Pulling Back from the Climate Change Precipice

Richard B. Rood
University of Michigan
Climate and Space Sciences and Engineering
rbrood@umich.edu
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The Climate of the Earth Is Changing

We live at a time of rapid climate change, characterized by accumulation of heat at the Earth's surface. Through science-based investigation, we know the causes of our changing climate, and we have knowledge of how the climate will continue to accumulate heat and, hence, warm. We, also, know how to intervene and limit the warming. And, if we do not limit the warming, then the disruptions to global, civil society will far exceed any which we have experienced.[1]

Though climate is defined as the prevailing or average weather over a long span of time, a more robust measure of our changing climate is the heat stored in the ocean. Because of its large mass compared to the atmosphere, if there is a persistent increase in the heat held in the ocean, it is an important indicator of planetary warming. Also, as heat is traded back and forth between the ocean and the atmosphere, the surface air temperature varies. This heat exchange is an important cause of internal variability of air temperature. This variability complicates the ability to easily detect atmospheric trends. As seen in Figure 1, there is a convincing trend in the amount of heat held in the top 2000 meters of the oceans.

The additional heat in the ocean causes water to expand, which causes sea level to rise. As heat accumulates in the environment, ice stored in mountain glaciers and polar ice sheets melts. This contributes, further, to sea level rise, and it is the sea level rise associated with melting ice sheets that will most alter the coastlines of continents and drown islands.[2] At polar latitudes, the accumulating heat melts long-frozen land, the permafrost.[3] Aside from changes to ecosystems, the melting land has the potential to greatly increase the ability of the Earth to accumulate heat.

We already observe increasing ocean heat content, melting ice, and accelerating sea level rise. This is a measure of the movement of heat, a form of energy, in the environment. The motions in the atmosphere which represent our day-to-day weather are the response to energy imbalances; the air moves to reduce the contrast between warm and cold. With the accumulation and redistribution of energy at the Earth's surface, the weather must change. Given that there is an increasing amount of energy stored in the environment, the weather systems have more energy to move. This is expected to lead to weather events that are outside of the extremes that we are accustomed to experiencing.

Indeed, all of this accumulating energy at the Earth's surface will lead to, on average, the increase of the Earth's surface air temperature. The measurements show that in the past century, the global averaged surface air temperature has increased about 1°C (Celsius).[4] The north and south polar regions have seen much larger changes than the global average. We observe that each of the last three decades is warmer than any in the previous century. The decade of 2011 – 2020 will be warmer still. For the span of those now alive, it is likely that from one decade to the next, each will be warmer, still. This is a daunting change, which we have not fully internalized into our behavior and our thinking. Daunting, but one which we know is coming and, hence, one for which we can prepare. Such science-based knowledge of the future on the span of lifetimes is unprecedented in history. There is opportunity and peril.

