MODULE 1: Three S's of Climate Change -- Simple, Serious, Solvable

MODULE OUTLINE

1. Climate Change is Simple
   a. Heat in minus heat out equals change of heat (conservation of energy)
   b. Days vs night; summer vs winter; Phoenix vs Fargo – easily understood
   c. Weather is heat in & out "sideways" but Earth has no "sides"
   d. Heat can move three ways but ONLY radiation can change Earth's heat
   e. Incoming radiation from the Sun is balanced by outgoing IR radiation
   f. Air is selectively transparent: sunlight gets through but IR doesn't
   g. 99% of the air is diatomic N2 and O2 which don't interact with IR
   h. <1% of gases (esp CO2 and H2O) are responsible for GHE
   i. Every doubling of CO2 adds 4 W/m2 (night light bulb)
   j. We've understood this since before light bulbs were invented

2. Climate Change is Serious
   a. Without strong policy, as much warming by 2100 as 100 centuries after ice age
   b. 2xCO2 -> 3C globally = 6 C over central USA = 10 F (DEN -> ABQ)
   c. 10 F = 3000' elevation (DEN -> Estes; Estes -> Trail Ridge)
   d. Drought
   e. Fire
   f. Floods
   g. Every bit of coal/oil/gas ever burned adds CO2 & warms for millennia
   h. We have enough fuel to warm Earth catastrophically & permanently
   i. Have to eliminate carbon combustion in a generation

3. Climate Change is Solvable
   a. STOP SETTING CARBON ON FIRE!
   b. Kaya Identity P x $/P x E/$ x C/E (Work on $/E and C/E)
   c. Energy efficiency costs negative dollars
   d. Use savings from efficiency to offset other capital costs
   e. Abundant & affordable low-cost energy (wind, solar, hydro, geo)
   f. Intermittency must be managed
      i. Transmission (HVDC)
      ii. Storage (batteries & other)
      iii. Firm clean power: geo, hydro, nukes
   g. Costs! ~1% of GDP
      i. More than US DoD budget!
      ii. Barely more than brand-new cell phones
      iii. Much less than coal/oil/gas
      iv. Every generation gets a chance
      v. We must & we will do this!

1. Climate Change is Simple

1.1 Heat in, heat out, change of heat, and temperature

There are lots of complex aspects to the climate problem, but the basic mechanism is so simple that everybody understands it. It's stuff we learn in grade school, not grad school! Allow me to remind you of some basic science you already know.

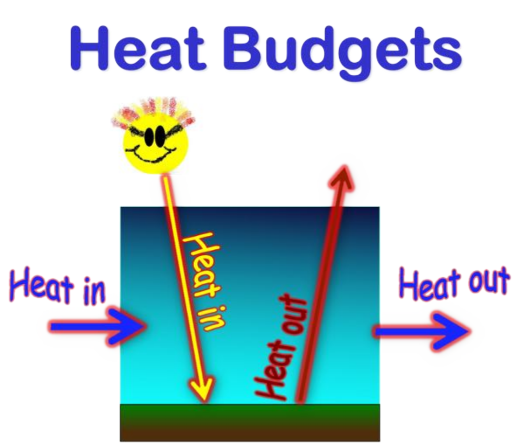
When more heat is added to something than is removed, it warms up! This is the reason the temperature of a pot of water placed on a hot stove increases: more heat is added by conduction to the bottom of the pot than can escape by conduction and evaporation from the top, and this accumulation of heat energy in the water is measured as an increase in its temperature.

For the pot of water, we can write

HEAT IN – HEAT OUT *equals* CHANGE IN HEAT CONTENT

and

CHANGE IN HEAT CONTENT *is proportional to* CHANGE IN TEMPERATURE



This intuitive observation is an example of a very fundamental concept called the conservation of energy. Obvious examples of energy conservation in the climanate system are the simple facts that

- Day is warmer than night
- Summer is warmer than winter
- Phoenix is warmer than Fargo

During the day, more heat is added by sunlight than escapes on the wind or by upward radiation. During the summer the days are longer and the Sun is higher in the sky, so heat piles up and the temperature rises. These conditions apply more in Phoenix than they do for Fargo every day and all year long.

As I said: Simple!

1.2 Weather vs climate

Day to day changes in the weather are all about heat coming and and going out of your location through the sides. The warm dry air on Tuesday can easily blow away and be replaced by cold damp air the next day. It's actually different air over our location from one day to the next, and the contrast can be really dramatic.

Those day-to-day swings in our weather don't change the temperature of the Earth at all – they just rearrange the heat that's already here. The world is round! You can reshuffle the heat all you want sideways and it won't change the total amount.

The ONLY way to change the Earth's temperature is via heat flowing and out through the top. We're not accustomed to thinking of the Earth having a top, but it does – the top of the atmosphere.

The heat coming in through the top of the atmosphere is in-your-face obvious – it's Sunlight. We can see it. We can feel it beating down on our faces. I have to wear a hat or it will burn my bald forehead.

But that's just heat IN. Remember heat in minus heat out equals change of heat so if Sunlight were the only game in town the Earth would get hotter and hotter and hotter and the temperature would rise forever. Pretty soon the Earth would melt. Then boil. Then vaporize. Aaaaghhh!

The incoming heat from Sunlight must be balanced by heat going out someplace, or we wouldn't be here to wonder why.

Remember back in grade school you learned that there are three ways to move heat around? Conduction is when fast-moving molecules (hot stuff) bang into slower-moving molecules (cooler stuff) and the slow molecules get kicked into faster motion. It pretty much only happens in solids. Convection is when hot gases or liquids move to a colder place and vice versa – think of the hot air rising from a campfire. (What was that third kind of heat transfer again?)

The Earth can't cool itself off by conduction. It's floating in a vacuum. There's no such thing as heat conduction to a vacuum because there's nothing to conduct the heat *to*. (That's the secret of thermos bottles). The Earth as a whole can't convect its heat out to space either. That would require rising plumes of heat being carried off into space. Thankfully, gravity holds the air down so that it's a permanent part of our planet, so it's no fair shotting off jets of hot air to cool Earth off.

So how come the Earth doesn't just get hotter and hotter without bound? Actually, this problem is the same for any planet or moon. Absorbed sunlight adds heat and the temperature goes up. How is it that Earth (or the Moon or Mars) doesn't just get hotter and hotter until it's vaporized?

Radiation!

Just as the Sun radiates energy we can see, the Earth radiates too. The Sun is a LOT hotter than the Earth, so it radiates *way* more heat and its radiation is mostly in short waves that we can see. The Earth is 20x cooler than the Sun, so it emits radiation with waves that are 20x longer than the Sun's rays. This "Earthshine" is exactly the same stuff as Sunshine, but it's a different color (wavelength, frequency). It's a color WAY beyond the red end of the visible spectrum, a color our eyes can't see. It's thermal infrared.

