Global Warming

So What?

Dr. Gene Fry
August 2023

Climate has been changing for hundreds of millions of years (MY).

Mostly, it's been much warmer, with much higher CO_2 levels.

Eons ago, vast lava eruptions (Siberian Traps, etc.) put lots of CO_2 in the air.

When continents collided & mountains rose, rock weathering speeded up.
This removed CO_2 from the air, into silt & then the oceans.
Himalayan weathering has driven CO_2 levels down for some 50 MY.

Algae, plants and seashells also removed CO_2 from the air,
making coal, oil, gas & limestone, as conditions permitted.

CO_2 levels were lower than today's during ice ages over the past 2 MY.
Small variations in Earth's tilt, and how round its orbit is, drive their timing.

Solar changes* affect Earth's temperature.

So do Earth's natural cycles, like El Niño / La Niña.

* sunspot cycles ±0.1%.
Also, the sun slowly brightens, warming Earth ~2ºC / 100 MY.

Hotter than 2014 has become the new normal.

Climate is changing 15-30 faster than than the old record, eons ago.

Earth's 100-year surface warming rate
is 7-30 x the previous record.

The last times CO_2 exceeded 400 ppm
(~4 and 14 million years ago),
Earth's surface was ~7º and 10ºF warmer
and seas were 65 to 135 feet higher.

Kansas was Las Vegas hot &
Florida was mostly under water.

We should stop putting carbon in the air
&
remove carbon from the air
as fast as we put it in now.

So What?

WATER

Rainfall becomes more variable.

Wet areas tend to get **more** rain than now.
Dry areas tend to get rain **less** often than now.

Around the Arctic gets lots more rain
(&, at **1st**, more snow, then less), but
mid-latitudes (20 to 45º) tend to dry out.

Worldwide, we get a little more rain, but
except around the Arctic, we get
more hours and days without rain.

In other words,
we get more downpours* and floods,
yet also longer‡, drier, hotter droughts.

* +3.9% / ºF

‡ +2.6% / ºF

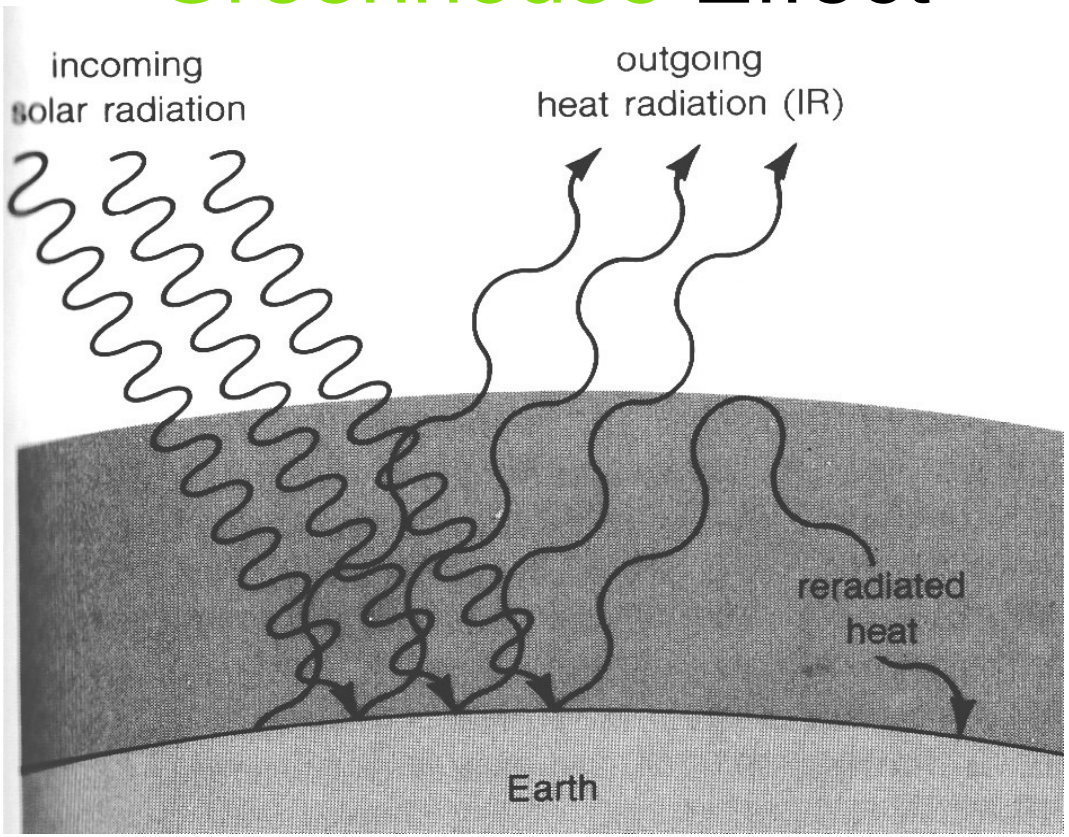
Droughts Worsen.

Deserts Spread.

The Culprit?

Evaporation

Greenhouse Effect



Dark Earth absorbs sunlight.
Earth warms up and
radiates heat.

Greenhouse gases in the air (GHGs) intercept some outgoing radiation and re-radiate it back down.
This warms Earth more.
More GHGs = warmer still.

Cyclic changes in solar output have warmed and cooled Earth modestly.
By now, human GHGs warm Earth much more than solar changes do.

Light surfaces reflect sunlight. Those surfaces don't warm Earth much.

Changing a light surface (ice) to a dark one (water) warms Earth.

Changing a dark surface (forest) to a lighter one (desert) cools Earth.

Greenhouse Gases (GHGs)

- GHGs warm Earth by 33ºC (60ºF).

  Earth's surface would average 0ºF without them.

- Water vapor (H_2O) does ~ 53% of this warming.

  Its concentrations vary many-fold over time and space.

  As Earth warms up, evaporation increases H_2O in the air.

  This **amplifies** warming from other GHGs (& albedo changes) a lot. So, scientists often treat H_2O not as a GHG, but a feedback for other GHGs.

  Still, more water in air 1ºC warmer
  warms Earth 1/2 as much as GHGs added since 1750.

- Of the other GHG warming, carbon dioxide (CO_2) does 52%.

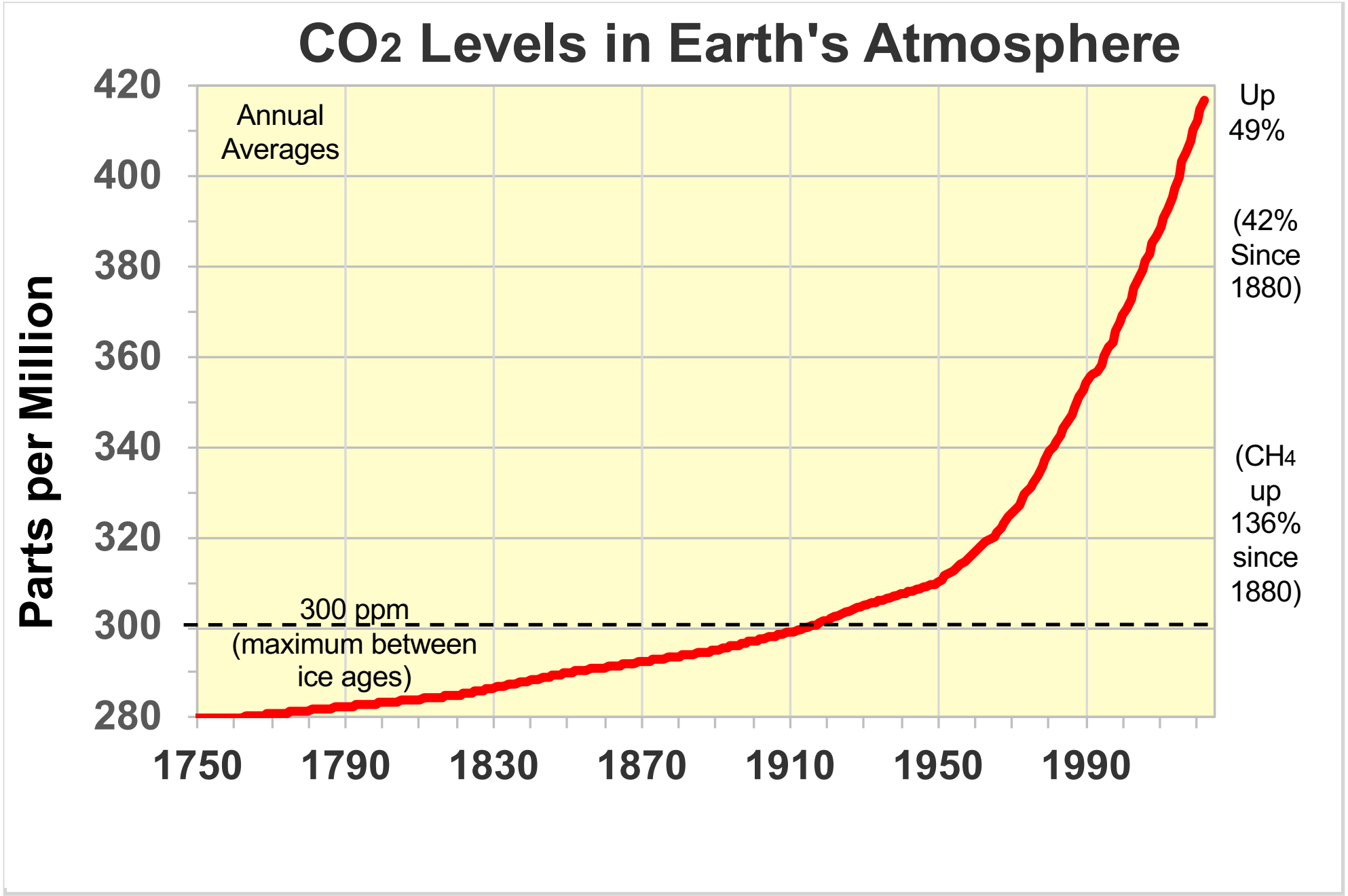
  Almost all US CO_2 comes from burning coal, oil & natural gas.

  Per unit of energy, coal emits 4 units of CO_2, oil 3, natural gas 2.

- Methane (CH_4, natural gas) does 30%. (20% direct, 10% indirect: O_3, H_2O)

  leaky oil & gas wells & pipes, permafrost, coal mines, wetlands, cows, rice, landfills

- CFCs (old air conditioners, ozone hole) do 7%, nitrous oxide (N_2O, fertilizers) 5%, other gases 6%. Black soot adds 20%, but aerosols (sulfates+) subtract 30%.


CO2 Levels in Earth's Atmosphere
Parts per Million
420
400
380
360
340
320
300
280
Annual Averages
300 ppm
(maximum between ice ages)
1750
1790
1830
1870
1910
1950
1990
Up 49%
(42% Since 1880)
(CH4 up 136% since 1880)

Today's CO_2 level is the highest since 14.1-14.5 MY ago (430-465 ppm).

Tripati 2009

The deep ocean then ranged from 4.6 to 6.6ºC warmer than now.

Shevenell 2008

Seas then were 25-40 meters higher.

CO_2 levels were **almost** as high (357-405 ppm) 4.0 to 4.2 Million Years ago.

Sea surfaces then were ~ 4ºC warmer.

Csank 2011, Dwyer 2008

Seas then were 20-35 meters higher.

This means ice **then** was gone from almost all of Greenland
and West Antarctica, plus some of East Antarctica.

2/3 of West Antarctic ice is grounded below sea level.
So is 1/3 in the much bigger East.

The ocean eats away at this ice from below.

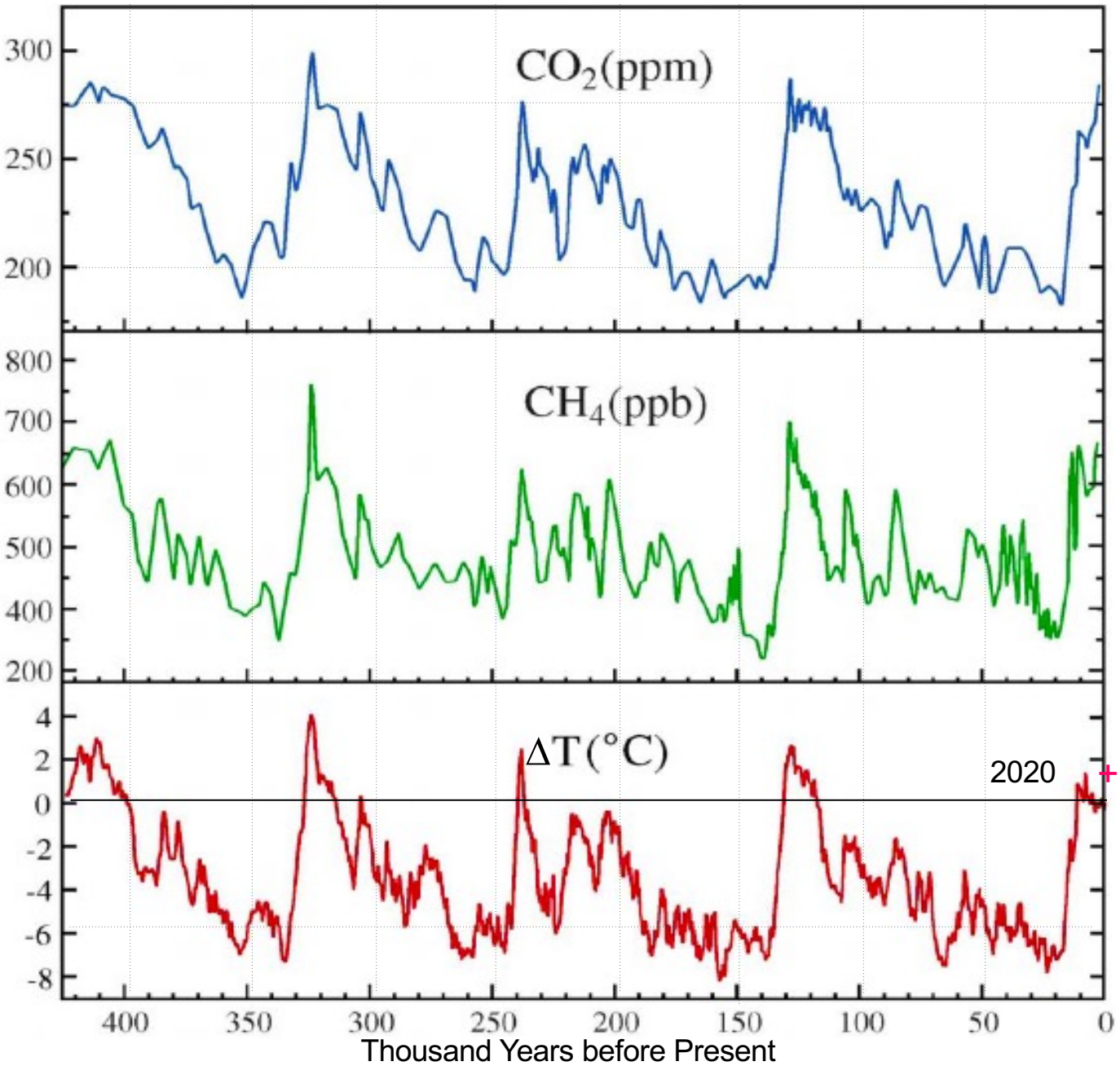
This ice melts over decades to centuries, the rest over millennia.

Sediments show East Antarctic ice 2.6-5.3 MY ago retreated 100s of km inland.

Cook 2013

We face BIG lag effects.

Vostok Ice Core Data



ppm = parts per million

ppb = parts per billion

+ 2020 CH_4 level ~ 1890 ppb
+ 2020 CO_2 level ~ 414 ppm

For 100s of 1,000s of years, temperatures and levels of GHGs CO_2 and CH_4 in the air have tracked each other closely.

The difference between 190 and 280 ppm of CO_2 was 10ºC (18ºF) at Vostok and ice almost a mile thick covering Chicago.

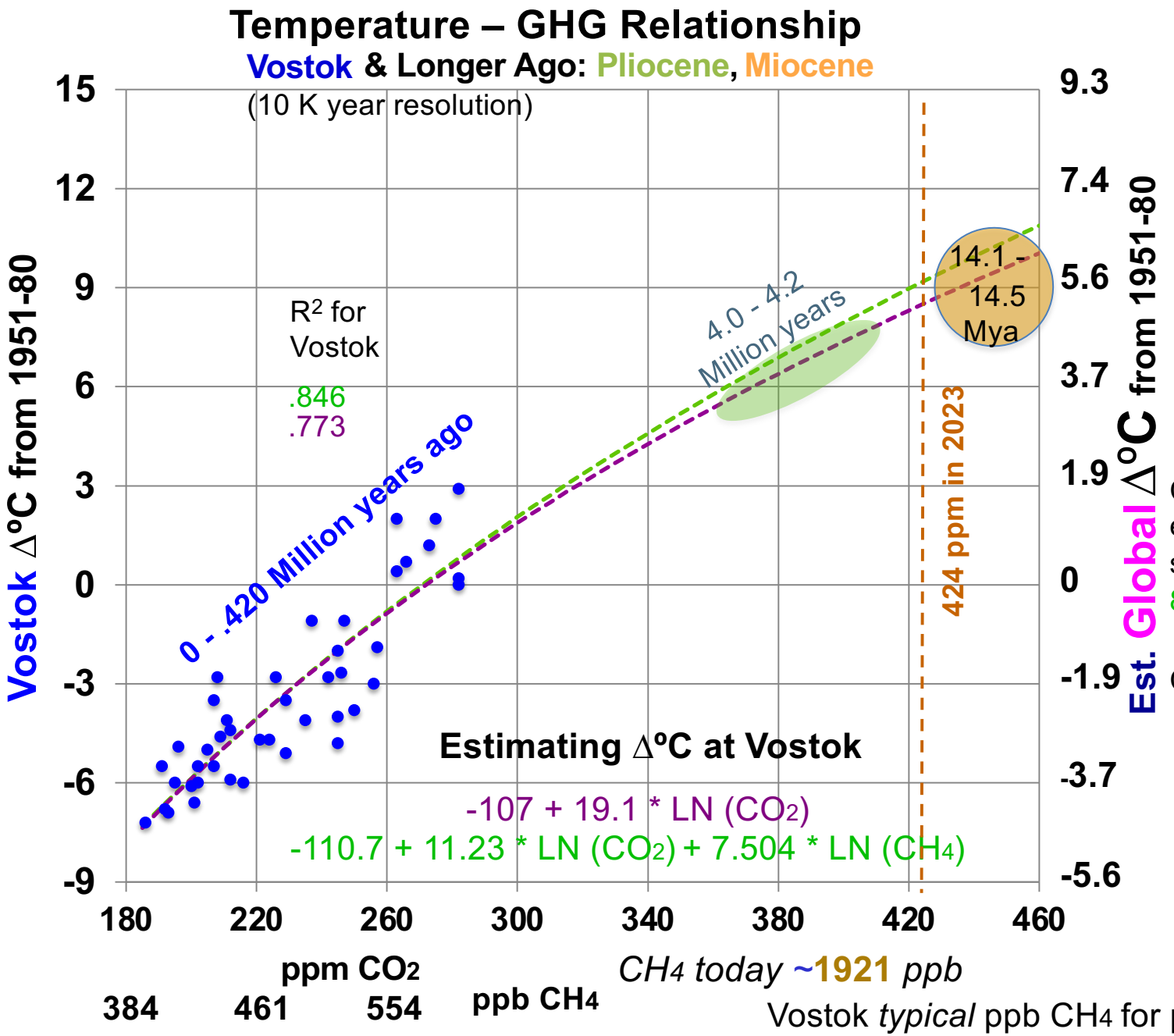
Warming led CO_2 & CH_4 increases by centuries, moving carbon from soil, permafrost and the oceans into the atmosphere.