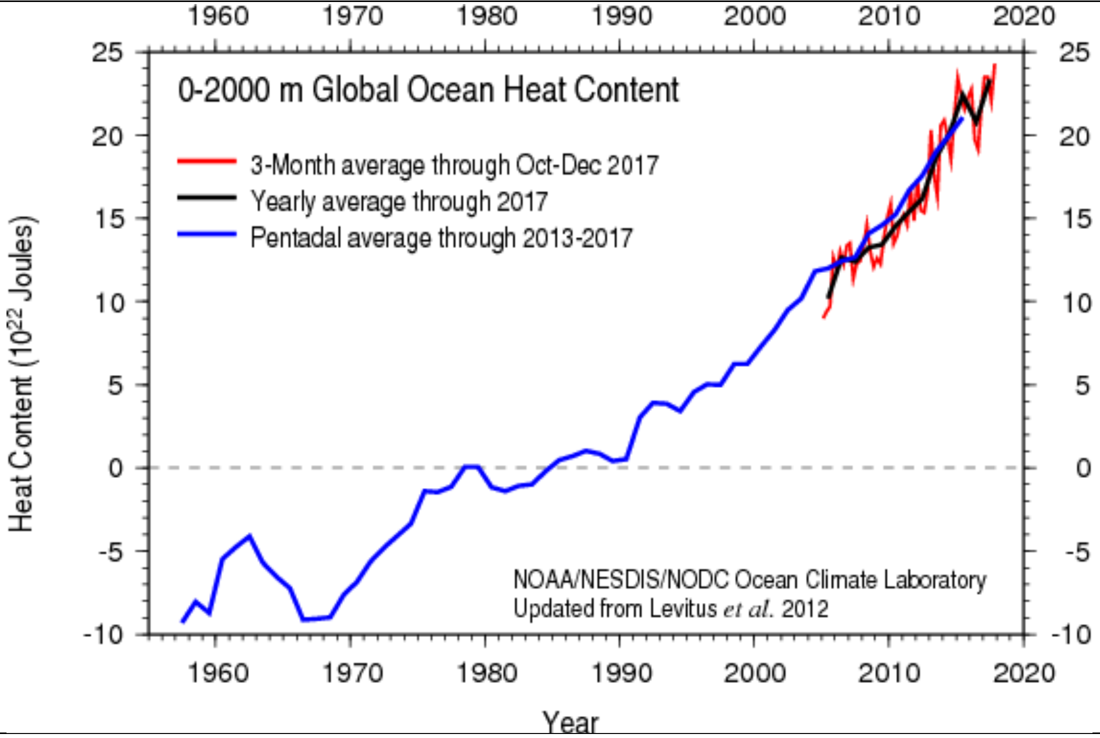


Figure 1: Ocean Heat Content in 0 – 2000 meter depth of the ocean. These data are compared to (subtracted from) the reference period 1955 – 2010. The heat content shows an upward trend relative to the reference period. Three different averaging periods are show (3 – month, 1 – year (annual), and 5 – year (pentadal).

What Causes the Accumulation of Heat?

The basic answer to this question is easy. It is based on physical principles that have been known and used for hundreds of years and our ability to measure and count. The most important physical principle is the conservation of energy.[5] If the climate at the Earth's surface is stable, then the amount of energy provided, primarily by the visible light of the Sun, must equal the amount of energy that is given up by the surface. The energy given up by the surface is, ultimately, emitted back to space as thermal or infrared radiation. Hence, to a good approximation, the balance in a stable climate is that visible radiative energy from the Sun is equal to the infrared radiative energy emitted by the Earth.

This conversion of visible to infrared energy is familiar to most people. Consider a car with closed, glass windows, a house with a Sun-facing window, or an agricultural greenhouse – in all of these cases the visible energy comes into an enclosed space and heats that space. The glass impedes the emission of infrared energy from the greenhouse. The enclosed space heats until the energy it releases is equal to the energy it absorbs.

The counting problem is to measure and count the ways that energy is captured, stored, and released at the surface. Our climate is directly related to how much energy is stored and how it moves from one storage place to another. Hence, anything that changes the ability to absorb and emit energy at the Earth's surface has to change the climate. That leads to another counting problem, is that change large enough to matter?

The focus of our changing climate is the atmosphere. Above, the comparison to a glass (or clear plastic) enclosed greenhouse was made. In the case of the Earth, the notional window is the atmosphere, which is largely transparent to visible radiation. With regard to infrared radiation, however, the atmosphere is somewhat opaque. The infrared radiation associated with the Earth's release of heat must make it through blankets of different gases that absorb and emit the radiative energy. These are greenhouse gases. We are making the blankets thicker.[6]

The greenhouse gas that is most important for holding heat near the Earth's surface is water vapor. The next most heating comes from carbon dioxide. There are other greenhouse gases including methane, nitrous oxide, and a portfolio of gases that are manufactured by humans. Water vapor, carbon dioxide, methane, and nitrous oxide all occur naturally. The amounts of carbon dioxide, methane, and nitrous oxide are also strongly influenced by things that humans do – what we burn, what we eat, and what we throw away.

Water vapor is the greenhouse gas responsible for holding the most heat near the Earth's surface, about two thirds of it. Aside from the role that humans have in influencing the Earth's temperature, however, we have little influence over the amount of water vapor in the atmosphere. Enormous amounts of liquid water exist in rivers, lakes, oceans, and the ground. Solid water is stored in snow, glaciers, and ice sheets. There is continual exchange of water between ice, liquid, and vapor. We feel this exchange as evaporation (drying), rain, and snow. Because energy is required to melt ice and evaporate water, the cycle of evaporation and precipitation (*i.e.* rain and snow) represents the transfer of energy. In an important way, the Earth's climate can be measured by how much water, a proxy for energy, is being stored in ice.