Everything radiates heat. You. Me. Rocks. Walls. Floors. Desks. Stuff at room temperature emits thermal infrared light. Stuff that's thousands of degrees (the Sun, lightbulb filaments, hot burners on a kitchen stove) emits visible light.

The Earth emits heat to space through the top of the atmosphere at a rate that's almost precisely equal to the rate at which it absorbs sunlight. How can we tell? Because the Earth didn't boil away billions of years ago! Next week I will show you thermal infrared Earthlight with a special instrument attached to my phone in class.

So here's the thing: if the Earth absorbs more heat (Sunlight) than it emits (Earthlight), it warms up. If it emits more heat (Earthlight) than it absorbs (Sunlight), it cools off. Duh! Just like everything else! In fact this is the ONLY WAY the Earth can warm up or cool off. All climate change is caused by a temporary imbalance between Sunlight and Earthlight. The hotter the Earth gets the more Earthlight it emits. The temperature adjusts until the Earthlight exactly balances the Sunlight again.

1.3 Weather is Unpredictable but Climate Is Predictable Because of Forcing

As we've seen, weather is just the rearrangement of the heat Earth already has whereas climate can only change by varying heat inputs and outputs through the top of the atmosphere. This has profound implications for predictability.

The motions of airmasses around our spinning are wildly chaotic, especially outside the tropics. We can't predict with any confidence what sort of airmass will sit over any given location more than a week or so in advance.

At the end of this course we will have a final exam. This semester it's due on Friday December 16. I've lived in Fort Collins more than 40 years and I can tell you that almost anything can happen to the weather here in mid-December. It might be sunny and calm and 70 degrees Fahrenheit. We might have a blizzard. It might be 20 below. Seriously!

The weather in Fort Collins on December 16, 2022 is very unpredictable. But not the climate!

I can predict with complete confidence that the high temperature in Fort Collins on the day of our final exam will be lower than 100 F, and higher than -50 F. That day won't have a foot of rain. The wind won't blow more than 200 miles an hour. More substantively, I can predict that Fort Collins' average temperature in December 2022 will be much lower than the average temperature in August 2022.

How is this possible? How can it be that we can make very confident predictions about climate when we have no idea what the weather will be on the day of our final exam?

This curious fact is due to something called "climate forcing." We're going to learn a lot about climate forcing in this class. Climate forcing is the difference between heat in and heat out. We can also say it's proportional to the rate of temperature change.

Climate Forcing = Heat In minus Heat Out = Change in Heat

The reason climate can be predictable when weather isn't is that sometimes the forcing is both strong and predictable.

The seasons are a perfect example of the predictability of climate. The Earth's rotational axis is tilted about 22° to the plane of its orbit.

When Earth's orbit swings around so the Northern Hemisphere points toward the Sun, our days are longer, and Sunlight hits the surface almost straight on. This increases the rate at which our part of the world absorbs Sunlight. Heat in exceeds heat out, so the Northern Hemisphere warms up. Eventually the hotter ground and ocean and air emits enough Earthlight to balance the increased Sunlight and our summer temperature stabilizes around July or August.

As Earth's orbit swings around to the other side and the Northern Hemisphere points away from the Sun our days get short and Sunlight strikes the surface at a glancing blow. Absorbed Sunlight is cut by more than half compared to summer but the warm Earth still radiates a lot of Earthlight out to space. Heat out exceeds heat in, so the Northern Hemisphere cools off. Eventually the colder ground and air emits less and less until the winter temperature stabilizes around January or February.

Remember this the next time somebody says "Hah! They can't even predict the weather next Sunday – and they expect us to believe they can predict global warming in 2100!"

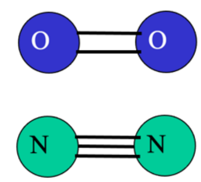
The two keys to climate predictability is that climate forcing (heat in minus heat out) is both strong and predictable. This is certainly true of seasonal changes, and it's true of changes caused by rising atmospheric CO_2 as well.

1.4 CO2 Makes the Air Selectively Transparent

All the outgoing heat radiation that cools the Earth has to pass through the air.

Air is made of gas molecules. Nearly all of those molecules are just two kinds: nitrogen (N2, about 80%) and oxygen (O2, about 20%). By coincidence, virtually all the molecules through which the thermal infrared radiation has to pass are diatomic molecules. This means they are perfectly symmetric, with no concentration of positive or negative charge at either end.

Electromagnetic radiation is an oscillation of changing electric fields that cause changing magnetic fields and vice versa. The fields propagate through space at the speed of light. This is the main way that energy gets around in the universe. I realize that you may not have learned much about this in high school so I will cover it in more detail in the next module. For now, just imagine wavy magnetic fields moving through space past some air molecules that are exactly the same at both ends.



Diatomic molecules can vibrate back and forth like balls on a spring, but the ends are identical

We can imagine nitrogen (and oxygen) molecules as two little balls of positive charge (protons and neutrons in the nucleus) that are glommed together by a bunch of tiny negative charges (electrons) that fly back and forth from one ball (atom) to the other. The flying (shared) electrons are the chemical bond between the two atoms of nitrogen (or oxygen).

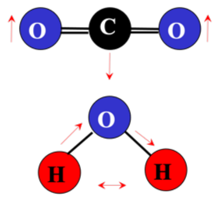
Then along comes this wavy (electric and) magnetic field that was emitted by the Earth's surface below as a way for it to cool off. Maybe you learned in high school that electrons get accelerated by an electric (or magnetic) field? Even if you never learned this, they do. So as the waves of electromagnetic fields pass through the N2 or O2 molecule, the electrons kind of smush together in the middle and then stretch out to the sides. The molecule gets longer and shorter along its axis, vibrating in resonance with the wavelength of the Earthlight (thermal infrared radiation) that's passing through.

Because both N2 and O2 are diatomic gases where each molecule is formed of two identical atoms of the same element, no matter how much the molecule stretches and contrast back, the positive nuclei and negative electrons stay perfectly symmetrical. There's no "plus end" or "minus end" of the wiggly molecules. This means they don't absorb much thermal infrared radiation in this interaction. They are transparent to thermal infrared radiation.

A teeny tiny fraction (less than 1%) of the molecules in our air have molecules made of more than two atoms. By far the most abundant of these multi-atom molecules in the air are water vapor (H2O) and carbon dioxide (CO2). Because they have three atoms instead of two, these molecules have many more interesting ways to rearrange their geometry in response to the thermal infrared radiation the Earth emits (Earthlight).

In its "resting" (a.k.a. "ground") state CO2 is symmetric. The central carbon atom is bound just as tightly to the oxygen atom on one side as it is to the oxygen atom on the other side and the electrons in the two chemical bonds are evenly distributed to the left and right.

