Article

Climate Uncertainties: a Personal View

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Abstract: This essay takes a brief personal look at aspects of the climate problem. The emphasis will be on some of the greatest scientific uncertainties, as suggested by what is known about past as well as present climates, including tipping points that likely occurred in the past and might occur in the near future. In the current state of knowledge and understanding, there is massive uncertainty about such tipping points. For one thing there might, or might not, be a domino-like succession, or cascade, of tipping points that ultimately send the climate system into an Eocene-like state, after an uncertain number of centuries. Sea levels would then be about 70 m higher than today, and surface storminess would likely reach extremes well outside human experience. Such worst-case scenarios are highly speculative. However, there is no way to rule them out with complete confidence. Credible assessments are outside the scope of current climate prediction models. So there has never in human history been a stronger case for applying the precautionary principle. Today there is no room for doubt—even from a purely financial perspective—about the need to reduce greenhouse-gas emissions urgently and drastically, far more than is possible through so-called 'offsetting'.

Keywords: climate uncertainties; tipping points; carbon-cycle instability; palaeoclimate; Dansgaard–Oeschger warmings; weather extremes; Eocene; whales; dolphins.

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1. Introduction

The climate problem is by far the most complex of all the problems confronting humanity today. It involves not only the complexities of human behaviour and the human brain but also a vast, multi-scale jigsaw of other interacting pieces, from global-scale atmospheric and oceanic circulations through cyclones and thunderstorms all the way down to the scales of forest canopies, soil ecologies and mycorrhizal networks, coral reefs, phytoplankton, bacteria, archaea, viruses, and molecules. Millimetre-scale ocean eddies shape global-scale deep-ocean structure and carbon storage (e.g., [1]), alongside deep overturning circulations and plankton ecologies (e.g., [2,3]). Ice sheets flow and melt, or shatter, in dauntingly complex ways, eluding accurate modelling. Many of the processes are strongly nonlinear, leading to chaotic dynamics and belying the linear-theoretic assumptions behind such terms as 'climate sensitivity'.

Nearly all the real complexity is outside the scope of any climate prediction or assessment model, or carbon-cycle model, or ice-flow model, or purely data-based statistical or machine-learning model. Of course the models can be valuable and important when used in ways that respect their limitations (e.g., [3–5]).

This short essay reflects the author's belief, based on a lifetime of research experience, that to develop the best possible scientific understanding of any problem one has to keep looking at it from all possible viewpoints. It is important to maintain a certain humility and to resist the urge to rely on a single viewpoint, based for instance on a particular kind of model.

So the idea here is to step aside from climate-model predictions and to explore some other ways to think about the most troublesome uncertainties. They include the uncertainties about how climate and weather might or might not behave over the next few decades and centuries, and whether human civilization might or might not survive.

The discussion will pay special attention to climates over the past several tens of millennia. Past climates are our main source of information about the workings of the real system, taking full account of its vast complexity. It is for the past several tens of millennia that we have the most detailed information. Also, by comparison with the range of climate-system states in the more distant past—including the hothouse, ice-free early Eocene beginning around 56 Ma (millions of years before present)—the states of the system during past tens of millennia were relatively close to its present state. See for instance Section 1.9 of [6]. That said, we need to remember that the system is now moving toward new, unfamiliar, and unprecedented states, with unprecedented rapidity.

During past tens of millennia there were abrupt climate changes called Dansgaard–Oeschger warmings. The temperature changes were huge, at least several degrees Celsius and perhaps even ten degrees or more, in the North Atlantic area. As discussed in Section 2 below each change took only a few years, in some cases at least, and showed up in palaeoclimatic records across most of the Northern Hemisphere [7–11]. Changes taking only a few years, or even decades, are practically instantaneous from a climate-system perspective. They warn us that we must take seriously the possibility of so-called tipping points in the dynamics of the real climate system, possibly in a domino-like succession or cascade; see also [12–14] and references therein. The warning is needed because it is sometimes thought that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamical-systems researchers; see for instance pp. 138–141 of [5].

It has been suggested that for the real system a tipping point some of whose mechanisms resemble those of the Dansgaard–Oeschger warmings might well be reached in the near future, meaning sometime in the next few decades or even sooner; see [10,11] and references therein. One consequence would be a sudden acceleration in the rate of disappearance of Arctic sea ice. That possibility will be discussed in Section 2. As far as the author is aware, no such tipping points have shown up in the behaviour of our biggest and most sophisticated climate-prediction models. As will be recalled in Section 2, the suggested tipping-point behaviour depends on fine details that are not fully resolved in the models, including details of the sea ice and the layering of the upper ocean.

