Climate Change From the Deep Past To the 22nd Century

What we learn from Earth's deep past is that its climate never stops changing. Tropical alternates with arid over multiple time scales. Major ice ages cycle over millions of years. Glacial eras cycle over thousands of years—down to El Niño cycles of a few years. The evolution of life on Earth has been shaped, driven, and goaded by climate change, and it has in turn changed Earth's climate. The most important lesson we can learn from climate history is that, while climate change can be destructive, it is invariably constructive, catalyzing the emergence of ever more remarkable expressions of life, science, and culture.

Dr. Michael Towsey

The beginning of climate science

It is now 200 years since the French mathematician and physicist, Joseph Fourier, asked a prescient question which launched the science of climate change: why is the earth so warm? (NASA, 2023) His studies of heat transfer suggested that the earth, given its distance from the sun, should be much cooler. Something in the atmosphere was acting as an insulating blanket. But what?

The beginnings of an answer came in 1856 when American scientist, Eunice Foote, demonstrated that both CO_2 and water vapor trap heat (Huddleston, 2019). Unfortunately, Foote was far from the European center of the scientific world at the time. And she was a woman. Consequently, it was the Irish physicist John Tyndall, three years later, who was credited with Foote's discovery. The next step came in 1896, when Swedish scientist, Svante Arrhenius, predicted that changes in atmospheric CO_2 levels could substantially alter surface temperatures through the so-called *greenhouse effect*. The atmosphere is transparent to the visible light rays emanating from the sun, but its CO_2 and water vapor components absorb the infra-red rays re-emitted from the earth's surface. Just like a greenhouse.

Meanwhile, during the 19th century, geologists were accumulating evidence of climatic extremes throughout Earth's history—tropical conditions alternating with arid, and at times ice covering much of the planet. Through the 1920s-30s, the Serbian mathematician, Milutin Milanković, painstakingly established that this waxing and waning of ice could be linked to slight variations in Earth's orbit around the sun and to the tilt and wobble of its axis. The resulting changes in insolation were amplified by the CO_2 greenhouse effect to create large changes in surface temperature. (For more detail see Buis, 2020). But, once again, it was a case of a scientist being in the wrong place at the wrong time. World War II delayed publication of his discovery until 1941, and then only in German. It was not until 1969 (11 years after his death) that Milanković was published in English, and his theory immediately revolutionized our understanding of climate dynamics (Flannery, 2018).

In the meantime, during the mid-1950s, Canadian scientist, Gilbert Plass, wrote the first computer programs to model the link between atmospheric CO_2 and temperature. His models made predictions for the 20th century that have turned out to be remarkably accurate (Schmidt, 2010). The science concerning CO_2 was now compelling enough that President Johnson included a reference to it in his 1965 Special Message to Congress:

> *Air pollution is no longer confined to isolated places. This generation has altered the composition of the atmosphere on a global scale through radioactive materials and a steady increase in carbon dioxide from the burning of fossil fuels.* (Johnson, 1965)

The Great Ice-Ages

We can define an ice age as a period where there is permanent ice on one or both polar caps. By this definition, Earth is currently in an ice age, albeit in a warmer "interglacial" period of the Quaternary ice age that started several million years ago. Despite speculation that Earth has at times been completely covered in ice (the so-called "snowball earth"), tropical refugia have always persisted at the equator and equatorial ocean temperatures have always been within 2°C of current values (Fairbridge, 1987). In other words, temperature fluctuations were greatest at the poles but less marked towards the equator.

Dr. Michael Towsey, researcher at Queensland University of Technology, applies Machine Learning approaches to biological questions. But he finds any excuse for fieldwork in Australia's outback!

There are six recognized "great ice-ages" over the past 1.2 billion years (Table 1), and it is immediately apparent from their dates, that the average interval between them was 200-250 million years. This suggests a periodic forcing and there are two possibilities: 1. It is known that the solar system circles the galaxy once every 230 million years and is likely to pass through a fluctuating galactic environment as it does so, dust clouds for example; 2. A more promising explanation, because it permits immediate investigation, is that the ice ages are linked to cycles of continental drift during which continents assemble into a supercontinent followed by disassembly. The most recent of these cycles is the well-known splitting of the supercontinent Pangea into southern Gondwana and northern Laurasia, followed by the splitting of these into the continental configuration we know today. Estimates of the duration of the supercontinent cycle range from 250 to 500 million years (Nance and Murphy, 2013) which suggests a link with the great ice-ages.

Continental drift

Continental drift is accompanied by volcanic activity, mountain building (orogeny) and the creation and erasure of highly productive shallow marine habitats. Volcanoes spew cooling ash and heating greenhouse gases into the atmosphere. Mountain building, particularly within the humid tropical zone, lowers global temperatures because increased weathering of silicate rocks sucks CO_2 from the atmosphere. It is believed, for example, that our current Quaternary ice age was initiated by the uplift of the Himalayas as the Indian subcontinent pushed northward into Asia. However, it is important to understand that there is no single or simple explanation for the great ice ages. Continental drift may be accompanied by extensive volcanic activity and CO_2 sucking orogeny, but another important factor at any one time is the disposition of the continents. Ocean currents help to disperse heat around the planet (thereby ameliorating extremes of hot at the equator and cold at the poles), but the effectiveness of this depends on how the arrangement of the continents directs ocean current flows. There is no doubt however, that the waxing and waning of the great ice ages has been a major determinant of the evolution of life on earth, with each event being accompanied by both mass extinctions and the emergence of new life forms (Table 1).

Polar Wandering

The earth's rotational poles appear to wander over vast geological time but also measurably in the present day. *Polar wander* was a puzzling observation in the early 20th century until the discovery of continental drift. The apparent movement of the rotational poles could then be explained in terms of the continents *drifting across* them. Nevertheless, the location of the rotational poles on the earth's surface can now be measured to centimetre precision and they do indeed shift *independently* of continental drift. This independent movement consists of a wobble (which causes the poles to spiral in and out around a central point, Figure 1, blue crosses) and a secular wandering of the central point (true polar wander, Figure 1, green line). It is the secular or true polar wander that has greatest significance for climate change. True polar wander over the past 200 million years has been "episodic" (Besse and Courtillot, 2002), with periods of standstill

Table 1: **The great ice ages and biological evolution**

	Millions of years ago	Biological evolution
Early Proterozoic	1250	Life is unicellular, confined to the oceans. This ice-age possibly triggered by 1: a new kind of photosynthesis, that further reduced atmospheric CO_2 and increased oxygen; or 2: reduced CO_2 due to weathering of elevated supercontinents.
Mid-Proterozoic	900	Complex multicellular life emerges. Oxygen is now an important component of the atmosphere. The adaptation to living with oxygen may have initiated this ice age.
Precambrian	650	This ice age may have prepared the way for the Cambrian explosion of new life-forms around 550 million years ago, when most major animal groups first appear in the fossil record.
Late Ordovician	450	This era includes the earliest known mass extinctions; Two waves of extinctions: first as climate cools, second as climate warms again. Most life lives in the sea; many marine invertebrate species become extinct.
Permo-Carboniferous	250	Supercontinent, Pangea, centered on the South Pole; this land configuration dries and cools the planet. Mass extinctions of the dominant plant groups and tetrapods. Amphibians suffer greatest losses because dependent on wet environments. At same time the amniotes emerge, a group that ultimately gives rise to dinosaurs, modern reptiles, birds and mammals.
Quaternary	2	The Quaternary Period, starting 2.58 Ma, is marked by many cycles of glacial growth and retreat, the extinction of numerous species of large mammals and birds, and the evolution of hominids and Homo sapiens.