As we think about how water moves through our environment, not only by the weather, but by plants and animals, the simplicity afforded by a focus on the conservation of energy is challenged. We have a problem of simple physics in complex systems. The complexity embraces basic chemistry and biology, as chemical and biological processes use energy. Simple physics in complex systems is analogous to rocket science. The difference, however, is that in rocket science we build the system which becomes the rocket. In climate, however, we are unraveling the complexity. That complexity, ultimately, involves everything that moves and lives, and how they interact. This is an enormous problem of natural science. It is a problem that we must face as long as our population and behavior significantly alter the atmosphere, ice, oceans, and land.

If we look at the past few thousand years, human society has emerged and population has increased to billions. The temperature during most of this time has been relatively stable; sea level has been stable. This suggests that the energy received at Earth from the Sun has been in balance with the heat energy emitted by the Earth back to space. This balance can be changed in a number of ways, these can be divided into human-caused changes and those over which humans have no control. These will be termed human-caused (anthropogenic) and natural causes.

An obvious natural cause of climate change would be variation of the energy coming from the Sun. We can measure variations due to changes on the Sun, for example, sunspot cycles. We can also measure variations that come from the fact that the Earth's orbit around the Sun takes it closer and farther away from the Sun.

If we take as our measure of climate and climate change the surface air temperature, then the temperature varies day-to-day because of the transport of heat by the weather. For longer spans of times, years to decades, there is exchange of heat between the atmosphere and ocean.

The El Niño – La Niña phenomenon is such an exchange. During an El Niño the air temperature is warmer, and during a La Niña the air temperature is cooler.[7]

Finally, there are changes to the composition of the atmosphere that are not related to humans. An easy example is a volcanic eruption. The most important change that comes from a volcanic eruption is the presence of small particles in the atmosphere. These particles, called aerosols, can be particles of dust, ash, or droplets – notably sulfuric acid droplets.

It is also possible for carbon dioxide and methane to undergo large natural variations. This is related to transfer of carbon dioxide and methane between oceanic and land storage reservoirs. These exchanges are related to temperature and biological activity on the land and in the ocean. Large fluctuations of temperature, carbon dioxide, and methane are measured with the ice age cycles. There is lower carbon dioxide and methane during ice ages. There is higher carbon dioxide and methane during the warmer times between ice ages.

There is no doubt that carbon dioxide and methane can undergo large changes in the absence of human enterprise; in fact, in the absence of humans. But, during the last hundred years, humans have emerged as a force of nature that is taking carbon dioxide stored in coal, oil, and natural gas and moving that carbon dioxide from deep in the ground to the atmosphere and ocean. We know this, again, from simple physics. We can measure and count all of places that carbon dioxide comes from and all of the places it goes. We do that counting problem and the largest cause of carbon dioxide increase in the atmosphere comes from us.

Humans also cause changes in other greenhouse gases. Notably there is methane that is released as we mine fossil fuels. There is methane from decomposing garbage and human and animal waste. There is nitrous oxide that is a result of agriculture and nitrogen-rich human-made fertilizers. There are many industrial greenhouse gases. Again, we can count that which is related to human activities and that which is not. It, mostly, comes from us.

We also change the particles, the aerosols, in the atmosphere. There is the soot and ash from industrial and agricultural burning. There is dust from tillage. There are droplets caused by water droplets associated with polluted air – smoke plus fog, smog.

Finally, we change the surface of the Earth, especially, the land. This changes how much of the Sun's energy is reflected or absorbed.

When we look at all of these pieces and count up the energy in the Earth system, we find that some things heat, some things cool. We call the changes to the balance between incoming and outgoing radiative energy the "radiative forcing." That is, how much are we forcing change in the balance. We add up all of the natural and human-caused changes. We find that the largest changes come from carbon dioxide. The next largest change comes from methane. If we take the year 1750 as the baseline before global industrialization, we find discernable changes in radiative forcing by 1950. That forcing doubles from 1950 to 1980. It doubles, again, between 1980 and 2011.[8] The planet is warming, and changes to the atmosphere that come from the waste products of energy and food production are the primary cause.

What Are the Impacts?

