Climate tipping points: A personal view

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CLIMATE TIPPING POINTS: *A personal view*

Michael Edgeworth McIntyre

The worst uncertainties about climate change are outside the scope of climate models but can be thought about in other ways—especially by learning from past climates.

Earth's future climate might or might not have a domino-like succession of tipping points that turns the system into a hothouse after an uncertain number of centuries. Sea levels would rise by about 70 m, and new extremes of surface storminess would likely lie well outside of human experience. Such worst-case scenarios are highly speculative. But they cannot be ruled out with complete confidence in the present state of climate science and climate modeling. So there has never in human history been a stronger case for applying the precautionary principle. Today there is no room for doubt about the need to reduce net greenhouse gas emissions urgently and drastically, far more than what is possible through so-called offsetting by, for example, planting trees, which can compensate for the emissions but not quickly enough.

I come to such issues not as a mainstream climate scientist but as an expert on fluid dynamics—more specifically on problems such as understanding atmospheric jet streams and their oceanic cousins like the Gulf Stream. My research group was never funded for climate science. My work on the fluid dynamics of jet streams has, however, brought me close to mainstream climate science.

Arguably, the climate problem is by far the most complex of all the problems confronting humanity today. It involves not only the complexities of human behavior and the human brain but also a vast, multiscale jigsaw puzzle of other interacting pieces, from global-scale atmospheric and oceanic circulations, through cyclones and thunderstorms, and all the way down to the scales of forest canopies, soil ecologies and mycorrhizal networks, phytoplankton, bacteria, archaea, viruses, and molecules. Millimeter-scale ocean eddies shape global-scale deep-ocean structure and carbon storage.[1] Also crucial to carbon storage are deep overturning circulations and plankton ecologies.[2] Ice sheets flow and melt or shatter in dauntingly complex ways, which elude accurate modeling. Some scientists dismiss some pieces of the jigsaw puzzle as unimportant, but I think that there can be no such certainty about any of them.

Nearly all the climate system's real complexity is outside the scope of any model, whether it's a global climate model that aims to represent the climate system as a whole or a model that only simulates the carbon cycle, ice flow, or another subsystem. The same goes for purely data-based statistical or machine-learning models. A common misconception is that uncertainties about the real climate system can be estimated from the variability within and between climate models. Of course, the models can be valuable when used in ways that respect their limitations.[3]

I believe that to develop the best possible scientific understanding of any problem, one must keep looking at it from all possible viewpoints and lines of evidence. It's important to maintain a certain humility and to resist the urge to rely on a single viewpoint based, for example, on a particular kind of model.

This article steps aside from model predictions and instead explores 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 will survive.

Information from the past

Paleoclimates are our main source of information about the workings of the real climate system. That information takes full account of its complexity. Researchers have the most detailed observations on the last several tens of millennia, when the system was fairly close to its present state.

During that time, there were abrupt climate changes called Dansgaard–Oeschger warmings, which occurred at irregular intervals of several millennia or so. In the North Atlantic area, the temperature rose by at least several degrees Celsius and perhaps even more than 10 °C. In some cases, warming events took only a few years and appear in paleoclimate records across most of the Northern Hemisphere.[4–8] Changes taking only a few years are almost instantaneous from a climate-system perspective. They're a warning to take seriously the possibility of tipping points in the dynamics of the real climate system.[9] The warning is needed because some modelers have argued that tipping points are less probable for the real climate system than for the simplified, low-order climate models studied by dynamic-systems researchers.[3]

Other researchers, however, have suggested that such a tipping point may be reached sometime in the next few decades or even sooner.[6,7] Some of its mechanisms resemble those of the Dansgaard–Oeschger warmings and would suddenly accelerate the rate of disappearance of Arctic sea ice. As far as I am aware, no such tipping points have shown up in the behavior of the biggest and most sophisticated climate models. The suggested tipping-point behavior depends on fine details that are not well resolved in the models, including details of the sea ice and the layering of the upper ocean.

Also of concern are increases in the frequency and intensity of destructive weather extremes. Such increases have already been observed in recent years. Climate scientists are asking how much further the increases will go and precisely how they will develop. That question is, of course, bound up with the question of tipping points. A failure to simulate many of the extremes themselves, especially extremes of surface storminess, must count as another limitation of the climate models. The reasons are related to the resolution constraints of climate models.