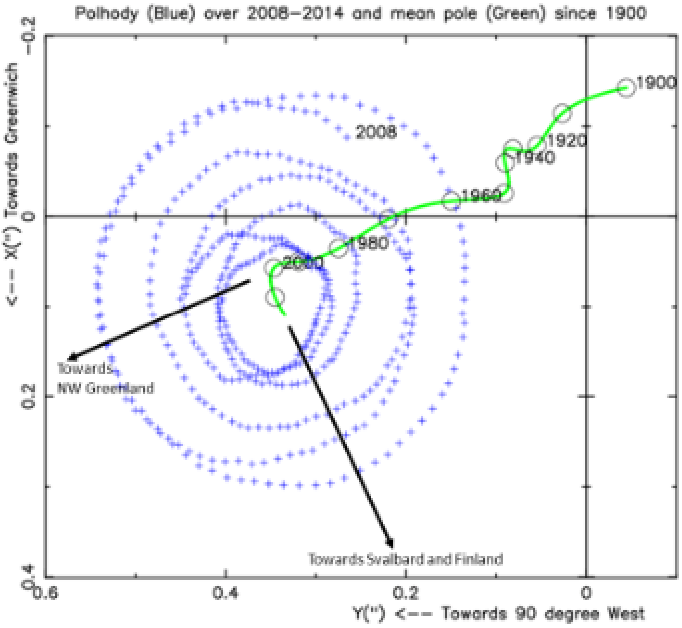

Figure 1: Poles both 'wobble' and 'wander'. Blue crosses illustrate recent wobbling (2008-2014), also known as polhody. The wobble has a radius varying from 3–15 meters. Wandering of the spiral centre (green line) is called true polar wander. The north pole wandered some 20 meters to the west in the 20th century (average 20 cm/year) but turned eastward around 1995. (Image from Dick and Thaller, 2014).

alternating with periods of speed (100km/million years). Besse and Courtillot conclude that true polar wander is "a truly global feature of Earth dynamics".

The earth behaves like a spinning top and is highly sensitive to the distribution of mass around its spin axis. Spin is stabilised by the planet being 43 kilometres wider at the equator than through the poles. But convection currents in the viscous upper mantle (asthenosphere) (Figure 2), that are responsible for driving continental drift, also push around denser lumps of mantle, especially near *subduction* zones where one plate is pulled under its neighbouring plate. Such mantle 'anomalies' can unbalance the planet's spin. Stability is restored by a swivelling of the complete crust and viscous asthenosphere around the liquid outer core so as to shift the balance of excess mass towards the equator of a new spin axis. (Think of an intact orange rind that swivels slightly over its inner flesh.) Note that the spin axis still points to the same star in space. Rather, the mantle/crust swivels so that the spin axis passes through a different point on Earth's surface.

In 1997, geologist Joe Kirschvink (Caltech, 2023) proposed that true polar wander has played an important role in the evolution of life on earth. The idea was at first controversial but has since gathered support. There is evidence that the Cambrian explosion (Table 1) coincided with a true polar wander of some 75^{o} over 20-million-years (Mitchell et al., 2015), equivalent to an average wander of about 40 cm per year. Studies in China have found that the Late Ordovician mass extinctions (Table 1) coincided with a polar wander of 50^{o}, equivalent to an average speed of about 55 cm per year (Jing, 2022). Another study in Italy discovered an interesting wander event 84 million years ago, when the poles wandered some 12^{o} and then returned to their original location, chalking up 55 cm per year of wandering over 5 million years (Mitchell, 2021). Finally, Woodworth and Gordon (2018) found that the poles, after being stationary from 48 to 12 million years ago, have since wandered, with Greenland moving towards the north pole and parts of the Pacific Ocean towards the south pole. The authors find it "impressive that such a small change in the location of the spin axis [only 3.4^{o}] could have such a large effect" and conclude that it "may have played an important role in triggering [the Quaternary] Northern Hemisphere glaciation."

True polar wander helps to explain why northern and southern hemisphere temperatures have sometimes moved in opposite directions. With true polar wander, it is possible for a

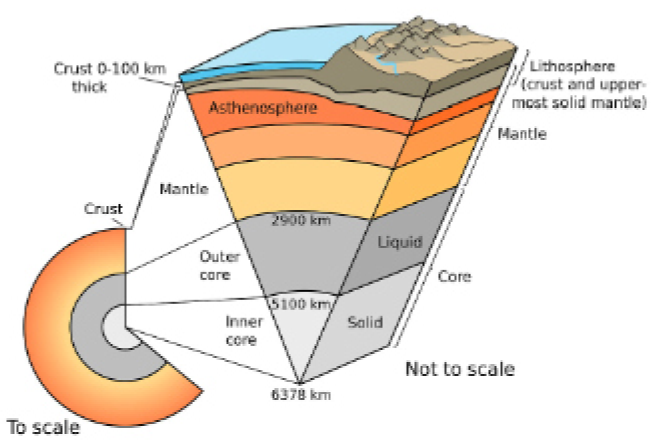

Figure 2: Inner structure of Earth. The liquid outer core generates the earth's magnetic field. The asthenosphere drives plate tectonics and continental drift. (Image from USGS, 2023)

> *There are now thousands of litigation cases around the world targeting governments and their duty of care. Some 30 were brought by young people. And they are beginning to have an effect.*

continent in one hemisphere to move towards its pole (with a consequent cooling and reduction in species diversity), while a continent in the opposite hemisphere necessarily moves toward the equator (causing warming and increased species diversity).

When searching the literature on movement of the earth's poles, one must be careful to distinguish shifting of the rotational poles from a shifting of the magnetic poles. There is no evidence that fluctuations or reversals of the earth's magnetic field have had any effect on climate or biological evolution over geological time scales (Buis, 2021). However, NASA scientists are carefully watching an ongoing diminution in the magnetic field over South America and the South Atlantic (Johnson-Groh and Merzdorf, 2020).

The transition from hot to cold

We turn now to Earth's cooling over the past 50-million years and its transition into the Quaternary ice age (Figure 3). The temperature maximum around 50 million years ago was some 14°C higher than today. And the atmospheric CO_2 concentration was 1500 ppm (parts per million), an extraordinary value given our concern about today's 420 ppm. The fall in temperature from that 28°C peak appears to coincide with the collision between India and Asia and was mediated by falling atmospheric CO_2 levels. Many groups of mammals made their first appearance in the Eocene, ancestral elephants, bats, whales, ungulates, and horses. Carnivorous predators also evolved with these herbivores, and, of course, the early primates!

Temperatures appear to stabilize with the opening of the Drake Passage (when Antarctica becomes surrounded by a circumpolar Southern Ocean) but fall again with the closing of the isthmus between North and South America. These transitions illustrate the important influence that ocean currents have on global climate. The North Pole began to ice over much later, around 5 million years ago.

