Moving to Higher Ground: Rising Sea Level and the Path Forward

Online Supplemental Science – rev. 1.1. effective 1/1/2022

“Deeper Dive Notes”

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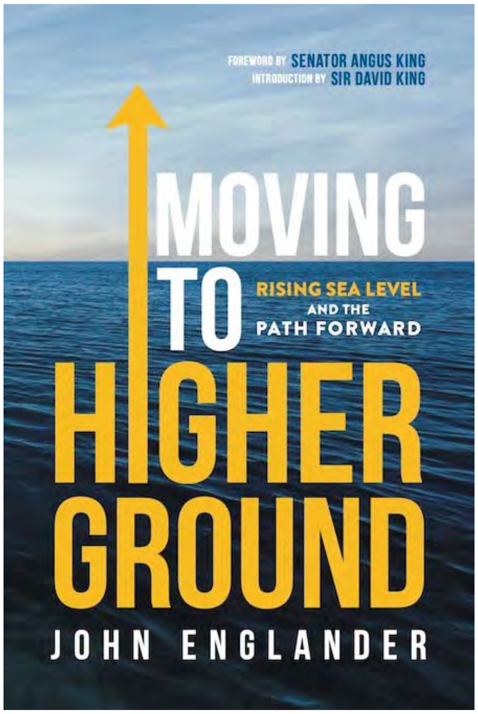
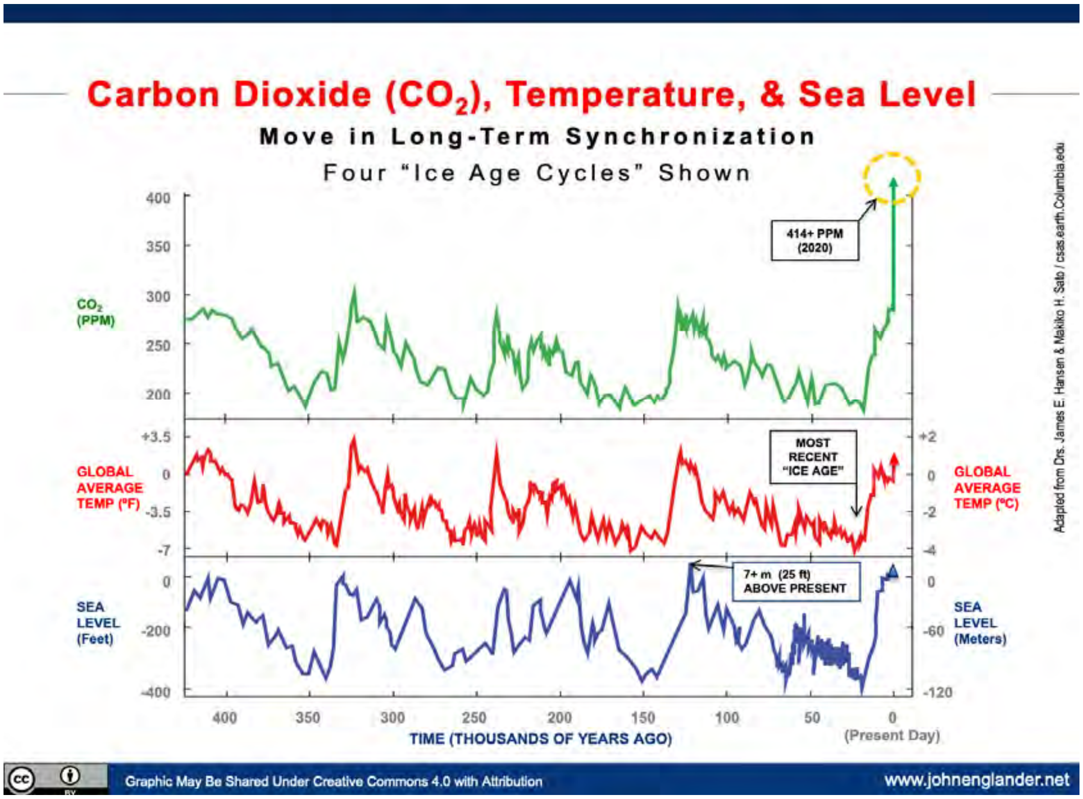


Note #1 – Ice Age Cycles and Causes [page #9 in book]

The idea that the ice sheets go through cycles of growth and retreat was first proposed in the 1830s by the legendary geologist, Louis Agassiz. It took almost a half century for the idea to be accepted as a fundamental principle of geology. Today, geologists define an ice age as any period when ice sheets and glaciers cover large masses of land. Given that the north and south poles both currently contain year-round ice, Earth is technically still in an ice age.

To keep things simple, I use the term "ice age" to describe the colder eras when thick ice sheets covered most of the Northern Hemisphere, though scientists may refer to these as glacial periods.

A century ago, Serbian scientist Milutin Milankovitch brilliantly identified the trigger agent for the ice age cycles. Now known as the **Milankovitch Cycles**, he theorized that the ice ages resulted from the combined effect of three cycles of Earth's planetary movement: its varying elliptical orbit around the sun, its "tilt", and its "wobble," properly referred to as the *eccentricity*, *obliquity*, and *precession*. With more precise measurements, it is now generally accepted that the elliptical orbit is the dominant influence.


Carbon Dioxide (CO_2), Temperature, & Sea Level
Move in Long-Term Synchronization
Four "Ice Age Cycles" Shown

Adapted from Drs. James E. Hansen & Makiko H. Sato / csas.earth.Columbia.edu

Figure 1: For thousands of years, CO_2, global average temperature, and sea level have moved in close synchronization. The middle (red) graph depicts four ice age cycles. (Adapted from James Hansen / Makiko Sato).

Over the last 400,000 years, the red line (Global Average Temp) of Figure 1(repeated from the main text here for convenience) shows the heating and cooling repeating in the range of 95,000 to 125,000-year cycles. Sea level, global temperature, and CO_2 all move in near-perfect synchronization.

These ice age cycles correlate precisely to the range of the orbital variation cycle. The changing orbit that determines how far we are from the sun results in a one percent difference in heat received and is the main trigger for the ice-age pattern of the last few million years. Thus, we not only have a correlation of timing, but also a mechanism for causation.

Skeptics about climate science often say that correlation is not causation. However, when there is a known mechanism that can cause a result and it correlates with a wide range of observations, it is valid cause and effect and is scientifically accepted.

EARTH'S 50-MILLION-YEAR COOLING PROFILE LEADS TO THE "ICE AGES"

Thinking about the ice ages often leads to a related question: how long have they been occurring*?* The current heating and cooling cycles in which sea level moves up and down several hundred feet over 100,000 years, have been going on for just over 2.5 million years. Yet even this ancient history is just a blink of an eye when compared of the overall 4.6-billion-year history of our planet.

Some people who are confused by climate change or want to dismiss it as something beyond our understanding, throw around assertions about sea level or climate "a billion years ago." Looking back a billion years is of limited value and may actually add to the confusion. Today's continents didn't exist then, the oceans had a very different configuration, and there was very little oxygen in the atmosphere. In other words, there was very little similarity to the world as we know it.

Whether there was ever a time when Earth was colder, forming a so-called "snowball Earth" in which glaciers reached the equator, is a matter of some controversy. But scientists agree that some more distant very cold periods occurred one or two billion years ago, a very early stage in the development of the planet. And, at its most extreme, sea level has varied at least 600 feet (some 200 meters) over our entire geologic history.

Until the Cambrian explosion 540 million years ago, life forms were very primitive, mostly single-celled organisms, and the atmosphere would not have supported higher life forms, including humans.[1]

Over the last several hundred million years the continents slowly moved from the single southern hemisphere land mass, known as *Gondwana* or *Pangaea,* to their present positions. The migration of these land masses into the northern hemisphere slowly changed the Earth's climate.

Figure 2 depicts temperature changes over the past 66 million years and is based on isotope analysis of temperature markers, primarily from deep sea sediment cores.

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[1] Peter D. Ward, *Out of Thin Air: Dinosaurs, Birds, and Earth's Ancient Atmosphere*, (Washington, DC: Joseph Henry Press, 2006).

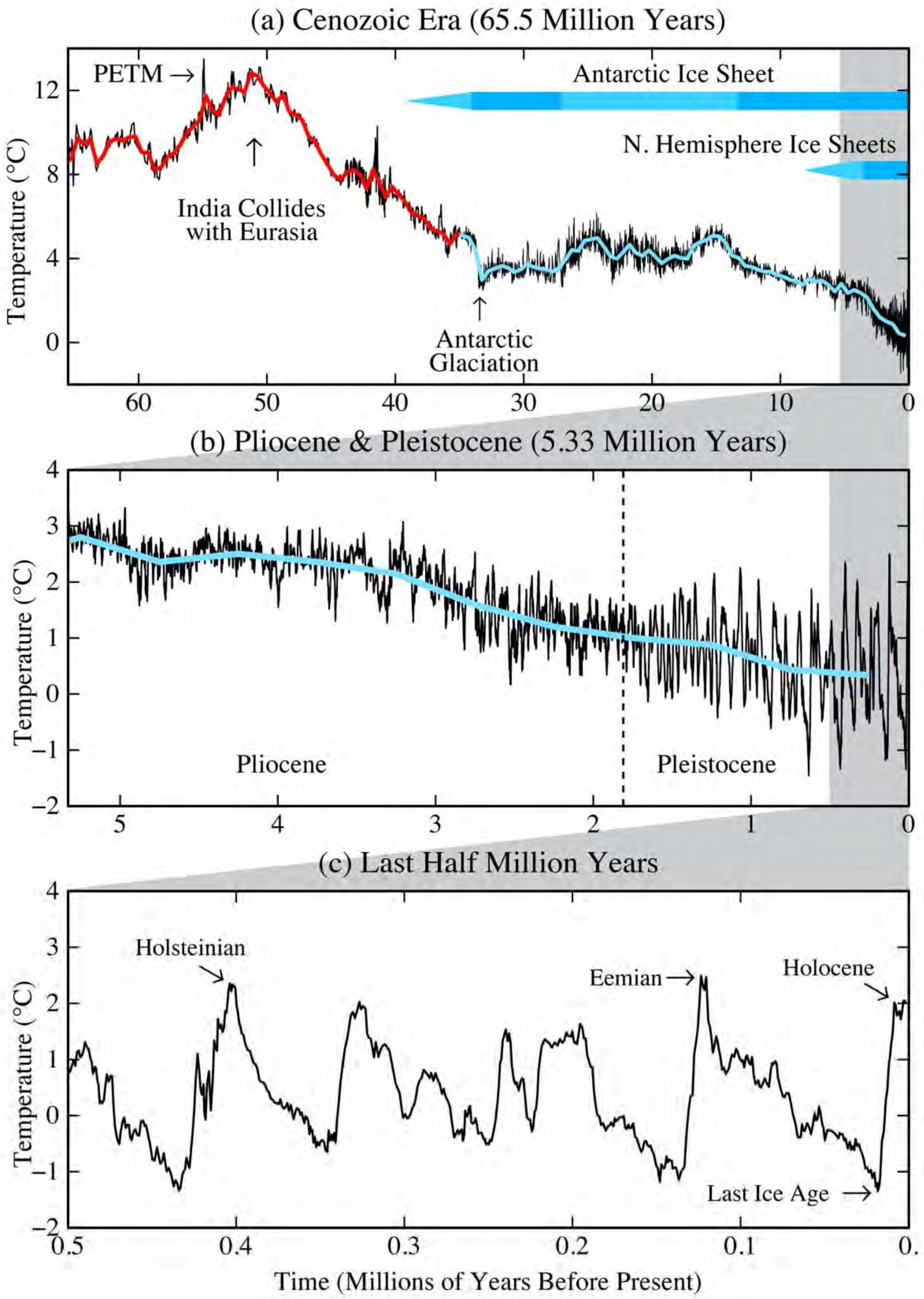

Figure 2: Earth's temperature profile. The top section (a) depicts 66 million years to present, with sections (b) and (c) expanding the recent five million years and last 500,000 years with more detail. (Courtesy Dr. James E. Hansen).