If the balance of energy at the Earth's surface changes, then there must be alterations at the surface in response to those changes. That energy has to do something, to go somewhere. That is, if we "force" the Earth with extra energy, the Earth will "respond." First, how does the Earth's climate respond to additional radiative energy? Does it return to a balance? Does it amplify the forcing? This is the concept of a feedback. How does the Earth respond to a change in forcing?[9]

The short answer is that the Earth responds to warming by greenhouse gas increases by warming more – a positive feedback. As before, this is a problem of measuring and counting energy balances. Compared to the description of natural and human-caused changes in radiative forcing discussed above, the calculation of feedbacks is far more complex.

Most simply, if the temperature increases, more water evaporates from the ocean and there is more water vapor in the air. Water vapor is a greenhouse gas, and hence, there is more warming. Ice and snow are white and reflect visible light. If the Earth gets warmer and ice and snow melt, less light is reflected and more energy is absorbed; hence, there is more warming.

There are feedbacks that cool. Most notably, if there is more water vapor in the atmosphere, there are, likely, more clouds. Clouds are bright on top, and they reflect visible light back to space. Hence, they cool. However, viewed from below, clouds are dark and they block heat from leaving the surface. Therefore, they also warm. Clouds become their own counting problem; they cool and warm. Which effect is larger?

The complexity of clouds is increased even further when aerosols, small particles in the atmosphere, are considered. Aerosols can cool or warm. Aerosols change the properties of clouds.

Ultimately, all of our accounting of energy leads to the conclusion that when the Earth is warmed by adding greenhouse gases, the response of the Earth is to warm even more.

We know with near certainty that the Earth will continue to accumulate heat and warm. We know that ice and permafrost will continue to melt and that sea level will rise. We know that weather will change.

When the impacts of climate change are discussed, we often hear that there will be more extreme weather, more droughts, and more floods. Some of this information is, perhaps, abstract or ambiguous. What characterizes more extreme weather? Isn't both more droughts and more floods somewhat contradictory? If the world is warming, then why are there still sustained periods of cold weather? Why are there so many record snow falls?

From the point of view of the physics of the climate, there are no scientific contradictions. All of these phenomena can be understood by the measuring and counting that is represented in models of climate – models based on foundational principles of physics, chemistry, and biology.

The impacts, however, are not something notional and in the future.[10]

The impacts on the built environment, ecosystems, agriculture, and national security are already being felt. Cities and natural coastlines are experiencing increased sea level rise and amplified flooding due to storm surges on top of the sea level rise. Cities are being flooded as extreme precipitation overwhelms aging infrastructure designed for smaller storms.

Large swaths of forests are being challenged by water stress as higher temperatures amplify the effects of drought. New insects and plant species enter these stressed environments. Agricultural is challenged by too wet fields in the spring, and too dry fields in the late summer. In water-scarce countries like Syria, political, economic, and security challenges are, again, amplified by drought and higher temperature.

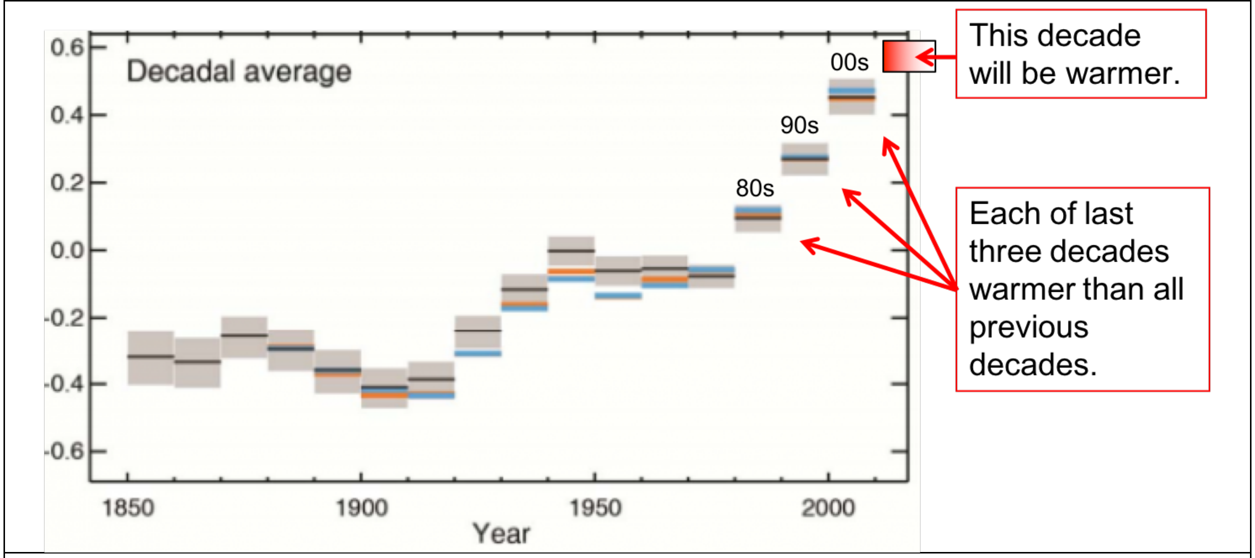
It is not that climate change "causes" these stresses, but that climate change, in many cases, amplifies vulnerabilities. Changes in the weather stress our buildings, our infrastructures, our forests, our fields, our exposure to pathogens – the list goes on; we are, simply, beginning to live outside of the environmental parameters in which our civilizations were built and evolved.