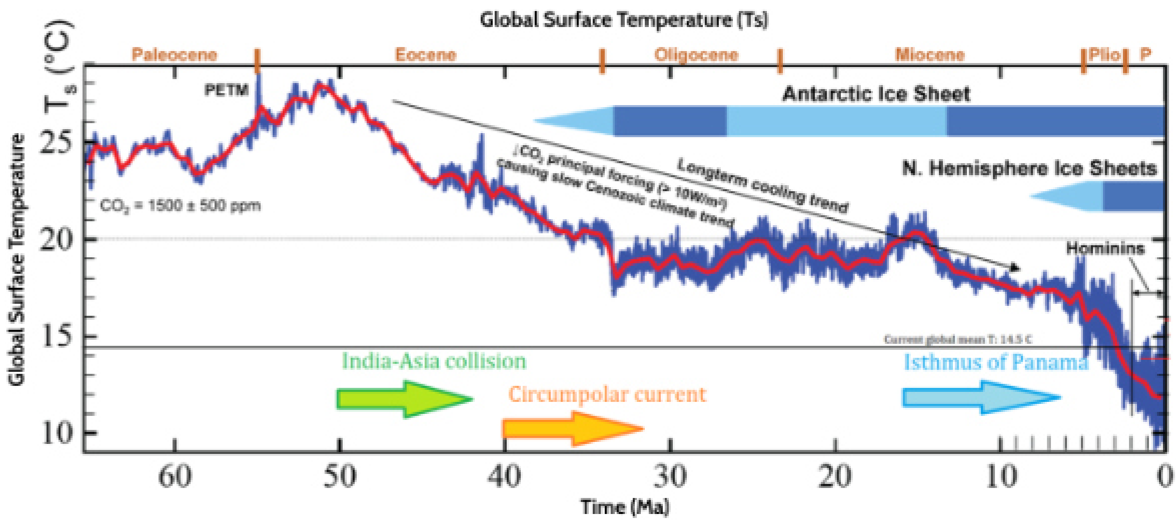

Figure 3: The global temperature transition over the past 65 million years from the Eocene thermal maximum (PETM) to the Pleistocene Glaciation, also called the Quaternary. Global average temperature dropped by about 14°C in concert with a long-term decline in CO_2. (Graphic from Routledge, 2013.)

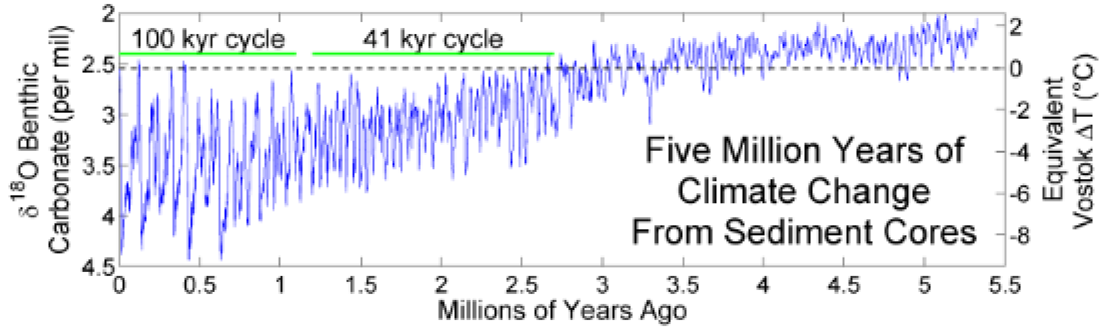

Figure 4: There is a transition around 3 million years ago, where temperatures not only begin to drop but also to cycle. This is where the forcing effect of the Milanković cycles becomes apparent. The accepted start date for the Quaternary is 2.58 million years ago. (Brunetti and Prodi, 2015)

Figure 4 illustrates the onset of temperature cycling around 2.58 million years ago, which is the accepted start date for the Quaternary. This is where the forcing effect of the Milanković cycles to produce glacial cycling becomes apparent. Which raises a question: if the idiosyncrasies of Earth's orbit that produce the Milanković cycles have been unchanged far into the indefinite past, why have they only become apparent in the last 2.58 million years? Flannery (2018, p148) suggests that the configuration of the continents and high greenhouse gas levels probably prevented the small insolation cycles from being amplified.

The Quaternary Ice Age

We take up the story around 800,000 years ago, from which time the 100,000-year Milanković cycle was the dominant climate forcing mechanism. This time span is conveniently recorded in Antarctic ice cores. These not only contain a record of the chemical composition of the earth's atmosphere (small air-bubbles trapped in the ice), but also its temperature. It is immediately apparent in Figure 5, that there is a strong correlation between CO_2 and temperature fluctuations over the past 700,000 years.

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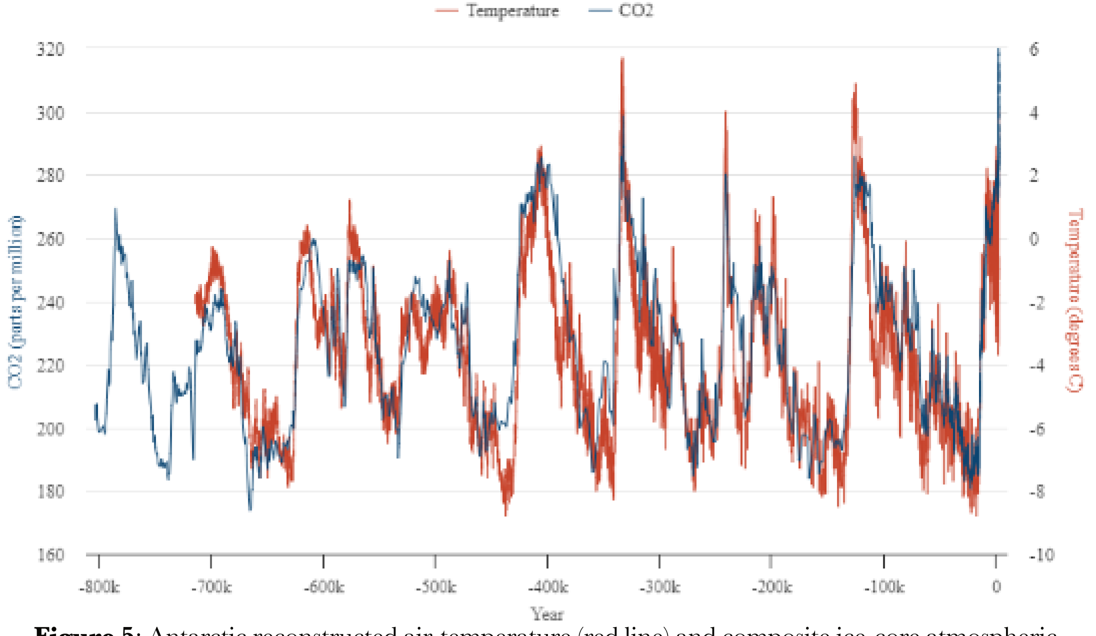

Figure 5: Antarctic reconstructed air-temperature (red line) and composite ice-core atmospheric CO_2 (blue line). The data spans the period from 800,000 BCE to 1980 CE (Hausfather, 2020).

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The CO_2 data are replotted in Figure 6 to clarify the recent rapid increase in atmospheric CO_2. The current level of 420 ppm is unprecedented in the past 800,000 years and can be traced to the onset of burning fossil fuels in the mid-19th century. Without human intervention, we would expect CO_2 levels to fluctuate between 180 ppm during a glacial to around 280 ppm during an inter-glacial as they did for the past 800,000 years (NASA, 2023).

Why hasn't the extraordinary increase in CO_2 already had an extraordinary effect on climate? Partly because the oceans have a large buffering capacity for both heat and CO_2 and partly because air pollution from industry, traffic and aircraft partially masks solar radiation reaching the earth's surface. In other words, we are living on borrowed time.[1] But it is certain that the rapid increase in CO_2 will act as a long-lasting punctuation to the natural cycle of ice ages experienced over the past 800,000 years (Ganopolski, 2016).