Vostok data trends say that 400 ppm CO_2 yields 5.0-8.4ºC warmer there than now.

Are lag effects on the way?

Vimeux, Cuffey & Jouzel, *Earth and Planetary Science Letters* 203: 829-843 (2002)

Lessons for Our Future from Ages Ago



For the ratio of the **global** average ∆°C to Vostok ∆°C,

I use 0.62, the ratio of global change to polar, over the last 2 million years, from Snyder (2016).

With 2023 CO_2 & CH_4 levels, the equations yield global surface warming of 8.6°C,

but only **5.3**°C **if** CH_4 is neglected.

Warming how fast?

30-60% in decades, the rest over centuries.

Vostok *typical* ppb CH_4 for ppm CO_2: 2.13 x

Global Surface Δ°C = 0.6 *
(-110.7 + 11.23 * LN (CO_2) + 7.504 * LN (CH_4))

+2ºC globally requires (*e.g.*)

314 ppm CO_2 and

700 ppb CH_4.

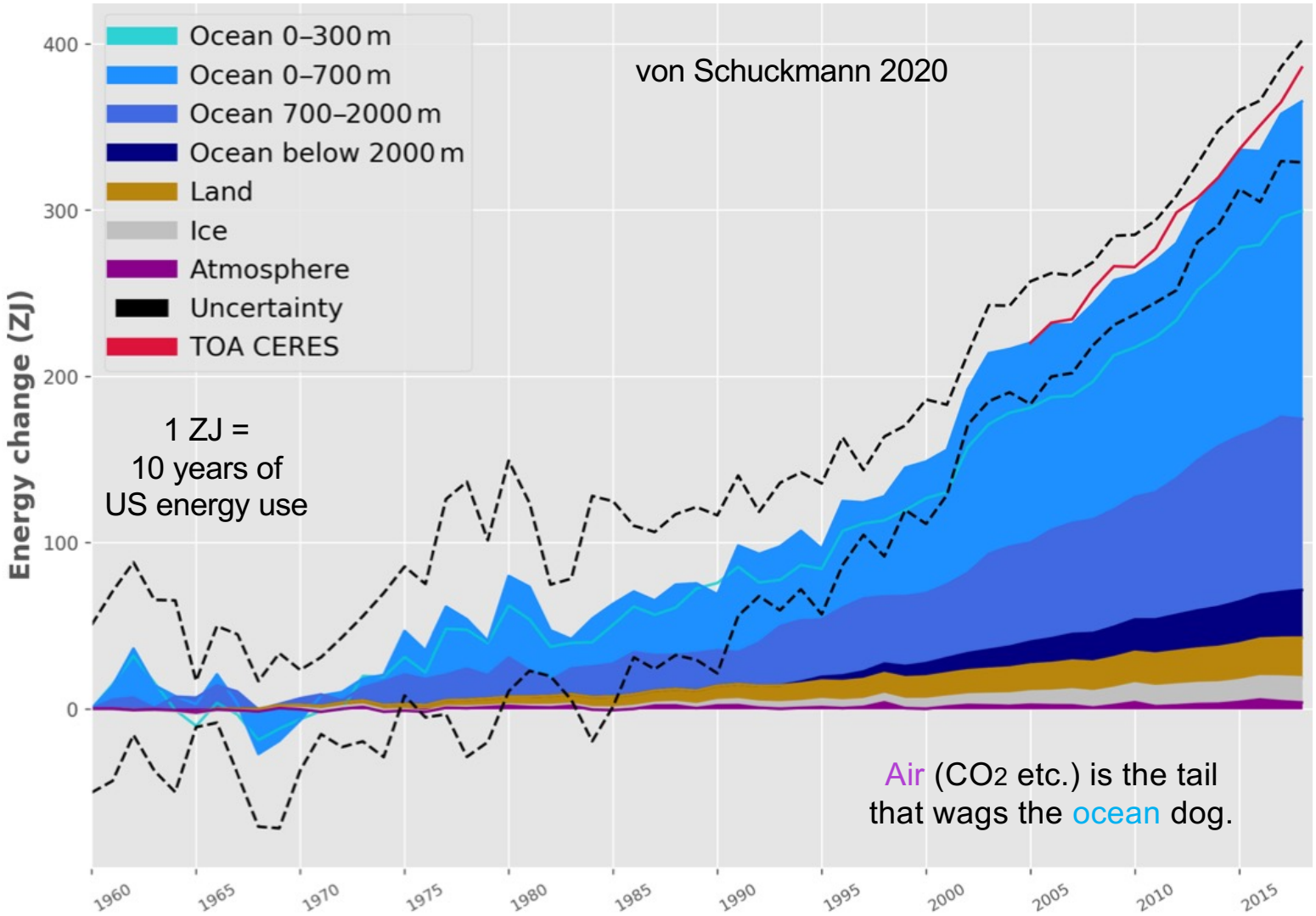
This means removing 3/4 of the CO_2
that humans have emitted,

any future CO_2 emissions

and all of our CH_4.

Humanity's remaining carbon budget
for burning fossil fuels is about
NEGATIVE 325 GT of carbon.

Global Heat Gain



Oceans 89-90%.

0-0.7 km 52%.

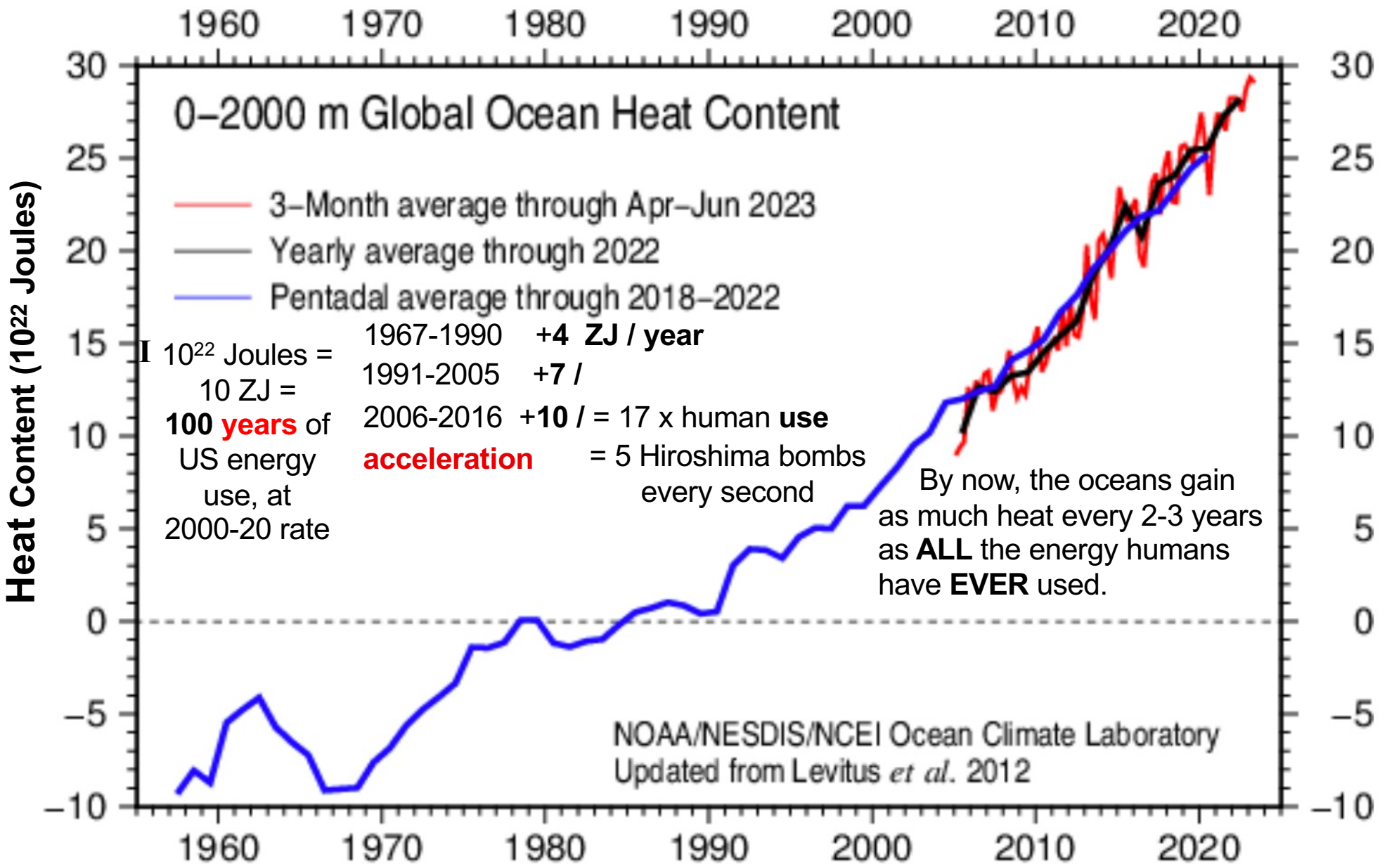
0.7-2.0 km 28-30%.

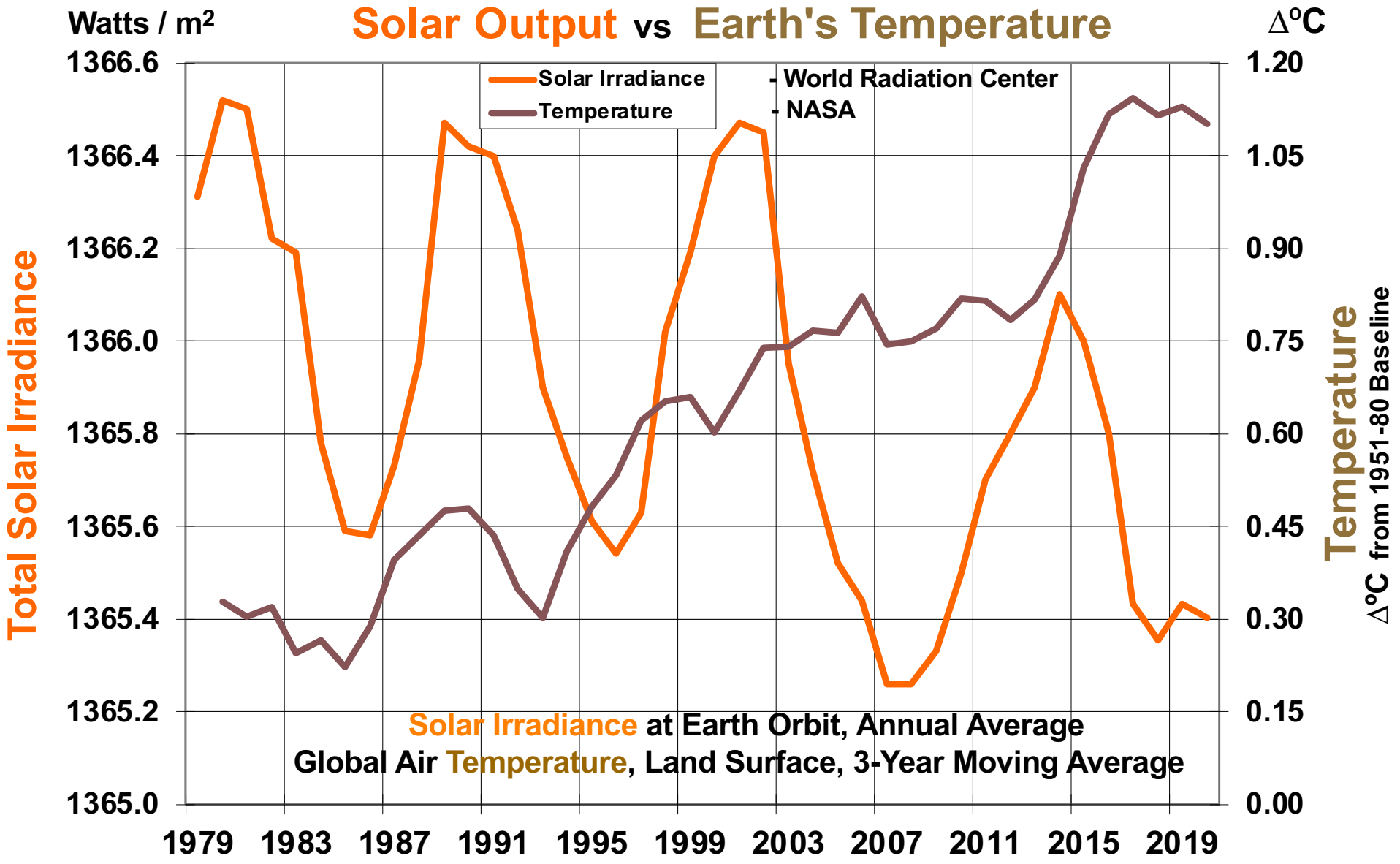
below 2 km 8-9%.

Land 5-6%.

Ice 3-4%.

Air 1-2%.


0–2000 m Global Ocean Heat Content
3–Month average through Apr–Jun 2023
Yearly average through 2022
Pentadal average through 2018–2022
Heat Content (10^{22} Joules)
1960
1970
1980
1990
2000
2010
2020
30
25
20
15
10
5
0
−5
−10
I 10^{22} Joules = 10 ZJ = **100 years** of US energy use, at 2000-20 rate
1967-1990 **+4 ZJ / year**
1991-2005 **+7 /**
2006-2016 **+10 /** = 17 x human **use**
acceleration
= 5 Hiroshima bombs every second
By now, the oceans gain as much heat every 2-3 years as **ALL** the energy humans have **EVER** used.
NOAA/NESDIS/NCEI Ocean Climate Laboratory
Updated from Levitus *et al.* 2012



In 2007, solar output was the **lowest** recorded (in 41 years), but Earth's air temperatures (land surface) were the **highest** yet recorded.

Over 2015-2018, solar output fell steeply, while temperature rose steeply.

- **Half** the sunlight reaching our atmosphere makes it to the surface.
  Barriers include blue sky (not **black**), **clouds**, haze & the ozone layer.

Clouds

- Clouds reflect some sunlight away, cooling Earth.
  They also keep outbound heat in, warming Earth, esp. at night.
- Many factors affect cloud formation & distribution.
  At night & going up over mountains, air cools.
  Cool air holds less H_2O, so it will often cloud up & rain.
- Clouds cover a little more than half of Earth. On balance, they cool it.
- Low clouds cool Earth more than they warm it; high ones do the reverse.
- Changes in cloud area, altitude & opaqueness affect global temperature.
  Earth's cloud cover area is shrinking a little, for a warming trend.
  We get more high clouds & fewer low ones, for a warming trend.
  Low clouds are growing more opaque, for a cooling trend.
  The net result is a warming trend: ~10% of the total warming trend.

Sulfates & Cooling

- Dark sulfates in the air block sunlight. That cools Earth.
- Sulfates make haze & become cloud condensation nuclei.

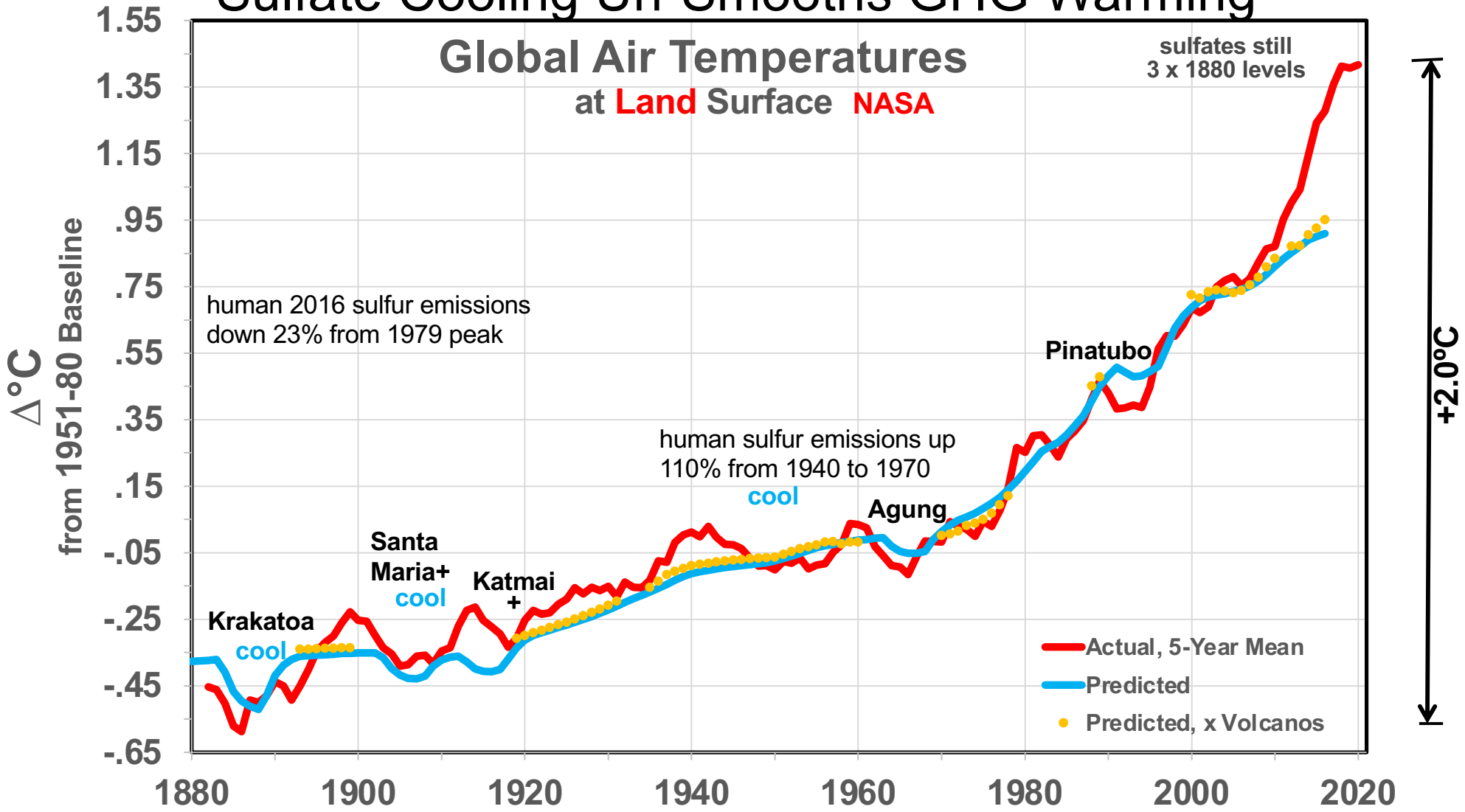
More sulfates = cloudier = cooler.