We have entered a period of rapid climate change. Rapid meaning on the time span of a human lifetime – on the time span of the buildings we build. A critical challenge is to limit this climate change, so that we can adapt.

Pulling Back from the Climate Change Precipice

What is the climate change precipice? Figure 2 is a measure of the global average surface air temperature of the Earth from 1850 through 2012.[11] The measurements are from near the Earth's surface, relevant to what we as humans feel, say, 2 meters above the ground. The figure shows a global average, which is smaller than some of the regional changes, such as those in the Arctic. There is another average in this figure; the temperatures are averaged in 10-year, decadal, time spans. Precisely, what is shown is the difference of a decade's average temperature from a 1961 – 1990 average.

What is remarkable about these observations is that starting in the 1980s, there is an acceleration of the warming. The decade in which we currently live, 2011 – 2020, will be warmer still.



This decade will be warmer.

Each of last three decades warmer than all previous decades.

Figure 2: Observed global mean combined land and ocean surface temperature anomalies, differences from relative to the mean of 1961−1990, for 1850 to 2012 from three data sets. Bottom panel: decadal (10-year) mean values including the estimate of uncertainty for one dataset (black).

Putting this in human perspective, no one younger than 30 years old has lived in a decade when the temperature was below the 1961 – 1990 average. In fact, the data can be broken down to a month-by-month level, and this still holds up. Indeed, none of those young people have lived in a month when the globe was cooler than the 20th century average.

In someone's city or even country, there might have been a cool month here or there, but even that is becoming rarer.

Soon we will be able to say no person younger than 40 has lived on this planet when the temperature was cooler than the 20th century average. In fact, with the path we are currently on, it will, likely, be decades before there is a decade cooler than the previous decade. Compared to our grandparents, we already live in a changed climate, and it is still changing.

If there is a "new normal," it is change.

It is important to realize that we are not in our lifetimes going back to what it used to be. Our ideas of conservation and maintenance of ecosystems will have to change. We need to think of our possible futures and how to make good ones.

This is an enormous challenge to our identity - that with regard to our natural environment, we cannot go home again.

What, then, is the climate change precipice? In international climate change policy, our goal is to avoid "dangerous" climate change. To some, for example those living on the North Coast of Alaska, we, already, experience dangerous climate change. As a matter of policy, we have posed limiting warming to 2°C, twice that which has already occurred. The Paris Agreement honors this two-degree goal and strives for a more ambitious target of 1.5°C.[12]

For many years the 2°C limit was posed as avoiding dangerous climate change. In 2017, Xu and Ramanathan (2017) labeled 1.5°C dangerous, 3°C as catastrophic, and 5°C as unknown.[13]

There is, however, increasing evidence that if there is a basic shortcoming in our predictions, it is the underestimation of the melting of ice and permafrost. Hence, there is an underestimation of sea level rise. Through observational studies, we, now, anticipate significant melting and loss of some of the glaciers in West Antarctica. All of that heat which has accumulated in the ocean melts ice at the base of those glaciers.[14]

Our coastlines will be, profoundly, changed.