We can think of the last 66 million years, the Cenozoic Era, as having three phases:

1) A warming phase from 66 million years ago, peaking 50 million years ago;

2) A cooling phase from 50 million years ago, until it leveled off 2.5 million years ago (the Pliocene epoch), and;

3) The 2.5 million years of ice age cycles (the Pleistocene epoch) that has persisted until rather recently, in geologic time.

The warming phase began after a massive asteroid hit Mexico's Yucatan Peninsula, killing three quarters of all life on Earth, most famously, the dinosaurs. That extinction is known as the Cretaceous–Paleogene (K–Pg) or Cretaceous–Tertiary (K–T) extinction. It is the most recent of the five major known extinctions, and the only one that is widely accepted to be triggered by an extra-terrestrial cause.

The cause for the warming spike, known Paleocene-Eocene Thermal Maximum, or PETM, is not clear, but huge volcanic events and methane are high on the list of suspects (See Note #9 for more on methane).

Temperature peaked around 50 million years ago. Then, over millions of years, the land that is now the Indian subcontinent "slammed" into Asia. In super slow motion, the earth buckled upwards, five miles high, creating what we now know as the Himalaya Mountains. The creation of these enormous peaks had a transformative effect on planetary weather patterns, creating year-round mountain snow cover, and changing global air currents like the Jet Stream. This was the start of a long-term cooling trend.

The last five million years, the middle section of the graphic, shows the trend towards the ice ages. You can see that between three and four million years ago, the Earth started to hit a natural harmonic of oscillating climates, heating and cooling cycles every 90,000 to 120,000 years, following the Milankovitch Cycle.

But it wasn't until the last two and a half million years, known as the *Pleistocene* or the *Quaternary,* that glacial cycles were fully established. And the last several hundred thousand years have created a climate stable enough to support our species. Science now has good evidence that humans have been present for hundreds of thousands of year at least.

During the most recent cold period ("glacial máximum period") some 20,000 years ago, ice sheets and glaciers more than a mile-high extended south as far as the middle of modern North America, Europe, and Asia. During this glacial period, the ocean was as much as 390 feet (120 meters) below present sea level, the equivalent of a typical 30-floor building.

Other Influences on Climate

While the Milankovitch Cycle is arguably the most powerful influence on climate, we should not overlook some other physical changes that have had significant effects on weather and climate.

The connection of North and South America, separating the Atlantic and Pacific oceans, is one example. The Isthmus of Panama was created 2.8 million years ago when the Earth's plates collided. This, in turn, caused some major earthquake and volcanic activity. When ocean flow from the Pacific to the Atlantic was halted by the formation of what is now Panama, ocean currents changed markedly. The effect on global weather patterns was dramatic, creating the Gulf Stream in the Atlantic and the Humboldt Current in the Pacific, which are dominant factors for weather and fisheries.

Note #2 – Antarctica & Greenland Update [page #31 in book]

Antarctica and Greenland hold 98 percent of land ice. Combined, there is enough water locked in these ice sheets to raise global sea levels by 200 feet (60 meters) if it all melts. As this book goes to press, there are ominous signs of melting and destabilization in both polar areas.

Antarctica holds seven times more ice than Greenland, and therefore has that much more potential to contribute to SLR. Though it holds more ice than Greenland, it currently lags behind in terms of melt rate.

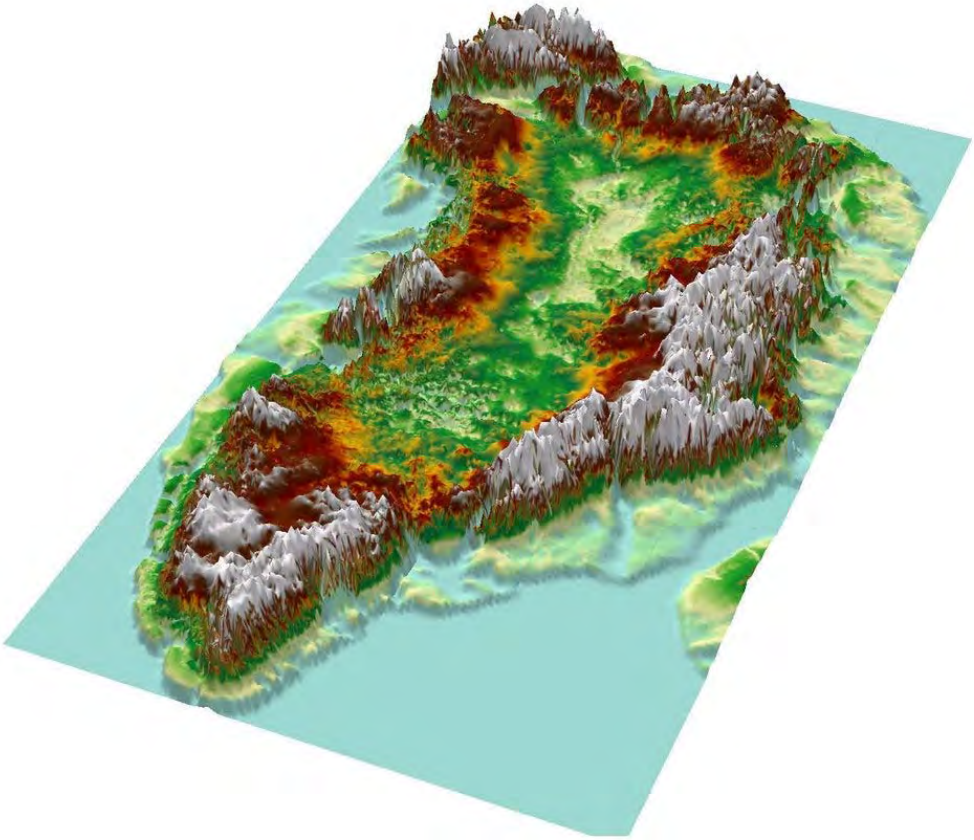

Figure 3: A topographic map of Greenland beneath the ice sheet from bedrock elevation data. (J. Bamber, University of Bristol).

One factor contributing to the speed of Greenland's melting is its topography. As you can see in Figure 3 without the ice sheet, much of its interior and outer coasts are below sea level, so the warm water is able to reach the glaciers from the surface and below. Greenland is losing ice mass seven times faster than it was three decades ago.[2] It went from losing 33 billion tons of ice a year in the 1990s to 254 billion tons in 2020, essentially doubling the amount of ice lost each decade.

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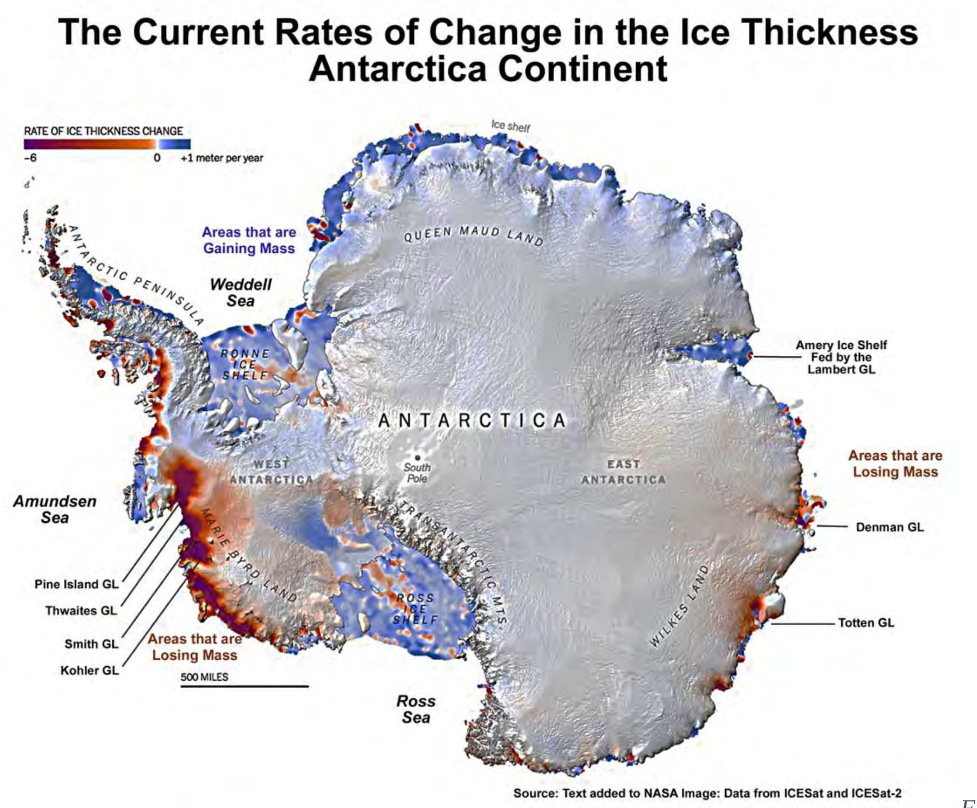
[2] Mass balance of the Greenland Ice Sheet from 1992 to 2018.
Shepherd, A., Ivins, E., Rignot, E. et al. Nature 579, 233–239 (2020);
https://doi.org/10.1038/s41586-019-1855-2

In August 2019, extreme heat waves in the Arctic that lasted for weeks, caused severe melting of the Greenland ice sheet. In one day, it was measured to lose 12 billion tons of ice, a new record.

Just since the year 2000, the rate at which the enormous Greenland glacier known by three different names – Kangia, Ilulissat, or Jakobshavn ("YOCK-obs-hav-en") – moves towards the sea has tripled.[3] James Balog's 2012 documentary, "Chasing Ice," captures this vividly. A four-minute trailer and the full movie are available at https://chasingice.com/. They show an amazing calving event that they managed to film. Similar events has happened at least twice since.



Source: Text added to NASA Image: Data from ICESat and ICESat-2

Figure 4: First complete map of the speed and direction of ice flow in Antarctica. (NASA).

Antarctica's mega-glaciers, Thwaites, Totten, Denman and Pine Island, will soon have better public recognition as they show increasing signs of collapse. Melt rate has increased 530 percent in Antarctica in just three decades. Ice shelves are calving icebergs up to 100 miles in length. There are troubling signs from all quadrants of the frozen continent.