But when it gets excited by passing electromagnetic fields (thermal infrared Earthlight), the carbon atom can bounce back and forth between the two oxygens. The electrons forming the bond on one side squash closer together while the ones on the other side stretch further apart. Like the N2 or O2, the molecule deforms back and forth in time with the passing fields. The resonance between the oscillating positive and negative charges moving in time with the swing of the fields is a molecular dance called the "asymmetric stretch."



Molecules that have many ways to wiggle are called "Greenhouse" molecules

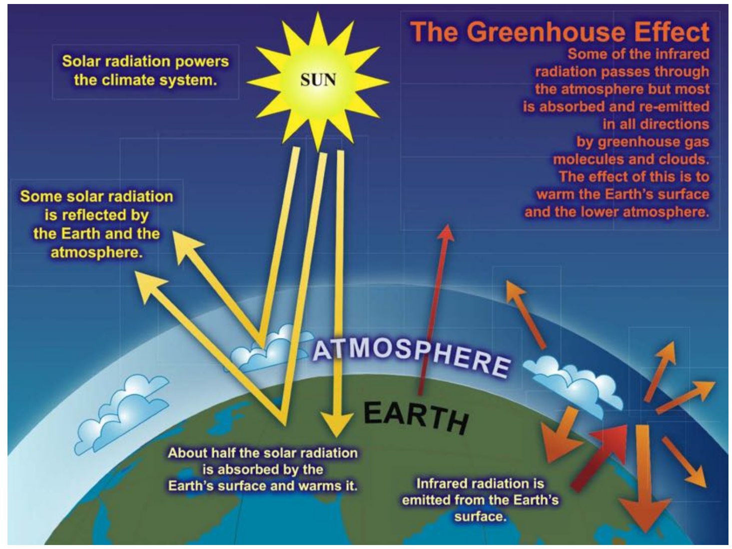
Unlike O2 and N2, when the central carbon atom is way over on one end or the other of the CO2 molecule, there are more positive charges on that end and more negative charges on the other. This asymmetry of electrical charges is called an electric dipole, and it's the deep secret at the heart of the greenhouse effect!

The oscillating electric dipole formed by a CO2 molecule vibrating in asymmetric stretch mode has converted some of the propagating electromagnetic energy (Earthlight) into the vibrational energy of the molecule. There's less Earthlight propagating forward (upward) because some of it has been transformed to the resonant vibration of the molecular dance. We say that some of the radiation has been *absorbed* by the CO2 gas molecule.

There are other ways for CO2 to absorb Earthlight as well. The molecules can bend, with the oxygen moving in a direction perpendicular to the axis (bonds, shared electrons). Bending CO2 molecules also rearranges the electrical charges to produce an electrical dipole with a plus and a minus end. Each of the ways that the charges can get rearranged has a different resonant frequency with the electromagnetic waves passing by. This means they absorb different frequencies (wavelengths) of Earthlight.

Water vapor is even better at absorbing thermal infrared radiation (Earthlight than CO2 because it's already bent, so it has a permanent electrical dipole. We say water is a "polar" molecule, which incidentally is why it's so easy for stuff to dissolve in water. There are a whole bunch of ways for water molecules to rearrange the geometry of their charges in resonance with electromagnetic radiation. Another way to say this is that water vapor is a very strong absorber of infrared radiation. Yet another way to say it is that water vapor has a rich absorption spectrum in the infrared.

So the presence of H2O and CO2 in our air makes the air selectively transparent. Air is transparent in the visible part of the spectrum (you can tell because otherwise you couldn't see very far!). But in the thermal infrared, even these tiny amounts (less than 1%) of CO2 and H2O absorb most of the light. Carbon dioxide and water vapor are opaque at the wavelengths whose frequencies resonate with their dipole vibrations.



This is what makes CO2 a greenhouse gas. It's not greed or capitalism or Al Gore. It's just bad luck that the gas created when we burn (oxidize) carbon has three atoms instead of two.

Water vapor is an even more powerful greenhouse gas than CO2 because it's bent. But what happens when there's a whole lot of water vapor in the air? It rains. So the amount of water vapor can't just go up and up. The maximum amount is set by the temperature.

But there's no such thing as CO2 rain on Earth. The CO2 we add when we burn stuff made of carbon (like coal) just gets added to the air. It can hold ginormous amounts, hundreds of times more than it has these days. And every bit of extra CO2 that we put up there makes the air more and more opaque to the outgoing thermal infrared Earthlight that has to balance the incoming Sunlight.

1.5 Climate Forcing and Climate Sensitivity

Extra CO2 absorbs part of the "heat out" of the Earth. Some of the "heat in" from absorbed sunlight is trapped. Then the temperature has to rise until the extra emission of Earthlight through the partly opaque atmosphere can balance the incoming Sunlight again. Remember that the *difference between the rate of incoming and outgoing heat is defined as climate forcing*.

It turns out that *every doubling of CO2 absorbs about 4 Watts of heat per square meter* of the Earth, if everything else stays the same. We say that the climate forcing is 4 Watts per square meter per doubling of CO2.

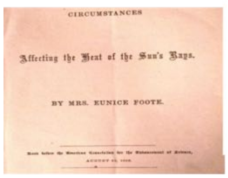
Remember those little incandescent bulbs that your parents used as nightlight in the hallway to help you find the bathroom when you were a kid? Every time the amount of CO2 in the air doubles, the Earth begins to accumulate that amount of heat (4 Watts) in each square meter.

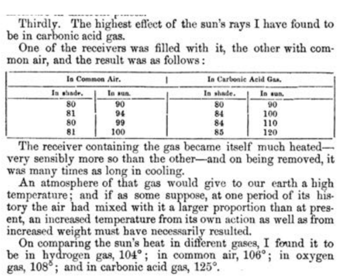
Look around you and find something that's about a meter on a side. Maybe your desk? Maybe a square on the carpet? Whatever. Now imagine a little night light bulb glowing there in the middle of that square meter. And in every other square meter of the room. Of course that will make the room a little warmer – not a lot because 4 Watt bulbs are pretty small. But it's not just your desk or your room or Colorado – imagine the whole Earth covered with little nightlight bulbs every 3 feet. And imagine that those 4 Watt nightlights stay on 24 hours a day, 365 days a year, for the rest of your life. That's heat in minus heat out – a.k.a. climate forcing!

What has to happen is that the Earth's climate warms up in response to this forcing, until the extra Earthlight emitted by the warmer Earth balances out the extra 4 Watts per square meter of forcing. We can calculate the amount of warming that's required to balance the forcing. That's called the climate sensitivity.

So the climate forcing scales as 4 Watts per square meter per doubling of CO2, and the sensitivity is about 3 Celsius of increase in the global average surface temperature in response to those 4 extra Watts of heat.

1.6 People Knew all this Before Light Bulbs Were Invented!





Thirdly. The highest effect of the sun's rays I have found to be in carbonic acid gas.