Other possible tipping points have been suggested for the real system, over a range of timescales. Some of them are briefly recalled in Sections 3 and 4.

Also of concern are increases in the frequency and intensity of destructive weather extremes—as already observed in the last several years—and the question of how much further the increases will go, how soon, and by precisely what stages. That question is, of course, bound up with the question of tipping points. Encountering a tipping point could produce a sudden worsening of the extremes.

A failure to simulate many of the extremes themselves must count as another limitation of the climate models, especially extremes of surface storminess. The reasons are again related to model resolution, and are briefly recalled in Section 5. Some concluding remarks are offered in Section 6, which despite everything dares to end on a note of cautious optimism.

2. Dansgaard–Oeschger Warmings

During the past 80 millennia there were twenty abrupt warmings called Dansgaard–Oeschger warmings, or Dansgaard–Oeschger events [9] of which the most recent, conventionally designated event number 1, took place around 14.5 ka (millennia before present). Event number 2 took place around 23 ka, number 3 around 28 ka, and number 9 around 40 ka. Event number 1 is also called the Bølling–Allerød warming. There was a later and somewhat similar, so to speak 'zeroth', warming event at around 11.5 ka [8], ushering in the relatively warm and stable Holocene that made agriculture and cities possible. It terminated a cold period, around 13–11.5 ka, called the Younger Dryas.

Broadly speaking, as [10] puts it, in each case the temperature evolution has a "qualitatively similar" palaeothermometric signature, "about 1000 years of relatively stable cold conditions, terminated by an abrupt (less than 10 years) jump to much warmer conditions that persist for 200–400 years." These jumps are well clear of the error noise. Palaeothermometry and its uncertainties are discussed in Section 1.7 of [6]. Timescales less than 10 years for the temperature jumps in question are most clearly evidenced in ice cores from Greenland, thanks to countable annual layers in the ice. As noted in [8], "these records provide annual resolution for some indicators through 110,000 years... and provide an exceptionally clear picture of events in Greenland (temperature and accumulation [of snow]), regionally (wind-blown sea salt and continental dust), and more broadly (trapped-gas records, especially of methane)."

These indicators, all within precisely dated ice-core records, provide strong evidence not only for the extreme rapidity, the step-like nature, of the upward temperature jumps, but also for accompanying impacts that were widespread and close to synchronous across the northern hemisphere. Other palaeoclimatic records, such as those in sediment cores from oceans and lakes, and in speleothems or cave deposits, are consistent with these statements after allowing for dating uncertainties and lower time resolution. See [7] and references therein, and again Section 1.7 of [6], for further discussion of the evidence and its uncertainties.

Zooming in to finer details, one can see that the warming events often seem to have involved more than one sharp jump. For instance [8] states that "For the best-characterized warming, the end of the Younger Dryas cold interval $\approx$ 11,500 years ago, the transition in many ice-core variables was achieved in three steps, each spanning $\approx$ 5 years and in total covering $\approx$ 40 years... most of the change occurred in the middle of these steps..."

The mechanisms in play are very complex, as discussed in a vast literature including, for instance, [7,9–11]. In particular, the warming events involved big changes in global-scale oceanic and atmospheric circulations, and in sea-ice cover especially in the Nordic Sea area between Scandinavia and Greenland. However, with one exception the mechanisms considered have timescales too long to produce sharp steps. The exceptional mechanism—the only mechanism suggested so far that is fast enough (see [10,11] and references therein)—involves the Nordic sea ice and the fine structure of upper-ocean layering just underneath the ice.

The suggested mechanism depends on the northward inflow of warm, salty subsurface Atlantic water under the sea ice. During cold intervals, so-called stadials, the uppermost layers of the Nordic Sea were stably stratified with a strong halocline separating the warm, salty subsurface Atlantic inflow from the colder, fresher, more buoyant upper layers capped by sea ice. This state of things during the stadials, including the presence of sea ice, is evidenced in ocean sediment cores from the Nordic Sea region [10,11] showing planktic and benthic species and isotope abundances. However, a sufficient increase in subsurface temperatures can lead to the subsurface water becoming buoyant enough to break through to the surface. That is a relatively sudden way of melting the sea ice.