Different parts of Antarctica have vastly different potential to affect SLR. The easiest way to grasp Antarctica is to break it down into four parts: West Antarctica, East Antarctica, the peninsula, and the ice shelves surrounding these three areas.

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[3] Ian Joughin et al., "Brief Communication: Further summer speedup of Jakobshavn Isbræ," *The Cryosphere*, no. 8 (February 3, 2014): 209-214, doi:10.5194/tc-8-209-2014.

West Antarctica, the peninsula, and the ice shelves are melting at increasing rates. Because they are floating, the ice shelves in the Antarctic peninsula do not directly contribute much to SLR. But this ice shelf supports land glaciers behind it, which do contribute directly to SLR. If Larsen C melts, the melting of those glaciers would almost certainly speed up. After the collapse of the neighboring Larsen B ice shelf in 2002, researchers observed melting ice from nearby glaciers flowing as much as eight times faster.[4]

The same holds true for the other major ice shelves in Antarctica. If the Ross ice shelf, which is the largest ice shelf in the world, were to completely collapse, it would potentially allow the land ice behind it to flow more quickly into the ocean, eventually raising sea levels by as much as 38 feet (11.5 meters). Up until about five years ago, the Ross Ice Shelf was thought to be relatively stable, but now scientists are seeing signs that warm surface waters are eroding it at the edges.

West Antarctica has the potential to raise sea levels by at least 10 feet (3 meters) and has been showing signs of collapse for years. Like Greenland, much of the rock floor underneath the glaciers lies far below sea level. This allows ocean water to get underneath and melt the ice from below.

The Thwaites Glacier is one of the largest sources of potential ice loss in Antarctica. It is one of six massive glaciers often grouped and identified as the Pine Island glaciers. They comprise about 4 percent of global ice that could melt. If Thwaites fully melts or slithers into the sea, it will raise global sea level more than 1.5 feet (~50 cm). Warm water at the grounding line is melting Thwaites from below so that recently, an enormous, thousand-foot-high cavern has been discovered inside the glacier, highlighting the rapid melting and destabilization in that region of Antarctica.

Thwaites is now moving into the sea at a speed of 2 miles per year (3 km) – very fast for a glacier – and the rate is accelerating. As this book is being finalized in the winter of 2019/2020 an increasing series of earthquakes in the West Antarctic glaciers are occurring, what I call "icequakes."[5] These occurrences add to concerns about possible collapse of those glaciers covered here. Based on the latest findings, glacioliogist believe Thwaites will soon reach an irreversible "tipping point" though it would likely take decades, possibly a century, for it to fully slide into the sea. While that gives us some time to adapt, we must act quickly. Even when only a quarter of this glacier slides into the ocean, sea levels will rise 4 to 5 inches, globally, and will be very disruptive for many low-lying regions.

East Antarctica is the real wildcard. Although once believed to be stable and much more impervious to climate change, it, too, is starting to show worrisome signs of melting. The Totten

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[4] Glaciers surge when ice shelf breaks apart.
Dunbar, Brian. *NASA Goddard Space Flight Center*, September 24, 2004.
https://www.nasa.gov/centers/goddard/news/topstory/2004/0913larsen.html

[5] "Glacial Earthquakes" Spotted for the First Time on Thwaites.
Kornei, Katherine. *Eos*, February 17, 2020;
https://eos.org/articles/glacial-earthquakes-spotted-for-the-first-time-on-thwaites#.XlGIEl95vwE.twitter

Glacier is the largest glacier in East Antarctica. Along with the neighboring Moscow University glaciers, they hold enough ice to raise sea levels over 16 feet (5 meters). That is more than the melting of all of West Antarctica.

Between 2002 and 2016, the Totten and Moscow University glaciers lost 18.5 billion tons of ice.[6] That's about a third of what the West Antarctic glaciers are losing each year. While most of the rock floor below the East Antarctic ice sheet is above sea level, helping to slow its melt, part of the ground Totten sits on is below sea level, just like much of the West Antarctic ice sheet. So, it seems to be vulnerable to melting in the same way as the West Antarctic ice sheet.

The Denman Glacier in East Antarctica has the potential to raise sea levels by nearly 5 feet (1.5 meters).[7] The glacier sits on a deep ocean canyon, exposing it to warming waters and making it the most vulnerable spot in East Antarctica. In the past 20 years, the glacier's grounding line has moved 3 miles inland, indicating the potential for ice sheet collapse in East Antarctica.

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[6] We Know West Antarctica Is Melting. Is the East In Danger, Too?
Borunda, Alejandra. *National* Geographic, August 9, 2018;
https://www.nationalgeographic.com/environment/2018/08/east-antarctic-ice-sheet-melting/

[7] Scientists just discovered a massive new vulnerability in the Antarctic ice sheet.
Mooney, Chris. *The Washington Post*, March 23, 2020;
https://www.washingtonpost.com/climate-environment/2020/03/23/denman-glacier-climate-change/

Note #3 – Why SLR is Unstoppable and Will Likely Accelerate [38]

As identified at the start of Chapter 3, there are three key points that are largely ignored or misunderstood, setting the stage for disaster from future sea level rise.

1. Sea level rise this century is unstoppable.
2. Science cannot precisely predict the rate of rise.
3. The rate of rise can accelerate quickly, possibly abruptly, greatly surprising us.

This note is to give a little more clarity to those three statements and the underlying concepts. To start, let's recognize that temperature measures how hot something is, but does not describe the amount of heat it contains. For example, it would take far more heat energy to warm a swimming pool 1 degree than to warm a cup of water that same 1 degree. Whereas temperature is measured in degrees, heat energy is most often measured in Calories, as commonly used regarding diets, food intake, and exercise.

> SIDEBAR: **Heat Units** - By definition, 1 Calorie will warm a kilogram of water (2.2 lbs.) 1 degree Celsius (1.8 degrees F). (Engineers and scientists may use other heat units, such as BTU's, joules, or single-calorie units, but the choice of units does not change the concepts described. I use the most common, kilo-calories, or Calorie with a capital letter.)

Heat can be applied to any substance, whether in the form of heat or radiant energy, like sunlight. That heat or energy is a measurable *thing* that can be added or removed. Cold may seem similar, but is fundamentally different. Cold is the absence of heat. To make something cooler, we have to take the heat energy out of it and move it somewhere else. You have surely noticed that refrigerators move the heat into the kitchen, just as air conditioners move heat from inside of a house to the outdoors. You can feel the heat coming out of each.

We have warmed the world's oceans by almost 2 degrees F in the last century or so, but cooling them is not like cooling a building. As refrigerators and air conditioners illustrate, cooling something requires a) considerable energy to power the system to move the heat, and b) a place to put the heat. With those requirements in mind, the naivete to think we can just cool the oceans should become clear.

First, it would take truly gargantuan, almost unimaginable amounts of energy to operate a refrigeration system to cool the ocean. That would add to the problem of *global warming*, since producing more energy produces more greenhouse gases and more warming, using our current mix of energy sources with heavy reliance on fossil fuels. And even if we could operate the imaginary ocean cooling system without producing greenhouse gases, perhaps from wind, solar, or nuclear fusion, we would still have the problem of where to put the heat. There is no practical way to get it outside the Earth system into the vacuum of outer space.

SMALL PERCENTAGE CHANGES SIGNIFICANTLY DESTABILIZE SYSTEMS

Earth continuously receives heat energy from an external source, the sun, and also emits energy to space. For the last 10,000 years, during this turning point of the ice age cycles that brought climate stability, the energy coming in and out of the Earth generally has been in balance. As shown on the illustration below (Figure 5), the incoming solar radiation averaged 342 watts on every square meter (Wm$^{2)}$ of Earth was balanced by the outgoing 107 Wm^{2} of reflected solar radiation plus 235 Wm^{2} of outgoing longwave radiation.

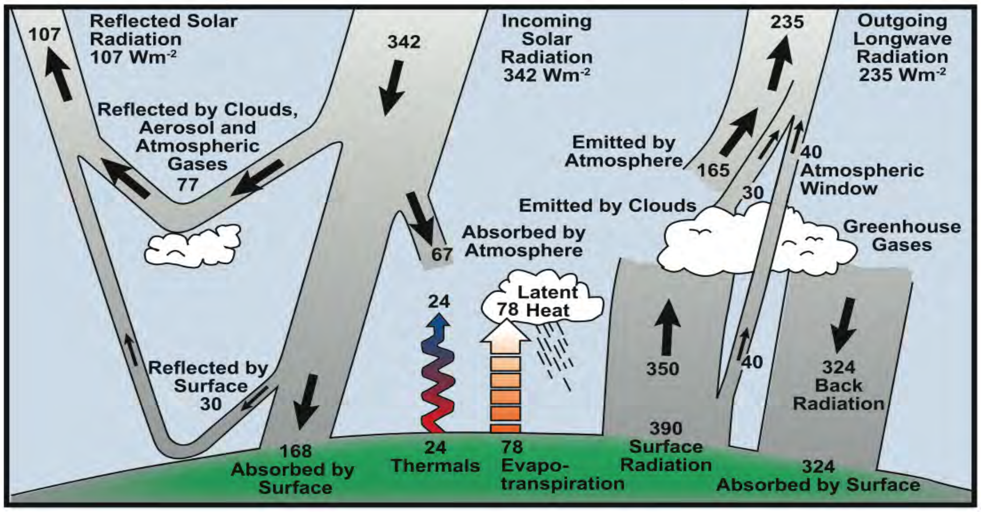

Figure 5: Earth's temperature depends on the balance of the "energy budget". If the incoming and outgoing quantities of heat are in balance in a closed system, despite the chaotic weather year to year, the overall planetary temperature stays stable. Increased greenhouse gases are causing an imbalance, gradually raising Earth's heat level (IPCC https://wg1.ipcc.ch/publications/wg1-ar4/faq/wg1_faq-1.1.html).

Now, the greenhouse gases depicted on the right-hand side of the illustration are altering what gets reflected and absorbed. The changes to the composition of our atmosphere have upset the energy balance by roughly 3 Wm^{2}, approximately one percent, causing the planet to warm. Just like we saw with the Milankovitch Cycles in Deeper Dive Note #1, small changes can have dramatic effects.

A good metaphor for the balance of incoming and outgoing energy is heat escaping from a house. If the heating system adds exactly the same amount of heat as escapes, the temperature in the house will stay constant. If you add insulation in the attic or install better insulated windows, you also must lower the heating system output, or the house will get too warm. The continued addition of insulating greenhouse gases to our atmosphere is very similar to adding insulation to your roof.

Referring back to Figure 1, if we were continuing the natural ice age cycles of the last few million years, Earth would be starting on a slow cooling path to another ice age, reaching the coldest temperature about 80,000 years from now. However, our ravenous appetite for energy is adding to atmospheric greenhouse gases. This has caused the Earth system to shift from the initial signs of a cooling phase early last century to what is now clearly a new warming mode. The measured warming force resulting from the greenhouse effect is currently about 100 times greater than the natural cooling force that brings on the ice ages. Like teams pulling on a rope in opposite directions in a *tug-of-war,* the warming force is 100 times stronger than the cooling force.

