ISSN 1471-0498

DEPARTMENT OF ECONOMICS
DISCUSSION PAPER SERIES

CLIMATE CHANGE: LESSONS FOR OUR FUTURE FROM THE DISTANT PAST

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Number 485
May 2010

Manor Road Building, Oxford OX1 3UQ

Climate Change:
Lessons for our Future from the Distant Past

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May 10, 2010

Abstract

We consider information from many sciences bearing on the causes and consequences of climate change, focusing on lessons from past mass extinctions of life on Earth. The increasing atmospheric levels of the main greenhouse gases are now established, as is their source in human activity. World-wide temperatures are rising on a high variance stochastic trend. Evidence from the past 500 million years provides a major warning: climate change is the main culprit in previous mass extinctions, with several different triggers–humanity is the latest trigger. The different approaches and sources of evidence across so many disciplines make a compelling case. Economic analysis offers a number of ideas, but the key problem is that distributions can shift, making action to avoid possible future shifts urgent. Adaptation ceases to be meaningful if food, water and land resources become inadequate, whereas the first mitigation steps are not costly and should stimulate innovation, creating opportunities as new technologies develop.

JEL classifications: Q54, Q51.
KEYWORDS: Climate change; Mass extinctions; Greenhouse gases; Location shifts.

Contents

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[*] I am grateful to Bob Allen, Chris Allsopp, Dennis Anderson, Tony Beatton, Alok Bhargava, Jennifer L. Castle, Simon Dietz, Neil Ericsson, Karen Florini, Paul Frijters, Bronwyn Hall, John D.R. Hendry, Vivien L. Hendry, Cameron Hepburn, Rick Katz, David King, Paul Klemperer, Katarina Juselius, Grayham Mizon and Nick Stern for numerous helpful discussions and suggestions, and to participants in a seminar at Queensland University of Technology during a visit in 2008. Prepared for *The Political Economy of the Environment*, Dietz, S., Michie, J. and Oughton, C. (eds.), Routledge. The chapter is dedicated to the memory of Dennis Anderson, who stimulated my interest in climate change.

1 Introduction

There seem to be potentially vital lessons from the distant past for our future, especially about how we might interpret present climate change and understand its possible impacts. By the distant past is meant from about 500 million years ago up to the present. As argued by Schmidt and Moyer (2008) and Barker (2008), interdisciplinary science is essential to understand climate change, and requires a genuinely multi-faceted approach that is all too rare in this era of deep specialization. Despite the ever present reminder that fools rush in......, and conceding that the extant literature is vast (see e.g., National Academy of Science, 2008), so a summary may inadvertently distort, this chapter is an attempt to look at a wide range of scientific and economic ideas and evidence that impinge on climate change. Few in academia, government or business seem aware of all the connections between the findings across a multitude of disciplines, but combining all the results should lead to a serious rethink of the potential risks, even by current skeptics. This chapter relates climate change to past mass extinctions of life on Earth, and presents a framework of shifts in the distributions of climatic outcomes as the relevant one for policy actions.

Long-run data from earth drilling, the presence of isotopes from air trapped in rocks, fossils, and shells, evidence of repeated glaciations by the movements of rocks from their sources to present locations, and the formation of coal and oil deposits from tropical forests, all reveal a huge range of past climates from very cold to very hot (see e.g., Hoffman and Schrag, 2000). Clearly, life has survived these great changes, as many species are alive today. Moreover, life has thrived when global temperatures, and associated levels of atmospheric carbon dioxide, were much higher than today: many stable levels can support abundant life. However, *huge numbers have also become extinct in the process of change*, even if long after major climate change, new species evolve and adapt to whatever the environment happens to be: but remember, these might just be bacteria clinging to deep-sea hot vents. Currently the global climate is about 4–5 degrees Celsius above that prevailing at the end of the last ice age, when Manhattan was under a mile of ice, as were most locations at similar northern latitudes. Such a ‘small’ temperature rise has transformed the planet, eliminating many species in the process, including *homo neanderthalensis*. A further rise of that magnitude could effect an equally large transformation on flora and fauna, making many more species extinct, and we cannot preclude that *homo sapiens* would suffer greatly. That would especially be the case if the resulting resource strains led to mass migration, social unrest or even nuclear wars. Thus, it is essential to form as clear a view as possible of the process of climate change, and what–if anything–can be done to alleviate any potentially adverse effects.

Since most of the relevant evidence is of necessity scientific, section 2 addresses the fallibility of scientific evidence in general, and yet its powerful contribution to our understanding of many aspects of the world. Despite the absence of certainty in the scientific approach, genuine knowledge has been acquired. Section 3 discusses the Earth's climate, leading to section 4 on the four key greenhouse gases, how they affect climate, and how humans may affect those gases. With that background, section 5 reviews the great extinctions over the last 500 million years, and the role of climate change in all of them. The processes behind those extinctions are often very different, yet they share many commonalities: all are due to climate change, either cooling or warming, and all are associated with high atmospheric levels of carbon dioxide, some before, some after. Section 6 discusses several of the processes leading to extinctions, and draws some implications for the present from those distant past events. Section 7 then considers seven of the entailed economic issues, and section 8 concludes.

2 Science and scientific evidence

Some of the skepticism about climate change and anthropogenic influences thereon derives from the fact that science is fallible, exacerbated by the criticism that individual scientists are not 'objective', so scientific evidence is not to be trusted. We consider these two strands in turn, and show that the resulting evidence provides genuine knowledge about the world.

It is undoubtedly true that all aspects of any science are uncertain, especially in non-experimental or observational disciplines. Adam Smith might have been the first thinker to propose that even Newton's theory of universal gravitation was not an immutable truth, but a model that might be changed by future astronomers (see Stewart, 1795), a prediction that has since been vindicated, without in any way impugning Newton's great contributions. In particular, empirical knowledge is always open to revision, and is certainly not robust truth. Nevertheless, the history of the scientific enterprise manifests great progressivity, overcoming many intellectual and social obstacles to gain the huge increases in knowledge taken as given today.