- Most sulfates come burning coal, also plankton & volcanos.

  SO_2 goes up the smokestacks. It changes to SO_4 (sulfate) up in the air.

- GHGs stay in the air many years, sulfates usually for days.
- GHG levels keep rising. Sulfate levels don't.
- Sulfates now offset 30% (formerly 40%) of GHG warming: 0.4ºC.
- As we stop sending up SO_2, warming will catch up.

Sulfate Cooling Un-Smooths GHG Warming



Predicted Δ°C = -20.51 + 2.223 * LN (CO_2 ppm) + 1.133 * LN (CH_4 ppb) - .00319 * SO_4 ppb

adjusted R^2 = **97.8**%. CO_2, CH_4 & SO_4 (all 5-year averages (SO_4 lag 1 year)) are all highly significant (|t| = 9.7 to 11.6).

SO_4 data includes industrial, occasional large volcanic, and plankton emissions.

Averages: 80 (100 now) 8 (episodic) 39

Predicted Δ°C, w/o Volcanos = -20.48 + 2.089 * LN (CO_2 ppm) + 1.252 * LN (CH_4 ppb) - .00393 * SO_4 ppb

adjusted R^2 = **98.3**%. CO_2, CH_4 & SO_4 (also 5-year averages) are all highly significant (|t-ratios| = 6.4 to 8.7).

Snow (Timing)

From 1982 thru 2013,

radiative cooling from northern snow cover

decreased by 0.33 W / sq m / ºC.

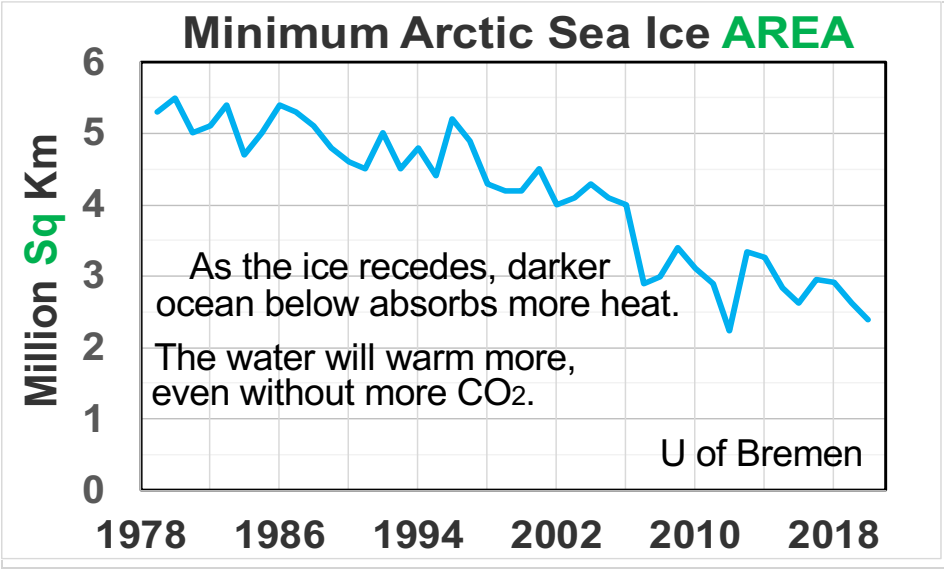
That was due to earlier snow melt.

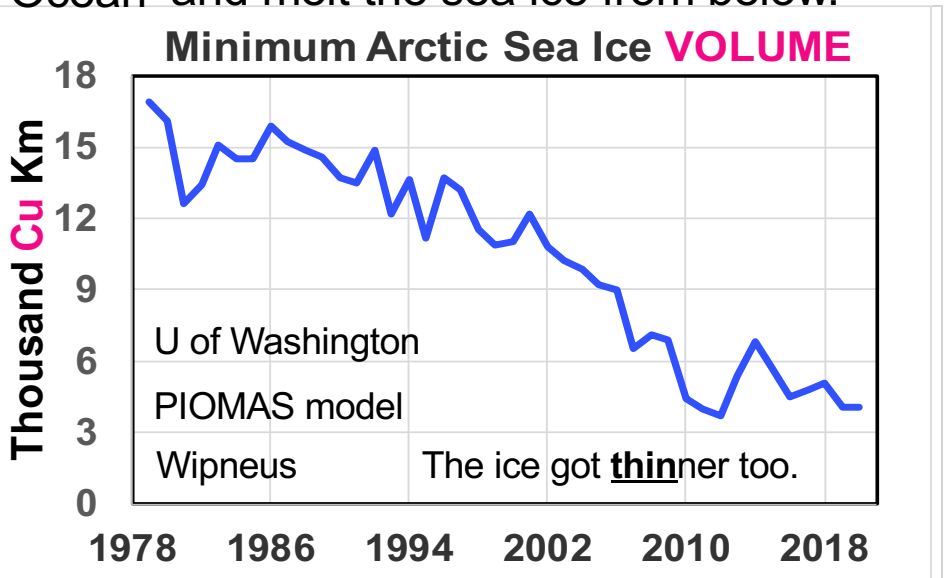
It added 12% to GHG warming.

Chen 2016

Arctic Ocean ice is shrinking fast.

Warmer Atlantic waters invade the Arctic Ocean and melt the sea ice from below.



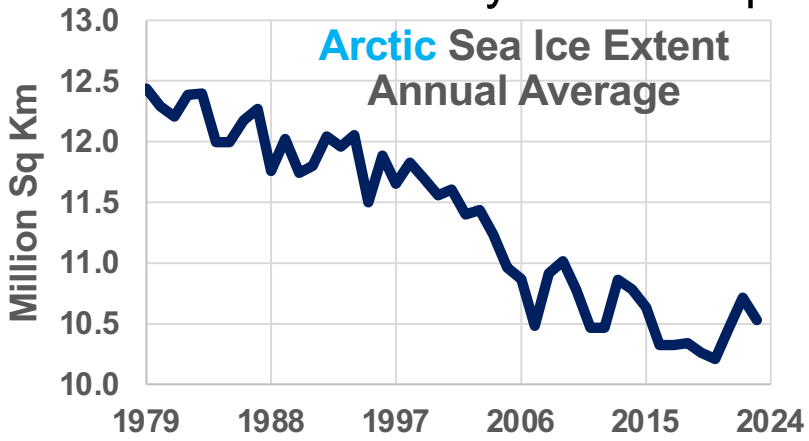


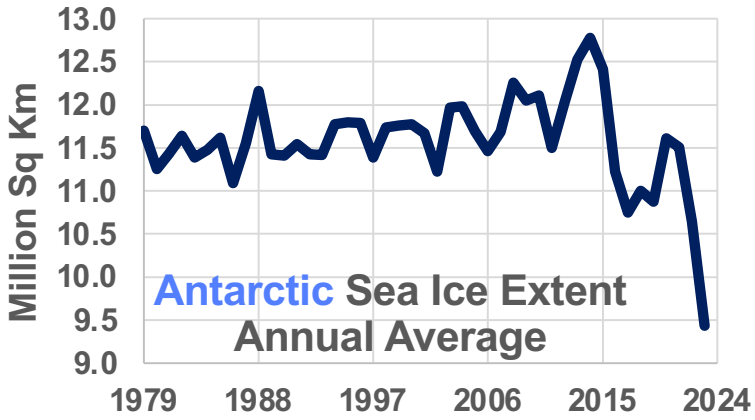
Minimum ice area fell 56% in 40 years, while volume fell 76%, 55% in the last 14.

The bright ice could melt away by fall in 5-9 years & be gone all summer in 9-30.

The dark water absorbs far more heat than ice: so far, like 20 extra years of CO_2.

Hudson (2011) estimated that total Arctic sea ice loss would warm Earth's surface by 0.7 W / sq meter, of which 0.1 had already occurred.





Estimated components of sea level rise (SLR), over 1993-2010, were (IPCC, 2014)

Ocean warming	1.10	mm / year
Glaciers outside Greenland & Antarctica	.76	
Greenland	.33	
Antarctica	.27	
Land water storage	.38	

That totals 2.8 mm / year, about 11 inches / century.

Greenland's net ice-melt rate rose 7 x in the past 17 years. Shepherd *et al.*

So, the ice cap's simple life expectancy fell from 60 millennia to 8.

Its annual net melt-water already exceeds US water use.

Antarctica's yearly net ice-melt (W minus E) was ~ 1/3 of Greenland's.

Its melt rate tripled over 2007-17. It has 9 x the ice. It will last longer.

Shepherd; Ringnot

Ice melt from Greenland and Antarctica each **accelerated** ~12% / year.

12% / year threatens 5.1 meter SLR by 2100 from the 2 ice sheets.

But acceleration should slow (how much?), in an S-curve, for less SLR:

2 meters at +10%/year (80-year μ), 0.5 meter at +8% μ, 0.1 meter at +6% μ.

Ocean warming will continue. Non-polar glaciers may mostly vanish by 2100.

Seas will likely rise 1 to 7 feet more by 2100 and up to 240 feet over millennia.

Seas rose 5 feet / century from 13,000 to 6,000 BC.

An estimated 39% of global surface warming over 1975-2016 came from **albedo** (reflectivity) changes –

direct plus

amplification by water vapor & cloud feedbacks.

Less sunlight reflected (more heat absorbed) was due to

fewer sulfur emissions: 22%

earlier snow melt: 11%

shrinking sea ice: 6%

& land ice loss: 0.1%.

Warming to 2100 and beyond will be dominated by albedo changes and their feedbacks:

62-79% of 21st century warming and

67-100% of 22nd to 24th century warming,

unless we remove most of the CO_2 we've added.

Snow (Mean Extent)

How do days of snow cover change as Earth warms up?

They decrease.

Contrast Winnipeg with New Orleans.

Using data for 14 US & Canadian cities,

indicates that the extent of northern snow cover

(mostly north of Winnipeg, especially in spring and fall)

decreases ~9% per 1ºC of global surface warming.

Fry 2018

How will albedo effects produce so much warming?

Earth will warm 3-4 x more, even if we stop emitting now.

Blame phasing out coal's sulfur emissions (almost .4ºC),

vanishing northern sea ice (about .4ºC = 0.7ºF),

receding northern snow cover (~.4ºC),

vanishing southern sea ice (~.4ºC),

permafrost etc.* (~.4ºC),

* = methane hydrates, outgassing from warmer soils and ocean, etc.

receding Greenland & Antarctic land ice (~.3ºC),

warming oceans enough so energy out = in (~.2ºC),

more H_2O vapor & less cloud cover (1.7 multiplier).

See
researchopenworld.com/albedo-changes-drive-4-9-to-9-4c-global-warmin
for details. The lines above include revisions to the albedos of what is under sea ice and snow, beyond what is in this journal article.

Air at the land surface has warmed
~1/3 faster than the sea surface.

Air warms more when & where it's coldest:
in winter,
at night,
& especially toward the poles:
10% faster than the global average at 40-45ºN,
100% faster in the Arctic.

Air in dry areas warms faster than wet areas.
Heat evaporates water if available;
otherwise it warms the air.
Since 1995, Kansas warmed at 1.44 x the US rate.

Even without more CO_2,
Kansas summers will become **Las Vegas** hot.

1.25 * 1.1 * 1.44 * 1.8 (ºC to F) = 3.6ºF warming in Kansas for each 1ºC worldwide.

~ means “approximately, roughly, is about equal to”
One MW can power several hundred US homes.

1ºC = 1.8ºF.

Earth Is Heating Up.

- Earth now **absorbs** 0.5% more energy than it emits –

a 680 (up from 450) **million** MW heat gain. (±60 million MW)

680 million MW = 100 x global electric supply = **45** x human energy **use**.

This absorption has been accelerating, from near zero in 1960.

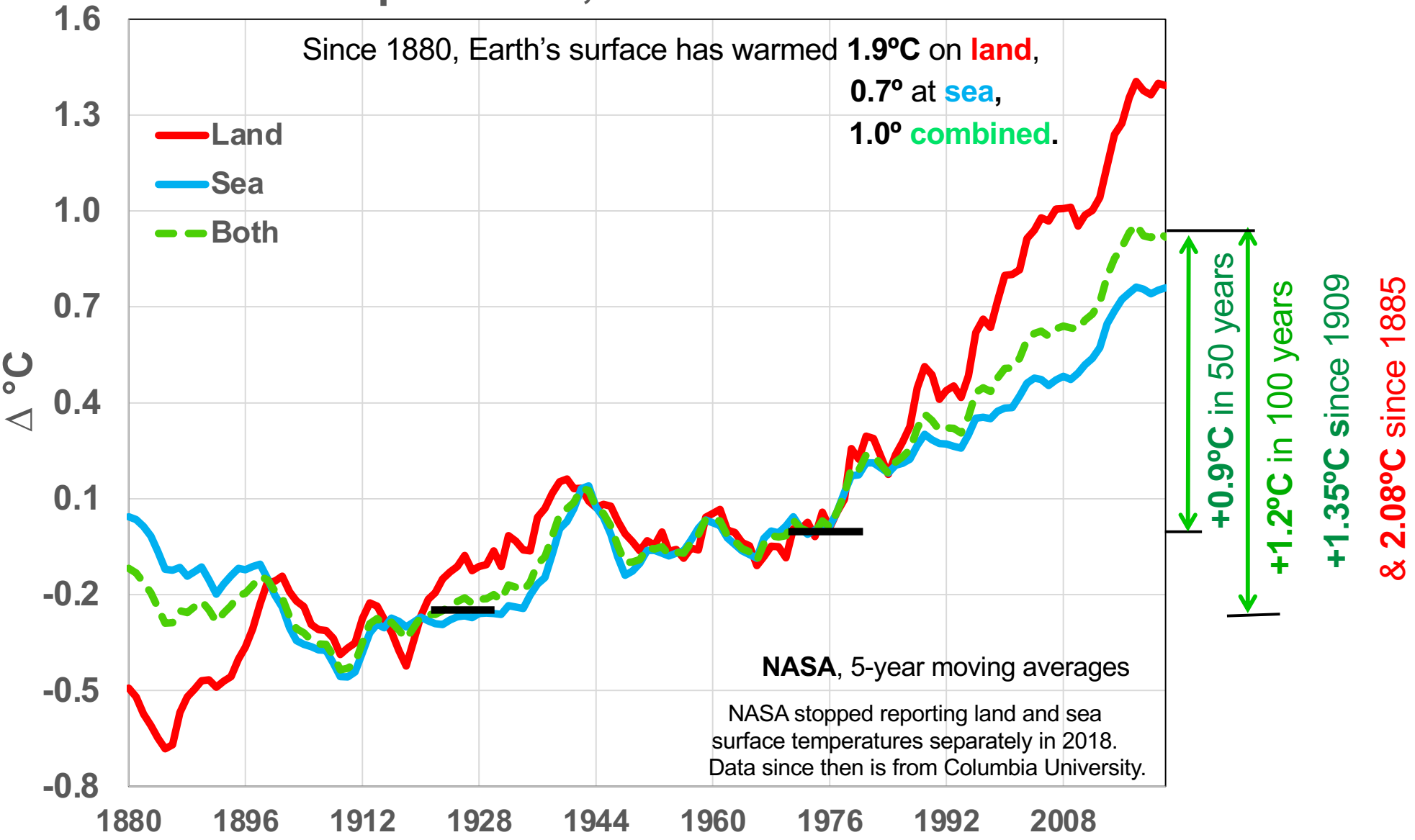
Earth will warm another 0.3ºC or more, so far,
just so it **emits** enough heat to balance absorption.

- Air at the land surface warmed 1.4ºC (5-year average) in 100 years,
  1.1ºC in the last 50 (1.5ºC since 1880).
- Air at the sea surface warmed 1.1ºC in 100 years , 0.9ºC in the last 50.

About 90% of the energy Earth absorbs heats the oceans.
If it all went to melt Greenland ice, the ice would vanish in 30 years.

- The oceans have gained > 15 x **more** heat in 40 years
  than ALL the energy humans have **EVER** used.

Temperatures, Global Surface



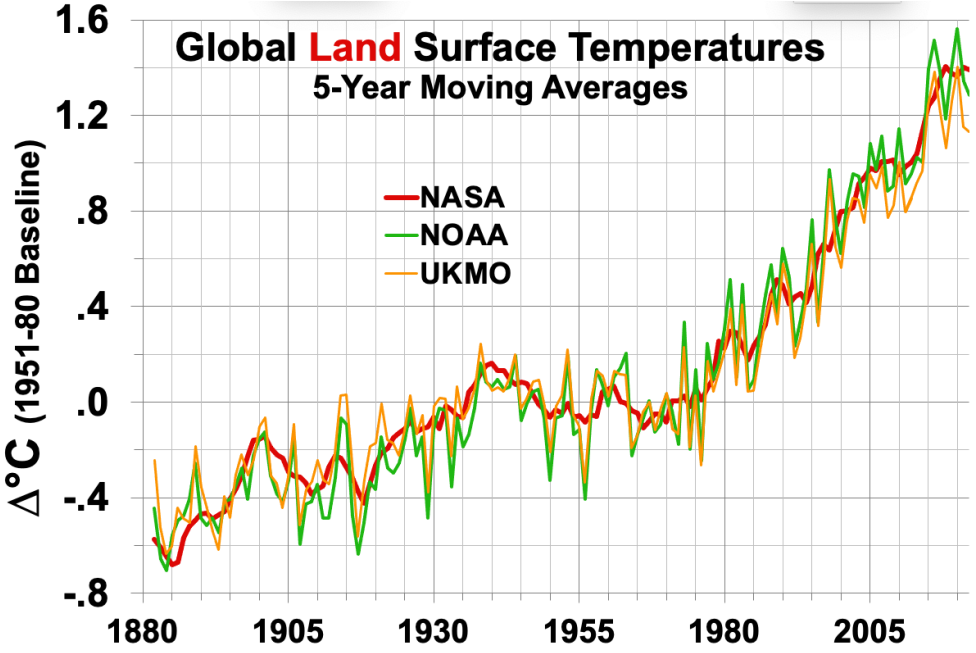
The 2002-2022 rate of change was
2.9ºC / 100 years for Land,
1.7 for Sea,
1.9 for Both.