MELTING ICE TAKES HUGE AMOUNTS OF ENERGY

In simple terms, to warm a cup of water from say, fifty degrees to sixty degrees, takes the same amount if energy as to warm it from sixty degrees to seventy degrees. Melting ice is something entirely different. It would take *eighty* times more energy to melt that same cup of ice into water, just above freezing. Thus melting ice consumes a tremendous amount of energy. You can actually prove this with a simple experiment, that is easy to do or just to imagine.

Put a large chunk of ice, or a lot of ice cubes, in a pot of water. Let the water cool for ten minutes or so, to near freezing, which of course is zero Celsius or 32 degrees Fahrenheit. Now put the pot on a stove on high heat and time how long it takes for the last piece of ice to melt. Let's say, just for example, that it takes 12 minutes to melt that amount of ice, in that pot, on that stove. At the instant when all the ice has melted, the water will not have warmed much because it still had ice in it moments before. As soon as the ice is gone however, things change dramatically. If you leave the heat level on the stove constant, for the same amount of time that it took to melt the ice (12 minutes in my example), the temperature will increase to scalding 80 degrees Celsius or about 175 degrees Fahrenheit. That's close to boiling temperature, 100 degrees Celsius or 212 degrees Fahrenheit from the same amount of heat, as melting the ice.

Translating this concept to the ocean, the melting ice in the Arctic and Antarctica is consuming a tremendous amount of heat energy just by the process of melting. But as our planet's ice disappears, there is less ice to absorb the heat energy. The heat energy that is not consumed by melting ice, will cause the water temperature to warm rapidly. In the ocean, the excess does not raise the temperature to eighty degrees, but warms eighty times the volume of sea water.

To summarize, as the ice volume is reduced, the heat energy goes into warming the oceans, which melts more ice, which warms the oceans even faster, which melts the ice even faster, etc. in a "feedback loop" of increasing warming. This warming pace could increase dramatically, possibly, exponentially, affecting the *rate* of sea level rise. We need to grasp the implications of that uncertainty.

MELTING 5% OF THE ICE THIS CENTURY – MORE OR LESS

To understand the problem of accurately predicting how high sea level will rise in the next hundred years, it helps to visualize the scale of things. As explained in the second chapter, 98% of the land ice is on top of Antarctica and Greenland. Thus just those two places define the issue rather simply, with Antarctica being about seven times larger that Greenland.

Combined the ice sheets of both would be roughly six million square miles, or sixteen million square kilometers. That's about twice the size of the continental (contiguous) United States with an ice sheet over a mile high, some six thousand feet. An ice sheet that size does not melt in any linear, smooth predictable manner. The ice sheet in Antarctica covers mountains, valleys, rivers, and volcanoes. Modeling the rate of melting over the coming century is a major challenge to the experts, the glaciologists. In the last few years there has been huge progress improving the models, but it is still a "work in progress" and will be for a *very* long time.

The latest estimates for SLR this century reflect some great scientific advances, but also the uncertainty described in the book. The latest ice sheet models are very intricate and detailed, but that is not the same as being able to make precise predictions one hundred years in the future, the normal *design life* of buildings and infrastructure. As with the numerical tools to project pandemics, life expectancy, and earthquakes, they are just *models*. That is, they are useful tools to understand complex variables and to see how they interact over a range of inputs.

As explained in Chapter 3, models for rising sea level this century now have increased up to ten feet, which would be catastrophic. That would be about five percent of the ice melting. From all of my work on this subject, I think planning for five percent of the ice to melt is about right. Like most estimates however, that should be understood to be plus or minus a few percent. Each percent means another two feet (60 cm) of higher base, global sea level. The implications are huge, in terms of designing and building communities that will be viable and durable.

Note #4 – Real-World SLR Planning Challenges, e.g. South Florida [47]

Unstoppable sea level rise is certainly a huge problem. The wide range of sea level rise projections adds to the problem, particularly for a world that wants a simple "solution" and certainty. The real world rarely gives us certainty. Also, as covered in Chapter 4, professions like science, engineering, transportation planning, and emergency management, can each look at SLR projections very differently.

For example, the four counties of southeast Florida – Broward, Monroe, Miami-Dade, and Palm Beach – joined together in 2010 to form the Southeast Florida Regional Climate Change Compact. The goal of the collaboration was to develop a unified view on projected SLR to pool expertise and yield some consistency for the counties regardless of which side of the county line one was on. The Compact,[8] covers the area from Key West to West Palm Beach and includes Miami and Fort Lauderdale.

Their graph below, Figure 6, is produced is based upon SLR projections from multiple studies, plotted for three different time horizons: the years 2040, 2070 and 2120. This is excellent for planning purposes, effectively two decades, a half century and a full century from present. The table above the graph compares the three rather different projections from two very credible sources: a) the United Nations Intergovernmental Panel on Climate Change, 5th Assessment Report, better known as the "IPCC"[9] and b) the U.S. National Oceanic and Atmospheric Administration (NOAA).[10]

This chart and embedded table give a good sense of the range of projections for the next 100 years. which vary considerably. On one end of the range is the IPCC Median projection of 40 inches (~ 1 meters) of SLR by 2120, and on the other end is the NOAA Extreme projection of 175 inches (~4.5 meters) by 2120. This is a huge difference of more than 11 feet (3.4 meters) between the two projections.

Even on the shorter-term scale of the next two decades, the range between the projections is significant; the NOAA High projection is more than double the IPCC Median projection, 21 inches (53 cm) and 10 inches (25 cm), respectively. Needless to say, the wide variation presents a big problem for something that will reshape the world and lead to trillions of dollars of redesign, re-engineering, and relocation.

As mentioned in the text (Chapter 3), there are several reasons for the variability of SLR projections, what I refer to as the "known unknowns." The biggest of these is due to uncertainty

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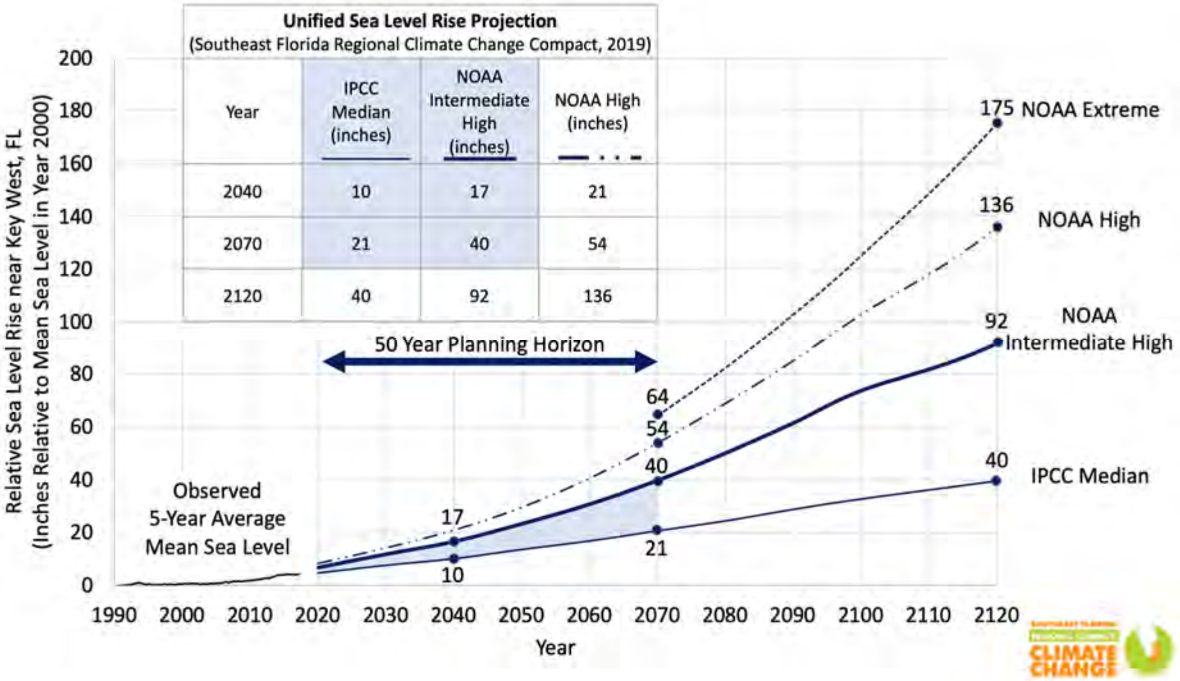
[8] Southeast Florida Regional Climate Change Compact Sea Level Rise Work Group (Compact), *Unified Sea Level Rise Projection for Southeast Florida*, 5 (October 2015), A document prepared for the Southeast Florida Regional Climate Change Compact Steering Committee, http://southeastfloridaclimatecompact.org/wp-content/uploads/2015/10/2015-Compact-Unified-Sea-Level-Rise-Projection.pdf.

[9] T.F. Stocker et al., eds., "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", *IPCC* (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013), doi:10.1017/CBO9781107415324.

[10] National Oceanic and Atmospheric Administration, *GLOBAL AND REGIONAL SEA LEVEL RISE SCENARIOS FOR THE UNITED STATES*, NOAA Technical Report NOS CO-OPS 083, Silver Spring, MD: January 2017, https://tidesandcurrents.noaa.gov/publications/techrpt83_Global_and_Regional_SLR_Scenarios_for_the_US_final.pdf.

about our policies and practices . While we can measure current levels of heating and greenhouse gas production, we cannot know with certainty what future levels will be. The world is still arguing about energy policy. No one can say if we are going to burn all the coal or tar sands, use nuclear, or how much we will subsidize renewable energy. That choice of energy source is fundamental, as well as the exact amount of energy demand between now and the end of the century. Without a clear understanding of those two factors, we cannot estimate how much the planet will warm.



Unified Sea Level Rise Projection
(Southeast Florida Regional Climate Change Compact, 2019)

Year	IPCC Median (inches)	NOAA Intermediate High (inches)	NOAA High (inches)
2040	10	17	21
2070	21	40	54
2120	40	92	136

Figure 6: Current sea level rise projections used by the Southeast Florida Regional Climate Change Compact to guide development in the four counties, revised in 2019 (Southeast Florida Regional Climate Change Compact).

Another factor that makes projections difficult is the unpredictability of exactly how and when the ice sheets atop Greenland and Antarctica will melt, as discussed in Chapter 2. The models for the melting and collapse of the great glaciers and ice sheets are getting much better, thanks to the good field science on the ice sheets and better data from satellites and aircraft. But the cold, hard reality is that we cannot know in advance precisely how those massive ice sheets will melt, collapse, and slither into the sea.

It is also important to note that each agency that publishes SLR projections represents different communities and professions, each with its own culture and requirements. For example, the scientific community is represented by the IPCC; engineers are represented by the Army Corps of Engineers; and flood forecasters are represented by NOAA. When those three professions look to the future, their concerns, methods, and professional methodologies are quite different.

Scientists are focused on the physical processes and nuances of climate change. They often look at hundred-year timeframes as benchmarks. They are constrained by methodology and the requirements of high levels of statistical confidence. Scientists do not like to go out on a limb and publicly state opinions or even make highly educated inferences. Doing so would put them at risk of professional criticism. While this approach preserves the integrity of the scientific process, it creates problems for real-world decision making. This “Achilles Heel” of the scientific approach is exemplified by the IPCC’s 5th Assessment, as covered in Deeper Dive Note #6 – *the most important asterisk ever*, explaining why Antarctica is largely missing from the projections.