One of the receivers was filled with it, the other with common air, and the result was as follows:

In Common Air.		In Carbonic Acid Gas.	
In shade.	In sun.	In shade.	In sun.
80	90	80	90
81	94	84	100
80	99	84	110
81	100	85	120

The receiver containing the gas became itself much heated—very sensibly more so than the other—and on being removed, it was many times as long in cooling.

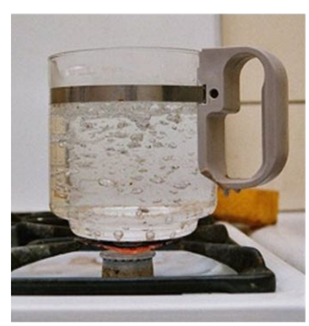
An atmosphere of that gas would give to our earth a high temperature; and if as some suppose, at one period of its history the air had mixed with it a larger proportion than at present, an increased temperature from its own action as well as from increased weight must have necessarily resulted.

On comparing the sun's heat in different gases, I found it to be in hydrogen gas, 104°; in common air, 106°; in oxygen gas, 108°; and in carbonic acid gas, 125°.

In 1822, the French physicist Josef Fourier was the first to realize that Earth's atmosphere was selectively transparent and retained solar heat like a greenhouse, though heh couldn't explain how. The first scientific experiments to measure the climate forcing of CO2 were conducted in the 1850s (170 years ago!) by a woman named Eunice Foote. She put jars containing different mixtures of gases (air, water vapor, methane, CO2, etc) in the Sun in her garden and measured changes in temperature of each jar. She published a paper in 1856 in which she presented her results and speculated that increases in CO2 might cause global warming. A scientist named John Tyndall published experiments in 1863 which were more quantitative and measured the dependence of the forcing on gas concentrations. And in 1896, the Swedish chemist Svante Arrhenius published calculations of the climate sensitivity to CO2: 3 Celsius per doubling, just as we know today.

A very widely-held misconception is that global warming led to the discovery of the greenhouse effect of CO2. Most people wrongly believe that first we noticed rising temperatures and that we slowly realized they were correlated with rising CO2. This is simply incorrect!

In fact the effect of CO2 on climate was discovered more than a century before the temperature rose enough to detect the warming.



The ***incorrect myth*** is that scientists are concerned about rising CO2 because they are extrapolating a correlation from the past to the future.

The reality is that the reason we're concerned about rising CO2 is that we understand that CO2 absorbs outgoing heat. We know that ***when more heat is added to the Earth than can escape, it must warm up*** to re-establish that balance. Scientists have known about this and written about it since before the US Civil War.

2. Climate Change is Serious

Unfortunately, climate change is a deadly serious problem. It will get worse and worse pretty much without any limits, until we stop making it worse. And then it will take many centuries or even millennia for the climate to recover. Without very effective action to prevent harm, this problem can very easily become the worst problem in the world!

2.1 How Much Warmer?

Since the beginning of decent temperature records in the late 19th Century, the average temperature at the Earth's surface has increased by about 1.1 Celsius (2 Fahrenheit). That's not very much but we can certainly feel the effects! The warming is a stronger over the land (about 3 F) than over the oceans (about 2 F) because some of the extra Watts of heat added to the ocean get used up evaporating water. The drier continents have warmed about 50% more than the oceans.

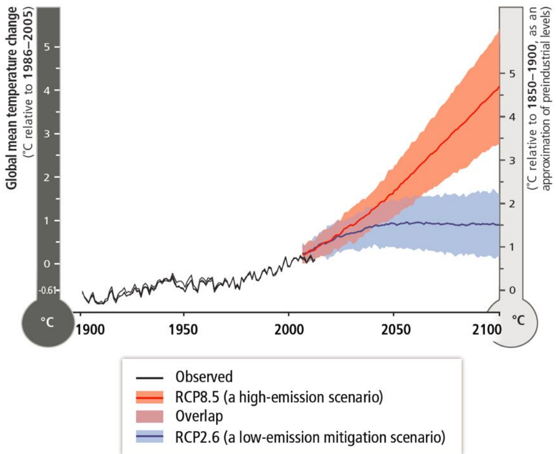
How much warming we get in the future depends almost entirely on how much carbon we burn, in the form of coal, oil, and gas. These fuels are made from fossilized plants so we call them fossil fuels. Every bit of carbon ever burned adds about the same amount of warming to the climate.

For centuries, people have burned more and more fossil fuels as economic development increases the demand for energy across the world. Today we burn about 10 billion tons of carbon each year. When I was in graduate school in the 1990s people burned only five billion tons of carbon per year. When I was a little kid we burned less than two billion tons per year. Emissions have increased about 500% in my lifetime. If developing countries continue to fuel economic growth by burning carbon, emissions could easily triple again over the next couple of generations.

Under such a fossil-fueled future scenario, CO_2 could very well double and then double again in 100 years. This would add not just one 4 Watt nightlight bulb's worth of heat but two bulbs (8 Watts per square meter). The global average temperature would increase by about 6 Celsius (10 Fahrenheit).

That's a little more than the warming at the end of the last great Ice Age. But 10 F of global warming during deglaciation took about 100 centuries, from 20,000 years ago to 10,000 years ago. We're looking at the possibility of a similar warming in a single human lifetime!

Thankfully, people have been raising the alarm about global warming for more than 60 years. The first official warning to the US government was presented by scientists to President Lyndon Johnson in 1965. Since the 1990s, there has been a general recognition that we will have to drastically cut or eliminate fossil fuel combustion, though progress has been painfully slow.



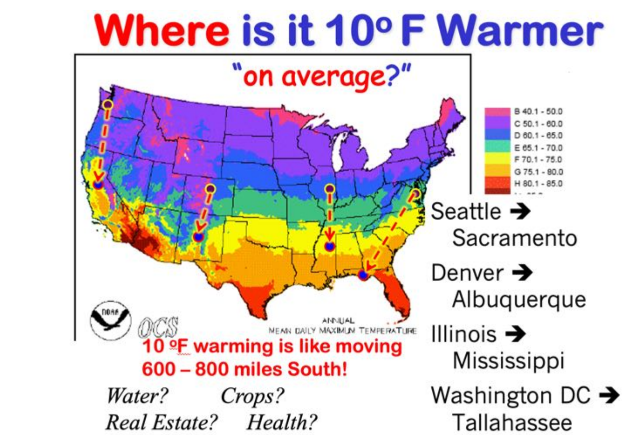
Careful reviews of scientific research on the global warming problem explore a range of future scenarios reflecting different policy choices. With very rapid decarbonization, it is still possible that warming will peak in the next 20 years less than 2 Celsius above preindustrial conditions. Without strong policy twice that much warming is likely (4 C by 2100).