The Paris Agreement did not solve the problem of meeting either a 1.5°C or 2°C target. It was a start on a voluntary agreement, and if the initial phases were successfully achieved, the Earth would warm to about 3°C at 2100. There is no evidence, yet, that we are managing our emissions consistent with meeting the early goals of the Paris Agreement. Hence, our path has to be concluded to be greater than 3°C

There are a number of ways to define a climate change precipice. An essential goal would be to assure that the permafrost does not melt and the Arctic does not warm to the point that the massive amounts of carbon dioxide and methane stored there are released. Another essential goal, limiting or slowing sea level rise to that which we are already committed.

Today, we have realized about 1°C warming. There is persistent glacial melt. There is melting in the high Arctic and heating is measured deep into the Arctic soil. The climate change that we have experienced is, already, dangerous. Warming of 1.5°C is more dangerous, of 2°C even more. We are not simply approaching the edge of the precipice, we are stumbling down the steep scree.

When we do the accounting of the heat we have added to the Earth we are faced with a hard fact. If through magical decree we were able to halt additional alterations to the Earth's energy balance, there is enough heat accumulated in the ocean to raise the air temperature to near that 1.5°C target. We need to go back.

I teach a class on climate change problem solving. Some years ago, I quit teaching the mantra of 2°C as avoiding dangerous climate change. It was both obvious that 2°C was quite dangerous and that our behavior was inconsistent with a 2°C goal. I started teaching about a 4°C world, because that goal seemed possible[15], and imagining a 4°C world provided concrete motivation to work more vigorously to a 2°C world. We always conclude in class that we have to remove carbon dioxide from the atmosphere. Humans are a fast-geological process bringing carbon from millions of years past to the atmosphere. Humans need to become a fast-geological process returning carbon dioxide to the soils and rocks.

The simple answer, then, is to pull back from the precipice we must reduce the amount of carbon dioxide in the atmosphere and allow the Earth to cool. The scientific and technological challenges of this are far easier than the political and behavioral challenges.

At the Climate Change Precipice

For the coming decades we will be living at the climate change precipice. Often when we talk about avoiding climate disasters, we focus on reducing our carbon dioxide emissions. This is mitigation, avoiding climate change by reducing or eliminating the human-caused alterations to the Earth's energy budget. We are, however, to the point that adaptation to changes in the climate is necessary. This includes anticipation of those changes and managing and limiting the impacts of those changes.

More controversial is the concept of geoengineering, which is the deliberate, large-scale intervention to manage the Earth's climate. This could be viewed, narrowly perhaps, as taking actions to alter the energy balance of the Earth by altering the reflection and absorption of energy. Living at the climate precipice, the boundaries between mitigation, adaptation, and geoengineering become murky. At some level, however, it is obvious that we must learn to manage the climate.

In order to frame how to pull back from the climate change precipice, it is necessary to consider the drive for humans to emit carbon dioxide. We have evolved to equate societal success, standard of living, and wellbeing with the consumption of energy. Our primary source of energy has been burning fossil fuels, and hence, the release of carbon dioxide.

Today, our population grows into the billions. Basic human drives to acquire and to provide security for ourselves, our families, and our nations mean that more and more people desire access to energy. For many, the drive is at the basic level of acquiring access to water and electricity. For others, it is a drive for private airplanes and exploration of the remote parts of the planet, indeed, the universe. To "use less energy" is a strategy that dismisses human drives and is doomed to failure.

Historically, the release of carbon dioxide into the atmosphere has been by a relatively small portion of the population – those in the United States and Europe. Hence, there is little purchase in the argument that climate change is, first and foremost, a problem of population. Climate change is a conflated problem of energy consumption, population, and the human drive for success and security.

With our easy energy being, primarily, from burning fossil fuels, we produce enormous amounts of carbon dioxide as waste. With our levels of population and consumption, this waste is not benign. And, to be explicit, the consequences of carbon dioxide waste are not limited to heating up the planet. There are other impacts such as the acidification of the ocean.

It makes sense, therefore, that our long-term "solutions" to the climate change problem are related to developing sources of energy that do not release carbon dioxide waste, but that are also cheaper, more accessible, and easier to use than fossil fuels. That carbon dioxide is not a waste product is the appeal of renewable energy such as solar, wind, and geothermal. It is the appeal of hydroelectric energy and nuclear power.

The need to control carbon dioxide pollution and the conflation of carbon dioxide emissions with economic success also motivates strategies that place a price on carbon dioxide waste. That is, we internalize it into the market.