Secondly, it must also be acknowledged that not all scientists are totally objective: excessive egos, career necessities, dogmatism blocking publication of critical results by others, and even outright fraud are far from unknown (see e.g., Waller, 2002). For example, to convince the 'establishment', Barry Marshall drank *Helicobacter pylori* to demonstrate that they caused stomach ulcers, followed by a dose of antibiotics to show he had identified the cure. That episode, humorously recounted in Marshall (2005), stresses a key attribute of the scientific process, namely that blockages and even previously undiscovered fraud are often relatively temporary, as the same human forces that create them also motivate others to overturn invalid claims. Research on climate change and the great extinctions of the past must intrinsically draw on dozens of disciplines' expertise, where few individuals can span the entire spectrum of sciences involved. That alone precludes any 'conspiracy' either of ideas, or to bolster funding as many of the subjects will always be in direct competition for research support.[1]

The cumulative weight of evidence gained by trying to refute existing views provides an invaluable basis for current decision making, since scientific knowledge is real: from an endless list, it is obvious that electric lights work, computers calculate, planes fly, and scanners can detect cancers. These have become efficient technologies because of scientific understanding. Rosenberg (1983) showed that initial technological developments often preceded the science, and provided the incentive for the latter: for example, the first airplanes flew well before there was a scientific understanding of flight, and prompted research on aerodynamics. Nevertheless, it is now possible to accurately 'predict' what improvements will increase lumens from lights (see Fouquet and Pearson, 2006, for a fascinating history), what changes to microchips will speed up computer calculations (famously captured by 'Moore's Law'),[2] what putative aircraft will not fly well (e.g., the Spruce Goose?), and why scanners can 'see inside us'. These inferences

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[1] I have been quoted that 'weather forecasters get increased budgets after failing to forecast major storms, whereas economists get their budgets cut when they fail to forecast crises', so have long been in competition for those scarce funds.

[2] That the 'complexity for minimum component costs has increased at a rate of roughly a factor of two per year....Over the longer term....there is no reason to believe it will not remain nearly constant': Moore (1965).

are far beyond any local set of experiments and available evidence, are not purely inductive, and can be generalized, though doubtless within limits. Thus, despite their fallibility, scientific findings have revolutionized the world and its living standards.

In the four cases just noted, a well-based theory was developed, which was in turn both embodied in the general framework of scientific thinking and led to further advances. However, even purely empirical findings can be invaluable. For example, aspirin (acetylsalicylic acid) lowers pain, especially from headaches, and was so used for many centuries before anyone knew how or why it worked. Based initially on 'folk medicine', brewing the bark of the willow tree as a hangover remedy, the active ingredient in aspirin was first isolated in the 1760s, synthesized in the 1850s and manufactured in the 1890s, but how it operated to alleviate pain is a late 20th Century discovery (see Weissmann, 1991).

Nevertheless, even after several centuries of major scientific discoveries and brilliant theoretical insights, there remain huge uncertainties in general about what is possible, why things are the way they are, and what can happen. Such a statement applies forcefully to our knowledge and understanding of climate change, but does not entail that all views are equally valid: we now know a great deal, and some implications are all too clear, as we now discuss.

3 Earth's climate and its atmosphere and oceans

A complex series of interactions seems to drive the climatic process, which can make it difficult to discern the causes of climate change. We first note two possible natural drivers of change, then consider the Earth's atmosphere and its oceans.

The sun may be warming endogenously, possibly for the last few millennia, with local fluctuations manifested by sun spots, and has clearly warmed substantially over geological time. But in recent decades, that effect is not large (see UK Met Office, 2008). Also, the Earth may still be warming on a natural 'bounce' common in interglacial stadia, following the end of the last ice age, just from the removal of the factors that cause ice-age cooling (reduced albedo, changes in tilt, etc.). The temperature impacts of both factors can be inferred within reasonable bounds from ice-core drilling records extending back for half a million years.

The atmosphere itself is a complicated process exhibiting surprisingly slow mixing between layers, and even with differential warming and cooling in different layers and at different latitudes. Temperature falls with height through the Troposphere till the Tropopause (somewhat above the height of Mt. Everest at 10,000m), stays relatively constant till the Ozone layer, then rises through the Stratosphere (50,000m), pausing before falling in the Mesosphere (to about 80,000m), then rising in the Thermosphere (where Aurora are observed). Again, the evidence is robust, these forces are fairly well understood and can be incorporated in analyses and models.[3] Earth's gravity and its magnetic field together are essential to 'hold on to' our atmosphere against the solar wind, and our ozone layer provides protection from damaging radiation.

Atmospheric gas constituents have changed greatly over the history of the planet, especially with the exchange of carbon dioxide for oxygen through photosynthesis, and may have altered considerably over the period considered here, as discussed in section 5. The central role of greenhouse gases and how they may affect climate is discussed in section 4, but it is clear that an atmospheric blanket is essential to life. National Academy of Science (2008) provides a clear explanation of why the Earth would be a frozen ball without a dense atmosphere, and provides an excellent picture of how greenhouse gases receive

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[3] Weather is affected by many factors that are hard to forecast over weeks ahead. The jet stream appears to have changed location over the last half century, perhaps both cause and consequence of climate changes, but its location is not easily forecast. El Niño and La Niña Southern Oscillations both greatly alter weather conditions over shorter time scales, as do major storms, and volcanic eruptions, etc., with possibly more eruptions as the polar ice melts.

and radiate at different wavelengths between ultraviolet and infrared, as well as their recent relative importance.

Mars and Venus are planetary neighbours whose climates have diverged horribly, now respectively being cold with a thin atmosphere and boiling with one that suffered from a runaway greenhouse effect. Atmospheric protection needs to be ‘just right’, albeit within a range that has included both world wide ice ages and tropical conditions. We conclude that the physics of radiation from greenhouse gases is well understood, as is the role of the atmosphere in sustaining life on our planet.

Next, there is a worldwide ocean ‘conveyor belt’ system whereby cold water is mixed with warm to carry oxygen to depths and circulate nutrients. As warm water from the Gulf Stream moves north, it cools and evaporates becoming more salty and hence denser, so eventually sinks and flows south again, passing by Antarctica, then gradually warming and rising to the surface as it travels north across the Pacific Ocean. From the Pacific Ocean, warm water flows south and crosses the Indian Ocean, then moves north and cools once more. Global warming may affect and slow down these ocean conveyor belts with potentially mixed outcomes (e.g., Northern Europe may cool and North America warm). While stable over most of the Holocene era (the last 10,000 years), larger longer-term variations have occurred (see Tziperman, 1997), and must have accompanied tectonic plate movements. As seen below, altering the flows of oxygen and nutrients round the planet can disrupt many species.

Thus, the key ingredients of the climatic picture are understood. Before we can ask if climate is changing, we must consider the four main greenhouse gases in more detail.

4 Four greenhouse gases

Greenhouse gases are crucial to life on earth, as they are fundamental to maintaining the planet’s temperature within limits supportive of life. There are four important greenhouse gases: water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4). The last two gases have carbon dioxide equivalents, discussed below. All of these greenhouse gases are presently increasing at different rates, and are likely to alter their relative impacts in the future.

The physics of greenhouse gases are quite well understood, and date from insights starting in the late 19th century (see Arrhenius, 1896, who argued that atmospheric temperature change was proportional to the logarithmic change in CO_2). Heat enters the earth’s atmosphere from the sun as radiation, warms the surface, then is re-radiated back through various atmospheric layers where greenhouse gases absorb some of the heat. This is then re-radiated, with some radiation therefore directed back towards the planet’s surface. Thus, greater concentrations of greenhouse gases increase the amount of absorption and hence re-radiation. In turn, that increases convection between the surface and sequentially through atmospheric layers, raising their temperatures and water vapour content, thereby changing cloud cover. Only a sophisticated general ‘equilibrium’ model of the system can capture the many complicated interactions and interdependencies between all the components. We now consider the four gases in turn.