The climate bellows in Eurasia

The transition from the 41,000-year glacial cycle to the 100,000-year cycle that occurred around one million years ago (Figure 4) had a devastating effect on Europe's ecology. The warm loving flora and fauna that had gradually adjusted to the 41,000-year glacial cycles, did not adjust well to the harsher 100,000-year cycle. Europe developed two assemblages of species, one cold-adapted (including reindeer, bison, mammoths, and wolves), the other warm-adapted (hyenas, rhinoceroses, lions and hippos), whose relative fortunes fluctuated with phase of the glacial cycles (Flannery, 2018). Both Flannery and Fagan (2004) liken these climate oscillations in Europe to a "bellows". During an advancing glacial period, freezing polar winds blew Europe's ancient assemblage of warm-loving plants and animals to the extreme south, against the Mediterranean coast. As the ice retreated the climate bellows 'sucked' cold adapted species back towards the Arctic circle and Siberia. With repeated cycles, many species did not survive. In North America, retreating flora and fauna did not face a Mediterranean-like barrier.

"The European ice age is thus marked by migration and extinction on a massive scale. More than half of Europe's mammal species disappeared with the onset of the ice ages; surviving was all about adaptation and migration" (Flannery, 2018, p149).

The Ice Ages and Human Evolution

It might be thought that the hominid species emerging during the Pleistocene were lucky to be doing so in Africa, closer to the benign conditions of the equator. But Africa was also subject to cycles of moist and arid climate, with the Sahara Desert periodically expanding southward and pushing refugee biomes to coastal regions (Carto et al., 2009).

[1] During the 1970-80s, climate scientists were concerned about global dimming caused by atmospheric aerosol pollution. Reductions in aerosol pollution are expected to result in accelerated climate warming (Wild et al, 2009).

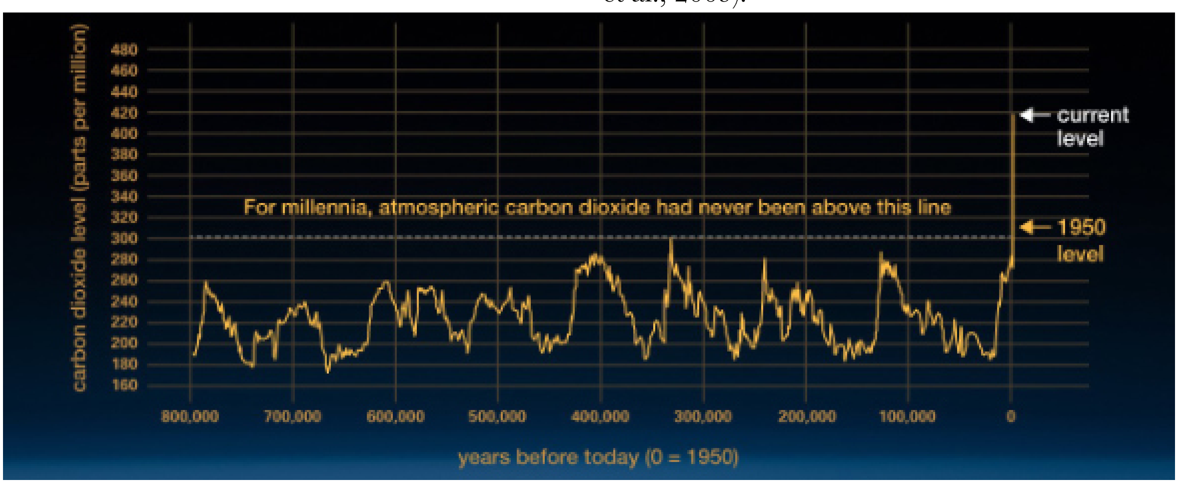

Figure 6: The extremely rapid increase in atmospheric CO_2 since 1950. (NASA, 2023)

There is a period in the African fossil record around 900,000 years ago which is devoid of hominid fossils. The gap is sufficiently puzzling to invite questions. In a recent fascinating paper, Hu et al. (2023) used a newly developed computer model to predict past human population sizes from variation in the genomes of 3154 present-day individuals. The results indicate that our human ancestors suffered a severe population bottleneck about 900,000 years ago, when the number of breeding individuals collapsed to just 1280! The bottleneck, which lasted some 100,000 years, brought our ancestors close to extinction. The authors attribute this event to a "major climate change" which happened to occur around the time that the Milanković glacial cycle in Europe switched from the 41,000-year cycle to the more severe 100,000-year cycle.

The Neanderthal in Europe were not so lucky. They appear in the European fossil record around 400,000 years ago and survived four cycles of glaciation. They even coexisted and interbred with modern humans (Cro-Magnon) who appeared in Europe about 40,000 years ago. But by the fourth (most recent) glaciation, remnant groups were pushed to caves around Gibraltar, never to be seen again. Why did they disappear? Although the traditional image of Neanderthals is as slow-witted, dumb cave-dwellers, the contemporary view is that Neanderthal had speech and a sophistication with tools. But they did not have the cognitive agility of modern humans. One thing to keep in mind is that the climate transitions in Europe were not steady progressions. Rather, the climate heading into the last glacial maximum became increasingly unstable, swinging severely and abruptly (Wong, 2012). Which of course, precipitated rapid ecological oscillations such that, over the course of a Neanderthal's lifetime, the plants and animals that she/he had grown up with could be replaced with unfamiliar species. And then, just as quickly, the environment could change back again (Wong, 2012).

Learning in modern humans is of two kinds, *conscious* and *unconscious*. We easily learn a language as a young child, unconsciously. But when conscious learning takes over in our teens, languages become more difficult to learn. It could be that Neanderthal had an excellent capacity for early unconscious learning that was successful in times of relative climate stability. But perhaps

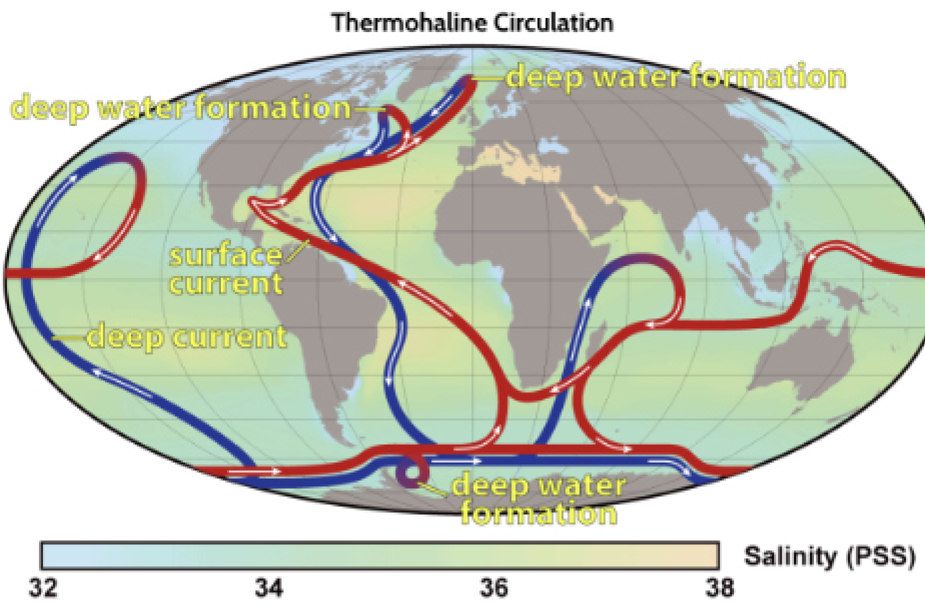

Figure 7: The great ocean conveyor belt. The red lines indicate warmer surface currents. The blue lines represent colder deeper currents. There are three locations (two in the North Atlantic, one in the Weddell Sea) where warmer waters 'overturn', release their heat and sink to the ocean floor. These overturning currents drive the entire conveyor belt. (Simmon and Rohde, 2008)

they were not as adept as Cro-Magnon with conscious learning at a time when climate instability required it.