There is no doubt that our efforts to develop and use renewable and nuclear energy have had important impacts – our emissions would, in fact, be much higher without them. There is no doubt that there is adequate energy available from renewables to supply our energy needs. The technological challenges to decarbonizing our energy sources are tractable.

On the other hand, our built energy systems and our demand for energy establish that for the decades immediately ahead we will still be using fossil fuels. Here, the need to capture, control, or use carbon dioxide become imperative.[16]

The transition to renewable energy, the placement of prices on carbon dioxide pollution, and carbon capture and reuse are, however, not easy to achieve. They challenge, deeply, economic power structures. They challenge our behaviors and what we know as societal success. The policy and political challenges are most difficult; the dismissal of these challenges as "just a matter of political will" is naïve.

Hence, carbon dioxide continues to accumulate in the atmosphere. Heat accumulates in the ocean. Ice melts.

The only verified way we have for reducing global carbon dioxide emissions is economic recession. This is not a viable political strategy; it is, perhaps, an outcome of ignoring climate change.

We are led to the conclusion, therefore, that our energy systems have to move beyond carbon neutral. We have to remove carbon dioxide from the atmosphere and ocean. We have to return it to the ground. We are compelled to manage the climate – with intent. This is in contrast to our current behavior of changing the climate with no intentional goals – and the knowledge that we are doing harm.

The need to remove carbon dioxide from the atmosphere and to move beyond carbon neutral is gathering more and more acceptance. However, there is not viable vision of such a carbon dioxide reality in the foreseeable time. Reduction, elimination, and reversal of carbon dioxide pollution are, unlikely, to be achieved as global policy; it will be realized by emergence of disruptive, affordable technologies. This emergence can be accelerated or impeded by policy – local, regional, national, and global.

Since we are already committed an increasingly warming climate, living in and ultimately pulling back from the climate change precipice will require us to adapt to climate change. This is most obvious at ocean coasts, where sea level rise already disrupts many cities. The heat accumulated in the Earth has already opened up a metaphorical floodgate of, likely, 10 meters of sea level rise. How fast this will occur is not certain but planning on a meter over the human life span is justified. This will be true for coming generations as well.

Adaptation to climate change is also becoming obvious for agriculture, ecosystem management, water resource management, urban planning, health impacts management, national security – the list goes on.

What becomes obvious as, for example, cities and regions cope with and plan for climate change is that there will be a need for infrastructure, technological innovation, and scaling personal and local efforts to regional and national efforts. Likewise, the applied research to inform decisions is needed. Education is needed on how to use the knowledge from that research.

We are faced with the challenge that solutions are often local and unique, but must fit into a global puzzle, whose solution is not known. We are faced with the uncertainty of the payoffs of our investments. We are faced with the fact that our solutions are, likely, ephemeral, because we are now living in a changing, not a stable, climate. The infiltration of these challenges into our self-identification, our planning, and our behavior alters the place of humans and human enterprise on the planet.[17]

To avoid the precipices of melting ice, melting permafrost, and untenable sea level rise, it is likely to require a different framing of adaptation interventions. Pulling back from these precipices is not likely to be assured by mitigation of carbon dioxide emissions. There is little evidence that achieving a 1.5°C goal will be reduce the ice sheet melting to which we are committed.

Regional interventions to protect ice sheets and cool the surface need to be considered.[18]

We are left, finally, with the need to consider geoengineering, the deliberate, large-scale intervention to manage the Earth's climate. First, intervention to control only the heating leaves open questions of what will happen with other measures of weather and climate, notably, water and water storage. Second, there remains other issues of carbon pollution such as ocean acidification.

Whether we call it geoengineering or not, we live with the fact that we need to manage our climate to promote stability of our society and allow our ability to adapt. Given our inability to build and maintain the relatively simple infrastructure of roads and waste management, the prospect of built infrastructure or global technologies to manage Earth's energy balance seems to place the planet on life support that requires attendants. Therefore, a strategy that places greenhouse gas composition to be part of our behavior and economy is needed – climate management must be internalized. Focusing the balance of carbon dioxide and methane on biological cycles is needed.