But remember that the world doesn't warm uniformly. In particular the oceans warm very slowly because the heat gets used up to evaporate water and also because oceans are very deep and have tremendous thermal inertia.

Continental areas warm about 50% more than the world as a whole. The Northern Hemisphere warms more than the Southern Hemisphere because the north is mostly land and the south is mostly ocean.

We can expect 4 Celsius of global warming to be around 6 Celsius here in the middle of the United States. Americans are almost unique in all the world because we don't use Celsius temperatures. Six Celsius of American warming is about 10 Fahrenheit.

Even that doesn't sound too bad except in July and August (I'm not looking froward to those 110 F days in Colorado!). If a February day topped out at 30 F instead of 20 F I'd probably be pretty happy. But we're not going to have global warming just in February.



The way to understand what 10 F of warming means is to look at a map of average temperatures. In the central United States, you'd have to move around 800 miles south to find a place that's 10 F warmer on the average. That's a lot! People around here can look at Albuquerque. People in Illinois can think about moving to Mississippi. People in Washington DC or Maryland can contemplate northern Florida. The land is different! The vegetation is different! The crops and jobs and livestock are different!

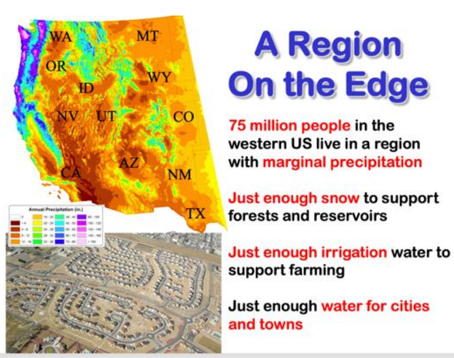
Here in the Mountain West we don't have to move hundreds of miles to experience a different climate. We can change our elevation by traveling up or down the mountains. Here in Colorado every 3000 vertical feet of elevation change equals about 10 F of change in average temperature. With 10 F of warming, Estes Park Colorado would have about the same average temperature Denver has now, and the top of Trail Ridge Road in Rocky Mountain National Park would have about the same average temperature than Estes Park does now.

At the end of the last great Ice Age, the vegetation zones in the mountain west moved up around 3000 feet as the temperature warmed. Ponderosa woodlands grew in the foothills. Lodgepole pines grew in high valleys. Spruce and fir climbed the mountainsides and alpine tundra retreated to the rocky summits. Ecosystems were able to adjust because the warming was very gradual – about 0.1 Fahrenheit per century for 100 centuries. Individual trees died along the lower slopes and grew along the upper edges of the range of each forest type. Seeds from pinecones developed into great trees.

Now we're contemplating a similar change, but in a single century. That's MUCH too fast for forests to migrate uphill! When the climate warms too much for individual trees to survive, they die. Often, they burn when summers are too hot for the amount of water their soils can retain from the spring snowmelt. Fire and other disturbance like beetlekill becomes constant. Sound familiar?

2.2 Water Supply and Demand in the Semiarid West

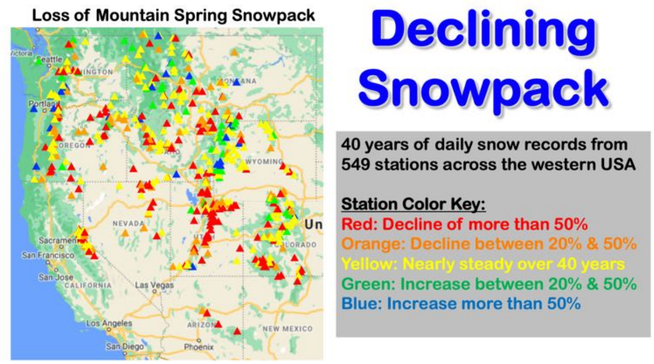
We happen to live in a region that is extremely vulnerable to warming because it's pretty dry here except in the high mountains. There are 75 million people in the western US. We live modern lifestyles, we farm and ranch, and we recreate in the mountain forests.



This is possible because the mountains gather water vapor as it passes high overhead all winter and convert it into deep persistent snowpack. Every May and June the accumulated water runs down to fill our reservoirs from which it waters our farms and lawns and parks, grows our forests and livestock. Spring snowpack in the mountains forms the water tower of the west. It's absolutely key to our lifestyle and economy.

Over the past 40 years, the US Department of Agriculture has measured the water in mountain snowpack every single day at more than 800 stations across the west. These stations telemeter data via satellite so they are called the Snow Telemetry (SNOTEL) network. I've analyzed the daily data at about 550 SNOTEL stations whose records go back at least 40 years (see map).

The peak spring snowpack at hundreds of these stations has decreased by at least 50% over the past 40 years. Hundreds more have lost 20% of their peak spring snowpack. A few show increases. Part of the problem is that snow starts accumulating later in fall and melts earlier in spring. In some places, it now rains in winter and erodes mountain snowpack. Everywhere, there's more evaporative loss from snow in a warmer climate. There's only been about 2 °F of warming in our region so far. The rapid loss of snowpack doesn't bode well for a future with 10 °F of warming!



Even more serious than the threat of warming to water supply is the increase in water demand. Evaporative losses increase exponentially with temperature. Everybody in our region knows that they have to water the lawn more in July and August than in May and June. This is simple physics and biology. But it's not just your lawn. It also affects farms, grasslands, and forests. Water demand increases dramatically with every degree of warming.

Just as heat in minus heat out equals change in heat,

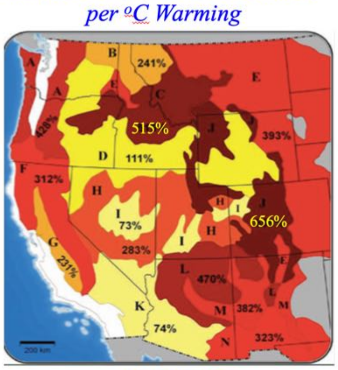
WATER IN minus WATER OUT equals CHANGE IN WATER

In a warmer climate, evaporative demand increases. If water supply doesn't increase at least as much as the increase in water demand, the deficit contributes to drought. Drought is the running sum of water out minus water in. Unless we get major increases in precipitation, the semi-arid western US will experience more drought as temperature rises.

2.3 Warming and Wildfire

Forests in the mountain west occupy that portion of the landscape where transpiration losses can be sustained by a combination of soil moisture from spring snowmelt and replenishment from summer rains. Evapotranspiration exceeds soil moisture supply for much of the growing season and when water is depleted, physiological stress makes forests susceptible to late-season wildfire.

Increase in annual Area Burned per °C Warming



NRC 2011

A warmer climate in the mountain west promotes wildfire by at least three mechanisms:

1. The increased evaporative demand of warmer air depletes soil moisture stores every day, leading to dry fuels earlier in the growing season than previously;
2. Longer hot seasons mean these water losses continue for more days each summer, leading to more late-season drought stress year after year;
3. Extremely hot, dry, windy days that promote extreme fire behavior and uncontrollable fire growth occur more frequently in hot summers than cool ones.