The global ocean conveyor belt

It is difficult to assign an end point to the last glacial age because the northern and southern hemispheres did not fluctuate in concert. Greenland ice-cores indicate that rapid warming 16,000 years ago was followed by a sudden reversal 13,000 years ago when glacial temperatures returned. Meanwhile, ice-cores from New Zealand glaciers indicate that southern hemisphere temperatures were warming rapidly 13,000 years ago as the north was cooling (Dybas, 2010).

To make sense of these rapid and confusing temperature fluctuations, we need examine the role played by the *global ocean conveyor* belt (Figure 7). This is a system of ocean currents that moderates global climate by transferring warm water from the equator to the poles. The conveyor belt moves slowly—a few centimeters per second, compared to wind-driven and tidal currents that can be 10-100 times faster. It takes about 1,000 years for a given body of water to complete the round-trip, but the volume of water moved is immense—more than 100 times the flow of the Amazon River (Ross, 1995).

One of the pumps that drives the conveyor lies in the North Atlantic and is known as the *Atlantic meridional overturning current* (AMOC). Warm surface water from the Gulf Stream heats the atmosphere in the cold, northern latitudes. This makes the water cooler and more saline, causing it to sink to the bottom of the ocean and move southward, eventually reaching Antarctica from where it returns via a circulation of the Pacific and Indian Oceans (Figure 7).

The rapid increase in atmospheric temperature starting 16,000 years ago caused a rapid melting of the glacial ice sheets covering much of Europe and North America. It appears that around 13,000 years ago a collapse of the North American icesheets was sufficient to flood the North Atlantic with fresh water and shut down the conveyor belt. It took 1000 years for the fresh water to disperse and for the conveyor belt to resume, so allowing warming to resume. A similar but not so severe event occurred 6000 years ago, likewise, initiating a measurable drop in northern hemisphere temperatures.

The point of describing this phenomenon is that for as long as glacial ice sheets persist on North America and Greenland, there is the potential for a rapid ice melt to reduce, if not to switch off, the global ocean conveyor belt. Brian Fagan who describes in much detail how the good fortunes of humanity have depended on the continued circulation of the global ocean conveyor belt, concludes his discussion thus:

> *Each flip of the [conveyor] "switch" changed ocean circulation profoundly, so that the great conveyor belt carried heat around the world in different ways. From what little we know of the cycles of cold and warm climate, we would be naïve indeed to assume that another cold oscillation will not descend on earth some time in the future.* (Fagan, 2004, p63)

And here we have a paradox, that a rapid warming of the planet such as is occurring today, could precipitate a return to glacial conditions in the northern hemisphere (Boers, 2021). It has happened before—more than once.

The Anthropocene

The term *Anthropocene* conveys the idea that the human species has sufficiently changed the physical and biological conditions on planet Earth that scientists hundreds of years hence will be able to identify the 20th century by a thin band of plastics in sedimentary profiles and by a unique signature of greenhouse gases and radioisotopes trapped in ice-cores. These processes are happening now as you read this.

But humans have likely made an impact on climate long before the 19-20th centuries. It is well known that Native American populations in both North and South America were decimated by the arrival of Europeans. Some 56 million Native Americans died within 100 years due to disease, famine, and violence (Koch, et al., 2019). This led, in turn, to the abandonment of agriculture and the reforestation of a land area the size of France. There was an accompanying drop in atmospheric CO_2 and global temperature (measured in Antarctic ice cores). About half of the 10 ppm drop in CO_2 from 1520 to 1610 was due to the "great dying" of indigenous Americans and this occurred before the onset of the Industrial Revolution. Another study (Darby, 2016) drew similar conclusions from the collapse of Native American populations in New Mexico in the 1600s. Another conclusion from these studies is that while reforestation of land is certainly desirable, it cannot be achieved on the scale required to deal with today's emissions which are increasing at the rate of 2.44 ppm CO_2 per year. Burning of fossil fuels must be reduced.

Is it worse than we thought it would be?

This is the question asked by *New Scientist* magazine in a recent Climate Special Report (Le Page, 2023), responding to recent, unprecedented extreme weather events around the world. The answer is mixed. The rise in global temperature has been well within predicted ranges but the impacts of extreme weather events were underestimated. A rise in the heat content of the atmosphere does not mean uniformly rising temperatures. Rather, the effect is increased temperature *gradients* which generate high winds, torrential rain, and violent storms. Drying of vegetation leads to extreme fire events.

Then New Scientist asks about tipping points. A tipping point refers to some large-scale climate related event that would be impossible to reverse should it occur, for example, the death of the Amazon rain forests or a collapse of the West Antarctic ice sheet. The most obvious candidate for a tipping point is the Atlantic meridional overturning current (AMOC) which seems to be slowing faster than expected. Recall that AMOC is the pump that drives the global ocean conveyor belt, and it is extremely sensitive to freshwater runoff from melting ice sheets. In addition, it is likely that rapidly melting Antarctica icesheets are also contributing to a shutdown of the conveyor belt (Gunn et al., 2023). Ditlevsen (2023) suggests that a collapse of the AMOC is likely to occur about mid-21st century under the current trajectory of CO_2 emissions. Such an event would have "catastrophic consequences" for northern Europe, especially for the UK and Ireland (Le Page, 2023).

Rising sea-levels

Another prediction that frequently appears in the media concerns rising sea levels. This occurs due to the expansion of water as it warms and the melting of land-based icesheets. (Melting of floating ice has no net effect on sea levels.) Average sea levels have risen by 16 cm over the past century but are expected to rise at a faster rate over the coming century. A complicating factor here is the changing shape of the ocean basins due to movements of the earth's crust. The icesheets over Greenland and North America in the last glacial age were several kilometres thick and their immense weight depressed the earth's crust by hundreds of meters, altering sub-crustal magma flows. As these icesheets melted, the underlying crust rose, an effect that continues today. For example, parts of Alaska, whose icesheets are melting faster than anywhere else on the planet, are, as a consequence, *rising* out of the water at 70 mm per year, even though that melt water is flooding other parts of the globe (Kelly, 2007). Furthermore, this readjustment of tectonic plates releases accumulated tectonic stresses as earthquakes (Chen, 2016). Scientists further speculate that evaporating glaciers may also be responsible for the unusually high volcanic activity in Iceland over the past five years (Chen, 2016).

Recall that Earth's axis of rotation is incredibly sensitive to changes in the distribution of mass around the globe. It is normal for the average spin axis to move a few centimeters each year. However, in 1995 there was a sudden directional change in true polar wander from 70° west (towards NW Greenland) to 26° east (towards Svalbard and Finland) (Deng et al., 2021). Another study found that this was due not only to glacial melting but also to groundwater extraction for drinking, irrigation, and manufacturing (Seo et al, 2023; Walther, 2021). Over the past 50 years, some 18 trillion tonnes of water have been removed from underground aquifers, which is as vast as it is unsustainable (Carrington, 2012). It ends up in the atmosphere and rivers, and represents a significant redistribution of mass over the planet.

It should be kept in mind that extensive polar wandering necessarily results in readjustments of the earth's tectonic plates and equatorial bulge, which in turn, creates and releases plate tensions.

The earth's crust is in a constant state of flux. Climate change is not just about climate. It is about the entire planet as a complex dynamic system, constantly adjusting and responding to external factors (Milanković cycles), surface disturbances (glacial melt, ground water depletion) and internal forces (magma convection). Humans don't experience any of this directly, but we experience the consequences in the form of climate change, extreme weather events and earthquakes. And surprisingly, the Inuit in NW Alaska, who by tradition watch the stars closely, report that they are moving slightly from their traditional orbits, a result that would be expected of polar wander (Climate, 2022).