Engineers take a different approach to SLR projections than scientists. They often think in terms of 50 to 100-year project life spans and like to have a margin of safety in their designs. Engineers will consider the higher projections for SLR, even where there is uncertainty about the projections. Then they will often overdesign to have a margin of safety.

Flood forecasters and a wider field of focus now described as *flood plain managers* have yet another perspective. They want the latest, most comprehensive models to give flood warnings on a dynamic basis. While they will work with scientists and engineers closely, their mission is public safety.

It is clear that these three entities have very different perspectives and concerns about future flooding and that these concerns affect which of the forecasts they choose to follow. While it is important to look at all of the projections and recognize why they differ and the limitations of each, it’s easy to understand the different approaches taken depending on the focus of each.

When these differences of approach are not understood, it can lead to bad planning and policy. It’s best to plan for multiple SLR scenarios with a range of outcomes, including some that would be considered extreme.

Note #5 – Lunar Cycle to Create More Confusion [48]

Most people are aware that the gravitational pull of the moon and sun on our oceans is the basic force causing the daily change of ocean height we refer to as tides. When the sun and moon are in alignment and pulling together, during a new or full moon, the force is greatest and the tides are highest. These are sometimes referred to as spring tides, though they have no relation to the season.

Four times a year, when the moon is closest to Earth and happens to coincide with one of those spring tides, the high tides become extra high. Properly called a "perigean high tide," they are more commonly referred to as "king tides."

In coastal areas all over the world, SLR has increased the flooding from king tides, creating ocean heights higher than at any previous time in human civilization, with the exception of short-term weather events like storms and high winds.

Now consider another natural phenomenon. About every 19 years, a *lunar nodal cycle* begins. This little-known occurrence was first documented by the Greek astronomer Meton of Athens almost 2,500 years ago in 432 BC. (In fact, the Meton cycle is incorporated into the Greek, Chinese, and Hebrew calendars and is still used to set the dates for events like Easter.)

Each up-cycle and each down-cycle lasts about 9.5 years, and changes sea level about 2.5 inches (6 cm). In other words, during each half of the 19-year period, this particular cycle will either add to peak high tide or subtract from it.

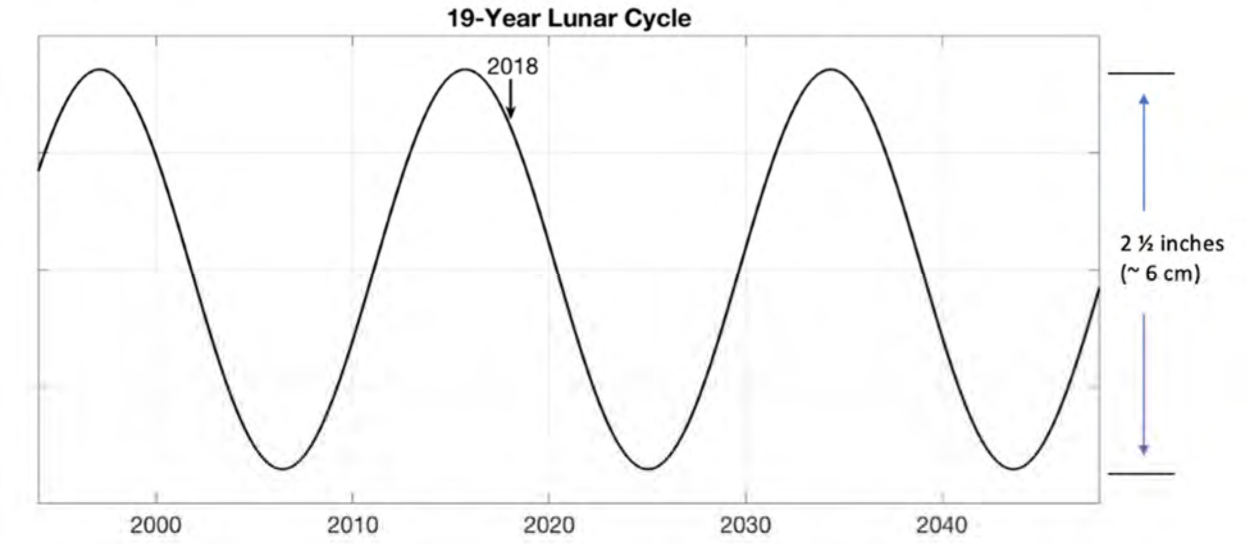


Figure 7: The 19-year repeating pattern of adjustments to high and low tides occurs because of the different angles and strengths of the sun and moon pulling on the oceans. Though only creating a 2.5 inch (~ 6 cm) variation in SLR, it adds a surprising element of confusion to discussions about sea level.

Presently, the global average rate of real SLR due to increasing ocean water volume is almost 2 inches (5 cm) per decade. During the most recent *up phase* of the lunar nodal cycle, from 2007 – 2015, the 2.5 inches from this tidal cycle added to the roughly 2 inches of global average SLR, causing roughly 4.5 inches of combined higher sea level at peak high tide. This accounts for the seemingly extremely high rate of SLR in the period ending around 2015.

In 2018, we started a *down phase* of the 19-year cycle. Global sea level will still go up another 2 inches, largely from the melting ice. But the 19-year lunar cycle has reversed and will subtract 2.5 inches from sea level over these nine years, effectively nullifying apparent SLR. This creates an impression that SLR is slowing, which may confuse or even falsely be used as support for those that do not believe in climate change.

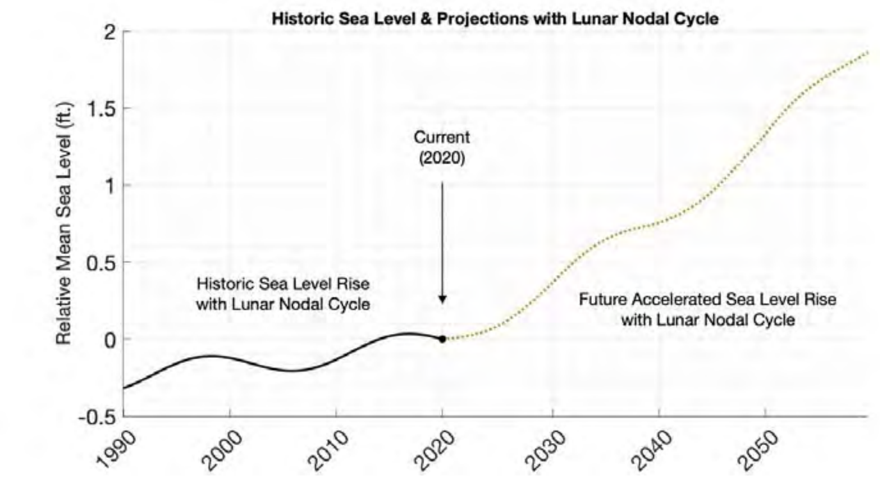


Figure 8: The graph overlays the 19-year cycle combined with SLR.

In the next up phase of the lunar cycle, which will occur from 2025–2034, it will very likely again appear as if sea levels have risen four or five inches in a decade, understandably causing confusion and surprising many. Figure 8 combines the lunar nodal cycle with projections for rising sea level. Though subtle, note how the slope of the line changes. Few appreciate how the roughly nineteen year pattern of tides identified thousands of years ago, adds to the confusion about rising sea level in the modern era.

Note #6 – The Most Important Asterisk Ever [50]

The most widely cited reference regarding climate change is the United Nation's Intergovernmental Panel on Climate Change (IPCC). Its 5th Assessment Report ("AR5"), released in 2013,[11] looks at possible future climate according to four scenarios, identified as RCP 2.6, 4.5, 6.0, and 8.5. It is excellent in most everything *except* its widely-cited sea level projections.

Figure 9 shows the IPCC's most common SLR projections, from lowest to highest, 28–98 cm (11–39 inches) in a very simple graphic showing the wide range of projections. Often overlooked, even in the worst-case projection, the total contribution from Antarctica is only 3 cm, just over an inch. Recall from Chapter 2 that Antarctica is far and away the largest source of potential SLR. If all of its ice melts, it would raise sea levels by 185 feet (56 meters) worldwide.

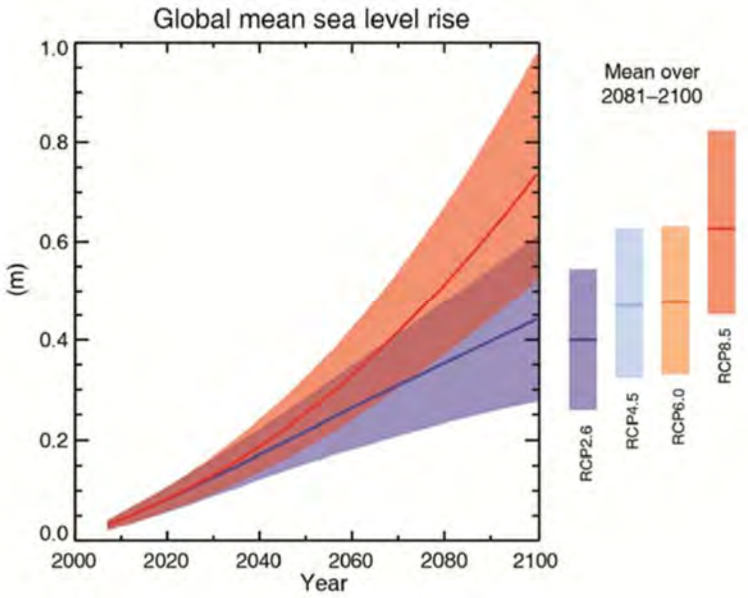


Figure 9: Projected sea level rise scenarios from the IPCC's 5th Assessment Report (UN-IPCC, AR5, pg. 26, Figure SPM.9).

Figure 10 on the next page is also from the IPCC Report and gives more detail. However, the format can be confusing to interpret, so I have taken the source data, from Table 13-5 (page 1182), and reformatted it as a more traditional stacked-bar graph just below, Figure 11. This shows the four different IPCC scenarios, with increased warming from left to right. The light-blue bars represent the contribution from the Antarctic ice sheet. The amount of ice contribution from Antarctica does not change over the first three projections (2 inches or 5 cm). But in the fourth and warmest scenario, it is reduced to 1 inch (3 cm). That decrease in a warming world would seem counterintuitive, but is based on a well-established scientific principle.

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[11] T.F. Stocker et al., eds., "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", *IPCC* (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013), doi:10.1017/CBO9781107415324.

