatures over wide regions such as the north Pacific (Kosaka and Xie, 2013;England et al., 2014), changes in the balance between shallow and deep ocean mixing (Trenberth and Fasullo, 2013) and/or variability associated with decadal-scale processes (Steinman et al., 2015).
2. Reanalysis of regions with poor coverage and overcoming sea-surface marine air temperature discrepancies to produce higher post-1998 trends (Cowtan and Way, 2014;Cowtan et al., 2015;Karl et al., 2015).
3. Contextual arguments stating that some researchers are taking on the opposition’s framing by arguing some form of exceptionalism from trends by using the terms pause or hiatus (Lewandowsky et al., 2015;Lewandowsky et al., 2016).

The first two arguments clarify trends but do not address the steps that exist within the data, so are physically consistent with both *H1* and *H2* but have reinforced the status of *H1*. This is typified by Finnis et al. (2015) who discuss the problem for social science in separating community perceptions of climate variability from the gradually changing signal of climate change, treating *H1* as a received truth. The third argument is based around the premise that post-1998 warming is a routine fluctuation in climate (Lewandowsky et al., 2016), so is reinforcing *H1*. Trenberth (2015) states: “There is speculation whether the latest El Niño event and a strong switch in the sign of the PDO since early 2014 mean that the GMST is stepping up again. The combination of decadal variability and a trend from increasing greenhouse gases makes the GMST record more like a rising staircase than a monotonic rise”, but remains true to there being an underlying monotonic trend. The alternative proposal is that the step-like behaviour is the signal (Jones and Ricketts, 2015a, b).

Discussion: reconciling theory, methods and values

Laudan's (1984) reticulated model of mutual adjustment and justification within scientific paradigms is built on the tripartite arrangement of theory, method and cognitive values shown in Figure 1. The methodological and theoretical narratives describing *H1* and *H2* in that figure are unreconciled. Within the literature, this disparity often occurs in the same paper or chapter (e.g., Kirtman et al., 2013), which as an IPCC report chapter, reflects the broader literature. In that literature, both hypotheses are described as being possible, but the methods in use overwhelmingly self-select *H1* over *H2*.

This incommensurability requires a reconciliation between theory and methods, with cognitive values potentially playing a mediating role. Says Kuhn (1977) "Historically, value change is ordinarily a belated and largely unconscious concomitant of theory choice and the former's magnitude is regularly smaller than the latter's". That seems to be the case here, where theories have changed significantly but some cognitive values (e.g., gradualism) have been retained as a core part of the climate change paradigm. This has hampered the development of methods that would better account for changing theories.

Balance (equilibrium) and gradualism are cognitive values closely associated with the scientific enlightenment. Back then, these values were epistemic and theories were expected to conform to them. The evolution of science to a multistep process of hypothesis, testing and evaluation means has eroded their epistemic status. However, these values remain tightly attached to methods central to climatology, whereas the theory has moved onto disequilibrium, Lorenzian attractors and quasi-periodic regimes (Tsonis and Swanson, 2012;Ghil, 2014;Lucarini et al., 2014;Park and Rao, 2014;Franzke et al., 2015). This confirms that theory change is insufficient to alter a paradigm if the cognitive values attached to the social aspects of those paradigms remain fixed.

Gradualism, as a conservative representation of change, underestimates risk (Jones et al., 2013). If climate change is nonlinear, changing in a series of shifts or regime changes, assessments of future risk will be understated because the greater risk from the impacts of nonlinear change (Tol et al., 2000;Jones et al., 2013). The construct of a hiatus or pause then becomes important because it is a representation of stable periods or regimes punctuated by shifts – it may in fact, be a normal state of climate (Franzke, 2014). It may a "routine fluctuation" as Lewandowsky et al. (2016) suggest, but not in the way they claim. Perhaps the best term is regime, but this remains to be determined by further research. Here, taking the non-orthodox position of explaining hiatus periods can shed light on what remains an unsolved puzzle: how the climate changes on decadal timescales.

Conclusion

Kuhn's definition of a paradigm as "scientific achievements that, for a time, provide model problems and solutions for a community of practitioners" (Kuhn, 1996) can be used to identify gradualism as a governing value that shapes how climate change is conceived, analysed and interpreted. Most quantitative methods used to describe problems and address solutions for climate change utilise a linear signal as a result. This is despite strong theoretical backing and evidence from both observations and models that climate change on decadal timescales is nonlinear.

The epistemological history of science reaching back to the enlightenment suggests that gradualism was applied as a cosmological value to describe natural world in the 17th to early 19th century. It has been particularly influential on physics, the earth sciences, biological evolution and economics. Gradualism later evolved into a cognitive value within the earth sciences, including climatology. Its continued dominance has hampered the development and take up of new methods that address theories of nonlinear behaviour in the climate system.

The history of scientific styles has also been summarised and two further styles affecting earth systems science are proposed, namely systemic reasoning and simulation. Systemic reasoning considers networks, feedbacks and nonlinear response in order to manage interactions that extend beyond simple chains of cause and effect. Simulation is different to experimentation in that it develops mathematical models that visualise a wide range of phenomena potentially involving decision makers. This process extends beyond standard experimentation in a controlled laboratory system to open systems involving interactions between researcher and subject, blurring the distinction between each. Both styles have been developed to understand and manage complex, nonlinear systems.

The main epistemological lesson for science, and especially climatology, is to become more reflexive with respect to theory, methods and values. Especially in terms of recognising and understanding the sociological aspects of science than is currently the case. The gradualist narrative originated within an enlightenment cosmology describing a rational universe (Baker, 2014), has become aligned with mainstream scientific values, but has failed to keep up with developments in theory. This paper supports Laudan's (1984) assertion that the Kuhnian concept of paradigm overturning is not a holistic revolution but is a reticulated process of reconciling theory, methods and values. Understanding how assumptions are being assigned variously to these three elements, instead of responding autonomously to a set of long-standing scientific styles, will aid the scientific effort enormously. A growing body of evidence shows that that on decadal timescales climate change is nonlinear, and is being used to support the proposal that *H2* is a more viable hypothesis than *H1* (Jones, 2015a, b). To paraphrase Kuhn, the development of a model set of solutions to represent nonlinear change and to better characterise risk for decision making, is of the utmost importance.

The history and philosophy of science can play a useful role in how science deals with real-world problems when both the science itself and its real-world outcomes are uncertain. In particular, the tripartite structure of paradigms consisting of theory, methods and values, and their different rates of change show that a scientific community of practice needs to be conscious of how all three affect their thinking in what may be difficult and controversial circumstances.

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