Climate change is not just about climate. It is about the entire planet as a complex dynamic system.

The backlash

In 1995, thirty years after President Johnson alerted Congress to CO_2 as a greenhouse gas, the Intergovernmental Panel on Climate Change (IPCC) published its Second Assessment Report. The major conclusions were that atmospheric greenhouse gas concentrations were increasing, and that global climate was indeed changing, most likely due to human activity. The report did not have the impact it should have because, in the intervening 30 years, there was a concerted drive by conservative thinktanks and a few likeminded scientists to cast doubt over the validity of the science. Even in 2006, *Time Magazine* reported that almost half of Americans did not believe global warming was a reality, despite virtually all climate scientists believing so (Oreskes and Conway, 2010, p169).

The alarming story of climate change denial is described in much detail in *Merchants of Doubt* (Oreskes and Conway, 2010) and is a must read for those who find it difficult to understand why governments have refused to act on sound scientific research. The authors point to two conservative thinktanks, the George C. Marshall Institute and The Heartland Institute and to three physicists, Bill Nierenberg, Fred Seitz and Fred Singer as being most responsible for spreading climate change denial. The three physicists, ardent supporters of President Regan's "Star Wars" program, were not active in climate research yet were able to exert a powerful frustrating influence on its acceptance.

Seitz and Singer (both associated with the Marshall Institute) had worked previously with tobacco companies to cast doubt on the link between smoking and cancer (Oreskes and Conway, 2010, p5). In subsequent years they published articles attacking the Environmental Protection Authority on issues such as the ozone layer and acid rain. The Heartland Institute was likewise working with tobacco companies in the 1990s and with climate deniers (Oreskes and Conway, 2010, p233).

What we learn from Merchants of Doubt is: 1. that a few well-placed powerful persons were able to cast a smokescreen of doubt over climate science; 2. that the reputations of targeted climate scientists were deliberately destroyed (universities and governments are unwilling to take on researchers whose work appears to be tarnished with controversy); 3. that even the reputations of deceased scientists are attacked to discredit environmental science in general—the Heartland Institute recently attacked the integrity of Rachel Carson, whose book, *Silent Spring*, led to the banning of DDT; and 4. that climate deniers learned their tools of obfuscation by working with tobacco companies. If you make enough noise in the right places, some mainstream media will give equal time to both sides of a debate, even when one side has no credibility. But a few global news corporations have inflicted incalculable harm on humanity by outright denial of climate change.

Governments and duty of care

So it is that in 2014, Australia was governed by a conservative government in the grip of the fossil fuel industry and climate denial. Prime minister of the day, Tony Abbott, declared that coal is "good for humanity" and will be the "world's main energy source for decades to come" (ABC-News, 2014). In 2017, prime minister to-be, Scott Morrison, brandished a lump of coal in parliament, daring members to touch it and ridiculing renewable energy, much to the delight of his colleagues (The Conversation, 2017).

In 2020, Australia's Federal Minister for the Environment, Sussan Ley, approved the enlargement of a major coal mine. Eight teenagers responded by bringing a court case arguing that she had a duty of care to protect young people from future harm caused by the climate impacts of the proposed mine. Surprisingly, they won the case in a lower court. The minister appealed to

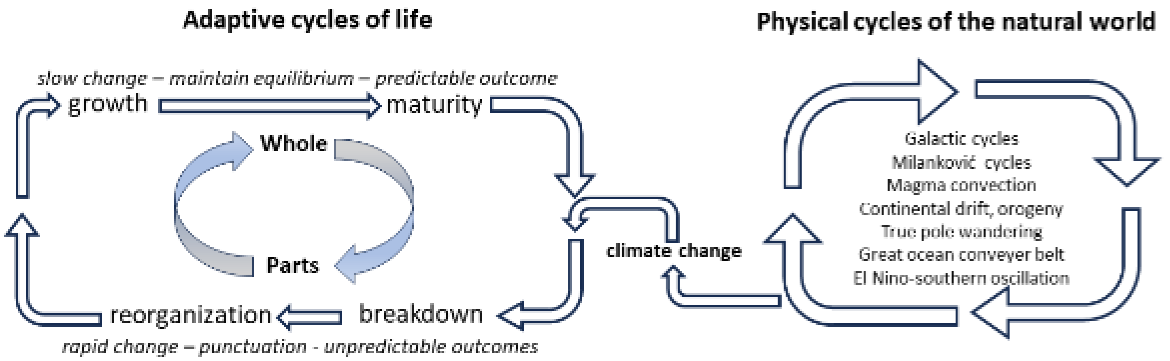

Figure 8: The adaptive cycling of living systems responds to climate change forcing.

Australia's highest court and continued to approve new coal mines. She argued that she had no duty of care to protect Australian children from the future harms of climate change. In 2022, the High Court agreed. Australian law does not require such care (ELA, 2023; Stocker and Hublet, 2022).

There are now thousands of litigation cases around the world targeting governments and their duty of care. Some 30 were brought by young people (BBC World, 2023). And they are beginning to have an effect. In an historic ruling, August 2023, a Montana state judge ruled in favor of a group of 16 plaintiffs, aged 5 to 22 years, arguing that the Montana state government was contributing to climate change by prohibiting government agencies from taking climate impacts into consideration when approving energy projects (Jaynes, 2023). In the same month, the United Nations issued a statement saying that the Convention on the Rights of the Child extends to environmental protection (United Nations, 2023).

"The appallingly bad neoclassical economics of climate change" (Keen, 2021)

In 1980, the aforementioned physicist, Bill Nierenberg, was asked to chair a committee that would report to Congress on the likely consequences of anthropogenic climate change. He selected Yale economist, William Nordhaus, to write a chapter on economic consequences. Nordhaus was carefully chosen because he was known to believe that climate science was uncertain and that the future economic consequences would be manageable. Nordhaus laid the foundations for the orthodox economic approach to climate change that persists to this day. The economic components of the 2014 IPCC report (the IPCC is the global body coordinating humanity's response to climate change) began by citing Nordhaus. Putting aside that the economic consequences are measured in terms of changes to GDP (increasingly recognized as a poor measure of economic wellbeing), the 2014 IPCC report concludes that a 2°C increase in world temperature would only result in a GDP drop of 0.2-2.0%—in other words, sufficiently small to be ignored.

Heterodox economist, Steve Keen, has made a careful examination of the 2014 IPCC report and accuses Nordhaus and followers of "making up numbers to support a pre-existing belief" (Keen, 2021). The assumptions underlying the Nordhaus approach deserve scrutiny:

- *Assumption 1*: Nordhaus argues that 87% of US GDP (for example, manufacturing, trade, finance, government services) is produced indoors "in carefully controlled environments that will not be directly affected by climate change". In other words, only outdoor production such as agriculture, mining, forestry, needs to be accounted for in climate change studies.

- *Assumption 2*: The states in the USA are situated in a range of temperature zones, and yet states in zones that differ by more than 10ºC can have similar economic activity. Nordhaus uses this observation to argue that temperature changes over time will have no more effect on economic activity than the differences we observe today between cold and hot locations. In a Twitter exchange described by Keen, orthodox climate economist Richard Tol argues that a temperature change of 10ºC is less than the temperature distance between the equally rich states of Alaska and Maryland. When asked if he is saying that a 10ºC rise in global average surface temperature would be manageable, Tol replies, "We'd move indoors, much like the Saudis have." (Keen, 2021, p1165).
- *Assumption 3*: Nordhaus ignores the problem of tipping points in his economic models. This may not be unreasonable because tipping points are difficult to model. So, Nordhaus ends up with a mathematical model that only permits smooth changes in GDP response to temperature change. But even such simple models require numbers (coefficients) to be inserted. How to choose their values? The best that can be said here is that one inserts numbers which appear to make sense. But it is noteworthy that over a period of 25 years, Nordhaus altered his coefficients several times to reduce the predicted damage caused by rising temperatures.
- *Assumption 4*: Nordhaus ignored the role of energy in estimates of production and GDP. If GDP is to continue increasing, energy consumption *must* increase. And if temperatures are increasing, additional energy is required to air-condition the 87% of economic activity located indoors, even as the outside burns. In other words, the decision to exclude 87% of GDP from consideration of the effects of climate change is "utterly unjustified" (Keen, 2021, p1163).