Warmings and sea ice

How do we know that the Dansgaard–Oeschger warmings were almost instantaneous? The answer comes from Greenland ice-core records, which have countable annual layers. As noted by ice-core expert Richard Alley, "these records provide annual resolution for some indicators through 110,000 years."[4] The indicators in the ice cores are measured variables such as chemical concentrations and isotope ratios in the ice, in trapped air bubbles, and in dust from various sources. Oxygen and hydrogen isotopes are known to be correlated with temperature

FIGURE 1. AN ICE CHUNK fell from Grey Glacier in Chile in 2009. Such collapses may happen for several complex, interrelated reasons, including friction patterns, hydrofracturing, and intruding seawater. To improve the scientific understanding of climate tipping points, all of those complexities and their uncertainties need to be observed and modeled as a whole. (Photo by iStock.com/gcoles.)

changes. The precisely dated ice-core records provide evidence not only for the extreme rapidity and the steplike nature of the North Atlantic temperature jumps but also for the consequences of those jumps, which were widespread and close to synchronous across the Northern Hemisphere.

When viewed in finer detail, the warming events often seem to have involved more than one sharp stepwise jump within a few decades, with each jump taking only a few years. The mechanisms in play are exceedingly complex. In particular, the warming events are related to global-scale oceanic and atmospheric circulations and sea-ice cover, especially in the Nordic Seas, between Scandinavia and Greenland.[5–8] With one exception, however, the mechanisms considered have time scales too long to produce the sharp jumps. The exceptional mechanism—the only mechanism suggested so far that is fast enough—involves the Nordic sea ice and the fine structure of upper-ocean layering underneath the ice.[6,7]

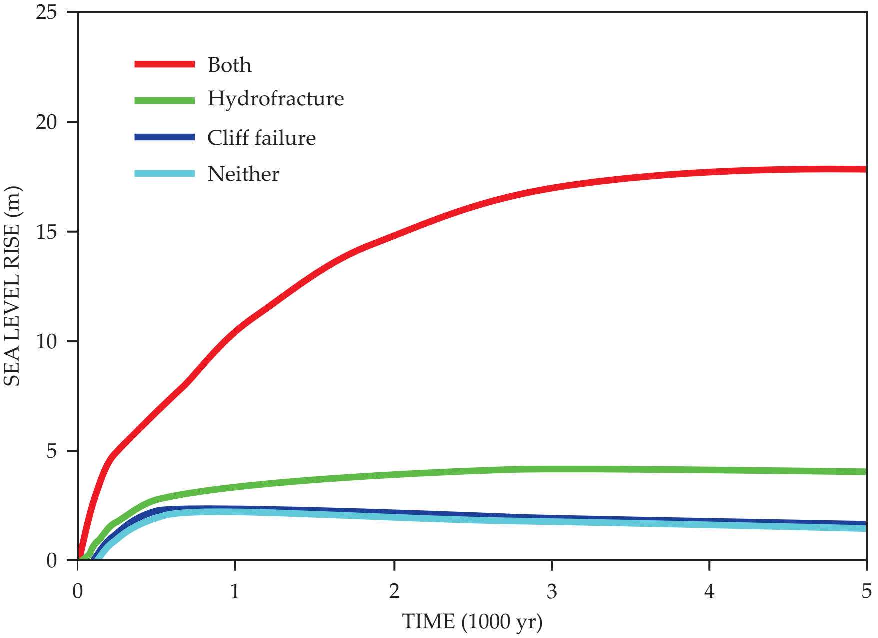

FIGURE 2. SEA LEVELS are predicted to rise with or without hydrofracturing and one of its consequences, ice-cliff failure, according to an improved ice-flow model. (Adapted from ref. 15.)

The exceptional mechanism depends on the northward inflow of warm, salty subsurface Atlantic water under the sea ice. During cold intervals, the uppermost layers of the Nordic Sea were stably stratified with a strong halocline—a boundary that separates the warm, salty subsurface Atlantic inflow from colder, fresher, more buoyant upper layers capped by sea ice. That stratification and the presence of sea ice is supported by evidence in ocean sediment cores from the Nordic Seas region that show planktonic and benthic species and isotope abundances.[6,7] But if the subsurface inflow warms enough, the water can become sufficiently buoyant to break through the halocline and up to the surface, where it quickly melts 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 on a hemispheric scale.

Today some areas in the Arctic Ocean may be approaching a similar state, albeit still short of buoyant breakthrough.[10] Recent underwater observations made in 2003–18 show a weakening halocline being eroded by turbulent mixing, which allows more subsurface heat to reach the surface, at rates that increased from 3–4 $\mathrm{W\,m^{-2}}$ in 2007–08 to about 10 $\mathrm{W\,m^{-2}}$ in 2016–18. As buoyant breakthrough conditions are approached, the current rate of sea-ice melting—already accelerating through the well-known ice-albedo feedback—may likely accelerate further and more drastically. As with the Dansgaard–Oeschger warmings, there could be several such episodes of increased acceleration as different areas of Arctic sea ice are melted in a stepwise fashion.