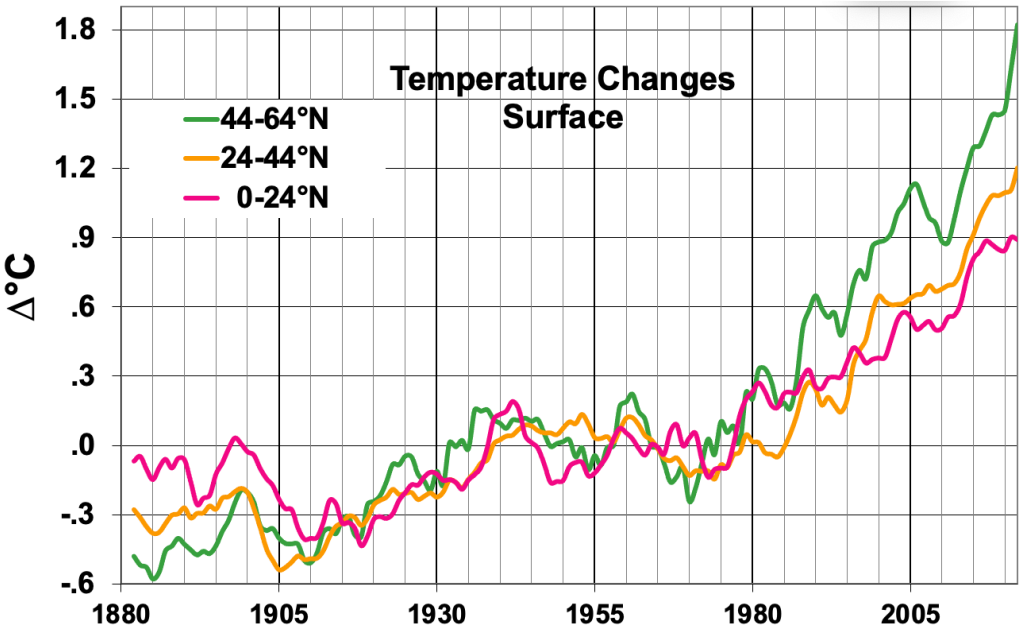
At that rate, "Both" will exceed 2ºC above 1880 levels in 2062.

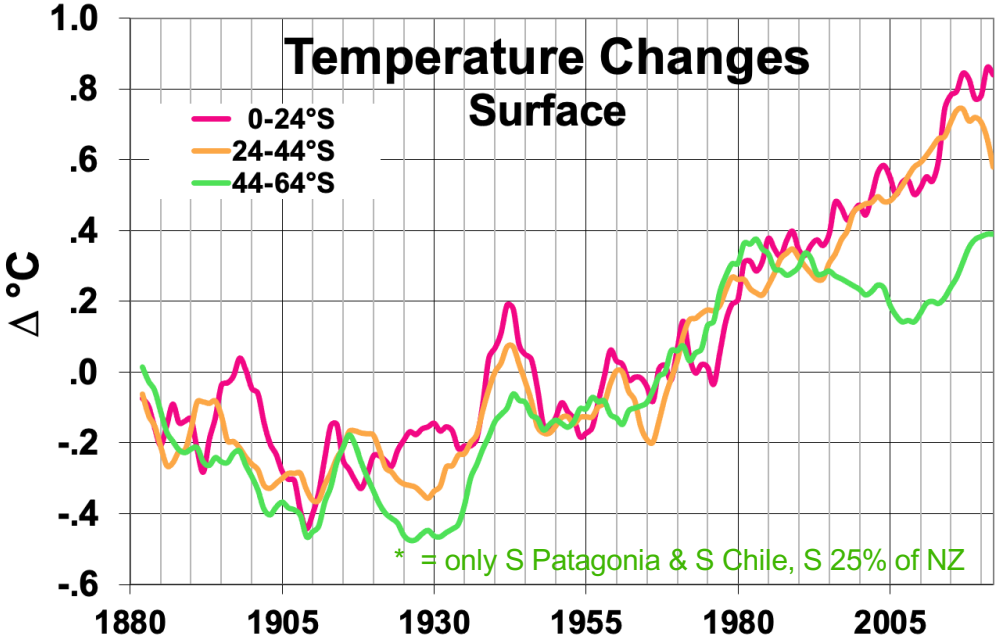
"Land" in 2025.

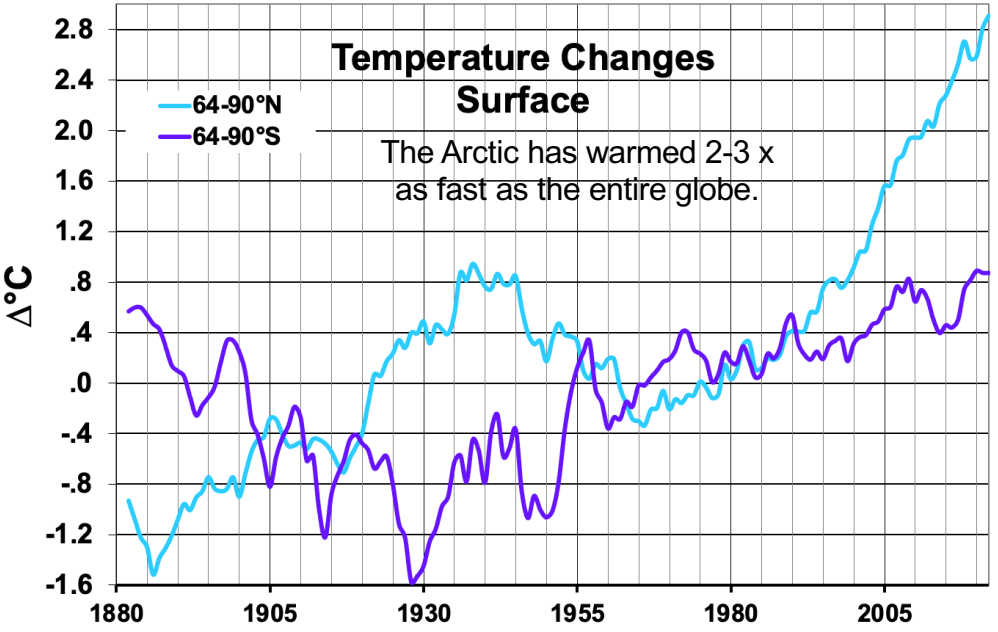
Temperature Changes at Earth's Land Surface

1951-80 Baseline
5-Year Moving Average
by Latitude - NASA GISS



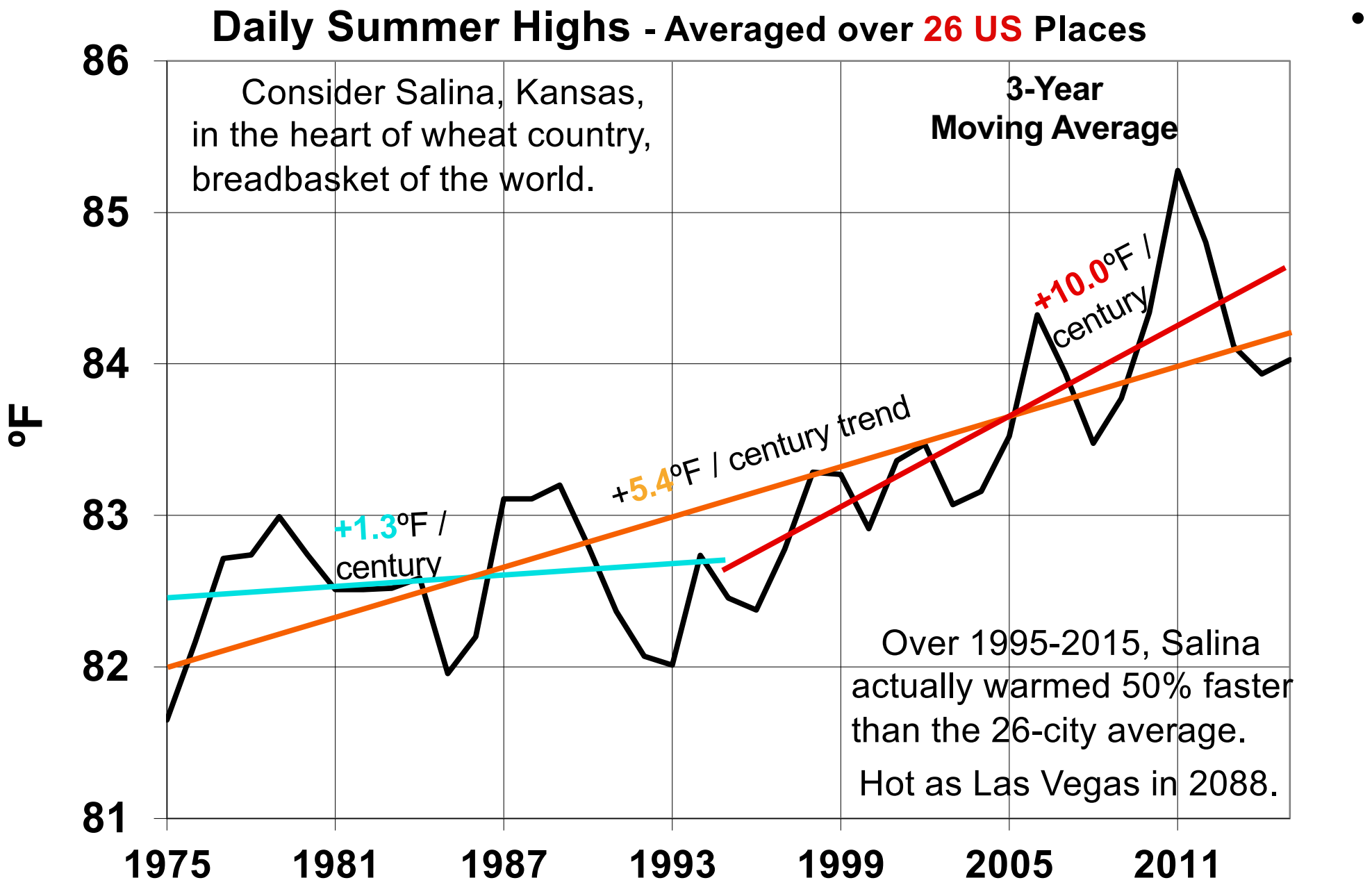






Consider 41 years of US daily high temperatures, June thru September, 1975-2015, in 26 places scattered around the US.

Jointly, these places have gained very few people since 1980 (0.03%/year), while US energy use per person shrank 0.28% per year. Thus, urban **heat island** effects in these places actually shrank.



At +5.4ºF / century, in 2100 summer in Salina would be as hot as Dallas now.
Warming at 10.0ºF / century, in 2111 it would be as hot as **Las Vegas** now.
We should PREVENT this.

The analysis was extended to 330 places across 48 contiguous states:

5.8ºF / century over 1975-2015 and **10.5**ºF / century over 1995-2015.

(Compare to 5.4º and 10.0ºF / century for the 26 places.)

Summer warming was **slow**est in the East North Central states.

It was **fast**est in the Rockies, S. Atlantic (x Florida) & southern Plains states.

Year When Daily Summer Highs Become as Hot as Las Vegas Ones Now

Selected Places (64 of 115 soonest): **Assuming Local** 1995-2015 Trends Continue

Phoenix	AZ	1993	Dodge City	KS	2068	Roswell	NM	2081	Biloxi	MS	2098
Laredo	TX	2019	Oklahoma City		2070	Columbia	SC	2083	Pasco	WA	2098
Fresno	CA	2036	Alexandria	LA	2072	Brunswick	GA	2083	Jackson	MS	2098
Austin	TX	2037	Dallas	TX	2073	Clemson	SC	2083	Sedalia	MO	2101
Waco	TX	2046	Augusta	GA	2074	Athens	GA	2084	Salt Lake City		2102
Redding	CA	2052	Twin Falls	ID	2076	Denver	CO	2088	St. Louis	MO	2103
Bakersfield		2057	Vernal	UT	2076	Bluefield	WV	2088	Hampton	VA	2103
Elko	NV	2058	Tulsa	OK	2076	Salina	KS	2088	Greensboro		2107
Tyler	TX	2058	Lewiston	ID	2076	Rock Spring	WY	2090	Missoula	MT	2110
Enid	OK	2059	Pueblo	CO	2077	Fayetteville	NC	2091	Memphis	TN	2110
Shreveport		2060	Wichita	KS	2078	Richmond	VA	2092	Charlotte	NC	2111
Monroe	LA	2060	Colorado Spring		2079	Tuscaloosa	AL	2093	Nashville	TN	2114
San Antonio		2062	Huntsville	AL	2079	Tallahassee	FL	2094	Trenton	NJ	2114
McAllen	TX	2062	Scottsbluff	NE	2080	Charleston	SC	2096	Casper	WY	2120
Reno	NV	2062	Modesto	CA	2080	Medford	OR	2097	Des Moines	IA	2120
Ft Smith	AR	2068	Montgomery	AL	2081	Bozeman	MT	2098	Arlington	VA	2123

When Do State Summers Become as Hot as Las Vegas Ones Now?

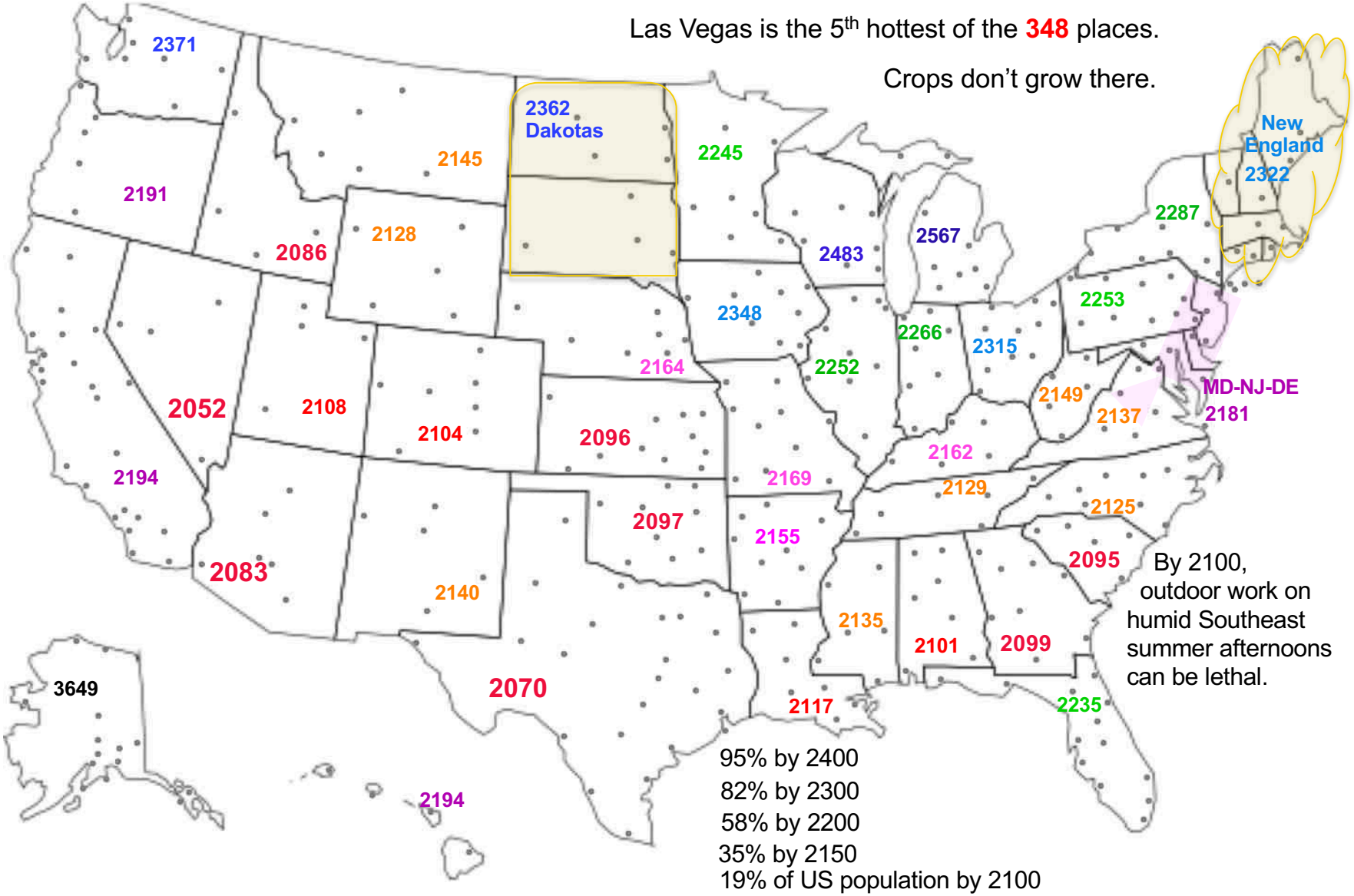
100.4°F

The **average** of daily **highs** in Las Vegas, June 1 thru September 30, 1995-2015, was **37.8**ºC.

Dates shown **assume LOCAL** daily high **trends** for **those 21 years CONTINUE**.

Las Vegas is the 5th hottest of the **348** places.