When such sudden sea-ice melting happens over a substantial area, or in steps over a succession of substantial areas, the atmosphere can respond quickly with major changes in its weather patterns, leading to the hemispheric-scale effects seen in the palaeoclimatic records of Dansgaard–Oeschger events.

Today it appears from recent underwater measurements, in the years 2003–2018 [15], that some areas in the Arctic Ocean, in the Eastern Eurasian Basin, may be approaching a similar state albeit still short of buoyant breakthrough. Figure 11 of [15] summarizes how the observed conditions show a weakening halocline being eroded by turbulent mixing, allowing more subsurface heat to reach the surface, at rates that have increased from $\sim$3–4 W m^{-2} in 2007–08 to $\gtrsim$10 W m^{-2} in 2016–18. So it seems likely that, as buoyant breakthrough conditions are approached, the current rate of melting of sea ice—already accelerating through the well known ice-albedo feedback—will accelerate further and more drastically. As with the Dansgaard–Oeschger warmings, there could be several such episodes of increased acceleration in quick succession as, stepwise, different areas of sea ice are melted.

It is extremely hard to predict exactly what will happen, and exactly when, since in climate models the fine structure of the upper ocean and its halocline and sea ice, and the associated buoyancy-related and turbulent mixing processes, are not accurately represented in enough detail. Nor are the subsurface ocean currents and eddies. However, an educated guess would be to anticipate a drastic acceleration of Arctic sea-ice loss quite soon, perhaps over the next decade or so, with knock-on effects that could include accelerated melting of the Greenland ice sheet.

3. Ice-Flow Uncertainties

The stepwise sudden shattering of the Larsen A and B Ice Shelves, off the Antarctic Peninsula, in 1995 and 2002 respectively, was a timely reminder of the complexities of real ice flow. See for instance [16]. The consequences of such shattering events are not confined to the marine side of the picture. As long as a marine ice shelf holds together across an embayment, it can have a buttressing effect that reduces the flow rate of ice coming off adjacent land surfaces. These and other ice-flow complexities are now under intense scrutiny by glaciological researchers. Inevitably, though, the complexities are far from being accurately represented in any climate model.

Ice-flow modelling is peculiarly difficult because of its dependence on fracture and stress patterns affecting, for instance, the frictional properties and velocities of the glacier-like ice streams found within ice sheets. There is a complex interplay with meltwater, for instance in meltwater flow networks beneath grounded ice and in ice-cliff instabilities [17–19].

An important process is the 'hydro-fracture' caused by surface meltwater chiselling its way down through an ice sheet. The meltwater, being denser than the surrounding ice, can in some cases force a crevasse to open all the way to the bottom of the ice sheet. That is how the Larsen B ice shelf was shattered [16]; and the phenomenon has also been observed on parts of the Greenland ice sheet [18], whose melting rate has accelerated in recent years [20]. Hydro-fracture can also be important in ice-cliff instabilities [4].

A major overall challenge to ice-flow modelling—a challenge as yet unmet as far as the author is aware—again comes from looking further back in time. It is the challenge of understanding what are called Heinrich events. During the past 80 millennia, for instance, there were six such events. Their imprint is conspicuous in North Atlantic ocean sediment cores, which contain layers of ice-rafted rocky debris originating on the North American or European land mass, or on both. The debris must have been carried by massive ice flows that eroded the rocks, then spread out into the ocean as icebergs. On melting, they dropped large amounts of rocky debris on to the ocean floor, in locations well away from land. The ice flows that began this process might have been large-scale versions of the ice streams observed today within the Greenland and Antarctic ice sheets. Surprising though it may seem, without exception they all occurred not in the warmest but in the coldest intervals, or stadials, in between some of the Dansgaard–Oeschger warmings. Geothermal heating at the base of the ice might have played a role, but the details remain obscure. Any claim to have created a comprehensive ice-flow model would need to show that it can explain Heinrich events.

In today's conditions, the Pine Island and Thwaites areas in West Antarctica are of special concern. Observations there point to the likely relevance of all the abovementioned complexities, including ice streams and their fracture and friction patterns as well as possible large-scale instabilities, associated with the fact that the West Antarctic Ice Sheet is grounded below sea level at depths that increase with distance into the ice sheet from its edge. Such an ice sheet can be subject to a large-scale instability in which seawater intrudes further and deeper underneath the ice, while the ice flow rate accelerates over a large area. The instability is another example of tipping-point behaviour. Some researchers believe that in the Thwaites area a tipping point of this kind has already been passed [19].