Exactly what will happen is extremely hard to predict since, in climate models, the fine structure of the upper ocean with its halocline and sea ice, the associated buoyancy-related and turbulent-mixing processes, and the subsurface ocean currents and eddies are not accurately represented in enough detail. But an educated guess would be to anticipate a drastic acceleration of Arctic sea-ice loss quite soon, perhaps over the next decade or two, with knock-on effects that could include accelerated melting of the Greenland ice sheet.

Ice-flow uncertainties

The stepwise sudden shattering of the Larsen A and Larsen B Ice Shelves off the Antarctic peninsula in 1995 and 2002, respectively, reminded scientists of the complexities of ice flow. 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. Those and other ice-flow complexities are under intense scrutiny by glaciologists (see the article by Sammie Buzzard, Physics Today, January 2022, page 28). Inevitably, though, the complexities are far from being accurately represented in any climate model.

Ice-flow modeling is peculiarly difficult because of its dependence on the fracture and stress patterns involved. Some of those include ice-cliff failure, as illustrated in figure 1, and the frictional properties and velocities of the glacier-like ice streams found in ice sheets. Ice streams flow faster than their surroundings because of fractures and weakened friction at their sides. In addition, there is a complex interplay with the meltwater flow networks beneath grounded ice, which can lubricate the bulk ice flow.[11,12]

An important process is so-called hydrofracturing that's caused by surface meltwater chiseling its way down through an ice sheet. The meltwater, being denser than the surrounding ice, can sometimes 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.[13] The phenomenon has also been observed on parts of the Greenland ice sheet,[11] whose melting rate has accelerated in recent years.[14] Hydrofracturing is also involved in ice-cliff failure.[15]

A major overall challenge to ice-flow modeling—a challenge as yet unmet as far as I am 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, 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 landmass. The debris must have been carried by huge ice flows that eroded the rocks and then spread out into the ocean as icebergs. While melting, the icebergs dropped the debris to the ocean floor. The ice flows that began the process might have been large-scale versions of the ice streams observed today in the Greenland and Antarctic ice sheets. Lubrication via geothermal heating at the base of the ice might have contributed, but the details remain obscure.

In today's conditions, the Pine Island and Thwaites areas in West Antarctica are of special concern. Observations at those locations point to many complexities, including those already mentioned. The complexities include ice streams and their fracture and friction patterns as well as a possible large-scale instability, which is 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. The instability is characterized by seawater intruding farther and deeper under the ice, allowing the ice flow rate to accelerate over a large area. The instability is another example of tipping-point behavior. Some researchers believe that, in the Thwaites area, a tipping point of that kind has already occurred.[12]

About 3 m of sea-level rise over the coming century, shown in figure 2, has been predicted by using improved ice-flow models that allow for hydrofracturing and ice-cliff failure.[15] That prediction is far more than in any intergovernmental climate report so far.

Other possible tipping points have been discussed elsewhere.[9,16] They include runaway deforestation scenarios in the Amazon, for instance, and the melting of methane hydrates or clathrates from ocean sediments and from below melting ice sheets. Another mechanism less often discussed is the carbon-cycle instability studied by Daniel Rothman of MIT, which suddenly decreases the rate at which upper-ocean phytoplankton remove carbon dioxide from the atmosphere.[17]

Weather extremes, whales, and dolphins

Another limitation of climate models is that they underpredict many kinds of devastating weather extremes. Admittedly, a few extremes are represented well in the models. Examples include the heat waves and firestorms of summer 2021 across western parts of Canada and the US and large-scale outbreaks of freezing weather, such as those of February 2021 and December 2022 that reached as far south as Texas, from amplified jet-stream meandering. Most of the extreme behavior, however, depends on scales of fluid motion far smaller than the scales resolvable by climate models.

The simplest and clearest case is cumulonimbus rainstorms and thunderstorms, which can produce devastating flash floods and mudslides. The airflow into cumulonimbus clouds takes place on spatial scales so small that, even with today's computing power, they are barely resolved even in the most computationally expensive local operational forecasting models.

The airflow into a single cumulonimbus cloud, however, is accessible to the simplest of fluid-dynamic intuitions. The cloud is like a tall vacuum cleaner that pulls air from its low-level surroundings. The flow is powered by water vapor—think of it as a weather fuel. Water vapor can reasonably be called weather fuel because of the latent-heat energy released when it condenses. The Clausius–Clapeyron relation says that air can hold around 6–7% more weather fuel for each degree Celsius of temperature rise. So global warming is global fueling.

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's a robust and powerful positive feedback mechanism that's capable of producing heavier and more sudden downpours and heavier flash flooding.

> “Global warming is global fueling.”