First, water vapour is currently the most important and prevalent of the greenhouse gases, and is obviously crucial to life on earth, inducing cloud cover and rainfall etc. However, increased concentrations of water vapor in upper levels of the atmosphere would reduce heat loss from radiation.

Second, carbon dioxide is also key to life, and like water vapour has been a major greenhouse gas long before the evolution of modern humans. The present half-life time of CO_2 in our atmosphere is 30–100 years, depending on factors like ocean absorption capacity and plant growth (see e.g., Lovelock, 2000). There is roughly a 30-year lag between emissions and their full effect on warming. Naturally, many other factors can impinge, some leading to cooling effects, such as particulate matter emissions from industrial activity and volcanoes (e.g., the 1815 AD eruption of Tambora leading to 1816 being ‘ the year without a summer’: see Stommel and Stommel, 1979), as well as aircraft vapour trails and changing cloud cover, La Niña, etc. Other factors lead to warming, such as re-release of CO_2 from the oceans as they warm.

Third, nitrous oxide comprises about 7 percent of gases influencing global climate. Measures suggest it is about 300 times more potent than carbon dioxide as a greenhouse gas. In addition, following the reductions in CFCs,[4] nitrous oxide is now the most potent destructive force attacking the ozone layer (see Ravishankara, Daniel and Portmann, 2009).

Fourthly, methane is about 20 times as powerful as CO_2 as a greenhouse gas, albeit that its half-life in the upper atmosphere is about 15 years. Methane gradually gets converted to CO_2 in the upper atmosphere so has a second effect on climate. Present estimates of the total volume of methane already show it is vast: worldwide, the amount of methane gas hydrates alone is estimated at over 6 trillion tonnes–about twice the amount of carbon equivalent in all fossil fuels.[5]

4.1 How we affect the four greenhouse gases

Anthropogenic effects on climate from greenhouse gases seem to date back to the origins of agriculture around 10,000–12,000 years ago (see e.g., Bellwood, 2004), beginning at the end of what is called the Weichsel glacial period,[6] and the start of our (Holocene) era. This was followed by pottery and domestication of animals, with a rapid rise in population and land clearance, leading to increased outputs of CO_2. Carbon dioxide output increased greatly during the industrial revolution, and is now mainly due to power generation from fossil fuel consumption, primarily coal, gas and oil, exacerbated by tropical deforestation.[7] As living standards rise and population growth is non-negative, 'business as usual' projections would lead to sustained growth in CO_2 emissions.

Nitrous oxide output has doubled since the 1970s, mainly from modern agricultural practices and burning gasoline (see Energy Information Administration, 2008, for US data). Catalytic converters in car exhaust systems break down the heavier nitrogen compounds, as well as oxidizing carbon monoxide, forming CO_2 and nitrous oxide in the process, producing more of the latter when the exhaust system is cold or stressed. Fertilizer overuse leads to run-off and the release of nitrous oxide: as Ravishankara *et al.* (2009) show, nitrous oxide is becoming an increasing component of greenhouse gases.

Methane is produced by living plants and animals as a by-product (e.g., cattle), and also by rotting vegetation. If warming substantially melts the Siberian permafrost, greenhouse gas output could jump. Already, at any lake in northern Siberia, drill a hole in the ice to fish, then hold a flame over the hole–but jump back to avoid being burned by the methane catching fire. That is one of several possible 'tipping points', including general release of subsea methane hydrates, and a collapse in rainforest ecology through changes in rainfall patterns.

4.2 Some evidence of our impact

There is a long list of evidence for a world-wide temperature trend.

Many plants flower in spring in both hemispheres about 2-3 weeks earlier than when accurate, reliable, and almost continuous, records began about 1850. Satellite pictures confirm the melting of the

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[4] Chlorofluorocarbons, including halons and other man-made halocarbons.

[5] Gas hydrates are crystalline solids similar to ice, where the building blocks are a gas molecule surrounded by a cage of water molecules, which acts as 'cement' for methane. The breakdown of one unit volume of methane hydrate at one atmosphere produces about 160 unit volumes of gas. All hydrates become unstable as the surrounding temperature rises, but most are in sediments too deep to respond rapidly at present. Conversely, finding a catalyst that inexpensively bound any of the greenhouse gases into hydrates would be invaluable.

[6] named after the Polish river Weichsel

[7] The weight ratio of CO_2 produced per octane molecule burned is roughly 3 to 1–roughly a ton of gasoline produces 3 tons of CO_2–as carbon atoms in hydrocarbons are mostly attached to light hydrogen atoms, and when the octane is burned, attach to oxygen which produces heavier CO_2.

Greenland and Antarctic ice shelves over the last 30 years, with concomitant rises in ocean levels of between 0.1 and 0.2 meters during the 20th century, partly offset by increased storage in dams. Evidence of warming of many parts of the oceans is associated with bleaching of some coral beds. Most directly, global air temperatures over the last century reveal that most of the warmest records occur in the latest decades, based on data collected sufficiently far from cities to avoid contamination from 'local warming'.

The resulting world-wide temperature 'trend' is both stochastic and slow relative to fluctuations from all sources, so it is easy to be skeptical about that trend and its rate of progress. As a related example, until recently, it was believed there had been essentially no growth in English gross domestic product (GDP) per capita over 1300–1700, because real wages seemed static. However, Apostolides, Broadberry, Campbell, Overton and van Leeuwen (2008) have shown that real growth was 0.13 to 0.16 per cent per annum. That is tiny against the huge fluctuations caused by the Black Death, famines, wars and so on, and therefore such a trend is hard to detect. Nevertheless, by nearly doubling living standards over 400 years, was a precursor to the Industrial Revolution from the resulting high cost of labour as documented by Allen (2009). Moreover, some 'counter arguments' are invalid, including the claim in the *Australian* that there was 'little world temperature growth from 1998 to 2006' (July, 2008): an economics student who selectively joined the peak of one boom to the trough of the next slump and claimed that proved there was no economic growth would be failed.

It is change in the climate, rather than the level within bounds, that causes problems for life, because adaptation is not instantaneous, as the following discussion of 'great extinctions' emphasizes.

5 Climate change and great extinctions

The fossil record suggests that there were a number of major extinction events even before land life evolved. One in the pre-Cambrian era, about 600 million years ago (abbreviated to mya) was so severe that almost all micro-organisms were wiped out. A probable explanation was large scale glaciation, which is the opposite form of climate change to global warming. Next, the Cambrian seems to have witnessed 4 major marine extinctions, possibly due to global sea cooling leading to oxygen depletion.