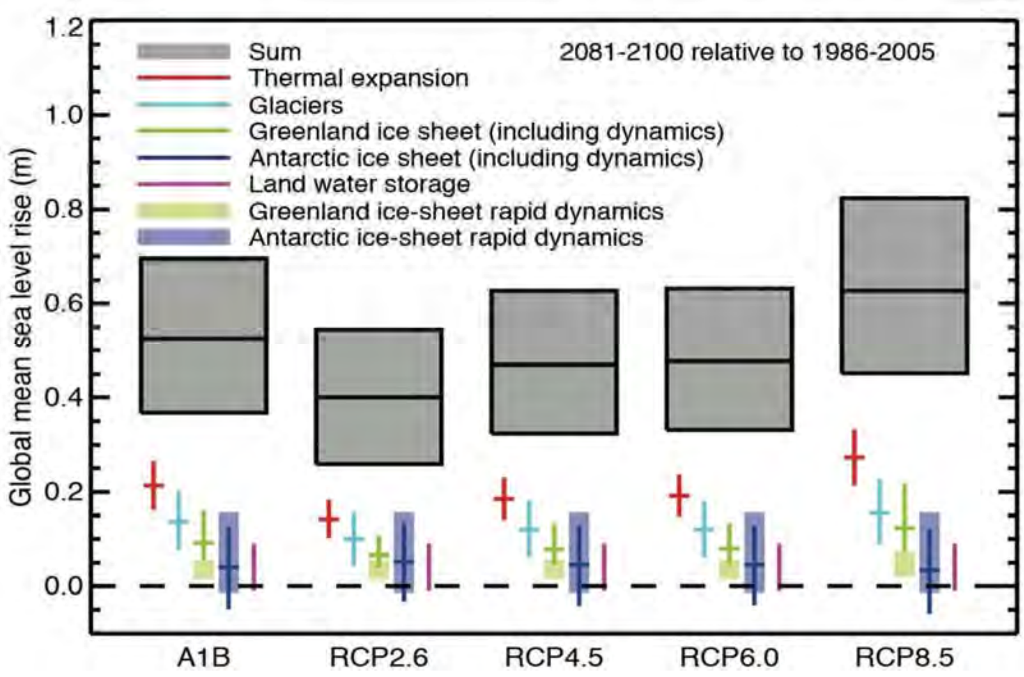

Figure 10: Projections from models with likely ranges and median values for global mean sea level rise and its contributions in 2081–2100 relative to 1986–2005 for the four SLR scenarios (UN-IPCC, AR5, pg. 1180, Figure 13-10).

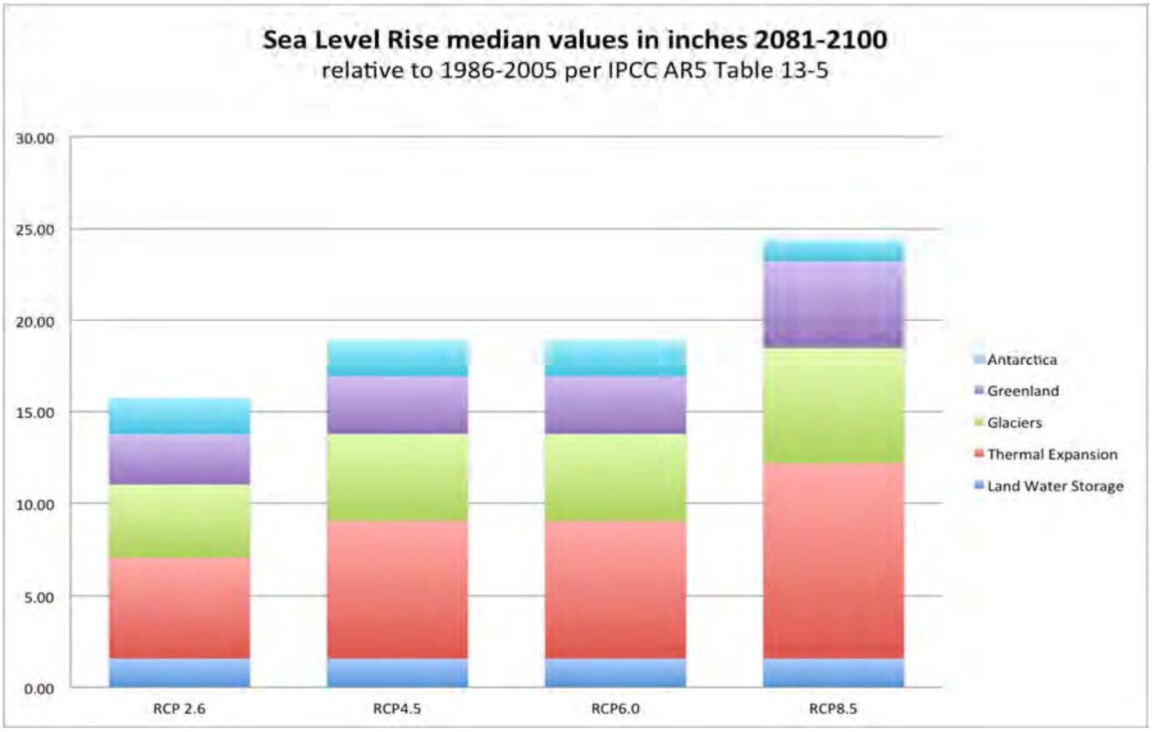

Figure 11: Median values and likely ranges for projections of global mean SLR and its contributions in meters in 2081–2100 relative to 1986–2005 for the four SLR scenarios (adapted from UN-IPCC, AR5, pg. 1182, Table 13-5).

Warmer water evaporates more quickly, so as the oceans warm, there will be more evaporation which will result in more precipitation, rain or snow. In cold areas, like East Antarctica, it's snow. Thus, in a warming world these models show East Antarctica could have more snow/ice, technically reducing sea level.

However, recall from Deeper Dive Note #2 that East Antarctica is now beginning to show signs of destabilizing, which could result in more rapid melting and a net loss of the massive ice sheets and glaciers making even the most extreme scenario of the IPCC projection too low.

An even larger problem with the IPCC projections is the contribution from West Antarctica. Since there is no way to quantify how much ice will likely melt by 2100, that component is simply left out of the IPCC tabulations.

Do glaciologists believe that Antarctica will only contribute 1 inch (3 cm) to global SLR by 2100? Not at all. Paradoxically, the gross underestimation of SLR from Antarctic melting this century actually results from a rigorous scientific process. Many scientists and climate change researchers have missed this, so it's worth explaining.

The First IPCC report, published in 1990, utilized an extremely rigorous scientific protocol, including multiple-level review by panels of experts, full disclosure of sources and calculations. Comment/question periods were open to any scientist in the world, as well as members of the public. All key concepts and data had to be published in peer-reviewed scientific journals. The projections had to be based specifically on the year 2100, and the data had to meet high standards of statistical significance.

Due to the uncertainty about the ice sheet and mega glaciers, Antarctica's contribution was hardly included at all. If you look at the report carefully, in the fine print - essentially the footnotes - you'll see the IPCC recognizes many diverging opinions from competent glaciologists concerned that the SLR contribution from Antarctica by the year 2100 could be as much as a meter or two (3 to 7 feet). But the data were too ambiguous to be included in the report with a projected value that met the IPCC's rigorous standards. That's why I refer to the omission of Antarctic contribution to SLR, as "the Antarctic Asterisk." The only component that met their criteria allowed for an estimated 1 inch (3 cm) of SLR from Antarctica, which is clearly a gross underestimation of Antarctic contribution to SLR. This situation with the IPCC reflects a larger culture of scientific caution.

When it comes to rising sea level, it does not help us plan for the worst-case scenario, or even the mid-range scenarios. In other words, inadvertently, the good scientific process has caused a major understatement of the risk. Increasingly groups of planners and scientists have come to the realization that the IPCC projections for SLR are far too low. Many of us are hopeful that the next IPCC report, the *Sixth Assessment*, due out in 2022, will rectify the misleading way that the IPCC frames potential sea level. I should note that as formal input to the IPCC, that in December 2020, I was a contributing author on a paper making the case that IPCC sea level projections are understated, "Twenty-First century sea-level rise could exceed IPCC projections for strong-warming futures."[12]

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[12] M. Siegert et al., *One Earth*, "Twenty-First century sea-level rise could exceed IPCC projections for strong-warming futures", December 18, 2020, https://doi.org/10.1016/j.oneear.2020.11.002

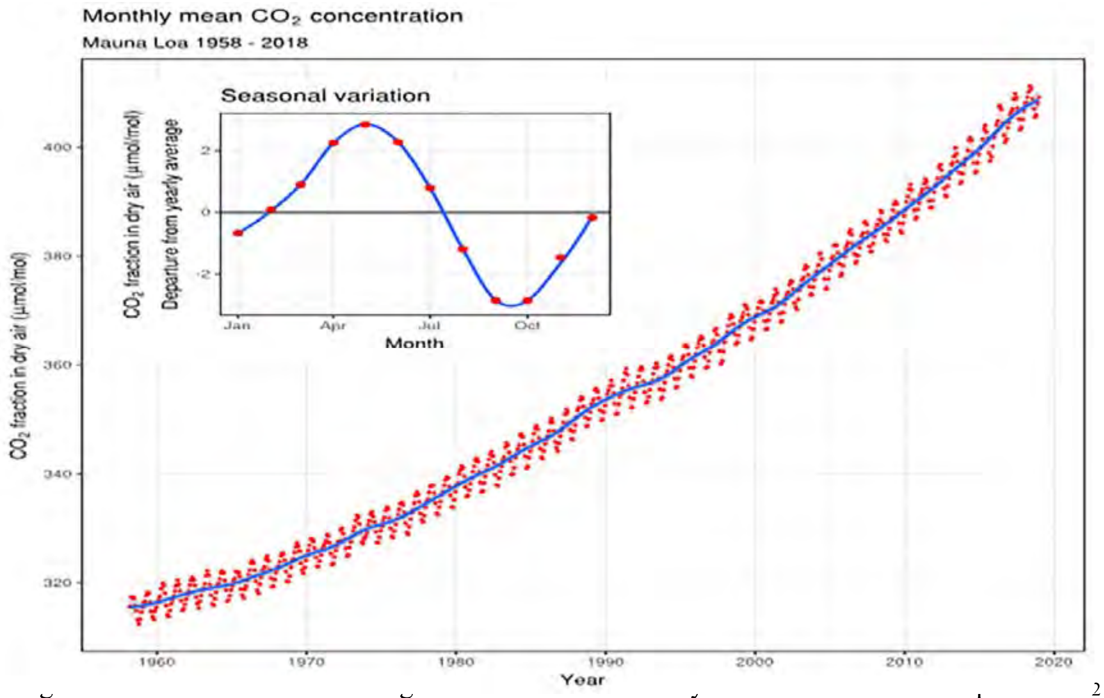
Note #7 – Clearing Up CO_2 Misunderstandings [65]

As discussed in Chapter 4 , the science behind the “greenhouse effect”, and the correlation between temperature and CO_2 (carbon dioxide) has been understood for almost two centuries. Over the long term of decades and centuries, global CO_2 and temperature move in close synchronization.

- As temperature increases, the oceans warm and release gases into the atmosphere, including CO_2.
- As CO_2 levels increase in the atmosphere, it functions like the clear roof of a greenhouse, trapping heat and warming the planet.

Either can lead; the other will follow. In the current era, the current rapid increase in CO_2 is driving up the global “thermostat” or heat level.