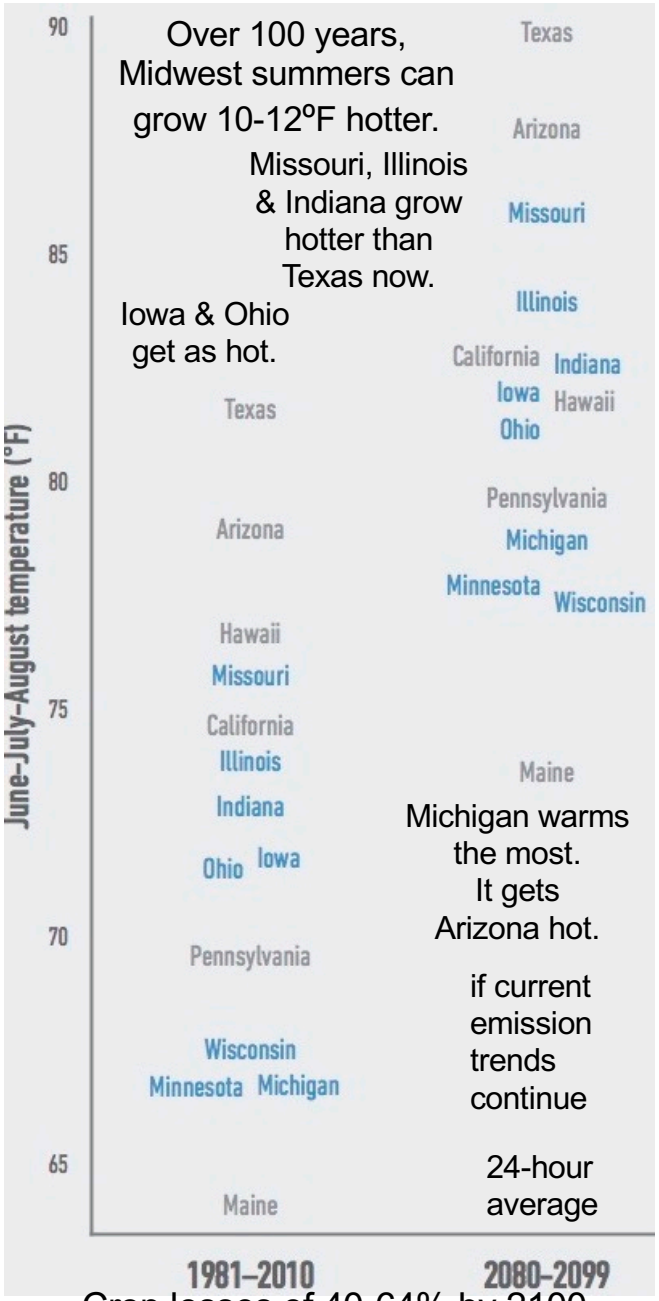
Crops don't grow there.



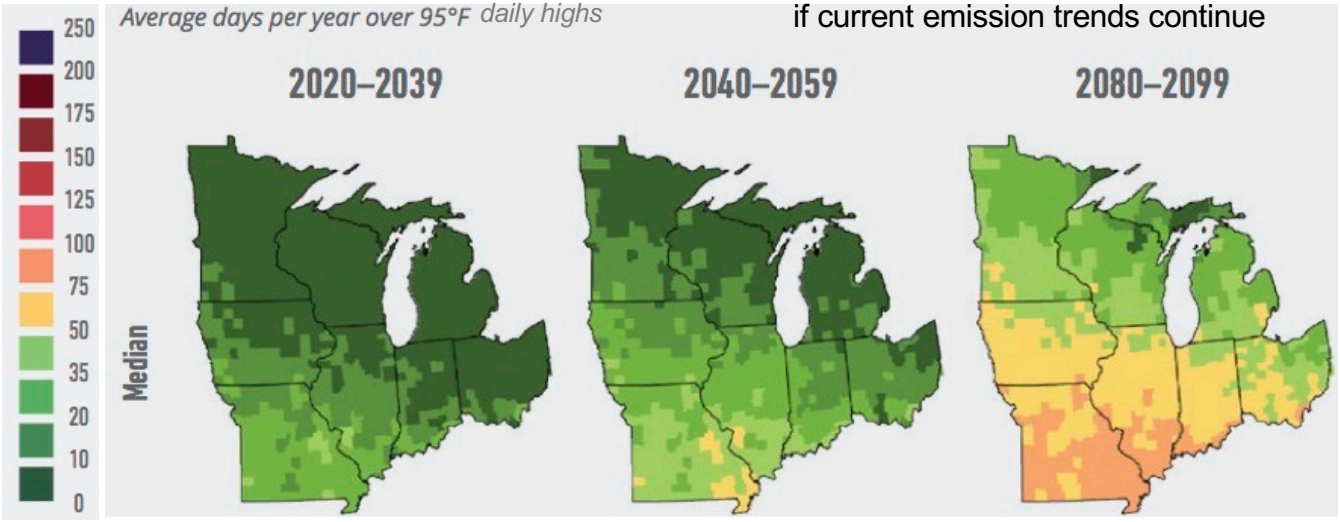
By 2100, outdoor work on humid Southeast summer afternoons can be lethal.

95% by 2400
82% by 2300
58% by 2200
35% by 2150
19% of US population by 2100

Heat in the Heartland, sponsored by Bloomberg, Paulson & Steyer, Jan. 2015

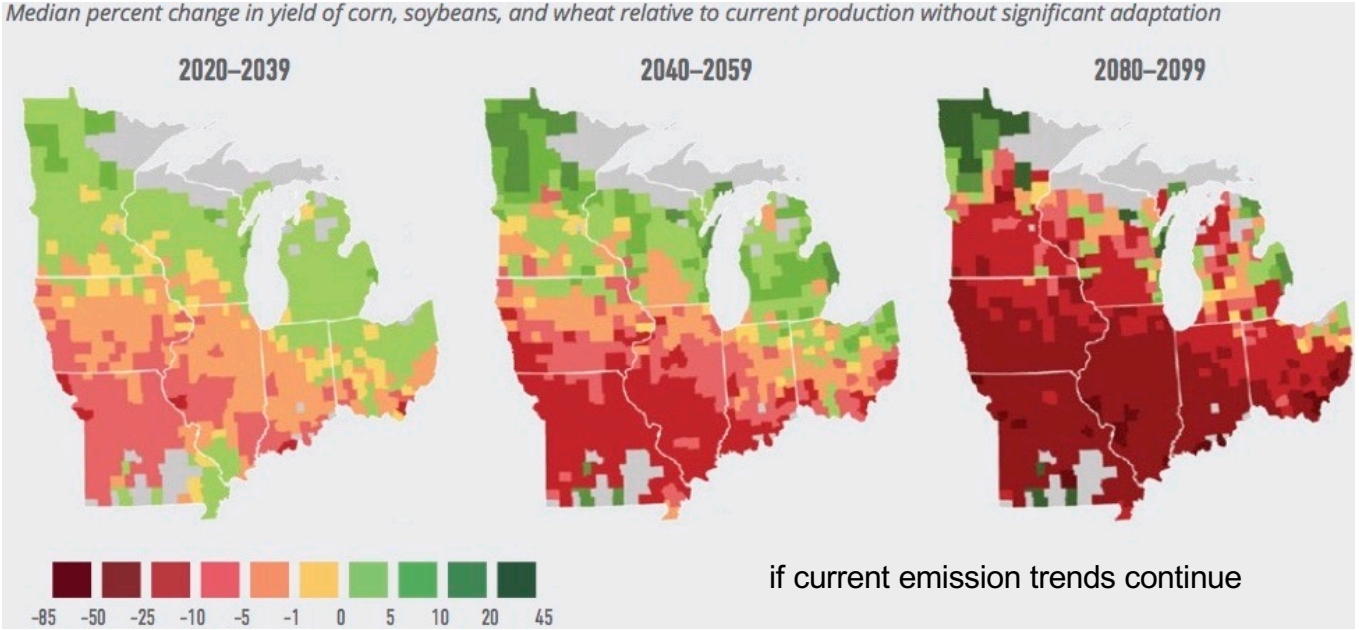


Crop losses of 40-64% by 2100 are likely for corn in the Corn Belt (IA, IL, IN, OH, MO) and 8-38% by 2100 for soybeans in the same states. Winter wheat is barely affected.



Las Vegas had 114, 99, and 115 days above 95ºF over 2012-14. If current emission trends continue, there is a 10-20% chance some orange area will be hotter than Las Vegas now by 2100.

Humidity and much more heat make Midwest heat stroke conditions skyrocket. 3 days a year would be worse than any ever experienced anywhere in the US.



Tipping Points

- Report to US & British Legislators - January 2006
  in the US, to Senator Olympia Snowe (R-ME)

What would make climate change accelerate,
so natural forces defeat our efforts to slow it?

1 Disappearance of sea ice
means more heat is absorbed by the water below.

2 Carbon sinks fade in oceans & forests.
Some become carbon sources.

3 Methane release from permafrost
revs up warming in a vicious circle.

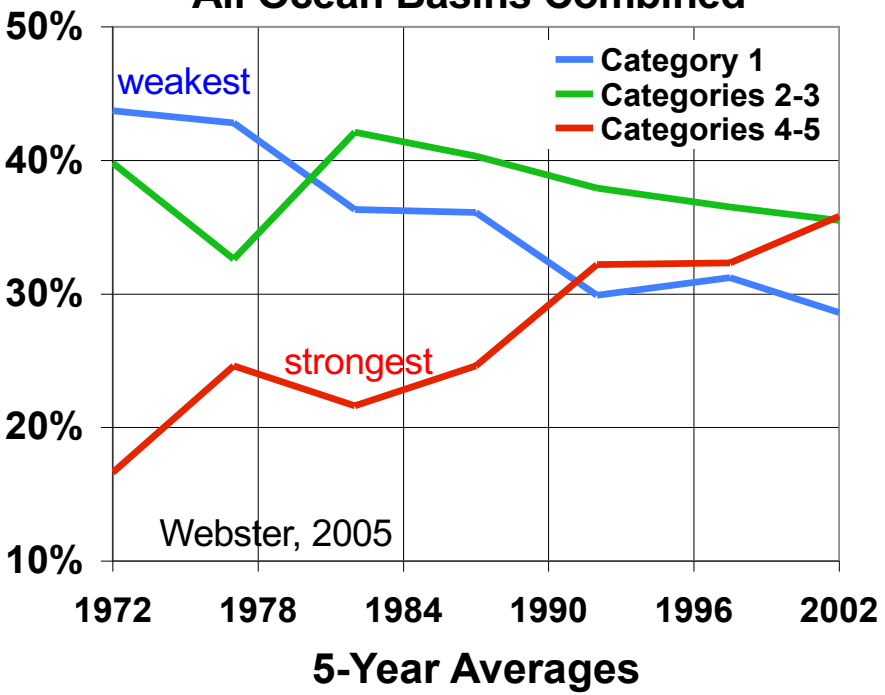
More Heat - So? Hurricanes

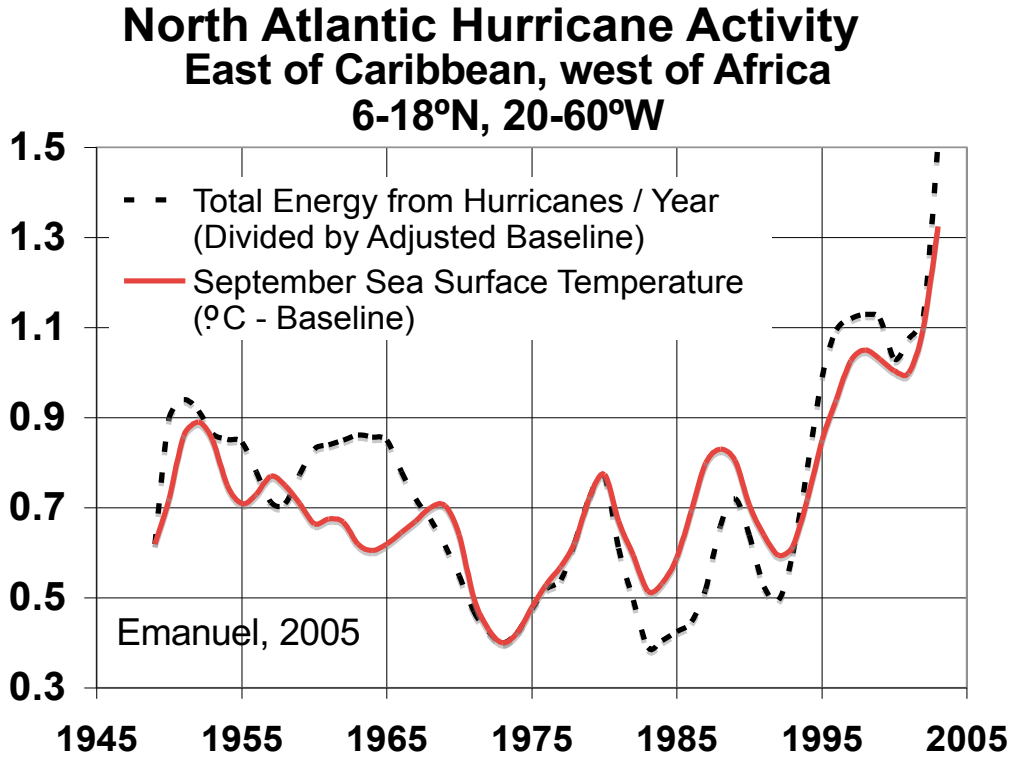
Hurricanes convert ocean heat to powerful winds & heavy rains.

Intense hurricanes are becoming more common.

Higher hurricane energy **closely** tracks sea surface warming.

Stronger hurricanes bring higher storm surges and worse floods.





Carbon in the Oceans

1/4 of our carbon emitted has gone into the oceans.

Added carbon has made oceans 30% more acidic, so far.

(Oceans are adding acid 100 times faster than in a million years.)

As a result, creatures find it ever harder
to extract calcium from seawater to build shells.

Consider corals.

Reefs of coral shells support myriad species, many billions of fish.
Already, 60% of corals cannot form shells.

At current rates, by 2100 ocean acidity would double or more.
No corals could form shells and reefs would all erode away.

Warmer water holds less dissolved oxygen.

Fish & mollusks suffer. Jellyfish prosper.

The mix of sea creatures will change, a lot.

Reservoirs in the Sky

Most mountain glaciers dwindle ever faster:
in the Alps; Andes; Rockies; and east, central & recently west Himalayas.
65% of the latter shrank from 2000 to 2008, including 80% in Tibet.
30% of Himalayan glacier ice vanished since 1980.

When Himalayan glaciers vanish, so could
the Ganges River (Indus, Yellow, etc.) in the dry season,
when flows already are only a few % of average.

As Andes glaciers vanish, so does most of Lima's water supply.

Mountain snows melt earlier.

CA's San Joaquin River (Central Valley, US "salad bowl")
dries up by July in most years, also Rio Grande now.
The Colorado River's recent 16-year drought was the worst in centuries.

Earth's forest fires burned 6+ x as much area / year as before 1986.

Record forest fires in 2018-20 briefly made San Francisco, Seattle,
Portland, and Vancouver the world's most polluted cities.

No seedlings were growing back at 1/3 of 1,500 fire sites in Rockies.
Western US forest fire area burned will **rise 2-7 x** / 1ºC warmer.

Methane Tipping Point?

Thawing Arctic permafrost holds 5 x **MORE** carbon
than **ALL** the carbon humans have emitted from fossil fuels.
In fact, it holds 2 x as much as Earth's atmosphere.

Permafrost area shrank 7% from 1900 to 2000.

It may shrink 75-88% more by 2100.

Already, Arctic permafrost emits more carbon than all US vehicles.
Part emerges as methane (CH_4), changing to CO_2 over the years.
Thawing permafrost can add ~**100** ppm* of CO_2 to the air by 2100,
and almost 300 more by 2300.

Seabed methane hydrates may hold a similar amount,
but so far they are releasing only 20-30% as much carbon.

* 100 ppm compares to 135 ppm from fossil fuels to date.

There may be far more permafrost carbon under **Antarctic** ice.

55 million years ago, scads of carbon

from thawed Antarctic permafrost & later CH_4 hydrates
warmed Earth by 6ºC over 4-10 K years, far more over the Arctic Ocean.

Warming now is 7-35 times as fast as then.

Bio Impacts

To escape heat, species move toward the poles and up mountains.
But some species cannot move fast enough.
Habitat for some vanishes entirely.

Cold-blooded species move around faster, warm-blooded ones slower.
More lizards, snakes, mosquitoes and beetles, fewer mammals.
Some places get too hot and humid for humans to survive.

Earlier springs set up timing mis-matches between
flowering green plants, pollinators, and herbivores, and
between prey and predators.

Warmer weather dries up forests.
They catch fire and burn much more.

Tropical diseases, mosquitoes, ticks, etc. expand their ranges.

Corals bleach more often and harder.
Earth's coral reefs vanish.

More acid oceans make shell formation harder. Jellyfish prosper.

Extinction rates are already 100s of times background rates.

What Else? **Hot** & Dry

From 1979 to 2005, the tropics spread.
Sub-tropic arid belts grew ~140 miles toward the poles,
a century ahead of schedule.

So our jet stream moves north more often.
In turn, the US gets hot weather more often.

With less temperature gradient between the Arctic & mid-latitudes, the jet stream **slows** and meanders N-S much more: 1-2 K miles. So hot dry air lingers longer (heat waves), as does moist rainy air (floods).

2012 was **America's** hottest year on record.

Over September 2011 - August 2012, relative to local norms,
33 states were drier than the wettest state (WA) was wet.
Over 2012, 44 of 48 states were drier than normal.

Severe drought covered a record 35-46% of the US, for 39 weeks.

Drought reduced the corn crop by 1/4. Record prices followed.
The soybean crop was also hit hard. Lake Michigan-Huron hit record low.
The Mississippi River neared a record low. Again in 2022. Platte vanished.

"Once a century" or worse droughts now happen once a decade.

US #3 now

When I was young, the leading wheat producers were the US Great Plains, Russia's steppes, Canada, Australia, and Argentina's Pampas.

China now #1 in wheat.

Notable Recent Droughts

When	Where	How Bad
2003	France, W Europe	record heat, 20-70K die. hotter in 2012 & esp. '21-22
2003-10	Australia	worst in 900 years. Record heat in 2016 & 2020.
2005	Amazon Basin	once a century. Worse in 2010 & esp. 2013-16.
1998-2012	Syria, Iraq, Jordan+	10% worse than any other in 900 years
2007	US Southeast	1x / 100 yrs. NW had record heat & fires in 2021.
2007	Europe	record heat, fires, worse in 2021-2, **rivers vanish**.
'07-9, '13-22	California & SW	record low rains. Drought worst in 1200 years.
2008-9	Argentina	worst in half a century
2008-11	north China	~worst in 200 yrs, & in Yunnan. 2022 water way down.
2009	India #2 in wheat	Monsoon rain down 10-20% in N & C-E (1901-2012).
2010	Russia	15K die. record heat, forest fires. Wheat prices up 75%.
2011	Texas, Oklahoma	record heat & drought
2012	US: SW, MW, SE	most widespread in 78 years; record heat

Is That All? No Water

Over 1994-2007, deserts **grew** from 18 to 27% of China's area.