There have been five other 'mass extinctions' in the past 500 million years when many of the world's life-forms ceased to exist. Of these, the first mass extinction came at the end of the Ordovician period, roughly 440 mya. The second, around 375 mya, occurred near the close of the Devonian era. The third, and worst, was at the Permian–Triassic (P/Tr) boundary, about 250 mya, and eliminated 80-90% of ocean dwellers and about 70% of plants, animals, and insects (see e.g., Erwin, 1996, 2006). The fourth extinction at the end of the Triassic, about 200 mya, opened an ecological niche for dinosaurs to emerge as a major fauna in the Jurassic. The fifth major extinction was at the well-known Cretaceous–Tertiary (K/T) boundary, roughly 60 mya, when a major lineage of dinosaurs called saurischia went extinct (all dates rounded for simplicity).

The science behind much of this dating has led to scanners, so there is no reason to doubt the occurrences of these extinctions. The key issue to which we now turn is whether, and to what extent, climate change was involved.

After a quarter century of searching for evidence, many palaeo-archeologists, paleontologists, palaeo-climatologists and palaeo-biologists seem to have concluded that of these five, only the K/T boundary extinction could plausibly be attributed to extra-terrestrial forces alone, probably a meteor impact. This left two visiting cards, namely, traces of iridium in rocks separating dinosaur from mammalian eras, and the Chicxulub impact crater near the Yucatan peninsula. Even so, volcanism may also have played a role.

The remaining four 'great extinctions' seem due to global climate change from endogenous changes on earth. The first mass extinction at the end of the Ordovician is currently viewed as due to global cooling. So is the second, at the end Devonian, possibly due to the rapid spread of plant life on land reducing atmospheric CO_2 by photosyntheis.

The third, and worst, extinction event at the Permian–Triassic boundary is associated with the formation of flood basalts on a massive scale from prolonged volcanic eruptions, technically a large igneous province (LIP). These often form layered hills looking a bit like stairs, called Traps. The LIP in Siberia covered more than 2 million square kilometers. Temperatures seem to have ended about 6°C higher than today. Gas hydrates are a possible cause of this 'Great Dying', especially methane and carbonates released from relatively shallow seas by the formation of these Siberian Traps. Heydari, Arzani and Hassanzadeh (2008) attribute the mass extinction to huge releases of marine gas hydrates. Direct outpourings of magma into oceans may also have perturbed their deep levels (see e.g., Ward, 2006), as undersea volcanism can lead to oceanic oxygen deficiency when LIPs disrupt the ocean conveyor belts (see Bralower, 2008). The resulting anoxia could have supported an explosion in bacteria that produce hydrogen sulfide. Ocean circulation may also have slowed or even stopped from a lack of ice at the poles. While that initially affects marine life, carbon dioxide dissolves more in cold water, so as water warms, it is released (as in sparkling water), sometimes by an overturn of water that releases huge volumes of carbon dioxide. Once released, carbon dioxide is about 1.5 times more dense than air so remains at ground level. Lake Nyos (a crater lake in the Northwest Province of Cameroon) is an example of the dreadful effects of the release of large volumes of carbon dioxide.

The fourth extinction at the end of the Triassic remains the most disputed, but is possibly also due to a massive LIP forming (the Central Atlantic Magmatic Province). The extinction may again have been due to excessive CO_2 from the catastrophic dissociation of gas hydrates inducing intense global warming, or possibly from sulfur dioxide leading to cooling. There is also some evidence near the Triassic–Jurassic boundary of a rise in atmospheric CO_2.

The fifth extinction at the K/T boundary is also associated with the formation of another LIP, called the Deccan Traps in India, where magma was extruded over a prolonged period, covering approximately 100,000 square kilometers by roughly 160 meters deep, with temperatures that were about 4°C higher than today (see Prothero, 2008, for an evaluation).

Based on the fossil record for the last 520 million years, Mayhew, Jenkins and Benton (2009) show that global biodiversity for both terrestrial and marine environments was related to sea-surface temperature, with biodiversity being relatively low during warm periods (also see Clarke, 1993).

Thus, climate change is a cause in every case: excessive warming or cooling have both led to large-scale species extinction on Earth.

6 Possible processes causing mass extinctions

There are many possible processes causing mass extinctions and we will consider several of the most likely, before linking these to the ongoing changes in Earth's atmosphere.

One hypothesized mechanism for the warming extinctions being so drastic is that the chemocline between oxygenated water above and anoxic water below rose with temperature (see e.g., Riccardi, Kump, Arthur and D'Hondt, 2007). When the chemocline reached the surface, archaea and anaerobic bacteria, such as green sulfur bacteria, proliferated and generated vast quantities of hydrogen sulphide (H_2S), with toxicity comparable to hydrogen cyanide. There is carbon isotopic evidence for the chemocline's upward excursion during the end-Permian extinction, with a large increase in phototrophic sulfur bacteria replacing algae and cyanobacteria, consistent with huge loss of ocean life. As with CO_2, hydrogen sulfide is heavier than air, so has a tendency to accumulate on the surface, although H_2S also attacks the ozone layer if driven to the upper atmosphere by volcanism, reducing protection from solar radiation.

The recent behaviour of the Black Sea is an indication of how fast a switch in the chemocline can happen, with the anoxic layer reaching the surface, albeit that it was probably due to excess nitrogen and phosphates from run-off, not global warming *per se* (see Mee, 2006). Fortunately that problem is now stabilized, but the eruption of sulfur bacteria round China's southern coast just before the 2008 Olympics is another example.

A second mechanism is the growing mis-timing of annual breeding cycles of many species, especially birds and amphibians: usual birth times move increasingly out of synchrony with times at which the necessary food supplies are maximal, and some species numbers have plunged. Others, of course, do well–wasps are now found in Alaska, and some tundra is greening (see e.g., Sturm, 2010), but insects and diseases may also spread.

Since all the great extinctions seem due to global climate change, albeit from possibly different causes, and since greenhouse gases lead to temperature changes, what is the evidence for the accumulation of CO_2 equivalents in the atmosphere? The records collected at Mauna Loa in Hawaii by Charles Keeling starting in 1958, show an unequivocal upward trend, with large seasonal variations around it. For a recent graph showing the increase in CO_2 levels from the low 300 parts per million (ppm) to near 400ppm since 1958, see Scripps CO2 Program (2010). Levels of 172-300 ppm are found in deep ice-core data over the past 800,000 years (see Lüthil, Le Floch, Bereiter, Blunier, Barnola, Siegenthaler, Raynaud, Jouzel, Fischer, Kawamura and Stocker, 2008). Moreover, Loulergue, Schilt, Spahni, Masson-Delmotte, Blunier, Lemieux, Barnola, Raynaud, Stocker and Chappellaz (2008) establish that methane concentrations in the atmosphere are double relative to the levels seen over that time scale, and also show that 'strong correlations of methane and CO_2 with temperature reconstructions are consistent back 800,000 years'. Weart (2010) provides an excellent history of the discovery of global warming.