Figure 4 of [4] supports such a scenario, on the basis of an improved ice-flow model that tries to allow for hydro-fracture. It predicts several metres of sea-level rise over the coming century—far more than in any intergovernmental climate report so far—and many more metres over longer timescales. Precisely how much more, and how much longer, remains highly uncertain.

There is a different, and much simpler, ice-sheet mechanism with tipping-point potential, though with a longer time horizon. It has been suggested as first becoming significant for the Greenland ice sheet [20]. This mechanism goes by the self-explanatory name 'melt–elevation feedback'. It kicks in as soon as the upper surface of an ice sheet is lowered significantly. Other things being equal, the upper surface is then exposed to higher air temperatures, and more rainfall relative to snowfall, speeding up the melting in a self-reinforcing feedback process that may well, again, involve hydro-fracture.

4. Two Other Tipping Points

There is no space in this short essay to discuss all the other tipping-point possibilities that have been proposed for the Earth's climate system. Many of them, including spontaneous-deforestation scenarios, have been extensively discussed elsewhere, for instance in [12–14]. One possibility less often discussed, but of possible importance in a future tipping-point cascade, is a carbon-cycle disruption in the form of a nonlinear instability linked to upper-ocean acidification. There is evidence that tipping points due to such instabilities have occurred in the past, some of them associated with mass extinctions [3].

The rate at which carbon dioxide, CO_2, is drawn down from the atmosphere into the oceans depends among other things on what is called the biological 'pump'. It is a complex set of processes whose net effect is to pull carbon out of the atmosphere and to export some of it downward into the abyssal ocean. These processes depend on ocean ecologies and their food chains, beginning with photosynthesis by phytoplankton.

The downward carbon export involves among other things the sinking of 'marine snow' containing excrement and plankton corpses. The rate of export is increased by the mineral shells of some of the plankton—both phytoplankton and zooplankton—through a 'ballast effect' from the relatively high density of the shells' material. None of this can be modelled accurately, if only because it depends on aggregation or clumping effects in the 'snow' as well as on the interplay with bacteria, archaea, and viruses encountered at various depths, and on active vertical transport by swimming organisms.

The point made in [3]—for further explanation see [21]—is that the biological pump might encounter a tipping point when the upper ocean is exposed to some threshold level of atmospheric CO_2. The threshold depends on the exposure time. Shorter times require larger atmospheric CO_2 concentrations, if the threshold is to be exceeded. When it is exceeded, a positive feedback kicks in, whereby upper-ocean acidification due to excess CO_2 kills increasing numbers of the plankton that form carbonate mineral shells, including phytoplankton such as coccolithophores, and zooplankton such as planktic foraminifera. The shells cannot form when the pH is too low. The ballast effect is reduced and the biological pump weakened, which in turn increases the rate of upper-ocean acidification and further reduces, or extinguishes, populations of carbonate-shelled plankton. On the basis of a simplified model and palaeoclimatic data, [3] concludes that we could be close to threshold conditions today.

Another mechanism of possible importance in a future tipping-point cascade is the release of methane from frozen methane hydrates or clathrates in cold marine sediments, or from the so-called tundra permafrosts now becoming impermanent, or from underneath an ice sheet such as Greenland's once it melts. Again there are large uncertainties. In particular, the amounts of stored methane are not accurately known, but are probably large. Table 1 of [22] lists total amounts of proven and estimated fossil-fuel reserves including coal, oil, shale gas, tar sands and methane clathrates. Subject to large uncertainties, the total amount of methane stored in clathrates is estimated to be of the order of 100 times that in proven reserves of conventional natural gas. Section 4.5.4 of [6] reminds us of the potency of methane as a greenhouse gas.

Here the time horizon is further away—probably by a few centuries—than for Arctic sea ice or the West Antarctic Ice Sheet. However, like other mechanisms with longer time horizons it could still be relevant to the possibility of an irreversible tipping-point cascade pushing the Earth toward an Eocene-like state, over an uncertain number of centuries. In that connection it is perhaps worth noting that, almost certainly, the Sun is nearly half a percent stronger today than it was at the time of the early Eocene [23,24], though this would be only a small added effect by comparison with the effect of elevated greenhouse-gas levels—mostly CO_2 at the time of the Eocene, but possibly added to in future by potent long-lived industrial greenhouse gases like sulphur hexafluoride.