Desert growth is worse where the Sahara marches into Africa's Sahel.

Yearly US groundwater withdrawals (irrigation +) grew, from 0.5% of today's water use, before 1950, to 5.4% now. So, the Ogallala Aquifer, etc. dwindle.

1/5 of wheat is irrigated in the US, 3/5 in India, 4/5 in China.

Central CA loses enough to irrigation yearly to fill Lake Erie in 100 years.

India's Ganges Basin loses enough groundwater yearly to fill Lake Erie in 10.

With more evaporation & **irrigation**, many water tables fall 3-20 **feet** a year.

Worldwide, irrigation wells chase water ever deeper. Water prices rise.

Many wells in China & India wheat belts must go down 1,000 feet for water.

Since 1985, **half** the lakes in Qinghai province (China) vanished.

92% in Hebei (around Beijing), as water tables dropped below lake beds.

Inland seas and lakes dry up: Aral & Dead Seas, Lakes Chad & Eyre.

Lake Mead water fell 173 feet over 2000-22. It may get too low to use soon.

Lake Michigan-Huron hit a record low in 2013, Lake Baikal in 2015.

More rivers fail to **reach** the **sea**: Yellow, Colorado, Indus, Rio Grande, etc.

Carbon Sinks Fading?

Severe drought hit 45% of North America in 2002,
so plants absorbed **50**% **less** CO_2.

The Amazon Basin's 2010 drought turned its rainforest into a
net carbon **source** for the year.

Its emissions exceeded China's - for the 2nd time in 6 years.
2016 was worse in the Amazon – and the Congo and Indonesia.

Things will likely get worse this century, as tropical rainforests dry out.

Since 1979, Amazon dry seasons grew longer by 1 week / decade.
Its trees hold 1/4 of carbon in fossil fuels burned to date: ~25 ppm.

Sea surfaces warmed 0.15ºC over 1997-2004, so
plankton absorbed 7% **less** CO_2.

Warming was far strongest in the North Atlantic.
CO_2 uptake <u>there</u> **fell** by **half**.

However, the % of the carbon we emit that <u>stays</u> in the air hasn't risen.
Temperate and sub-Arctic forests have taken up <u>more</u> carbon.

Phytoplankton levels in the oceans perhaps fell 40% since the 1950s: 1% / year since 1979.

Findings are based on opacity of near-surface water.

D. Boyce, M. Lewis, B. Worm, *Nature* 4/28/10

Phytoplankton declined 30% in the Indian Ocean since 1999.

Roxy, Modi, Murtugudde, et al., 1/19/16, using satellite chlorophyll data

But 111 years of ocean green color data shows no global trend; the north Atlantic grew greener, Pacific & Indian grew less green.

M. Weynand et al., *PLOS* 2013

1 The tiny phytoplankton form the ocean food web's base.

2 Warmer layers on top inhibit cold water below from rising.
Less turnover brings fewer nutrients up for plankton growth.

3 Plankton absorb CO_2. Perhaps not so much any more.

4 They have supplied half the world's **oxygen**.
Earth has a 2,000-year oxygen supply, always being refreshed.

In 2005-6, scientists calculated how climate would change for 9 Northeast and 6 Great Lakes states in 2 scenarios:

#1 - a transition away from fossil fuels, or

#2 - continued heavy reliance on them (business as usual emissions).

By 2085,
averaged across 15 states, the climate change would be like moving 330 miles to the SSW (coal & oil use dwindle), or moving 650 miles to the SSW (heavy coal & oil use).

Consider central Kansas, heart of wheat country.

330 miles to the SSW lies the area from Amarillo to Oklahoma City.

650 miles to the SSW lies the area around Alpine & Del Rio, TX.

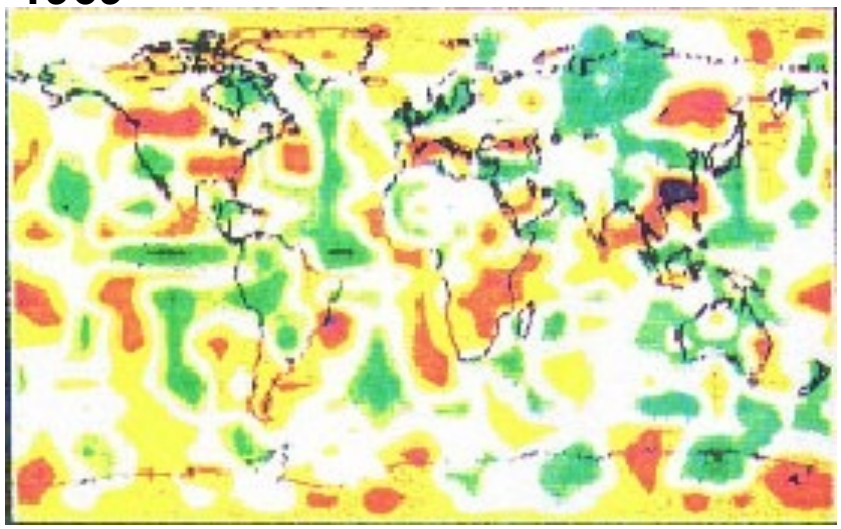
2 people / square mile. Cactus grows there.
Mesquite & sagebrush too.

No wheat

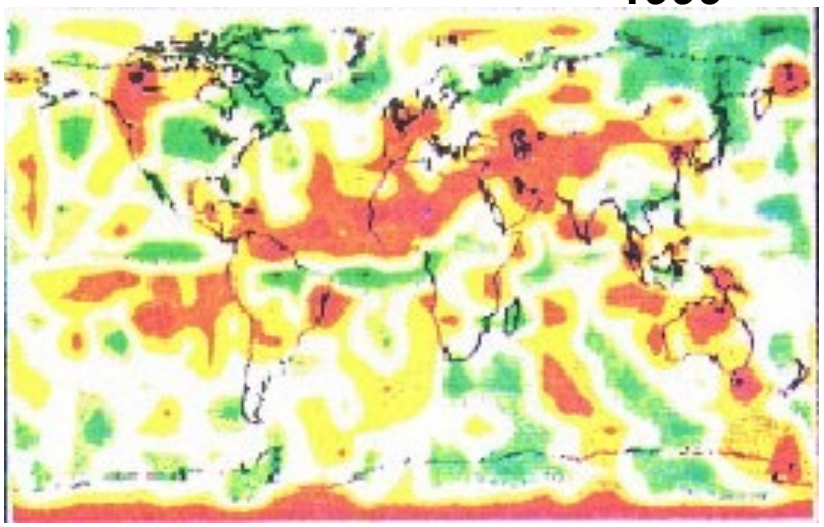
By 2059, "Once a Century" Drought Can Cover 45% of Earth.

Supply-Demand Drought Index

1969



1999

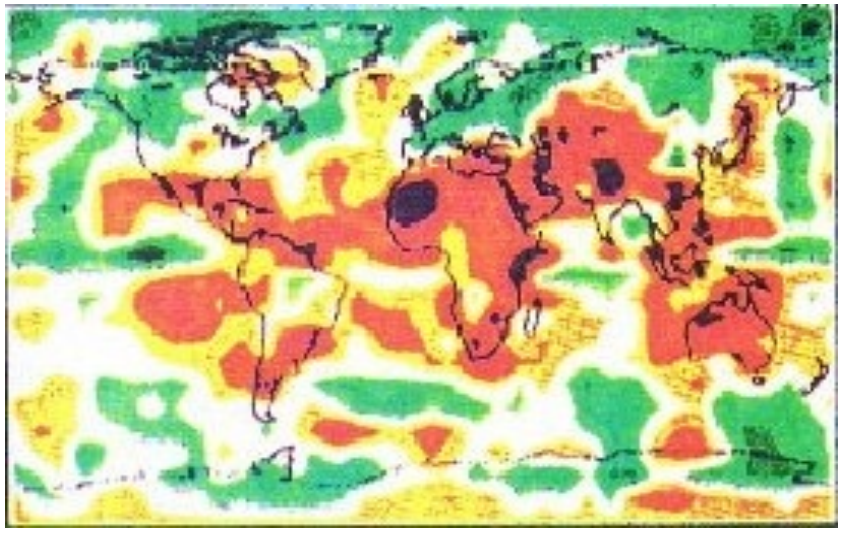


Business as Usual Emissions

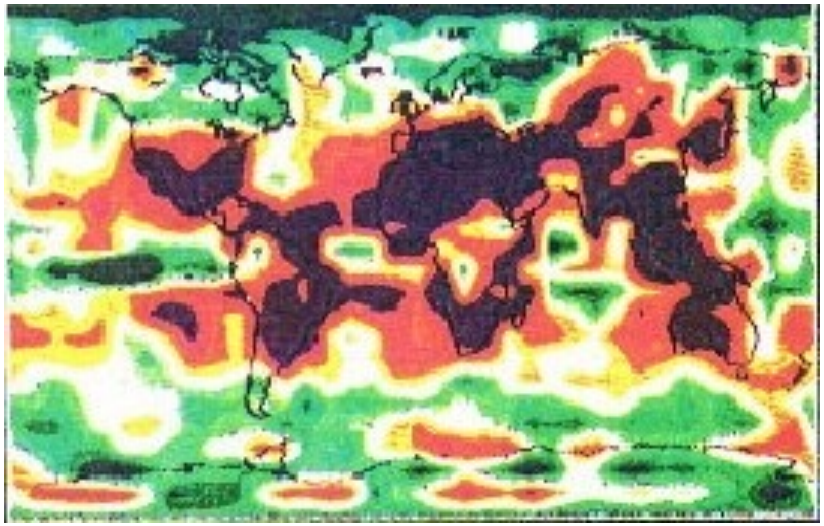
in **2059**
2 x CO_2

+4.2ºC
+14% rain

2029



2059



Climate Model: NASA Goddard Institute for Space Studies (GISS)

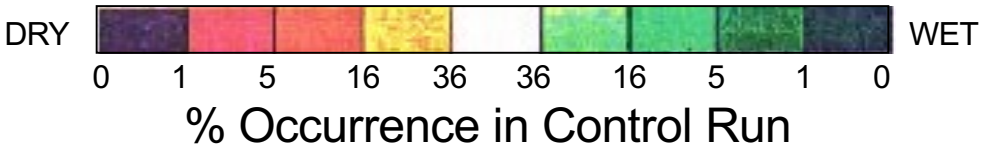


Fig. 1 in David Rind, R. Goldberg, James Hansen, Cynthia Rosenzweig, R. Ruedy, "Potential Evapotranspiration and the Likelihood of Future Droughts," *Journal of Geophysical Research*, Vol. 95, No. D7, 6/20/**1990**, 9983-10004.

Projected Drought Conditions

Land Surface, except Antarctica

June-August, **Business as Usual Emissions**

2x CO_2

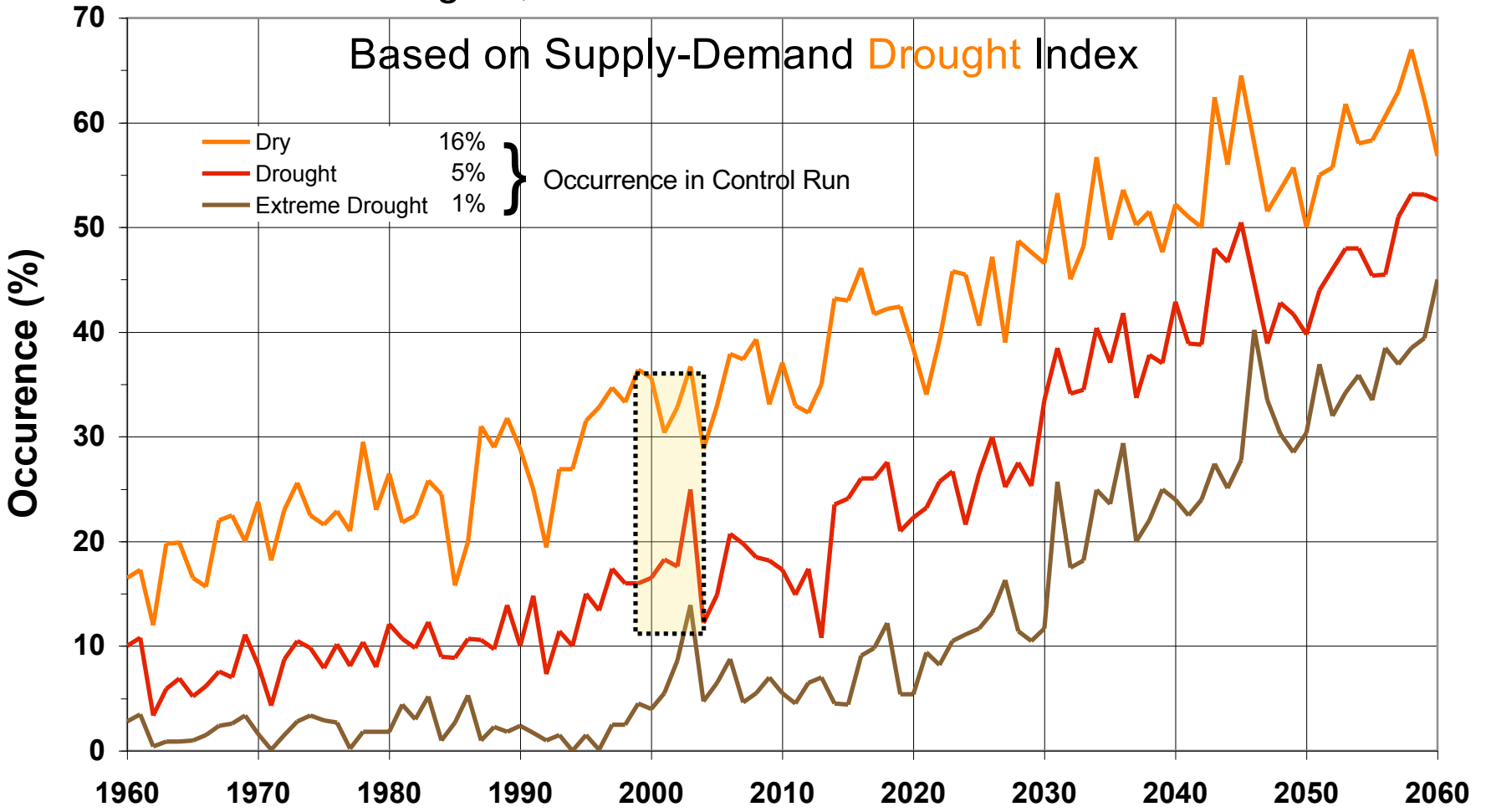


Fig. 2 in Rind *et al.*, 1990

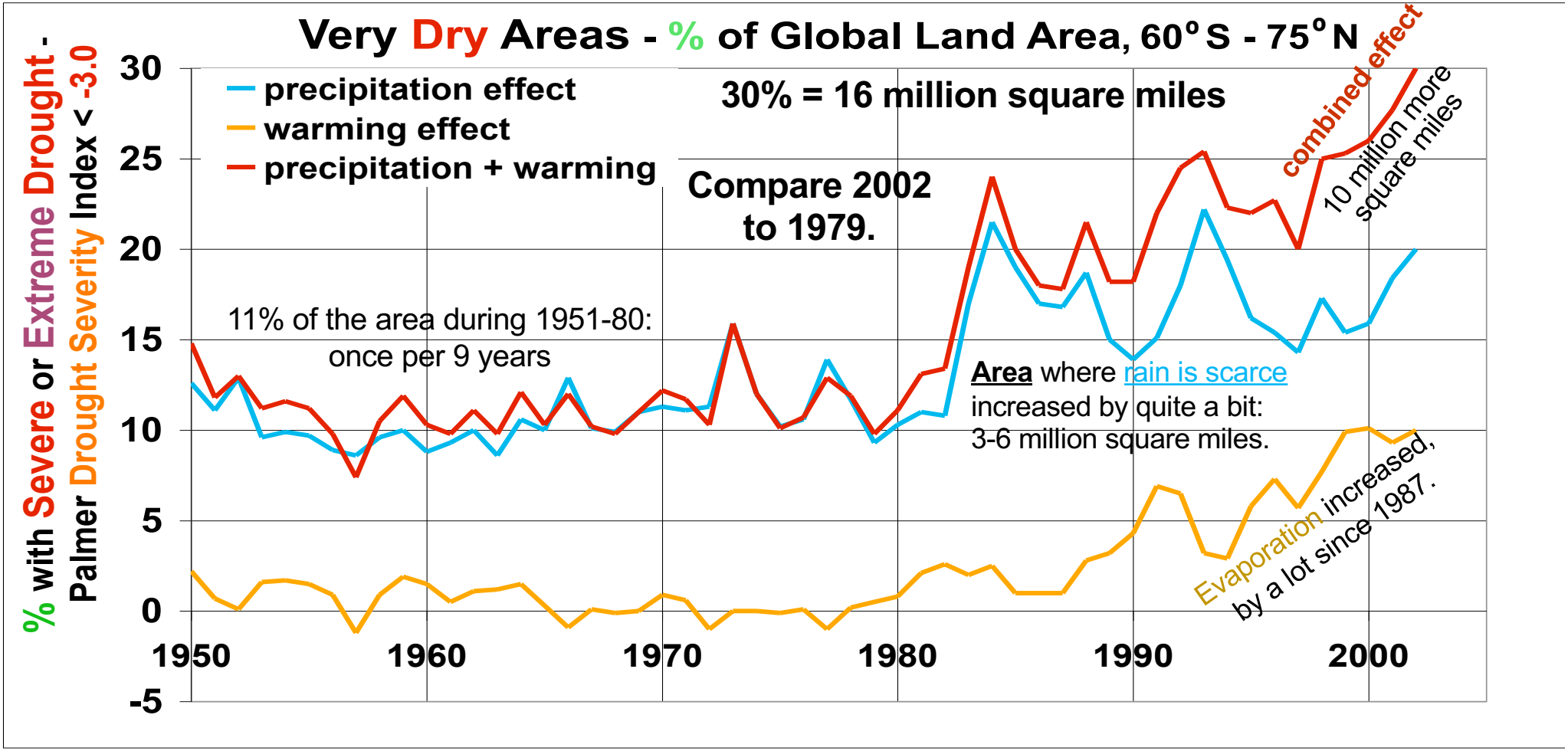
2x CO_2

"Once a century" drought can cover 45% of Earth's land by 2059.