As is now well recognized, such extremes of storminess are becoming more frequent and more intense today. Evidence of extremes can also be found in past climates. The most notable example comes from the hothouse climate of the early Eocene epoch. Peak temperatures were reached around 56 million years ago at the Paleocene–Eocene Thermal Maximum. With a far greater supply of weather fuel than today, the same robust feedback makes it likely that some of the storms were more violent and devastating than anything within human experience. Research has shown geological evidence of massive erosion by storm-flood events at that time, for example.

Furthermore, there's an independent line of evidence for storminess that comes from evolutionary biology. The whales, dolphins, and other aquatic mammals that exist today came from land-dwelling ancestors that, according to the fossil record, began taking to the seas around the same time, 56 million years ago.

What could have induced land-dwelling mammals to seek a new habitat and at that particular time? Why did some of them then become fully aquatic in a mere few million years? Selective pressures from extremes of surface storminess can begin to explain those extraordinary evolutionary events. Those events could have begun with hippo-like behavior in which the water was little more than a refuge from the storms. That of course is only a hypothesis. But in my judgment, it's strongly arguable. And today's whales and dolphins are related genetically to today's hippos.

The amplifier metaphor for climate

The uncertainties in climate science and climate-model limitations have long been used by the climate-disinformation industry to proclaim that there is no cause for concern, unless additional pending assessments say otherwise. The foregoing reminds us that those uncertainties and limitations were always reasons for being more concerned, not less. In my recently published book, I discuss the powerful psychological methods used by the disinformation industry that exploit, among other things, language as a conceptual minefield (reference 18, chapter 2). On climate, the book includes a discussion of extreme cyclonic storms and their meteorological complexities, including so-called conveyor belts that carry weather fuel across long distances. Climate-model limitations include an inability to represent the most extreme cyclones accurately, again because of resolution constraints.

Another theme in the book is the idea of an amplifier metaphor for climate. The metaphor emphasizes that some parts of the climate system are more sensitive than others, a point that the disinformation industry has always worked hard to conceal. Even in the scientific community, the point has been obscured sometimes by too much focus on gross energy budgets. What matters is that the system is far more sensitive to human inputs of noncondensing greenhouse gases, such as CO_2 and methane, than it is to human inputs of water vapor. Of course the climate amplifier is highly nonlinear and very noisy, quite unlike an ordinary audio amplifier in that respect.

In its role as weather fuel, water vapor can be seen within the metaphor as a part of the amplifier's power-supply circuitry. The rate at which latent energy in water vapor is exported from the tropics and subtropics, for example, is roughly of the order of one or two petawatts. That dwarfs any human input of water vapor.

By contrast, the noncondensing greenhouse gases can be seen as part of the amplifier's sensitive input circuitry. So when the disinformers say that atmospheric CO_2 is unimportant because there's much less of it than atmospheric water vapor, it's like saying that the input current to an amplifier is unimportant because it's much less than the power-supply current. Furthermore, the CO_2 input signal from fossil-fuel burning can hardly be considered small. Today that input has already pushed atmospheric CO_2 far outside its natural range of variation over the glacial–interglacial cycles of the past 400 millennia.

The natural range is about 100 ppmv (parts per million by volume). That 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, coming from a powerful line of research on Antarctic ice cores.[18] In round numbers, atmospheric CO_2 variations had a peak-to-peak amplitude of 100 ppmv across the huge range of climate conditions that were encountered during the glacial–interglacial cycles. Today's CO_2 value is well over 400 ppmv, which is more than 200 ppmv above the minimum values found in glacial times, when CO_2 was less than 200 ppmv. Atmospheric CO_2 has now increased by more than twice its natural range.

As with the earlier examples of the Antarctic ozone hole and tobacco and lung cancer, there is now reason to hope that the disinformation industry, although still powerful, may have ceased to be the overwhelming political influence that it was a decade ago. As noted in my book, "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" (reference 18, page 148). Another reason to be hopeful is the new economic reality around energy from renewables and battery storage. They're far cheaper and more reliable than fossil fuels, as demonstrated at scale in South Australia.

Economic forces and 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 so-called "offsets." Reference 16 discusses the scale of that deception. The word "offsets" well illustrates language as a conceptual minefield because it can embody an unconscious assumption that such activities fully compensate for the effects of fossil-fuel burning as they occur, when in reality they only partially compensate and not quickly enough. Younger generations, however, allow some optimism that more and more people will see through such deceptions as the weather extremes ramp up over the coming years.

Many expert colleagues have helped me on climate and paleoclimate research.[17,18] A foundational influence to my development as a scientist came from my PhD supervisor Francis Patton Bretherton, whose obituary appeared in the March 2022 issue of PHYSICS TODAY. *Francis was a brilliant lateral thinker and was one of the first scientists to think seriously about the real climate system in its full complexity, as summarized in the well-known "Bretherton diagram."*

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