How can we be sure human activity is responsible? Here is how. Keeling's records reveal that the seasonal surge in CO_2 coincides with Northern Hemisphere winters when more fossil fuels are consumed. There have been trend increases in our use of fossil fuels and in deforestation. Since Suess (1953) it has been known that radioactive isotope carbon-14 is created by cosmic rays in the upper atmosphere hitting CO_2 molecules, after which the radioactivity gradually decays. Since coal and oil deposits were laid down hundreds of millions of years ago, their radioactivity has dissipated, so carbon dioxide released by their burning lacks this radioactive isotope. The changing ratio of the isotopes of carbon detected in the atmosphere would point directly at anthropogenic sources. Unfortunately, atmospheric nuclear explosions have radically altered that ratio, making it inapplicable as an indicator of human fossil fuel consumption. However, the ratio of another heavier isotope, carbon-13, relative to carbon-12 in atmospheric CO_2 is also larger than its ratio in fossil fuels, and is not affected by nuclear tests. Consequently, if additional CO_2 output is due to burning fossil fuels, the ratio of carbon-13 to carbon-12 should be decreasing–as is occurring.

Oceans can probably absorb more CO_2–but with adverse effects for marine life (see Stone, 2007): acidification slows the growth of plankton and invertebrates, which are basic to the ocean food chain. Lower pH levels could prevent diatoms and coral reefs from forming their calcium carbonate shells (e.g., just from lowering the current pH level of 8.1 to pH of 7.9). Moreover, while oceans rapidly absorb CO_2 initially, much is evaporated straight back into the atmosphere (think sparkling water left unsealed), and while later recycled, takes a long time before much is stored in deep ocean layers.

Ward (2006) shows that the extinction at the K/T boundary began when atmospheric CO_2 was just under 1,000 ppm, and the extinction at the end of the Triassic when CO_2 was just above 1,000 ppm. If the Earth warms up enough to melt the permafrost in Siberia's tundra and under the Arctic Ocean, or other factors of which we are as yet unaware, lead to a sudden increase to the equivalent of 1,000 ppm, the jump in global temperatures could be essentially uncontrollable. To build on a familiar analogy, if you are unsure whether a basket covered with a cloth really has a solid base, be concerned about putting all your eggs in it. Which leads us to economics.

7 Economics of climate change

There remain uncertainties about many aspects of climate change from its long-run history, present evidence, theories of re-absorption of greenhouse gases and relevant models. Nevertheless, understanding that there may be serious risks to many life forms on earth should make us think very carefully about the economics of climate-change abatement as argued in Stern (2006) and Schneider (2008), and addressed in this section. Tol (2009) provides a relatively optimistic survey of the economics, which claims there are 'no more unknown unknowns', whereas the special issue edited by Helm (2008) is more pessimistic (e.g. p.236): 'The science suggests that it is probably more likely than not that rapid climate change will result later in the century with potentially quite catastrophic results.'

I discern seven important issues facing economics, related by climate change externalities needing to be either priced or regulated:
(1) the consequences for economic analyses of shifts in distributions;
(2) risk perceptions and attitudes to anthropogenic effects on climate;
(3) how to evaluate the future costs of climate changes and possible benefits from mitigation;
(4) designing mechanisms, permits and auctions to mitigate greenhouse gas emissions;
(5) global negotiations about emissions abatement;
(6) intellectual property rights and prizes for new technological investment; and
(7) modelling and forecasting climate change and reactions to any resulting price and income changes.
These seven issues are addressed in the following sections, linked in an analysis where sudden change is not just a more rapid version of gradual change. If sudden large changes can occur, consistent with the evidence from past great extinctions, different forms of analysis are needed, as we now show.

7.1 Shifts in distributions

A stationary variable is one whose distribution never shifts, so it has the same mean, variance and distributional form today as in 1066 AD. There are few such processes in economics. All other processes are non-stationary, in that some aspect of their distribution has changed over time.

There are two main sources of non-stationarity. The first is called a 'stochastic trend', where many small effects cumulate over time, altering the location of a variable and leading to an increasing variance relative to an initial period as time passes. Because such variables cumulate shocks, they are called 'integrated' time series, and their changes (first differences) then become stationary. Equity prices are classically regarded as integrated, with first differences that are random.

The second form of non-stationarity is due to location shifts in the mean (or variance). GDP growth per capita has experienced many such shifts over the last millenium–fortunately mainly upwards to date, as described in section 4.2.

There are important differences between a 'fat-tailed' distribution, where some very large outliers can occur, and a shift in the mean of a distribution, or its variance. A 'heavy-tailed' distribution (like a Pareto distribution) has even higher chances of very large outcomes, usually in one direction. Weitzman (2009a, 2009b) argues that: 'climate sensitivity is so uncertain at the upper end [that it] contains within itself a generic argument in favor of a very fat upper tail of temperature changes'. Dietz (2009) provides an empirical assessment of the likely economic costs from 'tail risks' to climate by perturbing integrated climate models for various parameter values, and concludes that time preferences matter even for substantial global consumption losses: Section 7.3 considers intertemporal evaluation. Katz (2010) discusses analyses of climate change, as well as their potential economic consequences, when allowing jointly for both non-stationarity and fat-tailed distributions, but favours the latter.

One cannot get too many extreme outcomes (say 25 standard deviation draws), especially in succession, as distributions must integrate to unity. However, one can have very many draws that are extreme relative to the original distribution's standard deviation if the original mean m_0 shifts to a new value m_1. Figure 1 illustrates this situation.