In 1958, a scientist at Scripps Institution of Oceanography, the late Charles David Keeling, perfected a very precise way to measure CO_2 levels. He set up an isolated research laboratory on Mauna Loa, a Hawaiian mountaintop and began recording daily CO_2 levels. That research continues to this day, as illustrated in Figure 12. The “Keeling Curve” shows a clear upward trend, along with a very consistent saw-tooth temperature pattern that correlates with the seasonal variation expected with the annual vegetation cycles. Plants in the Northern Hemisphere, which contains most of the Earth’s land mass and vegetation, photosynthesize in the spring and summer months, removing CO_2 from the atmosphere. This accounts for the annual decrease in CO_2 concentrations observed in the curve. When Keeling began his measurements, the level of CO_2 in the atmosphere was 313 parts per million (ppm).



$_2$ (carbon dioxide) showing the seasonal changes of vegetation and the steady increase of global CO_2 correlating with the burning fossil fuels. (Data: R.F. Keeling, S.J. Walker, S.C. Piper and A.F. Bollenbacher. Scripps CO_2 Program, Scripps Institution of Oceanography).

As Moving to Higher Ground is published in 2021, global CO_2 is at 419 ppm, a 32 percent increase in just 60 years. The increase in CO_2 levels correlates with the burning of fossil fuels and industrialization, just as one would expect.

- For the latest measurements from Mauna Loa and more graphics about CO_2, visit: https://esrl.noaa.gov/gmd/ccgg/trends/mlo.html

Some of those who dismiss the issue of higher carbon dioxide levels say things like, “It’s natural... and will help plants grow better.” While there is some truth in the statement that more CO_2 will increase plant productivity, there are upper limits to the benefit of this effect. The fact that more of something can be positive to a degree, does not mean it is benign or harmless. As an analogy, water is essential to life, but drink too much and you can die. Even life-sustaining oxygen will become toxic at a pressure above two atmospheres, putting the brain into convulsion. The point is that CO_2 is not harmless. It is an extremely powerful substance for humans, for animals, for plants and for the atmosphere. Furthermore, other factors are already damaging and destroying forests and plants, such as intense logging and farming practices, high heat, drought and deluge rain.

While CO_2 and temperature increase and decrease in close coordination over thousands of years, there is a delay in their synchronization. That is, an increase in CO_2 level will take decades to show up as warmer temperature. Warming temperature takes decades to release CO_2 from the oceans measurably increasing global levels.

Figure 13 illustrates the close correlation of CO_2 and global average temperature over the last 800,000 years. You can see that, at times, CO_2 increases precedes temperature increases and vice versa. The right side of the graph expands the timescale of the last century, where temperature increase since 1880 has lagged behind the increase in CO_2 level.

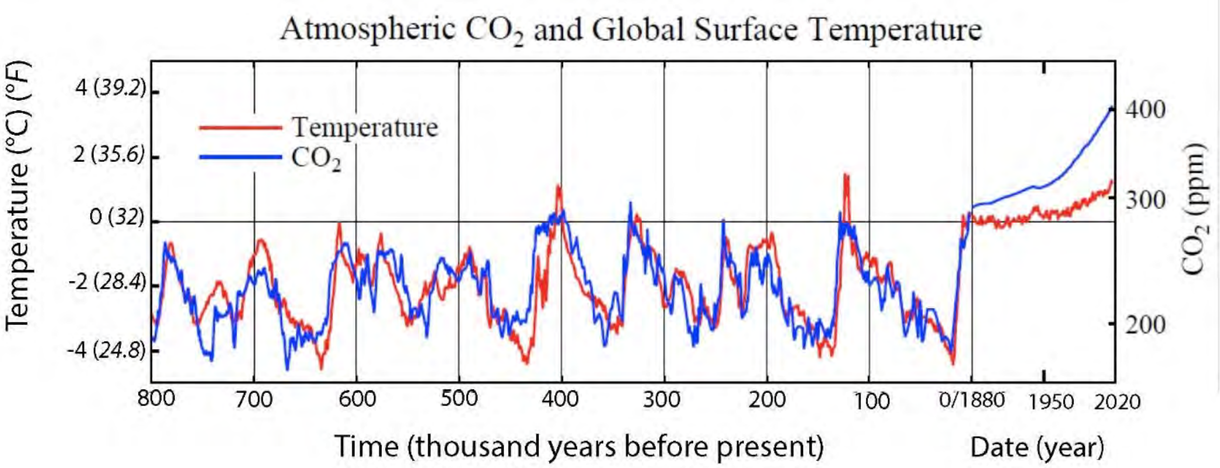


Figure 13: This chart shows the correlation between temperature and CO_2 over the last 800,000 years. The timescale for the last century has been expanded. Paleo global surface temperature change is from ocean core data of Zachos et al. (Nature 451, 279-283, 2008) via equations of Hansen et al. (Phil. Trans. Roy. Soc. A, 371, 20120294, 2013).

It can take decades for even the surface layer of the ocean—the top 600-700 feet (200 meters)—to fully adjust to a single degree of warmer air temperatures. Pioneering oceanographer , the late

Dr. Wallace Broecker estimated that it could take as long as a thousand years for the entire ocean to equalize to a new average global air temperature[13]. This is one of the reasons that sea level is projected to rise for centuries *after* the atmospheric temperature stabilizes again.

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[13] Robert Kunzig & Wallace S. Broecker, "*Fixing climate: the story of climate science - and how to stop global* warming", (Great Britain: Green Profile, 2009).

Note #8 – Ocean Acidification [67]

Ocean acidification is a rather obscure effect of CO_2 emissions that many climate and ocean scientists believe could be the single most important change on our planet over the next century.

Much of the carbon dioxide that we put into the atmosphere dissolves in seawater as carbonic acid. You have likely tasted this fairly mild acid. It's what gives carbonated beverages their slightly sharp, bitter taste. This increased carbonic acid lowers the pH of seawater, which affects every organism in the ocean, either directly or indirectly, through the marine food chain or habitat changes. The resulting damage can last for millennia.

As you may recall from science class, pH ranges from 1 to 14. Anything above 7 is alkaline; anything below 7 is acidic. Fresh water is neutral with a pH of 7. At the start of the fossil fuel era, ocean pH was 8.2. Now it is about 8.1. The pH scale is logarithmic, which means that a change of one integer will change the concentration tenfold, so that the movement towards acidity represents a 30 percent increase in acidity over just 240 years. The rate of change has not been this fast in hundreds of millions of years. It is 100 times faster than the last significant pH drop that occurred 650,000 years ago, and ten times faster than the most recent mass extinction event 55 million years ago[14].

Many marine organisms, from shellfish to coral reefs to plankton, depend on a calcium-rich environment to build their shells and other calcium carbonate structures. These structures simply will not form in acidic water. Figure 14 illustrates how the additional CO_2 in the oceans is impeding the calcification process.

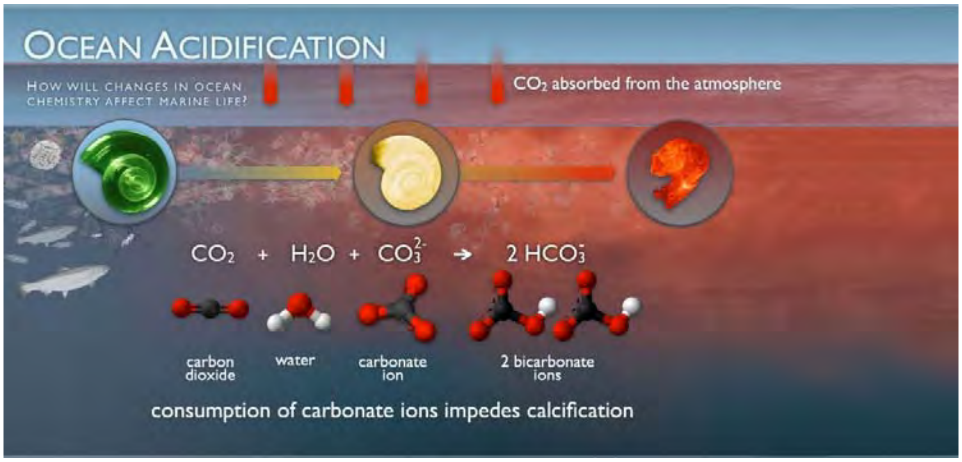

Figure 14: This graphic illustrates how carbon dioxide dissolved in seawater produces hydrogen ions that bond with carbonate ions to produce bicarbonate ions, which disrupt the calcification process in marine organisms with calcium carbonate shells or skeletons (NOAA PMEL Carbon Program).

To build their shells, a carbonate ion combines with a calcium ion to form calcium carbonate. Hydrogen ions also bond with carbonate ions to produce bicarbonate. The attraction between hydrogen and carbonate is stronger than the attraction between calcium and carbonate, so the

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[14] John M. Guinotte and Victoria J. Fabry, "Ocean Acidification and Its Potential Effects on Marine Ecosystems", *Ann. N.Y. Acad. Sci. 1134* (2008): 320–342. doi: 10.1196/annals.1439.013

additional hydrogen ions essentially outcompete the calcium ions for the carbonate ions. In some instances, hydrogen ions can even break apart existing calcium carbonate molecules, dissolving the shells that were already formed.

This has obvious repercussions for the shell-fishing industry, but it will also affect the entire marine food web. The base of the food chain is formed by tiny marine algae called phytoplankton. They are the food of planktonic animals, which in turn are eaten by larger animals, including the biggest animal on our planet, the blue whale. The phytoplankton also produce about half of the world's oxygen and absorb about one-third of the CO_2 in the atmosphere.

Ocean acidification will significantly reduce phytoplankton growth and, in turn, leave more carbon dioxide in the atmosphere, forming a feedback loop and further raising global temperatures. Even small reductions of phytoplankton growth can have large impacts on CO_2 levels.

Acidification is also extremely damaging to coral reefs. Among the most diverse ecosystems on Earth, coral reefs contain organisms from 32 of the 34 taxonomical phyla recognized by scientists. They provide shelter and habitat for millions of marine species. They also help to protect shorelines from damaging storm surges and erosion, and they play an important role in nutrient cycling. Reefs are a vital part of the recreation and tourism industry for many countries.

Corals have a relatively narrow tolerance range to changes in water pH and temperature. This is analogous to the body temperature range of humans. While we can generally tolerate a wide range of external temperatures, if our internal body temperature rises by about 5 degrees Fahrenheit (2.5 Celsius) for very long at all, we will almost certainly die. When a coral is stressed, such as from a change in temperature or pH, it will expel the colorful algae (*zooxanthellae*) that lives in it. This causes the coral to turn white, or "bleach." If a reef stays bleached for long enough, it will die.

Throughout the planet's history, the combination of ocean acidification and rising temperature have wiped out coral reefs at least five times.[15] Fossil evidence has revealed that the meteorite impact 66 million years ago that wiped out the dinosaurs, caused the pH of the ocean to drop by .25 pH units, killing three quarters of marine species.[16] This occurred in the centuries after the meteorite strike, and it took hundreds of thousands of years for carbon cycling to return to normal.

The increasing pace of reef destruction over the last few decades is unprecedented and is already affecting communities where coral reefs are central to the economy. Scientists have estimated that, at our current rate of acidification, we could see a drop of 0.4 pH units during this century, an additional 120 percent increase in acidification that will cause 70-90 percent of reefs to

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[15] Wolfgang Kiessling & Carl Simpson, "On the potential for ocean acidification to be a general cause of ancient reef crises," *Global Change Biology 17,* no. 1 (December 2010): 56–67. https://doi.org/10.1111/j.1365-2486.2010.02204.