In today's world, orthodox economists are considered high priests with something wise to say on every contemporary problem, whether it be poverty, aged care, or climate change. Yet their doctrine of neo-classical, free markets is incapable of understanding the relationship between an economy and the natural world. Nature is assumed to be a resource that can be consumed depending on cost-benefit analysis. The well-known US economist, Larry Summers, is quoted by Nordhaus as saying, "… the existence value [of species] is irrelevant". An endangered bat species can be worth millions of dollars to a mining company, but only if it enables them to offset the destruction of habitat elsewhere. Even in 2023, it appears that orthodox economists have zero understanding of how an economy functions within the natural world.

Postscript: In 2018, the Nobel prize for economics was awarded to William Nordhaus for his work on developing "a quantitative model that describes the global interplay between the economy and the climate".

A question of speed

What we learn from Earth's history is that climate has never stopped changing. There are forcing mechanisms operating at multiple temporal and spatial scales. The temporal scales range from millions, thousands, hundreds, to tens of years. The relatively benign climate of the past 10,000 years, what Brian Fagan calls the "long summer", is unusual. Predicting the outcome of our present pulse of climate change is difficult because different events may unfold over different timescales. The changes of climate in the Permo-Carboniferous were severe but they occurred over millions of years, time spans too huge for us to comprehend. On the other hand, we also know that some more recent transformative climate changes have occurred within the span of just one or two human lifetimes.

What makes short bursts of very rapid climate change possible is the interaction of multiple climate-forcing cycles operating at different temporal scales. And the *speed* at which climate changes is of fundamental importance. The high CO_2 and temperature levels in the Eocene (Figure 3) are sometimes used by climate sceptics to imply that current changes are small and nothing to worry about. But it took millions of years for life to adjust to that climate regime and it took millions of years for it to adapt to the cooler conditions we know today. Contemporary climate change is human induced, but its speed is what worries climate scientists. Rapid climate change is a killer. Which is why real climate scientists shake their heads pondering the Nordhaus logic.

Punctuated Equilibrium

Observation of the fossil record reveals that ecosystems, particular assemblages of plant and animal species, can persist for a long time, perhaps millions of years, and then be replaced relatively quickly by another assemblage of species. This led two biologists, Gould and Eldredge (1977), to propose a modified theory of evolution known as *punctuated equilibrium*. A particular assemblage of biota may be stable for a long time, making slight adjustments as climate changes slowly. But this era of equilibrium is eventually "punctuated" by a burst of rapid climate change, resulting in the formation of a different assemblage of biota. This is more than the simple idea that evolution is mostly slow but sometimes fast. It suggests that natural selection operates not only on the level of individual organisms but also on the species *inter-relationships* which define an ecosystem. Today human beings are somewhat isolated from the pressures of natural selection, but the concept of punctuated equilibrium can certainly be extended to social assemblages, whose cultural, economic, and political characteristics are exposed to climate selection.

A cyclical model of evolution

It is easy to become depressed about humanity's inability to respond adequately to climate change. One of the principal messages of this essay is that while climate change in the 21st century is likely to be destructive, it also heralds an entirely new chapter of experimentation and exploration for life on earth. In order to embed the positivity of this idea, it is helpful to have a model that illustrates how living systems are adaptive, that is, how they respond to external and internal pressures. A simple *parts↔whole* model is presented here. The *panarchy* framework offers a more sophisticated model and also addresses climate change (Gunderson and Holling, 2001; Sundstrom et al., 2023).

From a systems perspective, ecosystems, social and economic systems can be understood as wholes composed of parts (plants, animals, humans, as the case may be). The important insight is that the whole and its parts cannot be understood in isolation—they are interrelated and interdependent. Living systems cycle through four stages: growth → maturity → breakdown → reorganization (Figure 8). Each stage involves a different relationship between the parts and the whole. During *growth* the whole is incorporating more parts. The key characteristic of *maturity* is an increasingly tight integration of the parts, so that eventually the system becomes brittle. As an ecological example, the Australian swift parrot (*Lanthamus discolor*) requires a combination of blue gums for foraging and nearby old tree hollows for nesting (DCCEEW, 2022, p10). Logging is destroying this combination. A more versatile species might adapt. But the swift parrot's needs are highly specific, and the bird is sliding towards extinction.

The paradox of the *maturity* stage is that its stability breeds *instability*, which leads to breakdown. From a systems point of view, an economy is also a "living" system and mature economies also become brittle, fragile, unstable. Economist Mancur Olsen drew attention to the contradictory consequences of prolonged social stability, namely "the colossal economic and political advantages of peace and stability" as opposed to "the longer-term losses that come from the accumulating networks of distributional coalitions that can survive only in stable environments." (Olsen, 1982, p233) Over time, stable societies develop rigidities, cabals and collusions that become institutionalized rent-taking[1]. And the role of the political class at such times is to preserve them.

Hyman Minsky (1992), the economist who first coined the phrase "stability breeds instability", observed that stability in financial markets becomes destabilizing because overconfident investors take on increasingly risky debt. Euphoria inevitably leads to crisis. Indeed the 2008 Global Financial Crisis was described as a "*Minsky moment*".

The transition from *breakdown* to *reorganization* is the creative phase of a life cycle. It represents a punctuation-interrupt, where there is maximum uncertainty but maximum invention. The rapid onset of a cold, arid climate may

[1] Cabals and collusions are covert, often illegal agreements between businesses to gain unfair market advantages. Rentseeking or rent-taking is the manipulation of the economic, political and social environment by individuals or groups to increase their share of wealth without producing new wealth. Corporate subsidies are an example.

represent a punctuation that repels many species. But the return of warmer conditions will herald a creative phase where new combinations of species come to the fore. Life cycles are adaptive because they combine two alternating phases—growth, accumulation, and stability alternating with breakdown, release, creative reorganization, and invention.

Another important insight of the systems approach is that adaptive life cycles are nested within one another to create the hierarchy of life. This idea is more fundamental than might first be apparent. The social systems that humans have created are today intermeshed with the climatic, biological, and ecological systems that span planet Earth. To say that life is hierarchical is to say that planet Earth is an integral whole that operates on multiple spatial and temporal scales. It is no longer valid to think of biological and social evolution as two separate systems. Evolutionary selection pressures operate on multiple levels simultaneously, that is, on genetics, physiology, psychology, social relations, economic, political and cultural expressions. But life is not infinitely malleable. Not all change pressures can be accommodated at one time. All the parts and layers of life must dance in synchrony but how such synchrony is reorganized after breakdown is beyond our understanding.

More creative than destructive

In 1986, the Indian philosopher Prabhat Ranjan Sarkar, (who founded Ananda Marga Gurukul, the educational institution that publishes this journal) presented a discourse in which he suggested that the earth's rotational poles are shifting (Sarkar, 1986). This will disrupt the "ecological order" of Earth, and, as a consequence, there will be "physical and biological changes in the structures of all living bodies, all living creatures, including plants." And if such an event occurs rapidly, "another ice-age may occur".