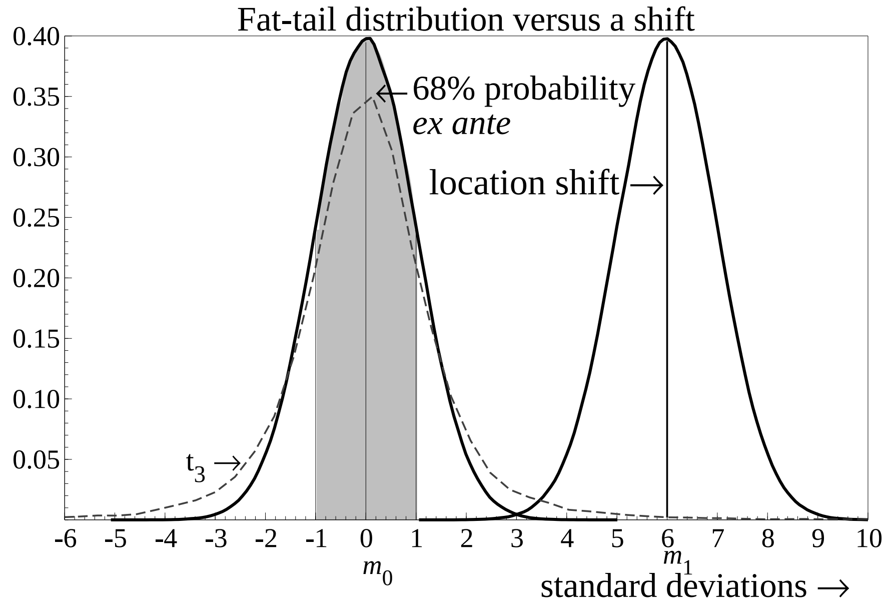

Figure 1: Mean shift in a probability distribution

The fat-tailed distribution in Figure 1 is a Student's t distribution with three degrees of freedom, denoted t_3. This distribution has a mean of zero and a variance of 3, but no other finite moments, so generates many outliers, as shown by the wide range of its distribution in Figure 1 (see e.g., Johnson, Kotz and Balakrishnan, 1995). Even so, there is a low probability of (say) 6 standard deviation draws, which become commonplace after the mean has shifted to 6. The combined distribution before and after the mean shift is bimodal (multi-modal after many shifts), with a much larger standard deviation, so still integrates to unity *ex post*. Climate change will not be a reversible draw that, once past, returns to the previous mean of the distribution–it will stay for millennia. The extinction of a species may be due to a large outlier, but changes the numbers of that creature forever. An appropriate method of analysis requires allowing for mean shifts of unknown magnitudes and timings, namely a non-stationary process.

Unfortunately, there also seem to be a number of potential 'tipping points' where rapid change occurs. These include ocean acidification leading to anoxia; slowing of the ocean conveyor belts; and melting of the tundra and the arctic ocean seabed releasing large volumes of methane. Thus, shifts in the mean seem likely to alter the probability of extreme events, since temperature rises lead to tipping points being reached.

Now economics faces really serious analytic problems: the very statistical theorems on which inter-temporal theoretical calculations rely also fail. As shown in Hendry and Mizon (2010), conditional expectations made today of an uncertain outcome tomorrow cease to be either unbiased or the minimum mean square error predictor when mean shifts occur. Moreover, the law of iterated expectations, namely that the expectation today of the conditional expectation tomorrow equals the unconditional expectation tomorrow, does not hold.

In a sense, it is obvious that such theorems fail when means shift, because the relevant integrals are over different distributions. However, their failure removes the applicability of most inter-temporal theory from precisely the situation when it is most needed, specifically when the world changes. If economists wish to make reasoned contributions to climate change policy they must urgently address this serious problem and develop modes of analysis that are valid despite mean shifts.

7.2 Risk perception and attitudes

Risk perceptions and attitudes to anthropogenic affects on climate are important if there is a potentially serious problem looming. Since democratic policy making requires public support, how the risks from climate change are perceived affect policy implementation.[8]

There is considerable evidence that people cannot accurately evaluate risks in many arenas of life (see e.g., Gigerenzer, 2002). For example, few are aware of the relative risks of travel modes such as cars, planes, trains, ships, bicycles, walking etc. per passenger mile travelled: most know that air travel is relatively safe, but many wrongly believe driving and walking are also relatively safe, and almost no one seems aware that cable cars are among the safest forms of transport per passenger mile travelled, rather most people incorrectly believe that cable cars are highly risky.

Realistic assumptions about climate change are that individuals do not have well-defined, complete orderings over all necessary choices as a basis for utility maximization. They also have incomplete knowledge about the process, its timing and its consequences. Certainty equivalence is not a viable basis for decision taking when distributions of events are essentially unknown. Thus, one must consider recent ideas from behavioural economics such as ‘cognitive dissonance’ (Festinger, 1957) and ‘prospect theory’ (Kahneman and Tversky, 1979). Economic actors may take anticipated regret into account when making decisions as suggested by ‘regret theory’, leading to ‘inaction’ biases (Butler and Loomes, 2007).

Behavior may be rather different from that predicted by conventional economic analyses, absent an all-knowing self-maximizer operating devoid of the social context, but facing potentially huge global externalities. Brekke and Johansson-Stenman (2008) is an ambitious attempt to apply ideas from behavioural economics to understand the economics of climate change, including risk perceptions, attitudes to anthropogenic effects on climate, negotiations about climate abatement, and how to evaluate intertemporal comparisons. We next consider that last aspect.

7.3 Intertemporal evaluations

Money today is more valuable than money next year, but by how much? The classical answer is that a discount rate of (say) 5% suggests \$100 next year is worth 5% less than \$100 now, namely \$95. Two year’s ahead, \$100 would be worth only \$90.25 now. Alternatively expressed, impatience entails that individuals will accept \$95 today in exchange for paying \$100 next year.

In the Nordhaus (2008) critique of Stern (2006), the appropriate size of the discount rate to evaluate future climate change damage played an important role in the economics discussions. However, the resulting analysis implicitly assumed that the situation was relatively stable and slowly evolving. If sudden large changes can occur, such a debate may divert attention from some key issues.

As Stern (2008) argues, analyses need a ‘different discount rate for each possible sequence of outcomes.’ Yet those sequences are also endogenous to the choice of discount rate (see e.g., Dietz and Hepburn, 2010). The important intertemporal evaluation problem is somewhat like a reverse ‘St. Petersburg paradox’. In the original form, a fair coin is tossed until a head appears, and you receive $\$2^{n-1}$ if the head first comes on the n^{th} toss. That event has a probability of $(1/2)^n$ of happening, so your expected payment, adding up the product of each event’s payment times its probability, is infinite. Thus, you should pay an infinite amount to enter the game. In practice, few people would willingly pay even \$50 to enter. The paradox was supposedly resolved by using the expected utility of money, rather than the expected amount of money, because marginal utility falls as the amount of money increases. When distributions shift in unknown ways, however, those expectations cannot be validly calculated. A different ‘solution’ is needed to evaluate what we should willingly pay to avoid a future catastrophe than

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[8] Major re-insurers worrying about the changing probabilities of extreme events and catastrophes are an indication of the growing awareness of possible risks.

‘discounting’ the costs to the present.

A possible analogy is that of being in a car at the top of a road down a very long hill, with a cliff at the end, an unknown distance away and of an unknown drop. The car starts slowly down the hill, gradually accelerating, when you discover that there are no brakes to slow or stop it. Since it will be a long time before the car falls off the cliff, do you:
(a) seriously ‘discount the future’ to decide when to jump later,
(b) hope that a rescue will somehow appear (e.g., there is a ‘runaway truck ramp’ at some point), or
(c) jump out now when you may survive given the present speed?
Here my cliff is the potential for mass extinction, which would seriously affect humanity and its present form of civilization if mitigating action is too delayed. Jumping corresponds to taking sensible action in the face of the evidence. The level of the ‘discount rate’ is hardly the key consideration for making this particular inter-temporal evaluation.

Portfolio diversification suggests taking some actions now not leaving–literally–all the world’s eggs in one basket. Many of the first steps could actually improve living standards yet reduce greenhouse gas emissions, such as mandating more efficient car engines within already known technologies, and better house insulation. The next issue, therefore, is to create the right incentives to do so.