For all these reasons and combined with fuel accumulation from decades of overzealous fire suppression, the area burned by wildfires in the western US has more than doubled over the past 40 years. A review of climate impacts of western wildfire by the National Research Council (2011) projected more than a 500% increase in annual wildfire area in the southern Rocky Mountains per degree Celsius of warming. With five Celsius or more of warming possible by the end of the century, this would mean fire return times would be shorter than the time it takes for forests to recover, leading to permanent forest loss over huge areas.

2.4 Water, Water Everywhere

Although water scarcity and drought are likely the leading climate impacts in our region, many places will instead be inundated with water. The intensity of precipitation increases with warming because warmer air can hold more water. Warming causes ocean water to expand, raising global sea level. In addition, melting glaciers and ice sheets on land contribute to rising seas. Many of the most densely populated and affluent areas of the world lie at very low elevations long coasts. Coastal storms bring damaging storm surges that impact low-lying cities much more frequently when the mean sea level starts form a higher baseline.

Tens and perhaps even hundreds of millions of people will be displaced and massive economic damages will occur if fossil fuel emissions continue to increase.

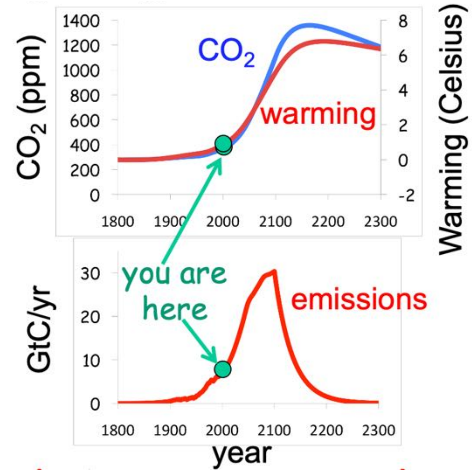
The combined impact of drought, fire, floods, displaced people, and the resulting social and political problems have the potential to severely impact the global economy. Unchecked climate change could very well reverse the unprecedented rise in standards of living that has improved the human condition for centuries.

2.5 The Long Tail

Perhaps worst of all, when we finally stop setting fossil carbon on fire the CO2 isn't going anywhere. Unlike toxic air pollution that makes people sick, CO2 is not chemically reactive in the air. It's fully oxidized. There's no further energy to be extracted from the molecule by reacting it with the air. It's the inert, spent thermodynamic ashes of the carbon cycle.

Of course, CO2 derived from the combustion of fossil fuels is removed from the atmosphere by photosynthesis. But virtually every scrit of plant material formed by photosynthesis is decomposed by microbes and respired back to CO2 when plants die and rot. Long-term removal of CO2 from the air by plants requires that the total amount of plant material (living and dead) actually builds up over time. Stuff has to grow faster than it dies. This can happen under special circumstances. In fact the biosphere has been accumulating carbon for decades. But the total amount that can be sequestered in biological organic matter is limited by land, by water, and by nutrients. Only a relatively small amount can be taken up in this way, much less than is available for burning in fossil fuel reservoirs.

After people completely stop burning carbon for energy, most of the remaining excess atmospheric CO2 must come into chemical equilibrium with the oceans. How does this work?



Carbon dioxide reacts with seawater to form carbonic acid, which forms a buffered solution with bicarbonate, carbonate, and calcium carbonate (CaCO3). This is essentially the same carbonation chemistry that makes soda and beer tickle your tongue and pair well with fatty foods like pizza. Unfortunately carbonation lowers the pH of seawater and makes life very difficult for marine life that's based on CaCO3. Most mass extinctions in the geological record are associated with ocean acidification due to high levels of CO2 dissolved in the water.

The oceans are not well-mixed. Warm water floats at the top in the tropics and temperature zone. This thermal stratification prevents the vast body of the ocean from exchanging gases like carbon dioxide with the atmosphere. The solubility of CO2 in warm surface water is very limited for the same reason that beer or soda goes flat when it warms up on the kitchen counter. Only in the Arctic and Antarctic does the water get cold enough to sink into the deep ocean, carrying fossil fuel CO2 to Davy Jones Locker. Most of the ocean has not touched the atmosphere in 1000 years. It doesn't know we're here yet!

Once we stop burning coal, oil, and gas and the excess CO2 has fertilized plants as much as it can, the surface oceans will quickly equilibrate with the atmosphere, probably in a few decades. Then the 1000-year overturning of the oceans (driven by the sinking of cold polar water) will slowly bring the deep ocean into equilibrium over a period of many millennia.

The smaller the eventual total fossil carbon injection into the atmosphere, the larger the fraction of this carbon that can be taken up by the deep oceans. If the pulse is too big, there will still be a lot of it (10% to 30%) remaining in the air after the oceans have done all they can. After that, geology will have to take over. Just as with major pulses of CO2 in the deep past, chemical weathering of minerals and rocks on land will slowly remove fossil carbon from the atmosphere over hundreds of millennia.

We have plenty of fossil fuel reserves to alter Earth's climate catastrophically and permanently, at least on human-relevant timescales. To avoid these terrible outcomes, we must reduce fossil fuel combustion as fast as we can, eliminating carbon-based energy in a generation.

3. Climate Change is Solvable

So, what's to be done?

Obviously, this isn't all that easy and it isn't going fast enough. But that's really what we need to do. This means we have to substitute other forms of energy for fossil fuels as fast as we possibly can. And we have to do it in a world that's hungry for energy and the products and services made possible by abundant energy. It sounds daunting, but it has to happen and necessity is a powerful motivator!

3.1 The Kaya Identity

We can think about the drivers of CO_2 emissions using a simple formula developed by Japanese economist Yoichi Kaya in the 1990s

$$CO_2 \text{ EMISSIONS} = P \times \$/P \times E/\$ \times CO_2/E$$

where P is population, $/P is per-capita income, E/$ is the energy it takes to make a dollar of income, and CO_2/E is the CO_2 released by making a unit of energy.

You can tell that the "Kaya Identity" is true by doing some trivial algebra on the right-hand side: the P cancels the P, the $ cancels the $, and the E cancels the E, leaving just $CO_2 = CO_2$.

So how do we get to zero emissions? Recall from high school that if any of the four numbers on the right-hand side is zero then the product is also zero.

So according to the Kaya Identity, CO_2 emissions would go to zero if everybody died! Well THAT'S completely unacceptable, so we'll have to dig deeper for solutions! On a more serious note, population growth has fallen by half since the 1970s, and is on track to reach zero by 2100. The population bomb has been defused.