In a subsequent discourse, Sarkar (1990) elaborates the idea that history moves in "rhythmic waves – in a systaltic flow" where sometimes movement is slow and then suddenly there is an "epoch-making" event. This is a clear reference to the theory of punctuated equilibrium. He then asks a rhetorical question: what would be the effect on the hydrosphere if the north pole shifted eastward and the south pole westward (towards the South Pacific)? Interestingly, these directions are consistent with those recently observed by Deng et al. (2021). Sarkar answers this question by noting that parts of the Pacific will freeze and some of its existing ports will close. But the main idea to emerge from these two discourses is that the impact of coming changes to the earth and climate will affect all living species (plant, animal, human), at all levels of the hierarchical structure of life (cellular to global) and all the myriad of interrelationships between them. In short, we and our planet are facing an epoch-making event.

Even without climate change, global society is on the edge of breakdown. Climate change is hastening the process. It's frightening because what we face is the breakdown of a relatively stable living system that has been our planetary home and refuge for the past 10,000 years. But it is important to remember that climate punctuations in the past have been more creative than destructive. The great Permo-Carboniferous ice-age, 250 million years ago (Table 1) was responsible for mass extinctions, but it also ushered in an entirely new suite of experimental taxa, the reptiles, birds, and mammals. And the Quaternary ice-age cycles that pushed multiple species, including the Neanderthals, to extinction, also sculptured and burnished modern humans to become an extraordinary manifestation of life on Earth.

A question of spatial scale

According to Fagan (2004, p68, p124), our Cro-Magnon ancestors were "unfazed by climatic change". They had three survival qualities, "opportunism, flexibility, and mobility". For "opportunism" read fast learning. When the climate changed, they moved.

As the climate warmed 10,000 years ago, the option arose to stay in one place, and so began the development of agriculture. But anchored to their fields and irrigation systems, sedentary populations quickly became vulnerable to the vagaries of smaller climate-change events. Irregular fluctuations of the El Niño–Southern Oscillation (Flannery, 1994, p81), the Indian Ocean Dipole, the Intertropical Convergence Zone and the Atlantic meridional overturning current, all conspired to inflict periodic drought, sometimes with catastrophic consequences (Fagan, 2004, p187). With each passing catastrophe, the response was to centralise population and to build bigger irrigation systems. Humans discovered "the ingenious strategy of centralisation", that "an organised landscape, was the best defence against an unforgiving world" (Fagan, 2004, p145). But there was a trade-off. "In our efforts to cushion ourselves against smaller, more frequent climate stresses, we have consistently made ourselves more vulnerable to rarer but larger catastrophes" (Fagan, 2004, p xv).

Globalisation in the 21st century is the ultimate expression of centralisation. Consider the production of automobiles. The Ford Focus (assembled in the USA) imports more than 40% of its parts from Mexico, China, Canada, Japan Germany, South Korea, to name just the largest suppliers (Johnson, 2017). And of course, those countries depend on imports of raw materials from other countries. The vulnerability of globalisation became apparent during the 2020-2022 pandemic when global supply chains were disrupted, and the necessities of life were threatened. Which invites a policy question. What is the appropriate spatial scale to produce a community's necessities of life?

What to do?

A collective response to climate change comes within the jurisdiction of *public* policy. A fundamental tenet of public policy is that it should be informed by both *virtue ethics* and *science*. Virtue ethics (MacIntyre, 1984) inform us in what direction society should move. Science informs us how to get there (Towsey, 2021, p53, 83). The most important quality of virtue ethics is its ability to take human beings, individually and collectively, beyond their narrow selfish concerns. Virtue ethics is expansive, it encourages a person to embrace humanity as one family and it encourages humanity to embrace the natural world as part of itself. Importantly, virtue ethics transcends local custom because its ability to inspire is universal. Virtue ethics informs us that 21st century humans have a duty to consider the well-being of life on earth in the 22nd century. See Bussey (2023) for an elaboration of these ideas.

Concerning science, it ought not be idealized. Science is not a dogma—it can and should be questioned. But importantly, there are rules for how questions are formulated. For better or worse, science in our time of social breakdown has become another dimension of social struggle. And the outcome of that struggle determines what is accepted as knowledge and therefore permitted to inform public policy. Here we restrict ourselves to what a rational society could do based on current science. Space permits just five policy proposals:

1. Obviously, greenhouse gas emissions must be rapidly reduced by replacing fossil fuels with renewable energy sources and by changing agricultural practices.

2. Current science also tells us that the huge pulse of greenhouse gases and heat already injected into Earth's spheres (atmosphere, cryosphere, hydrosphere, biosphere) must eventually have serious consequences. Quite apart from the extreme weather events that are already with us, we should prepare for a breakdown in the global ocean conveyor belt and increased volcanic and earthquake activity as Earth adjusts to a redistribution of mass about its crust. Science does not tell us when these (tipping-point) events will occur, or where, but uncertainty ought not become inaction. Sensible preparations can be started.

3. There is an urgent need to *decentralize* the world's economies. The 2020-2022 global pandemic revealed the fragility of globalized production. An immediate start should be made to decentralize the production of the minimum requirements of life, most obviously, staple foods, housing, medical supplies, fibers, energy, and transport needs. There is no one rule. The staple foods of one country are not those of another. The orthodox investor's usual measure of efficiency (cost-benefit analysis) is not an adequate index here. The important goal is to maintain security of supply of the essentials of life in the event of prolonged and serious disruptions to extended supply chains. Different necessities of life will require different scales of production. In the economic system promoted by Sarkar, different scales of industry serve different purposes (Towsey, 2009a). As an example, consider how a country goes about the adoption of renewable energy. In Australia, the abundance of (decentralized) solar power does not interface well with its existing highly centralized electricity grid. The orthodox response has been to extend the grid and keep electricity distribution under the control of a few powerful suppliers. A better approach would be to build local area networks, each with its own storage. Local networks can

later be connected in such a way that one local failure does not disrupt other local networks.

4. An important policy issue is the part that carbon capture and storage, nuclear energy and hydrogen might play in the future. In the opinion of this author, none of these options currently deserves serious investment because they are highly complex technologies that demand centralized control. That is why they are promoted by powerful interests, but they do not satisfy today's requirement that to survive is to be agile.

5. As discovered by early settled communities, "an organised landscape" is an essential defence against an "unforgiving world" (Fagan, 2004, p145). This will be especially true in coming decades. But it will require global coordination because a balance of ecosystems is necessary across the planet (Towsey, 2009b). Reforestation and afforestation programmes must certainly be part of the policy mix but, by themselves, they will not keep pace with current CO_2 emissions. As a step in this direction, the 2022 United Nations' biodiversity agreement to protect 30% of the world's land and water as wilderness by 2030 is a truly momentous agreement (UNEP, 2022). Likewise, global conservation efforts are both encouraging and heartwarming. But the requirement for global coordination raises another question: how to mesh global coordination with decentralized economies? Sarkar's reply is to combine political centralization with economic decentralization (Sarkar, 1982, 1988). How to achieve this is a topic for another time.

> *It [climate change] may be for the good, it may be for the bad, but change is a must. In the case of such a change in the physical order and also in the physico-psychic order, the change is sure to take place [also] in the realm of spirituality. We hope that the movement – that is, the movement of humanity, and of each and every living being – is from matter to consciousness, from extroversion to introversion. So, the thought waves of human beings will be more of a spiritual nature than they are at present.* (Sarkar, 1986)

The complete article with references is available at: theneohumanist.com/2023/10/23/climate-change-from-the-deep-past-to-the-22nd-century