5. Weather Extremes, Whales, and Dolphins

Another limitation of climate models is that they underpredict many kinds of devastating weather extremes. With the exception of large-scale heat waves and firestorms, such as that of summer 2021 in western parts of Canada and the USA, and large-scale outbreaks of freezing weather, such as that of February 2021 in Texas—both of which were associated with amplified jet-stream meanders—most of the extreme behaviour depends on scales of fluid motion far smaller than the scales resolvable by climate models.

The simplest and clearest case is that of cumulonimbus rainstorms and thunderstorms. Recent real-world examples include the extreme rainfall and flash flooding of July 2021 in northwestern continental Europe, the Kentucky tornado holocaust of December 2021, and the devastation of Petrópolis, near Rio de Janeiro, in mid-February 2022.

Such extremes are well outside the scope of any climate model. The airflow into cumulonimbus clouds takes place on spatial scales so small that, even with today's computing power, they are only just beginning to be resolved in the most computationally expensive local operational forecasting models. The parametrizations used by climate models, and by global forecasting models, to allow for unresolvable small-scale motion are unsuited to capturing sharply-localized extreme behaviour.

However, the airflow into a single cumulonimbus cloud is accessible to the simplest of fluid-dynamical intuitions. The cloud is like a tall vacuum cleaner, pulling in air from its low-level surroundings. The flow is powered by the 'weather fuel' it pulls in.

Water vapour can reasonably be called 'weather fuel' because of the latent energy released when it condenses. The Clausius–Clapeyron relation says that air can hold around six or seven percent more weather fuel for each degree Celsius of temperature increase. So global warming is global fuelling.

Other things being equal, a cumulonimbus cloud that happens to be surrounded by more weather fuel will pull the fuel in faster and reach a greater peak intensity sooner. That is a robust and powerful positive feedback mechanism, leading to heavier and more sudden downpours and heavier flash flooding.

In the early Eocene, the same robust feedback would likely have made some of the cumulonimbus storms more violent and devastating than anything within human experience. There is geological evidence of massive erosion by storm-flood events in the early Eocene [25], especially at the time of the PETM (the Palaeocene-Eocene Thermal Maximum around 56 Ma), with temperatures $\sim 5\,^{\circ}$C higher than today. Furthermore, there is an independent line of evidence. Whales, dolphins, and other aquatic mammals exist today. According to the fossil record and genetic evidence, their land-dwelling ancestors began taking to the seas around the time of the early Eocene; see [26] for instance, and references therein.

Was this a mere accident? What could have induced land-dwelling mammals to take to the seas, and to do so at that particular time? Why did some of them become fully aquatic within a mere few million years? Selective pressures from extremes of surface storminess can begin to make sense of those extraordinary evolutionary events. They could have begun with hippo-like behaviour, in which the water was no more than a refuge from the storms [26].

6. Concluding Remarks: the Amplifier Metaphor

The climate disinformation industry—see for instance [27]—has long proclaimed that the uncertainties, and the climate-model limitations, mean that there is no cause for concern pending further assessment. The author hopes that the points made above might reinforce the case, and suggest additional ways of communicating that, on the contrary, those uncertainties and limitations have always been reasons for being more concerned and not less. Further discussion and literature references on the issues involved—and on the powerful psychological methods used by the disinformation industry, exploiting 'language as a conceptual minefield'—can be found in a recently published book [28].

On climate, [28] includes a discussion of extreme cyclonic storms (pp. 140–143). Climate-model limitations include an inability to represent such extremes, for extratropical as well as tropical cyclones. The scientific issues for such extremes are much more complex and difficult to argue than for cumulonimbus storms. They involve not only cumulonimbus clouds embedded within the cyclones and, in the extratropical case, local extremes of baroclinicity and low-altitude "conveyor belts" bringing in weather fuel, but also jet stream meanders and the whole jigsaw of global teleconnections. The same difficulties impede assessments of extreme cyclones in the Eocene.

In today's world, however, real examples have been accumulating. A recent example was Storm Arwen, which in November 2021 devastated parts of the northern UK, and took the utility companies by surprise with electrical power outages lasting several weeks.

Of course models of weather and climate remain a valuable and important part of our scientific arsenal, as was acknowledged at the start; and there has been much excellent work on improving the models and on developing the art of exploiting them in suitable ways [5]. Included are remarkable efforts at combining coarse-resolution climate models with high-resolution operational weather-forecasting models, in a nested configuration; see [28] and references therein. As noted there, however, regarding such developments, the challenge of bringing them closer to the problem of weather extremes "is still one of the toughest of all the challenges facing climate science" (p.142). Even in the nested models the most highly resolved regions do not yet accurately capture, for instance, the sharply-localized details of the airflow through individual cumulonimbus clouds. The main point here, though, is the precautionary principle. We cannot now afford to await further model developments.