[16] Michael J. Henehan et. al. "Rapid ocean acidification and protracted Earth system recovery followed the end-Cretaceous Chicxulub impact", *PNAS 116*, no. 45 (October 2019): 22500-22504, https://doi.org/10.1073/pnas.1905989116.

disappear in the next 20 years, and all of them to be gone by the end of the century.[17]

Figure 15: Bleached coral on a reef (ARC CoE for Coral Reef Studies/ Laura Richardson).

Because ocean acidification starts at the ionic level, it is hard to imagine ways to reverse the effect. There are efforts to find and develop more resilient corals that might be propagated and implanted in the ocean. But given that the fundamental chemistry of all those calcium-based shells only functions in a high alkaline environment, I am skeptical if there is a solution to the assault on the marine ecosystem, as long as we keep pumping more and more carbon dioxide into the atmosphere.

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[17] Lauren Lipuma, "WARMING, ACIDIC OCEANS MAY NEARLY ELIMINATE CORAL REEF HABITATS BY 2100", *American Geophysical Union*, February 17th, 2020, https://news.agu.org/press-release/warming-acidic-oceans-may-nearly-eliminate-coral-reef-habitats-by-2100/.

Note #9 – Methane [67]

Methane is a powerful greenhouse gas that is extremely effective at heating the atmosphere. In its pure form, at the molecular level, methane (CH_4.) is over 100 times more potent than CO_2 as a greenhouse gas, or atmospheric warming agent. Averaged over 20 years from its release in the atmosphere, methane has 86 times more heat-trapping ability than carbon dioxide. Methane is relatively unstable. Over the course of decades it breaks down in the atmosphere, ultimately transforming to CO_2, which is extremely stable and has a lasting effect on global temperature for thousands of years. Averaged over 100 years, methane is 34 times more powerful than carbon dioxide in terms of warming, on a unit for unit basis.[18]

Methane has been responsible for extreme, rapid warming in the geologic past. Roughly 55 million years ago, a dramatic event, known as the Paleogene-Eogene Thermal Maximum, occurred when a huge amount of undersea methane was released into the atmosphere. Scientists sometimes refer to it as the "methane mega-fart."[19] There is debate over what caused this gigantic release of methane, but it triggered sudden global warming and a subsequent mass extinction event.[20] In less than 20,000 years, the average global temperature rose about 11 degrees F (six degrees C). That huge change even made the Arctic rather balmy, with ocean temperatures as warm as 50 to 60 degrees F (10-20 degrees C).[21]

Atmospheric methane levels have surged by more than 30 percent over the last decade and currently account for about 16 percent of all greenhouse gas emissions. This rapid increase has created serious cause for concern.

The four major sources of methane emissions include:

1. Hydraulic fracturing. Escaped methane from the "fracking" process to develop natural gas wells, as well as the transport and handling of the product. Methane from fracking has been rapidly increasing due to the boom in natural gas production and use in the U.S. and internationally. Recent research shows the volume of methane from fracking is much larger than previously believed. https://www.ccacoalition.org/en/resources/global-methane-assessment-full-report

2. Agriculture, particularly cows. Best estimates suggest that the elimination of eating meat on a global scale could reduce greenhouse gases by about 17 percent.

3. Permafrost thaw. The rapidly thawing Arctic tundra releases a tremendous quantity of methane in Alaska, Canada, Scandinavia, and Russia. In areas of Siberia, methane eruptions

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[18] T.F. Stocker et al., eds., "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change", *IPCC* (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press, 2013), Table 8.7, doi:10.1017/CBO9781107415324.

[19] M. Ruhl et. al., "Atmospheric Carbon Injection Linked to End-Triassic Mass Extinction", *Science 333*, no. 6041 (2011): 430-434.

[20] D.J. Thomas et. al., "Warming the fuel for the fire: Evidence for the thermal dissociation of methane hydrate during the Paleocene-Eocene thermal maximum", *Geology 30*, no. 12 (2002): 1067-1070.

[21] C.J. Shellito et. al., "Climate model sensitivity to atmospheric CO_2 levels in the Early-Middle Paleogene", *Palaeogeography, Palaeoclimatology, Palaeoecology 193*, no.1 (2003): 113-123.

have created huge craters, which seem similar to the giant releases of methane tens of millions of years ago that likely caused rapid warming.

4. Hydrates (or clathrates): This frozen, slushy type of ice under the seabed is essentially pure methane and believed to be the largest potential quantity on the planet. In fact, it is estimated that there is more of this form of methane than there is petroleum in the world. As the ocean warms, this methane will be released. Several scientific ships working in the far north off Siberia have reported massive areas of ocean that look like a carbonated beverage with endless tiny bubbles of methane venting from the seabed. Japanese researchers are actively testing the potential to access this frozen methane as an energy source.

In 2021, methane levels reached a record high at 1,893 ppb (parts per billion).[22] This increase coincides with the escalation of oil and gas drilling that began in 2006, with more than half directly attributable to shale fracking operations.[23] Figure 17 shows methane levels since 1983 with a spike starting in 2006. The current rate of increase is 27 times faster than during the methane mega-fart that caused the last mass extinction event.[24]

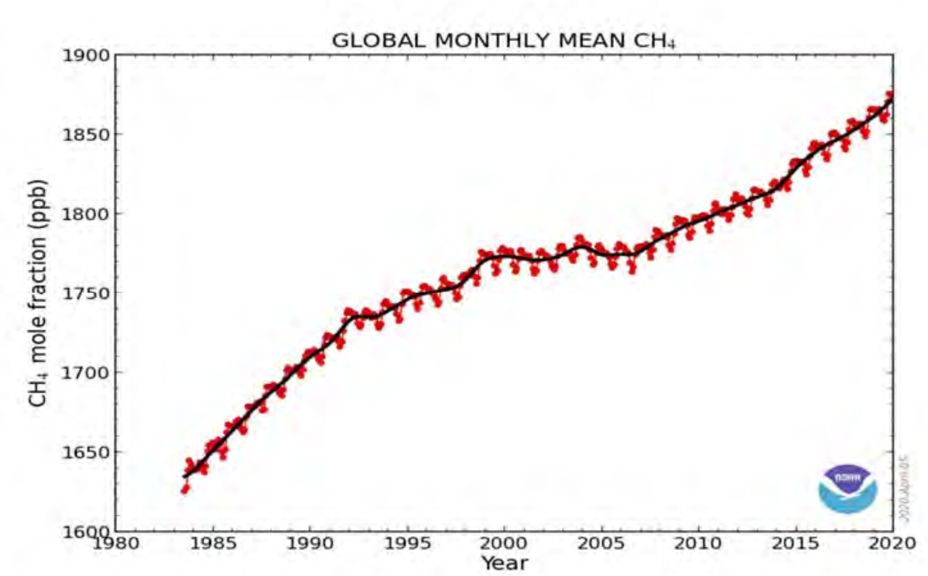

Figure 17: Global monthly mean concentration of methane in the atmosphere (Global Monitoring Lab, Earth System Research Laboratories, NOAA) https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/ .

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[22] Jeremy Deaton, “Methane Levels Reach an All-Time High”, *Scientific American*, April 12th, 2020, https://www.scientificamerican.com/article/methane-levels-reach-an-all-time-high/.

[23] Robert W. Howarth, “Ideas and perspectives: is shale gas a major driver of recent increase in global atmospheric methane?”, *Biogeosciences 16*, (August 14th, 2019): 3033-3046, https://doi.org/10.5194/bg-16-3033-2019.

[24] Ying Cui et. al., “Slow release of fossil carbon during the Palaeocene-Eocene Thermal Maximum”, *Nature Geoscience*, no. 4 (2011): 481-485, https://doi.org/10.1038/ngeo1179.

Adding to the complexity and confusion is that natural gas is generally viewed as positive for climate change, under the theory that it is a much better alternative to energy sources like coal. That theory presumes that natural gas is completely burned. In the process of developing more natural gas production, a great deal of methane leaks into the atmosphere, increasing the warming.

The prospect of this massive methane release should spur us to reduce the emission of all greenhouse gases within our control as the highest possible priority as a way to slow the warming. Research about the methane in the seabed and permafrost should continue, though I believe it is unrealistic to expect that there will be any way for us to control those sources that are widely dispersed over millions of square miles and that are being released as a result of the warming and thawing.

For the latest measurements of methane and more information, see:

https://www.esrl.noaa.gov/gmd/ccgg/trends_ch4/

Note #10 – Geo-engineering [Page #69 in Moving to Higher Ground]

As explained in Chapter 4, "Reducing CO_2 and Being Resilient are Not Enough" we have passed the point when reducing greenhouse gas emissions can return us to a stable climate, weather system, polar ice caps, sea level and coastlines. There is no plausible path to avoid the effects in the next few decades, even with the most aggressive proposals to slow the warming by switching to renewable energy.

With the level of carbon dioxide now approaching 420 ppm (parts per million) well above the range of 180 – 280 ppm for the last several million years, we now must look at ways to stave off the effects, even those that have been considered risky.

Often described as geo-engineering, these approaches generally are in two categories: One aims to reduce the level of carbon dioxide and other *greenhouse gases* in the atmosphere. The second aims to reduce the amount of solar energy received, the direct force of warming. Some examples are shown below in the two categories. No single concept will fully address the problem.

Carbon Dioxide Removal - Examples

- Massive tree planting

  Ref: article The Global Tree Restoration Potential by Jean-Francois Bastin, et al. https://www.science.org/doi/10.1126/science.aax0848

- Direct air capture and removal of CO_2.

  Climeworks is an operating example in Iceland. https://climeworks.com/

- Ocean iron fertilization of phytoplankton or kelp permaculture to sequester organic carbon reducing carbon dioxide in the atmosphere

  Ref: "A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration" (2021) https://www.nap.edu/catalog/26278/a-research-strategy-for-ocean-based-carbon-dioxide-removal-and-sequestration

- Synthetic limestone as a building material

  https://www.blueplanetsystems.com/products

Solar Radiation Management - Examples

- Marine cloud brightening, to reflect more sunlight

  For an example see the Youtube of Stephen Salter with his concept for ships to use saltwater to make clouds more reflective. https://youtu.be/ktcWQ2vLoTI

- Injection of sulfur dioxide into the atmosphere to reflect sunlight

  https://acp.copernicus.org/articles/16/2843/2016/

- Mirrors in space to deflect some of the incoming solar energy

  https://en.wikipedia.org/wiki/Space_mirror_(climate_engineering)

Various institutions and specialized nonprofits are now focused on this new field of research and have websites with further information, e.g.

- **Centre for Climate Repair at Cambridge** https://www.climaterepair.cam.ac.uk/
- **Foundation for Climate Restoration** foundationforclimaterestoration.org/start-here/
- **U.S. National Academy of Sciences** http://www.nasonline.org/

As this field of scientific study and engineering experimentation are rapidly evolving, it is important that anyone interested do a search for the latest information, publications, meetings and policy discussion.