7.4 Mechanism design, permits and auctions

We briefly consider three mechanisms, namely markets, permits and auctions, that might help create the correct incentives for mitigation.

Designing market mechanisms in general, and creating schemes to mitigate greenhouse gas emissions in particular, are both large literatures: see (e.g.) Roth (2002) for the former and Klemperer (2009) for the latter. Careful analyses are essential to ensure that incentives to reduce pollution are correctly aligned, are relatively accurately costed, do not create a ‘substitution’ to the least regulated or cheapest areas, nor undermine living standards, and yet protect the poorest sections of society. These are demanding, but not infeasible, requirements.

As the world economy emerges from the financial-crisis induced sharpest downturn since the Great Depression, there is a potential role for modern finance theory in designing options and permit trading, despite their reputation as ‘weapons of financial mass destruction’. Given a long-run emissions target, say, McKibbin and Wilcoxen (2002) propose that a fixed number of long-term permits be issued, designed to rise in value as carbon prices rise, and so could create balance sheet value to offset current increased abatement costs.

The theory of auctions also has an important role to play in the design of effective carbon trading schemes (see e.g., Milgrom, 2004). As shown by Klemperer (2002) and Binmore and Klemperer (2002) for the various different G3 telecom auctions, auction design can have a huge impact on the realized outcomes.

7.5 Negotiations about emissions abatement

There are many precedents of direct relevance to agreements about emissions reductions.

First, the various ‘Clean Air Acts’ led to consequential reductions in air pollution, especially smogs, but at the time (UK, 1956; various times in other countries) were accompanied by protests about the lack of smokeless fuels and their high costs. Garnaut (2008) argues that seeking a climate change agreement creates a ‘prisoner’s dilemma in international collective action’ (really a free rider problem). However, that only holds for countries small enough not to affect the world’s or their own climate in a way harmful to themselves. Many countries separately legislated on clean air, as well as on the next precedent, namely acid rain, for that reason. For example, Chatterji and Ghosal (2009) suggest that unilateral commitments combined with technology transfers could lead to cumulative emissions reductions.

Second, growing and high levels of acid rain due to sulfur dioxides (SO_2) prompted legislation for their reduction in an effort to save increasingly acid lakes and dying forests, based on a cap and trade system in the US. Even that move faced serious coordinated opposition despite the huge potential environmental benefits: see Dumanoski (1987), writing three years before the bill's passage.

Third, CFCs were initially believed to be inert, but were later found to be causing destruction of the ozone layer from release of their chlorine by solar radiation. A phased reduction and elimination of their use was agreed rapidly in the *Montreal Protocol*, signed in 1987, supported by a 'Multilateral Fund' to help developing countries adjust, one of the world's first global environmental funds with about $160 million to speed up the phasing out. The ozone layer appears to be recovering slowly. Unfortunately, the replacement gases, hydrochlorofluorocarbons (HCFCs), and hydrofluorocarbons (HFCs), seem to be highly problematic as greenhouse gases. Molina, Zaelke, Sarma, Andersen, Ramanathan and Kaniaru (2009) propose building on the *Montreal Protocol* to mitigate that growing problem.

In each case, there were objections at the time of the potential high costs of abatement–yet in no case has there been a notable impact on any country's GNP from solving those problems. Indeed, there were both beneficiaries in new industries as well as losers in old. The first two cases were usually domestically driven in a range of countries, but the third was explicitly an international agreement, as may be needed for climate change.

Thus, can we hope to forge the requisite international agreements? A partial answer follows.

In his *Theory of Moral Sentiments*, Adam Smith (1759) argued that humans act reciprocally and expect others to treat them likewise. In evolutionary terms, humanity may have survived because distant ancestors had a propensity to trade, barter and share, unlike many primates. His most famous phrase, the '*invisible hand*', first appeared in the *Sentiments*, and his better known *Wealth of Nations* was probably written as an attempt to reconcile his views about natural fellow feeling ('sympathy') with the apparently self-interested behaviour of economic actors: "Man has almost constant occasion for the help of his brethren, and it is in vain for him to expect it from their benevolence only..... It is not from the benevolence of the butcher, the brewer, or the baker that we expect our dinner, but from their regard to their own interest. We address ourselves, not to their humanity but to their self-love." (Smith, 1776, Chapter 2). In practice, most bakers probably provide fresh unadulterated bread, not just from 'self-love' and a rational investment in their future business, but also taking account of how they expect others to treat them. Negotiators committed to resolving the climate change problem need to augment self-interests with fellow feeling, as reinforced by modern findings about reciprocity and trust in (e.g.) Fehr, Fischbacher and Kosfeld (2005) and Gintis, Bowles, Boyd and Fehr (2005).

An altogether different, but related, precedent is international agreement on the United Nations Convention on the Law of the Sea, signed by most major countries (but not ratified by the US). Thus, although international climate-change negotiations will be far from simple, there is hope: see Sebenius (1991) and Barrett (2003).

7.6 Intellectual property rights and prizes

Intellectual property rights are one approach to creating incentives to develop ideas into outcomes. Hall and Helmers (2010) show that they often provide an incentive to produce both large and small technological innovations in response to climate change, although patent rights may also limit the diffusion of new technologies. What they term the 'double externality' problem, namely the presence of both environmental and knowledge externalities, may make the patenting solution to the R&D externality less attractive for climate policy. In any case, it may be hard to protect intellectual property rights for major advances resolving climate change.

An alternative approach is to offer a series of large prizes for achieving various pre-defined goals (on inexpensive carbon sequestration, efficient non-carbon producing energy systems, etc.), as with the '*Longitude Problem*' (see Sobel, 1995, eventually solved by John Harrison developing the chronometer), or the 'Rainhill trials' won by the Stephensons' *Rocket* (see e.g., Fullerton, Linster, McKee and Slate, 2002). There are two recent successful examples of responses to such prizes. The first is the Darpa Grand Challenge where a $1m prize was offered in 2004 for developing a self-controlled robotic vehicle that could cross the Mojave Desert in less than 10 hours. The prize would double each year thereafter that it was not won. In the first race in 2004, no unmanned vehicles went more than a few miles before crashing or suffering crippling technical problems. The next year, 4 finished the 241km race in less than the required time (see DARPA, 2005).

The second was the Ansari X Prize of just $10m for the first viable passenger spacecraft to accomplish two successive sub-orbital human spaceflights, which was achieved in well under a decade.