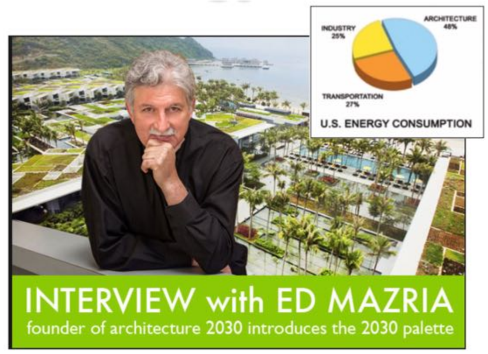
Moving on to the next term, emissions also go to zero when everybody's income goes to zero. Again, this is an unacceptable outcome in a world where billions of people are very poor. This term is by far the fastest growing at about 3% per year and threatens to undo progress in all the other terms. Accommodating rapid growth in the developing world is arguably the biggest challenge in the entire climate problem.

So the levers we're left with are the third and fourth terms in the Kaya Identity: E/$ is called the "energy intensity" of the global economy and CO_2/E is the "carbon intensity" of energy. Energy intensity and carbon intensity must fall very fast. In other words, we need to live well with less energy and we need to make energy without setting carbon on fire!

3.2 Energy Efficiency (E/$)

Energy efficiency costs negative dollars. When we make the economy more energy efficient, we have more money left over than we would have had if we had wasted a bunch of energy we didn't need. This is the foundation of affordability for cleaning up the carbon/climate problem.

The world's major economies have decades of momentum in becoming more energy efficient. A lot of this is simply the transition from energy-intensive manufacturing to cleaner service/information economies. In addition a huge range of infrastructure is getting way more efficient over time.



According to prominent architect Ed Mazria, nearly half of the energy demand in developed countries is associated with buildings (much more than transportation!). The energy intensive lifecycle of buildings includes the mining of ore, smelting of steel, a global transport and supply chain, construction, and the operation of our homes and places of work. There is tremendous room for improvement and efficiency at every step.

Improved design, materials, and construction methods are dramatically reducing the energy requirements of the built environment. Operating buildings is also much more energy efficient thanks to improvements in lighting, insulation, roofs, doors, windows, and HVAC. Mazria started a program called Architecture 2030 which has attracted most major commercial construction firms worldwide. They pledge that by 2030 all projects they design will be net-zero energy: they will generate more energy over their entire lifecycle than is used for construction. Architecture 2030 provides a comprehensive and evolving suite of tools to achieve these ambitious goals.

The cost savings of more efficient construction and operation are already manifest. In the US alone, these improvements will save more than $4.5 trillion by 2030 as we waste less energy we didn't need. Many other sectors (transportation, manufacturing, office work) are undergoing similar shifts. The energy intensity of the world economy has already improved by more than 30% since the 1970s and has a long way to go.

Ideally, savings from efficiency can offset much of the cost of deploying clean energy infrastructure.

3.3 Decarbonizing Energy (CO2/E)

In a provocative and insightful essay a few years ago, the writer Dave Roberts laid out a "Simple Plan for Deep Decarbonization:"

1) Clean up the electrical supply;
2) Electrify everything!

This program is in fact already well underway around the world.

Over the past decade, there has been a revolution in low-carbon sources of electricity. The cost of electricity from wind and solar power fell by more than a factor of 10 since 2010! A "virtuous cycle" of rapid development, cost reduction, increased deployment, and economies of scale has continued to drive the cost of clean electricity.

Solar and wind power are now by far the cheapest sources of electricity in the world, way less expensive than coal or gas. The transition of clean energy from the most expensive to the least expensive sources has happened faster than even the most wildly optimistic projections of futurists a decade ago.

The United Kingdom, which pioneered coal as an energy source during the industrial revolution of the 19th Century, has cut coal combustion by more than 90% and overall emissions more than 50%. Britain now burns less coal than it did in the 1850s!

Electrical grids gather power from hundreds or even thousands of separate plants and distribute it to users across a wide area. The grid allows clean energy to displace carbon combustion in a gradual way while minimizing disruption to consumers. But grids must balance electrical supply and demand at every second, so the intermittent nature of solar and wind power pose a substantial challenge. There are several key approaches to solving this problem, all of which are under rapid development:

- Taking advantage of the complementary timing of wind and solar resources (sunny days vs windy nights; sunny summers vs windy winters);
- Aggregation of resources over large regions (it's always windy someplace);
- Demand management ("peak shaving");
- Long-distance electrical transmission (via high-voltage direct current, HVDC);
- Storage via batteries and other technologies; and
- Other sources of "clean, firm power" (hydro, geothermal, nuclear).

Electricity is already a distributed resource that delivers energy to billions of consumers, so cleaning up the supply and delivery of this energy can dramatically reduce CO2 emissions very quickly. But a substantial part of current emissions is also produced on-site. Automobiles, heating of residential and commercial buildings, and manufacturing together produce almost half of today's CO2 emissions.

Universal electrification is therefore critical to leverage the huge opportunities in clean electricity generation and distribution. Electric vehicles are transforming the car and truck markets. Already more than 10% of new cars and trucks sold in the world are fully electric. In China the share of EVs is nearly 30% and in Norway it's over 80%. The European Union is moving toward a complete phaseout of internal combustion engines and every major automobile manufacturer is rapidly retooling their products to go electric.

Home heating with electric heat pumps (essentially reverse air-conditioners) has become feasible almost everywhere. I heat my 100-year-old home in Fort Collins this way and the house is quite comfortable year-round. Induction cooktops are even more responsive than gas ranges and fantastic for even the most discerning cooks. Electricity can be adapted to power all but a tiny percentage of manufacturing.

Grid-scale batteries storage is still very expensive, but the economies of scale in manufacturing electric vehicles has led to drastic cost improvements here as well. As they rapidly take over the market, EVs themselves represent a huge distributed energy storage medium. Long-distance transmission through HVDC lines can tap energy resources thousands of miles away. And electrical grids are getting "smarter" across the board to balance supply and demand in the new world of cheap fluctuating supply.

3.4 Costs of the Global Energy Transition

Will we be able to afford swapping out the energy infrastructure of the world economy?

In a word, yes! And given the alternative, we'd damned well better be able to!

Economists who specialize in climate and energy estimate that the transition will cost in the neighborhood of 1% of global Gross Domestic Product (GDP, the total value of all the goods and services sold each year worldwide). Of course this number is highly uncertain, with estimates ranging from near zero to the low single digits. Global GDP is currently around US$100 Trillion per year, so the consensus estimate of cost is around US$1 Trillion per year.

That's a LOT of money -- it's more than the annual budget of the US government's Department of Defense!

Costs in Context

Item	Cost
1% of global GDP	$1000 billion per year
New mobile phones (handsets only)	$785 billion per year
New cars & light trucks (90 million/year @ $25,000)	$2,250 billion per year
Coal, oil, and gas	$4,000 billion per year
Roads (64 million miles @ $5M/mile)	$ 320 *TRILLION* total

Rescuing civilization will cost a lot of money.