Another theme in [28] is the idea of an 'amplifier metaphor' for climate. It is a way of emphasizing that some parts of the climate system are more sensitive than others, a point that the disinformation industry has always worked hard to obscure. Even within the scientific community the point has been obscured, sometimes, by too much focus on gross energy budgets. What matters here is that the system is far more sensitive to human inputs of non-condensing greenhouse gases, such as CO_2 and CH_4 (methane), and fluorocarbons, and sulphur hexafluoride, than it is to human inputs of water vapour. Of course the climate 'amplifier' is highly nonlinear, and in that respect quite unlike an ordinary audio amplifier.

Water vapour, in its role as weather fuel, can be seen within the metaphor as part of the amplifier's power-supply circuitry, conspicuous in an energy budget. For instance the rate at which the latent energy in water vapour is exported from the tropics and subtropics—of the order of one or two petawatts, comparable to detonating a one-megatonne nuclear weapon every few seconds—dwarfs any human input of water vapour. By contrast, the non-condensing greenhouse gases can be seen as part of the amplifier's sensitive input circuitry.

The CO_2 input signal from fossil-fuel burning can hardly be considered small, as claimed by the disinformers when they compare atmospheric CO_2 with atmospheric water vapour. That input has already pushed atmospheric CO_2 far outside its natural range of variation in the recent past—now meaning the past few hundred millennia—despite the substantial fraction that has gone into the oceans. The natural range, ~ 100 ppmv (parts per million by volume), is the parameter against which present and future atmospheric CO_2 changes should be compared. It is one of the most securely known properties of the real climate system, being known from meticulously cross-checked work on Antarctic ice cores, taking advantage of the great chemical stability of CO_2 both when in the atmosphere and when trapped in unmelted ice. In round numbers, atmospheric CO_2 variations had a peak-to-peak amplitude $\sim$100 ppmv across the entire range of conditions, the huge climate contrasts, that were encountered in the glacial-interglacial cycles of the past few hundred millennia. See for instance Figure 3 of [28].

When viewed in this way, then, the climate change and weather extremes now apparent are no surprise at all. We have an amplifier subject to an increasingly large input signal—increasingly large, that is, by comparison with the natural range 100 ppmv, the natural benchmark of comparison—and continuing to increase at a rate that seems slow to us humans but is extremely fast from a climate-system perspective. In the 'business as usual' scenarios promoted by the climate disinformation industry, atmospheric CO_2 would reach values of the order of 800 ppmv this century, representing an increase since glacial times (when CO_2 was just under 200 ppmv) of the order of *six times* the natural range.

All this has been well recognized in scientific circles for some time but the implications are now, it appears, increasingly recognized in wider public communities as well. With climate, as with the earlier examples of the Antarctic ozone hole, and tobacco and lung cancer [27], there is now reason to hope that the disinformation industry, while still powerful, has ceased to be the overwhelming political influence. As noted in [28], "all three cases show the same pattern: disinformation winning at first, then defeated by a strengthening of the science along with a wave of public concern powered by real events" especially, one might add, within younger generations such as Generation Z, defined by sociologists as those born between 1997 and 2012. In addition—and another reason to be hopeful—there is the new economic reality around energy from renewables and battery storage, now inherently cheaper than fossil fuels as demonstrated at scale in, for instance, the state of South Australia. Indeed events in Ukraine now remind us of something that has become more and more conspicuous over the past two decades, that reliance on fossil fuels comes at a heavy geopolitical as well as financial cost.

Economic forces are powerful in themselves, and along with public concern may help to counter today's rearguard action by the disinformation industry, which includes the deception that fossil-fuel burning without carbon capture and storage can continue to be promoted and subsidized through being 'offset' at modest cost. Ref. [29] discusses the scale of this deception. The word 'offset' well illustrates language as a conceptual minefield because it embodies an unconscious assumption that the effects of fossil-fuel burning are fully compensated as they occur, instead of partially compensated decades into the future. The technologies required for a full and immediate offsetting are nowhere near being developed and implemented at scale. However, our younger generations, especially, allow some optimism that more and more people will see through deceptions of this kind, as the weather extremes ramp up over the coming years.

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