Both of these were prizes of a few $million, small relative to the potential benefits of solutions to climate change. Bilmes and Stiglitz (2008) claim that the US will have spent around $3 trillion on the Iraq war: a small fraction of that sum could fund a vast R&D program for improved technologies. The world is not short of ideas from direct greenhouse gas reductions or sequestration; new approaches to energy production; better catalytic converters; exploiting natural gas hydrates as a potentially vast energy resource; even using nitrous oxide as a fuel; more efficient solar energy conversion; deep sea deposition of CO_2 in hydrates; harnessing wave power; high-temperature super-conductivity to reduce power loss in grid transmissions, etc. 'Wireless transmission', 'heavier than air flight' and many other ideas have been ridiculed initially but worked. If we do not try we will not find out, albeit that anti-gravity or perpetual-motion machines look distinctly unpromising.

The above list are relatively small investments against potentially huge risks. Some dramatic 'solutions' have also been proposed, including geo-engineering with shields around the planet. However, careful evaluation of all new technologies is essential: remember supposedly 'inert' CFCs. Another warning comes from the demise of the Sumerian civilization, one of the first to develop writing and practice intensive, year-round agriculture about 7000 years ago. Although successful for over 2000 years, Sumeria faltered on a 'technological solution' to its increasingly saline soil, by *increased irrigation*. The idea was basically sensible, but flawed by retaining water, rather than having it flowing through. With poorly draining soil, day-time evaporation concentrated salts and minerals dissolved in the water, and seriously depleted agriculture output (see Crawford, 2004, p.47).

Nevertheless, we seem to be on the threshold of a potential energy revolution that could drive a rapidly growing yet low carbon world economy. Such investments have a triple advantage (see Grubb, Köhler and Anderson, 2002):
(i) reducing the risk of serious climate-related problems;
(ii) stimulating economies when there is a great deal of slack;
(iii) initiating the crucial 'learning by experience' that leads to dramatic cost reductions.

7.7 Modelling and forecasting

There is still much that is uncertain about the extent and speed of climate change itself, and about plausible responses to changes in energy prices and associated income shifts. The more traditional role of the econometrician lies in evaluating models that purport to provide 'realistic' simulations about such impacts. However, my skepticism is more about the validity and reliability of any models that are built 'as if' 20th century parameters will not change despite no action being taken. Even the concept of 'business as usual' as the baseline for model simulations becomes meaningless if a radically altered environment will occur. For example, a sudden jump in methane release, followed by a rise in temperature that triggers nuclear wars over failing water and food resources, or from trying to prevent mass migration from untenable areas, is inconsistent with the scenario supposedly being simulated.

Forecasting non-stationary processes is extremely difficult, increasingly so the further ahead the horizon: Clements and Hendry (1999) provide an extensive analysis, with an update in Clements and Hendry (2002) and a non-technical overview in Clements and Hendry (2008). Many of the implications from their analyses apply to forecasting in general.

Firstly, integrated and near-integrated processes, typical of stochastic, slowly evolving trend-like behaviour, lead to rapidly growing interval forecasts as shown analytically in Stock (1996) for the latter. Thus, uncertainty increases rapidly, the more so the shorter the period available for model building prior to the forecast.

Secondly, breaks in distributions are usually not predicted–the recent gyrations in food and oil prices are a typical example, but even the massive financial crisis of 2007–2010 came as a surprise to most, including some of the world's largest financial institutions that supposedly make a living by anticipating developments. Figure 1 above illustrated the problem. Once a shift has occurred in the mean of a distribution, what previously seemed like 'extreme' draws or outliers become central and are all too likely to recur. A mean change in the Earth's temperature has that property, and while one ill-matched breeding season, or one year's inappropriate weather for the given flora and fauna, can be recovered from, a sequence is much harder.

Third, life is adaptable, but mass extinctions painfully reveal the limits of that adaptability. Past breaks in turn distort estimates of models that do not allow for their occurrence, inducing systematic departures between fit and outcome, all too often 'patched' to camouflage the appearance of that difficulty (e.g., differencing can 'remove' a past mean shift, but the problem reappears if levels are properly evaluated). Forecasts may be unusually uncertain but that is no argument for 'doing nothing'; rather, the possibilities of very large losses require actions both to reduce uncertainties and to lower the chances that harmful outcomes will eventuate.

8 Conclusions

This chapter tries to connect the paths that have been cleared by a wide range of different sciences. A multi-disciplinary approach is essential to relate the many aspects bearing on the possible causes and consequences of climate change, and to draw whatever lessons the distant past may hold for humanity. The chapter, therefore, focused on mass extinctions and mean shifts in global temperatures due to increased greenhouse gases, rather than the many other changes that may be entailed, such as rising ocean levels due to thermal expansion and ice melting, through turbulent weather to changed rainfall patterns.

First, the limitations of empirical evidence were addressed against the undeniably huge successes of science over the last millennium. Results and theories may mislead for a period, but self-interest leads to correction.

Second, the science of how greenhouse gases re-radiate energy back to the ground is clear. There are four major such gases, water vapour, carbon dioxide, nitrous oxide, and methane, augmented recently by HCFCs and HFCs as replacements for ozone-destroying CFCs. The increasing levels of carbon dioxide equivalents in the atmosphere are now established, as is their source in human activity–we know we are burning fossil fuels, deforesting, and using large quantities of fertilizer. World-wide temperatures are rising on a stochastic trend, buffeted by many high variance influences, but with obvious markers discussed by Stern (2006). For unclear reasons, this evidence seems insufficient to persuade nay sayers.

Third, the evidence from the great extinctions of the past 500 million years is a major warning from the distant past, the dramatic relevance of which has become increasingly clear the greater the knowledge gained about their causes. That research activity, and the implications therefrom, must intrinsically draw on the expertise of dozens of disciplines, where few individuals can span the entire spectrum of sciences involved. The very different approaches, types of measurements, and sources of evidence across such a range of disciplines makes for a compelling case: climate change is the main culprit of previous mass extinctions, albeit with several different triggers. Humanity is the latest trigger.

Fourth, economic analysis offers a number of ideas around the common theme that externalities need to be either priced or regulated–and climate change is one of the largest world-wide externalities ever. Seven aspects were discussed, all affected by the possibility that abrupt changes can occur. The key problem is the unknown uncertainty when distributions can shift, which makes action more urgent to avoid possible, even likely, future shifts. Most home owners wisely insure against low probability, high cost events like fire risk: humanity needs to do likewise.

Fifth, adaptation ceases to be meaningful if food, water and land resources become inadequate following major shifts in climate. The first mitigation steps need not be costly, and a rising price of carbon could lower usage and stimulate innovation. International negotiations are more likely to succeed if some actions have already been taken at the country level–potentially creating opportunities as new technologies develop.

Planet Earth will survive whatever humanity is doing, so the crucial issues are the effects of continuing climate change on its present inhabitants, including humanity and its civilization, especially the ‘threat multiplier’ from unstable regions. It is a risky strategy to do nothing if that entails potentially huge costs when the costs of initial action are small. Thus, the obvious time to start is now, beginning with the many low cost implementations that will help mitigate greenhouse gases (see e.g., Stern, 2008, for a list). Just in case.

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