- **Probably in the neighborhood of what we spend on brand new phones or the military**
- **1/2 what we spend on new cars, ¼ what we spend on fuel**
- ***Vastly less* than we have spent on roads!**

But in the grand scheme of things, $1 Trillion per year isn't all that much. Worldwide, we spend more than $700 billion per year on brand-new mobile phone handsets and over $2 Trillion per year on brand-new cars and trucks. We spend more than $ Trillion each year on coal, oil, and gas. And in the past century, we've spent more than $300 Trillion building and maintaining roads for our automobiles.

So saving the world economy and human civilization will be expensive, costing us somewhere between what we spend on new phones and what we spend on new cars.

It's critical to remember that in a market economy, every dollar spent is a dollar somebody has earned. Spending $1 Trillion each year to save humanity means people will earn an extra $1 Trillion per year, or at least that $1 Trillion in lost spending on carbon is redirected into clean energy infrastructure.

To get a better sense of the impact of gigantic infrastructure projects, let's take a historical perspective.

A little over a century ago, rich countries retrofitted all their cities and towns with indoor plumbing. Imagine the cost if you had to do this today: hire union plumbing and construction contractors to rip up every street in London, Paris, New York, and Cleveland to install sewer systems. Tear out tenement walls 20 stories high to install hot and cold running water in every building. And knock out interior walls in every flat and apartment to install toilets, sinks, and showers. The cost of such a project is just staggering!

But my grandparents' generation really did all that work. And all those projects didn't ruin the world economy. In fact they built the most prosperous economy the world had ever seen and provided jobs for millions. Imagine the impact of all that money on plumbers and other working-class laborers! Imagine the impact on the grocery store down the street from the plumbers, or the children of those plumbers who used that money to go to college. Spent money is never "gone." It gets spent over and over again throughout the economy. When they were finished with indoor plumbing the Greatest Generation moved on to subways, automobiles, and rural electrification. Imagine hiring union electricians to string coper wire to every farm in Nebraska! When they were done with that, they defeated the Nazis!

My parents' generation did big infrastructure projects as well. They built the interstate highway system and a global aviation system. They fought and won the Cold War. They sent people to the Moon!

My own generation invented personal computers. In the 1980s a generic PC cost about $3000. By the end of that decade they'd been installed on 3 billion desks in every office in the world at a cost of more than $9 Trillion. Those office PCs were replaced every three years throughout my entire adult life at a cost of $trillions every year. These machines forced typewriter manufacturers (like IBM) to retool, but they didn't ruin the economy. Indeed the IT revolution produced phenomenal prosperity and untold millions of jobs.

But my generation was only getting started. We followed the PC work by replacing billions of land-line phones with pocket computers that play music and YouTube videos. And we rolled out a global internet and telecommunications system that connects the world and employs almost everyone.

This kind of transformation is not unusual. In fact it's happened over and over again in almost every generation since the Renaissance. This kind of change is what made the modern world. We replace cheap old stuff with expensive new stuff that works better. Chamber pot and buggy-whip manufacturers took it in the shorts, but the changes of the 20^{th} Century produced way more jobs than they destroyed.

Now my kids' generation gets to do it again! You get to replace creaky old energy systems that are literally destroying the world with a shiny new system that will be sustainable. And just like your parents and our parents before us, you will create all the jobs and prosperity of your lifetimes doing it. This is your calling. Stop whining and get with the program!

3.5 Hope is a Verb

These days it's hard not to look at the world and get depressed. I mean really, clinically depressed! I have suffered from it. My children have been wracked with life-threatening depression. I get it. It's a scary world, and predictions of impending climate doom resonate with the awful discordant melodies all around us.

It's true that every bit of carbon ever burned contributes to a large and permanent shift toward a hotter and more difficult future. And it's true that progress is hard and is being actively resisted by a loud and powerful but tiny minority that benefits from the status quo. And it's true that all this just sucks!

But it's DEFINITELY NOT true is that it's too late to stop climate change!

From a scientific, technical, economic and probably even political perspective, there is certainly still a window to prevent catastrophic damage. Clean energy is already cheaper than carbon combustion. We know how to overcome the problems of intermittency and provide abundant affordable energy to everyone. Billions of people around the world are pulling hard for a cleaner world.

There's a narrative floating around that "we have only 8 years to solve this." This is a mistranslation of the science, and it's just not true.

To quote the blogger Dave Roberts,

> there is no such thing as "game over" or "too late" or "screwed" or "no hope." It is certainly not the case that, as the latest slogan has it, "we only have 12 years to act." That is nonsense, even if, in some cases, it's motivational nonsense.
>
> The fight to decarbonize and eventually go carbon negative will last beyond the lifetime of anyone reading this post. That is true no matter how high the temperature rises. The stakes will always be enormous; time will always be short; there will never be an excuse to stop fighting.
>
> That said, if there is reason to hope that we can limit warming to non-catastrophic levels, that we can hit the target we've set for ourselves, it lies in the possibility of non-linear change — change that begins slowly and then radically accelerates. It lies in the possibility that we are on the lower slope of not just one but several S curves, that change will fuel more change and the lines will soon start rapidly rising.
>
> But rapid change is not just possible in technology. It is also possible in politics. In both domains, there are "tipping points" after which change accelerates, rendering the once implausible inevitable.
>
> We are rarely able to predict those tipping points. Relying on them can seem like hoping for miracles. But our history is replete with miraculously rapid changes. They have happened; they can happen again. And the more we envision them, and work toward them, the more likely they become.
>
> What other choice is there?

Perhaps more than anything else, we humans are storytellers.

One paralyzing story we tell ourselves is that our modern well-being is built on extraction. We tell one another that there is inherent value in a lump of coal somebody dug from the ground. They sell it at a profit to somebody who burns the coal and sells the energy for a profit to somebody who uses that energy to make products and services they sell for a profit. And we wheel and deal until pretty soon we have a global economy that produces $100 Trillion every year.

Maybe that really is the way history works, but oh god I hope not! Because that story is a tragedy! At the end of that story lies either a ruined burned-out world poisoned by global warming or a frozen dark world in which our descendants mourn the end of the bonanza when the coal runs out. What a dark and soul-crushing story to tell ourselves and especially our kids!

YUCK!

I prefer a different story. One in which WE make our own world with creativity, ingenuity, and hard work. A world in which our well-being springs not from rocks we prize from the ground but from the sweat of our brows and the sparks in our souls!

We aren't going to run out of those precious resources.

Another popular story going back dozens of generations in our collective consciousness is about guilt and penance. It says we misbehaved and must be punished. This is not a useful way to envision solving the climate problem. We must transcend the narrative of sin to redeem ourselves.

The kids are going to be alright after all.