Over 2000-04, the average frequencies are 18% for "Drought" and 33% for "Dry".
A weighted average for "as dry as 11% of the time" drought is ~ **27%**.

Droughts Are Spreading Already.

Switch from what could happen to what **has** happened already.

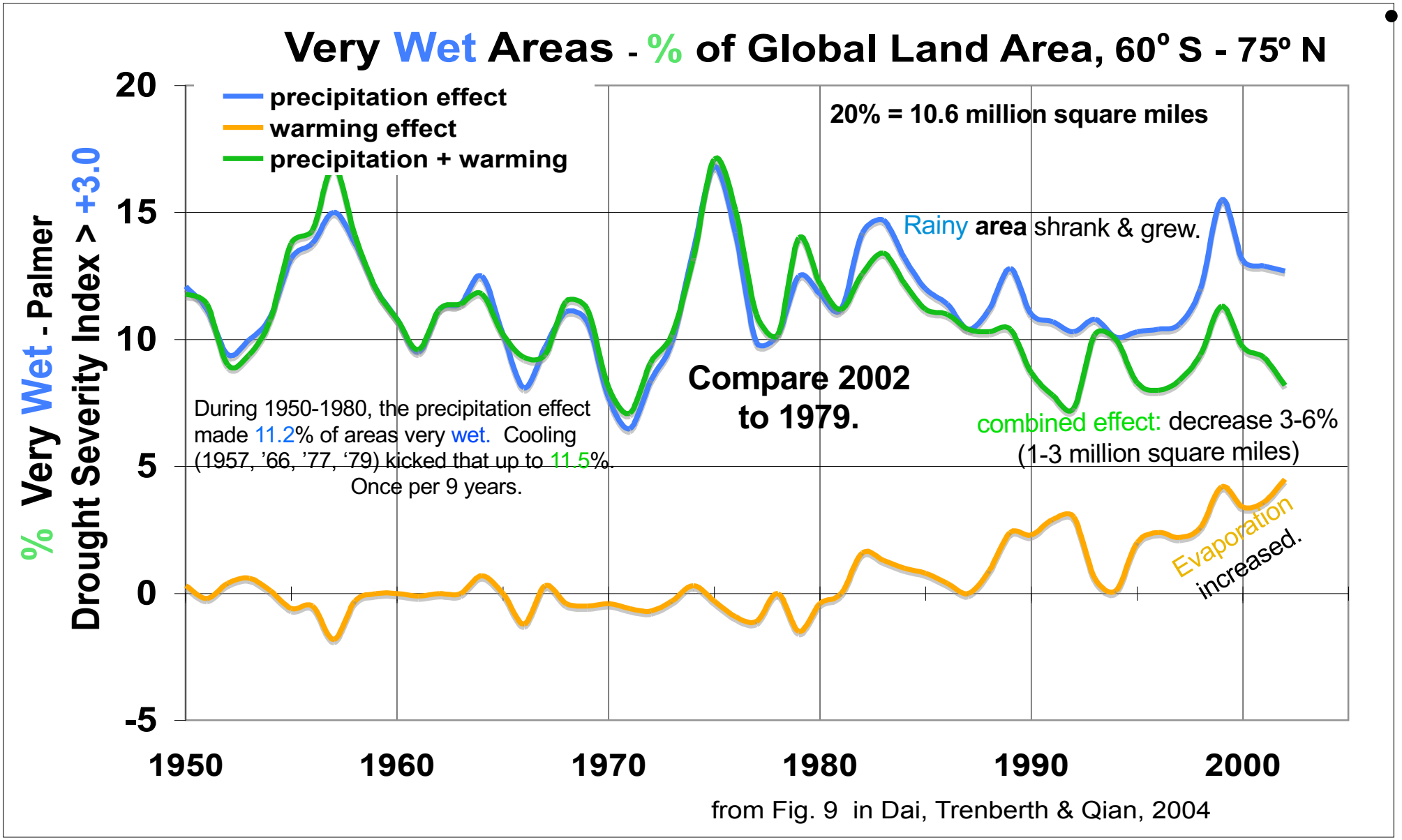


from Fig. 9 in Aiguo Dai, Kevin E. Trenberth, Taotao Qian [NCAR], "A Global Dataset of Palmer Drought Severity Index for 1870-2002: Relationship with Soil Moisture and Effects of Surface Warming." *Journal of Hydrometeorology*, December 2004, 1117-1130

Compare 30% **actual** severe drought area in 2002 (11% of the time during 1951-80) to 27% **projected** for 2000-2004 in previous slide. Droughts spread, as projected or faster.

Earth's area in severe drought has **tripled** since 1979. Evaporation at work

Over 23 years, the area with severe drought **grew** by the size of North America.



The combined decrease was 6% from 1979 to 2002,
but only 3% from the 1950-80 mean to the 1992-2002 average.

Over 23 years, the soggy area **shrank** by the size of India, more or less.

RECAP

Severe drought has arrived, as projected or faster.

Severe drought now afflicts an area the size of Asia.

So, farmers mine groundwater ever faster for irrigation.

From 1979 to 2002 (+0.5ºC)

1) The area where rain is scarce
increased by the size of the United States.

Add in more evaporation.

2) The area with severe drought
grew by the size of North America.

3) The area suffering severe drought **tripled.**

4) *The similarly wet area* ***shrank*** *by the size of* India.

What Drives Drought?

- The water-holding capacity of air rises

  exponentially with temperature.

- Air 4ºC warmer holds 33% **more** moisture

  at the same relative humidity.

(That's the flip side of "air cools. It holds less H_2O, so it clouds up & rains.")

More moisture in the air does **not** equal more clouds.

To maintain soil moisture,

~10% more rain is required to offset each 1ºC warming.

Warmth draws more water UP (evaporation), so
less goes DOWN (into soils) or SIDEways (into streams).
More water is **stored** in the **air**, **less** in **soils**.

Satellites are already showing more water vapor in the air.
Not quite all the water that goes up comes back down.

Droughts - Why Worry?

2059 - 2 x CO_2 (Business as Usual Emissions) Rind *et al.*, 1990

- More moisture in the air, but 15-27% **less** in the soil.
- Average US stream flows decline 30%, **despite** 14% more rain.
- Tree biomass in the eastern US falls by up to 40%.
- More dry climate vegetation: **savannas**, **prairies**, **deserts**

The vegetation changes mean

- Biological Net Primary Productivity falls **30-70**%.

SWITCH from PROJECTIONS to ACTUALS.

- Satellites show browning of the Earth began in 1994. Angert 2005 Zhao 2010

Crop Yields Fall.

Rind *et al.*, 1990

United States: 2059 Projections - doubled CO_2 - Business as Usual

– Great Lakes, Southeast, southern Great Plains

- Corn, Wheat, Soybeans - 3 of the big 4 crops (rice is the 4th)

2 Climate Models (Scenarios)

- NASA GISS Results (based on 4.2°C warmer, 14% more rain)

  Goddard Institute for Space Studies

  –Yields fall **30**%, averaged across regions & crops.

- NOAA GFDL Results (based on ~ 4.5°C warmer, 5% less rain)

  Geophysical Fluid Dynamics Lab

  –Yields fall **50**%, averaged across regions & crops.

CO_2 fertilization **not** included

Temperature effects of doubled CO_2 will grow to 4.2 or 4.5ºC after 2060, but continue to grow afterward, past 8ºC by 2400, as positive feedbacks continue to amplify direct effects.

CO_2 fertilization (2 x CO_2) boosts yields 4-34% in experiments, where water and other nutrients are well supplied, and weeds and pests are controlled. That won't happen as well in many fields. Other factors (esp. nitrogen) soon limit growth, so CO_2 fertilization will falter.

Besides, with higher CO_2, plants make more carbs but less protein.

Plants evaporate (transpire) water in order to

[like blood]

(1) get it up to leaves, where H_2O & CO_2 form carbohydrates,

(2) pull other soil nutrients up from the roots to the leaves, and

[like sweat]

(3) cool leaves, so photosynthesis continues & proteins aren't damaged.

When water is scarce,
fewer nutrients (nitrogen, phosphorus, etc.) get up to leaves.

With more CO_2, leaf pores narrow, so less water evaporates.
This slows water loss in droughts.
But it also heats up leaves, harming plant growth when it's hot.

So, with warming, more CO_2, and less water,
leaves make more carbohydrates, but fewer proteins.

Warming (’92-03) cut Asian **rice** yields by 10+%/ºC.
Warming (’82-98) in 618+ US counties cut **corn** & **soybean** yields 17%/ºC.

With more CO_2, 2ºC warming cut yields 8-38% for irrigated **wheat** in India.

Warmer nights (’79-’04) cut **rice** yield growth 10%± in 6 Asian nations.
Warming (’80-’08) cut **wheat** yield growth 5.5%, **corn** 3.8%.

Crop yields rise with some warming, but fall with more warming.
Warming helps crops in cool areas, but hurts in the tropics.

For 1ºC warming, with no change in weeds or pests, in general
US corn yields fall 8%, rice 10%, wheat 5-7%, soybeans 3%.

Add CO_2 (440 ppm) fertilization and irrigate, if **POSSIBLE** (not too costly).
US corn & rice yields fall 2%, wheat rises 2%, soybeans 5-9%.

But weeds and pests also grow better with warming & more CO_2.

For **wheat**, **corn** & **rice**, photosynthesis in leaves
slows a lot above 95ºF and stops above 104ºF [40ºC].

Tropical areas **suffer** most: *e.g.*, irrigated rice yields can fall 30% by the Ganges.

Heat Spikes Devastate Crop Yields

Schlenker & Roberts 2009

Based on 55 years of crop data from most US counties, and

holding current growing regions fixed,

average yields for corn and soybeans could

plunge 37**-46**% by 2100 with the slowest (#1) warming

and plummet **75-82**% with quicker (#2) warming.

Why?

Corn and soybean yields rise with daily highs up to 29-30ºC [84-86ºF],

but fall more steeply with higher temperatures.

Heat spikes on **individual days** have **BIG impacts.**

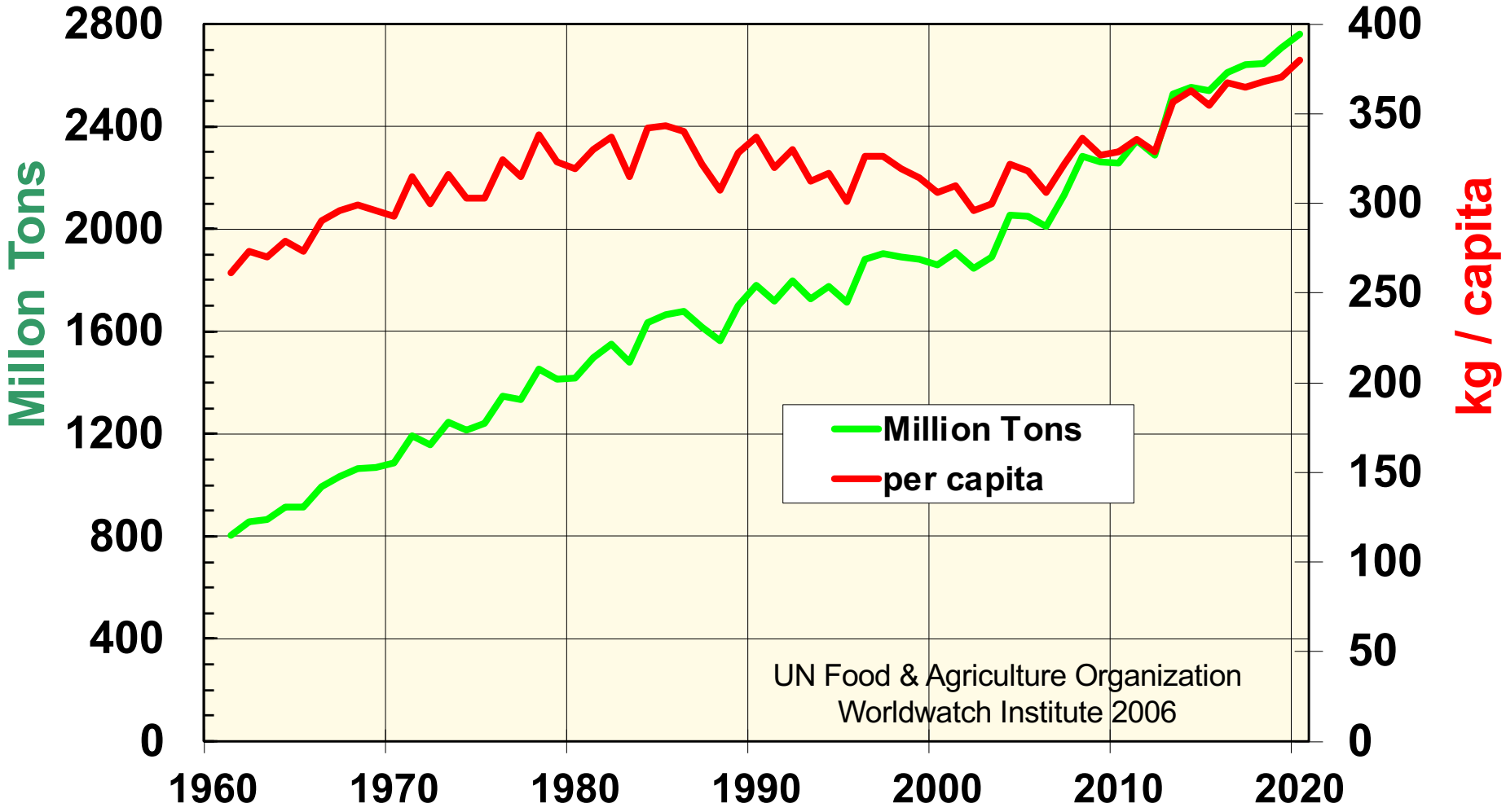
Other crop future models use average temperatures.

Thus they miss heat spikes on or within individual days.

More rain can lessen losses. Plants transpire more water to cool off.

Growing other crops, or growing crops farther north, can help too.

World Grain Production



80% of human food comes from grains.

World grain production rose little from 1992 to 2006.

Production per capita fell from 343 kilograms in 1985 to 306 in 2006.

Some scientists are saying publicly that if humanity goes on with business as usual, climate change could lead to the **collapse of civilization**, even in the lifetime of today's children.

UN Secretary General Ban Ki-Moon answered “I think that is a correct assessment.” He added carefully “If we take action today, it may not be too late.”

September 24, 2007

Continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system, increasing the likelihood of **severe, pervasive** and **irreversible** impacts for people and ecosystems.

IPCC Synthesis Report: November 1, 2014

UN secretary general António Guterres attacked fossil fuel subsidies, saying: “What we are doing is using taxpayers’ money … to destroy the world.”

May 2019

- Any future food production increases will occur away from the tropics.
  In the tropics, food production will **fall**.

- Soil erosion continues. Water to irrigate crops will grow scarcer, as glaciers and snowpacks vanish, water **tables** fall, and rainfall becomes more variable.

- Satellites show that, since 1994, hot dry summers outweigh warm, wet springs.
  A world that was turning greener is now turning browner.

With less food, feed fewer animals. Eat less meat.

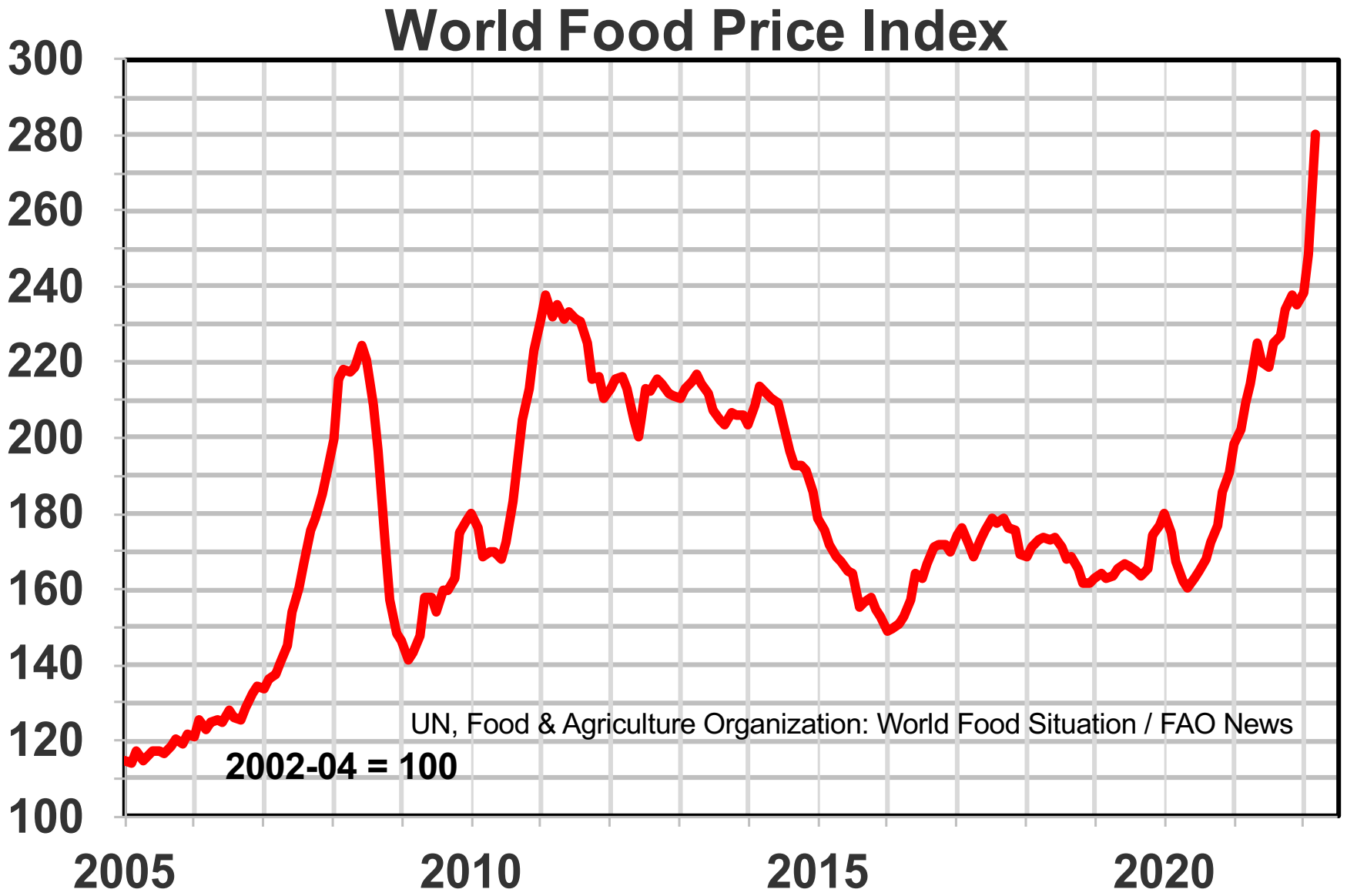
Farm Adaptations to Drought

- Plant more drought-resistant crops.
- Plant smarter, like System for Rice Intensification. More space between the roots cuts fertilizer & pests, **raises yields** & drought tolerance.
- Plant crops that **rebuild soil carbon**. Suck CO_2 out of the air.