Pulling back from the climate precipice will come, ultimately, from within as we learn to value our climate as part of our ability to succeed. As with many complex ecosystems, successful strategies will be rewarded and grow. We can find some comfort in finding solutions by realizing that throughout our span on the planet, we have dealt with weather. We have come to accept that the environment behaves in some expected range. We have incorporated this into our building codes, our behavior, and our sensibility. We now know that the climate will be changing; we know to look for new extremes in variability. This change will invoke a need to become, again, conscious of our weather and our environment. Compared to our species' emergence from the last ice age, however, we know what to expect.

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[1] As a general reference, Gettelman and Rood (2016) provides an introduction to climate science and climate modeling. Gettelman, A., and Rood, R. B. (2016) *Demystifying Climate Models: A Users Guide to Earth Systems Models,* Springer, Berlin, Heidelberg, 274 pp. The book is open source and available electronically at http://www.demystifyingclimate.org/ , which also includes a list of errata.

[2] Regularly updated data on ocean heat content can be found at the National Oceanographic Data Center, https://www.nodc.noaa.gov/OC5/3MHEATCONTENT/ ; Levitus, S., et al. (2012), World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010, *Geophys. Res. Lett.,* **39**, L10603, http://dx.doi.org/10.1029/2012GL051106 .

[3] Recent summaries of melting permafrost, *The Permafrost Time Bomb is Ticking*, https://www.yaleclimateconnections.org/2018/02/the-permafrost-bomb-is-ticking/ ; *Global Warming's Frozen Giant,* https://www.insidescience.org/news/global-warmings-frozen-giant

[4] See, for example, Henley, B. J.*, and* King, A. D. (*2017*), Trajectories toward the 1.5°C Paris target: Modulation by the Interdecadal Pacific Oscillation*, Geophys. Res. Lett.,* **44***,* 4256–4262*,* http://dx.doi.org/10.1002/2017GL073480 *, esp. Figure 1.*

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[5] Gettelman and Rood (2016), page 8.

[6] Gettelman and Rood (2016), page 14.

[7] Gettelman and Rood (2016), page 152.

[8] A good reference is Stocker, T.F., et al. (2013), Technical Summary. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (Available at, http://www.ipcc.ch/report/ar5/)

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[10] A good reference is Field, C.B., et al. (2014) Technical summary. In: Climate Change 2014: *Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma,,E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 35-94. (Available at, http://www.ipcc.ch/report/ar5/)

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[12] See, for example, Shaw, C. (2017), The Two Degrees Celsius Limit, Oxford Research Encylopedia, https://doi.org/10.1093/acrefore/9780190228620.013.15 ; For more on the Paris Agreement, http://unfccc.int/parisagreement/items/9485.php

[13] Xu, Y., and Ramanathan, V. (2017), Well below 2 °C: Mitigation strategies for avoiding dangerous to catastrophic climate changes, *Proceedings of the Natural Academy of Science of the United States of America*, 114 (39), 10315-10323, https://doi.org/10.1073/pnas.1618481114

[14] Observations suggest that we are already committed to approximately 10 meters of sea level rise from West Antarctica and Greenland. The rate of sea level rise is less certain. The literature suggests 1 meter per 100 years is, perhaps, the lower bound. Rignot et al. (2104) is an excellent reference on the observations and the analysis. Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B. (2014), Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, *Geophys. Res. Lett.,* **41**, 3502–3509, https://doi.org/10.1002/2014GL060140 ; Lecture by Eric Rignot at American Geophysical Union Meeting, 2015 https://www.youtube.com/watch?v=EbgMHe4Amc&feature=youtu.be

[15] Philosophical Transactions of the Royal Society theme issue, *Four degrees and beyond: the potential for a global temperature increase of four degrees and its implications*, http://rsta.royalsocietypublishing.org/content/369/1934

[16] A succinct summary of the challenges of replacing fossil fuels is provided here, *Why Meeting the Paris Climate Goals is an Existential Threat to Fossil Fuel Industries*, https://theconversation.com/why-meeting-the-paris-climate-goals-is-an-existential-threat-to-fossil-fuel-industries-85225

[17] A Fundamental Shift of Our Place in the World, http://blog.climatepolicy.org/2014/05/14/climate-change-a-fundamental-shift-of-our-place-in-the-world/

[18] What if we built a wall on top of the Greenland ice sheet? Can we "save" the Netherlands?, http://adsabs.harvard.edu/abs/2017EGUGA..1919057M