Use much more drip irrigation.

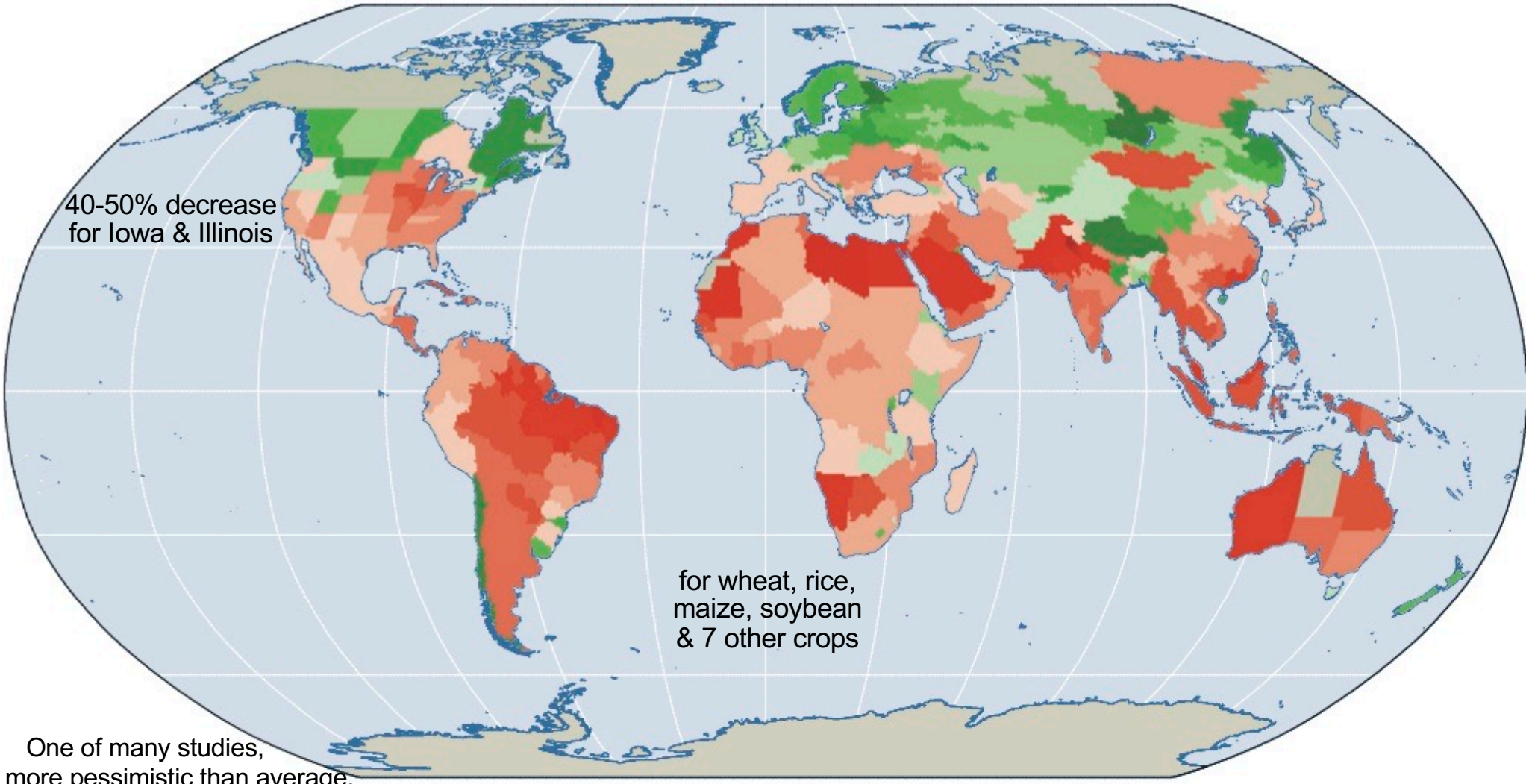
- Cover reservoirs and irrigation canals to slow evaporation.
- Plant more wheat, less rice. Rice is water-hungry.
- **Go North, young man!**
  - Mexicans to the US, Americans to Canada,
  - Pakistanis to Britain, Algerians to France, Kurds to Germany
  - Chinese to Siberia, Arabs to Russia,
  - Colonize Greenland.

With food stocks at low levels, food prices rose steeply in 2007-8 and 2010.
Food prices rose steeply in 2021-22, especially when Russia invaded Ukraine.



Poor people could not afford to buy enough food in 2007-8. Ditto 2010-11.
Malnutrition & starvation rose. Food riots toppled governments in 2011.

Estimated Impact of +3ºC on Crop Yields by 2050



One of many studies,
more pessimistic than average.

average of 3 emission scenarios, across 5 global climate models, no CO_2 fertilization

from Chapter 3 in *World Development Report 2010: Development and Climate Change*. by World Bank,

citing

Müller, C., A. Bondeau, A. Popp, K. Waha, and M. Fader. 2009. "Climate Change Impacts on Agricultural Yields." Potsdam Institute for Climate Impact Research

Deserts Are Already Spreading.

50 Year Trend in Palmer Drought Severity Index, 1950-2002

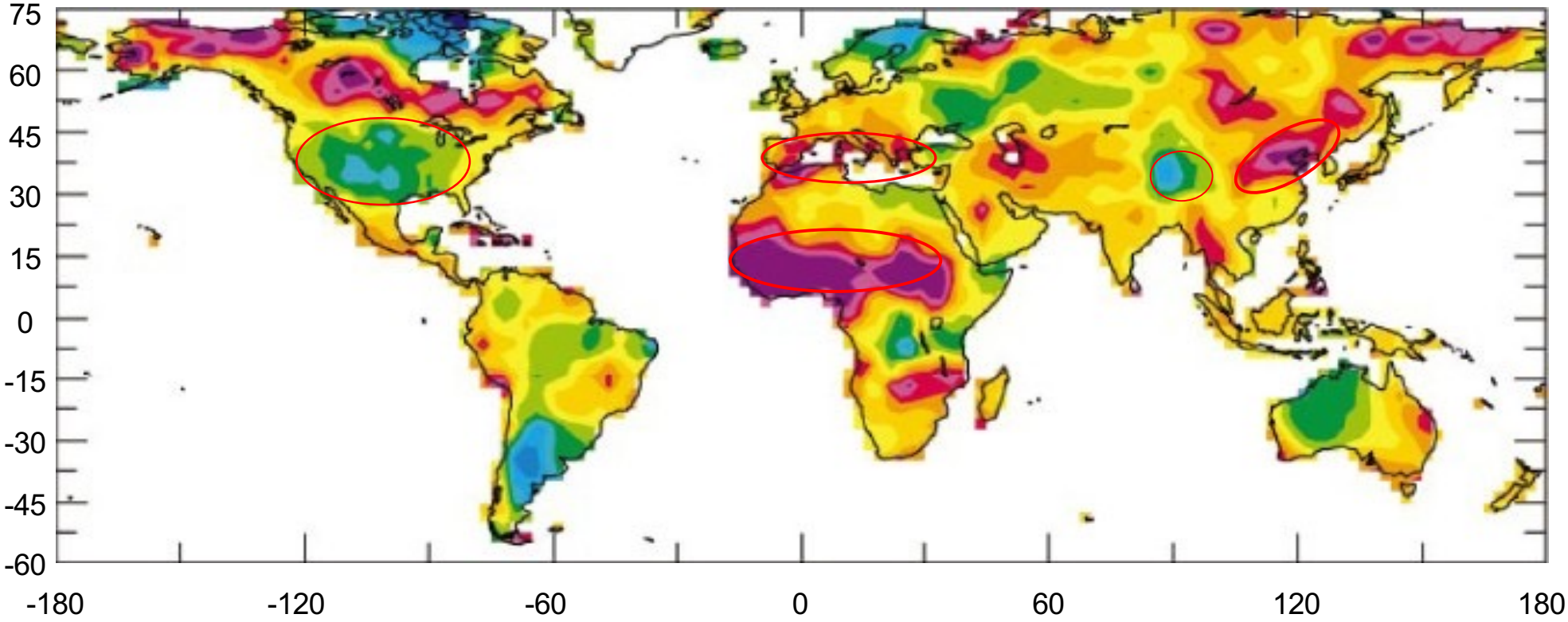


Fig. 7 in Dai, Trenberth & Qian, *Journal of Hydrometeorology*, Dec. 2004

More negative is drier. More positive is wetter.

The Sahara Desert is spreading south, into Darfur & the Sahel. See Spain, Italy, Greece.

The Gobi Desert is spreading into northeast China. More sandstorms visit Beijing.

Retreating glaciers moisten the soil in Tibet. The **USA** lucked out till 2007.

1.1ºC warming is here. 3-4ºC more is in the pipeline. **Emissions** continue.

2ºC warming is unavoidable, absent **MASSIVE** CO_2 removal.

Holding warming to 2ºC, not 4º, **prevents** these losses:

3/4 of Gross World Product

1/5 of the World's Food

2/3 of the Amazon Rainforest

1/8 of the world's **oxygen** supply

Gulf Stream +

West Antarctic Icecap - Norfolk area, much of Florida & Louisiana, central CA, Long Island, Cape Cod

1/2 of all Species

4ºC warming **threatens civilization itself**. **5ºC** is **worse.**

Details to follow: first 2ºC, next 3ºC, then 4ºC, finally 5ºC.

2ºC Warming

Stern Review, British government, Oct. 2006
(a report by dozens of scientists, headed by the World Bank's chief economist)

selected effects - unavoidable damages, absent **MASSIVE** CO_2 removal ASAP

- Hurricane costs double. Many more major floods
- Major heat waves are common. Forest fires worsen.
- Droughts intensify. Deserts spread.
- Civil wars & border wars over water increase.

CNA Corp. – 11 retired US Generals & Admirals, April 2007

- Crop yields rise nowhere & fall in the tropics.

e.g., Brazil soy yields fall 30-70%, wheat 50%, corn 60%. World Bank 2014

- Greenland icecap collapse becomes irreversible.

If we play it right, melting takes 3,000 years. If we play it wrong, 300 years.

- The ocean begins its invasion of Bangladesh.

It lasts for many centuries. We choose **now** how fast and how far.

3ºC Warming

Stern Review & CNA Corp.
World is on this pace for 2100.

additional damages – may be delayed or avoided with MASSIVE CO_2 removal

- Droughts & hurricanes get much worse.
- Hydropower and irrigation decline. Water is scarce.
- Crop yields fall **substantially** in many areas.
- More water wars & failed states. Terrorists multiply.
- 2/3 of Amazon rainforest may turn to savanna, desert scrub.

  Cox '00, Huntingford '08, Jones '09, Cook '10 Deforestation driving São Paulo drought. Nobre '14
- Tropical diseases (malaria, etc.) spread farther and faster.

  Lyme disease, West Nile virus, dengue fever too. Etc.
- 15-50% of species face extinction.

  Mammal extinction rates are already 200-500 x background rates.

4ºC Warming

further damages - **avoid**able

Stern Review & CNA

- Water shortages afflict almost all people.
- Crop yields fall in **ALL** regions, by **1/3** in many.
- Entire regions **cease** agriculture altogether, *e.g.*, Australia.
- Water wars, refugee crises, & terrorism become intense.
  This has begun: Somalia, Darfur, Rwanda, south Sudan, Mali, north Nigeria, Syria, Iraq.
- Methane release from permafrost accelerates more.
- The Gulf Stream slows by half, monsoons sometimes fail.
  "Gulf Stream" is shorthand for the world ocean thermohaline circulation, to which it's connected.
- West Antarctic ice sheet collapse speeds up. We played it wrong.

Adios to Miami, New Orleans, Norfolk & Venice by 2100,
to Amsterdam, Bangkok, Canton, Kolkata, Saigon, Shanghai & Tampa by 2200.
Goodbye also to parts of New York, London & Washington, as seas creep higher.

- At times in US SE, it's too hot & humid to survive work outside long.

Stouffer '13, Sommer '14, Kopp '15

my extrapolation

5°C Warming

US summer pace, by 2100

Deserts **GROW** by 2 x the size of the US.

Eventually, we'd gain US-sized polar forests , but we'd lose as much to rising seas.

Much of southern Europe would look like the Sahara.

Agriculture would be destroyed and life would be impossible,
over much of the planet. Lord Stern, 2009

World food falls by 1/3 to 1/2.

The result? Extended conflict, social disruption, war essentially,
over much of the world, for many decades. Lord Stern, 2009

Human population falls a lot,
to match the reduced food supply.

It won't be pretty. For perspective,
World War 2 killed 60 million , but worldwide, it did **not** reduce population.

Other species fare worse.

The 6th Great Extinction has begun.

China faces extremely grim ecological and environmental conditions, under the impact of continued global warming and changes to China's regional environment.

China's 2nd National Climate Assessment
December 2011

The costs of failing to tackle the climate change issue would be greater than the impact of both World Wars and the Great Depression combined.

Once the damage from unchecked emissions growth is done, no retrospective global agreement, in some future period, can undo that choice.

British Prime Minister Gordon Brown
October 19, 2009

DARA, Watkiss / Hope, Stern Review

Costs

inflation-adjusted 2015 $, Business as Usual

Costs of **Inaction**: **now** $695 Billion/Year (more than 1% of GWP),

including $120 billion (**$400** / American) in the US for 2012 (almost 1% of US GNP).

Already 0.5 million / year die worldwide, +4.5 million from coal sulfates.

Costs **GROW** over time. **$100 Trillion** (present value : 2005-2200)
(2%/year discount rate)

This exceeds GWP. annualized: $2 Trillion / year

Unchecked, by 2100 warming will cost, *e.g.*, India 8.7% of GNP. Asia Development Bank 2014

a **HUGE** hidden **TAX: $50,000** / American

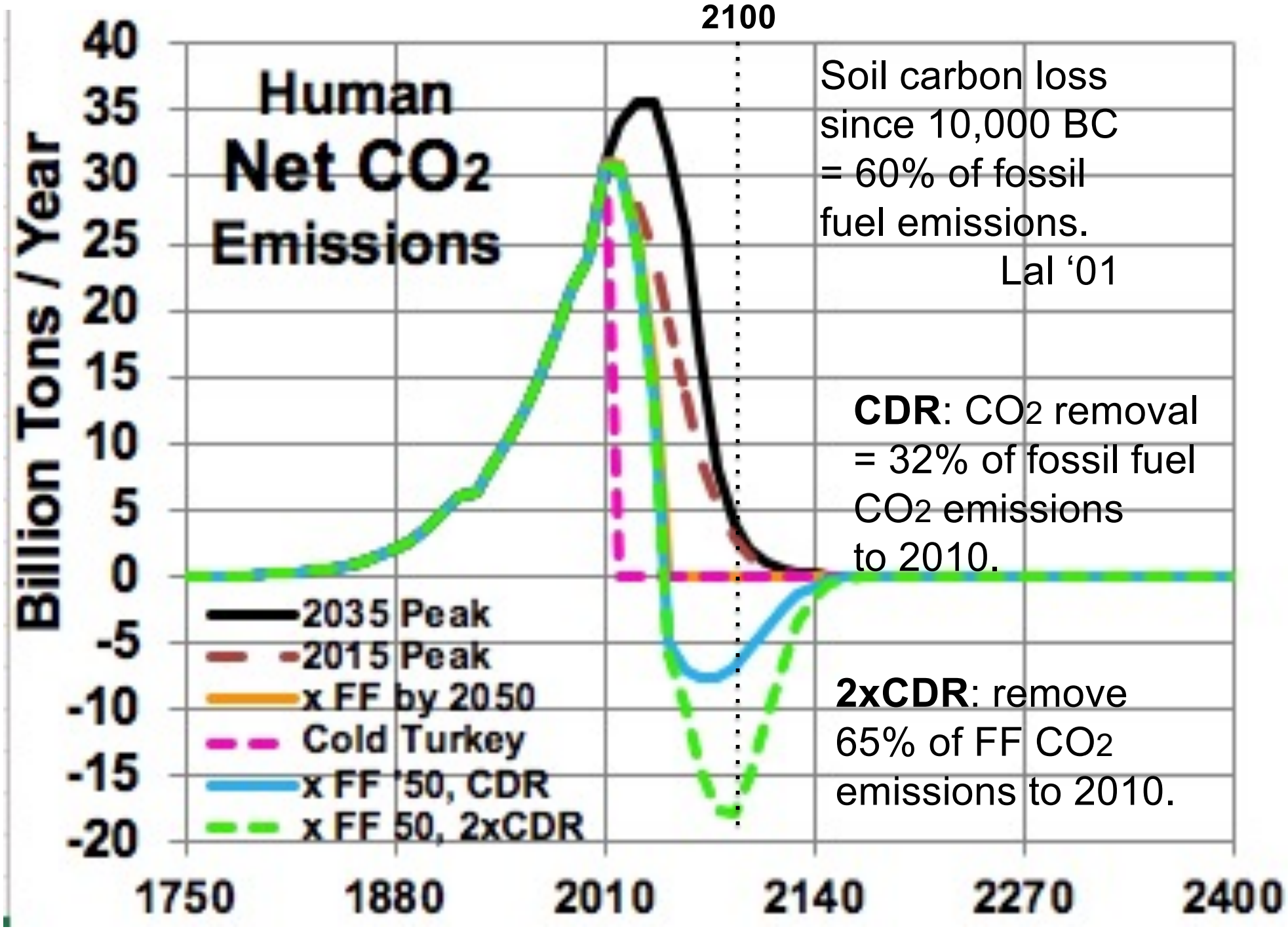
$85 / Ton of CO_2

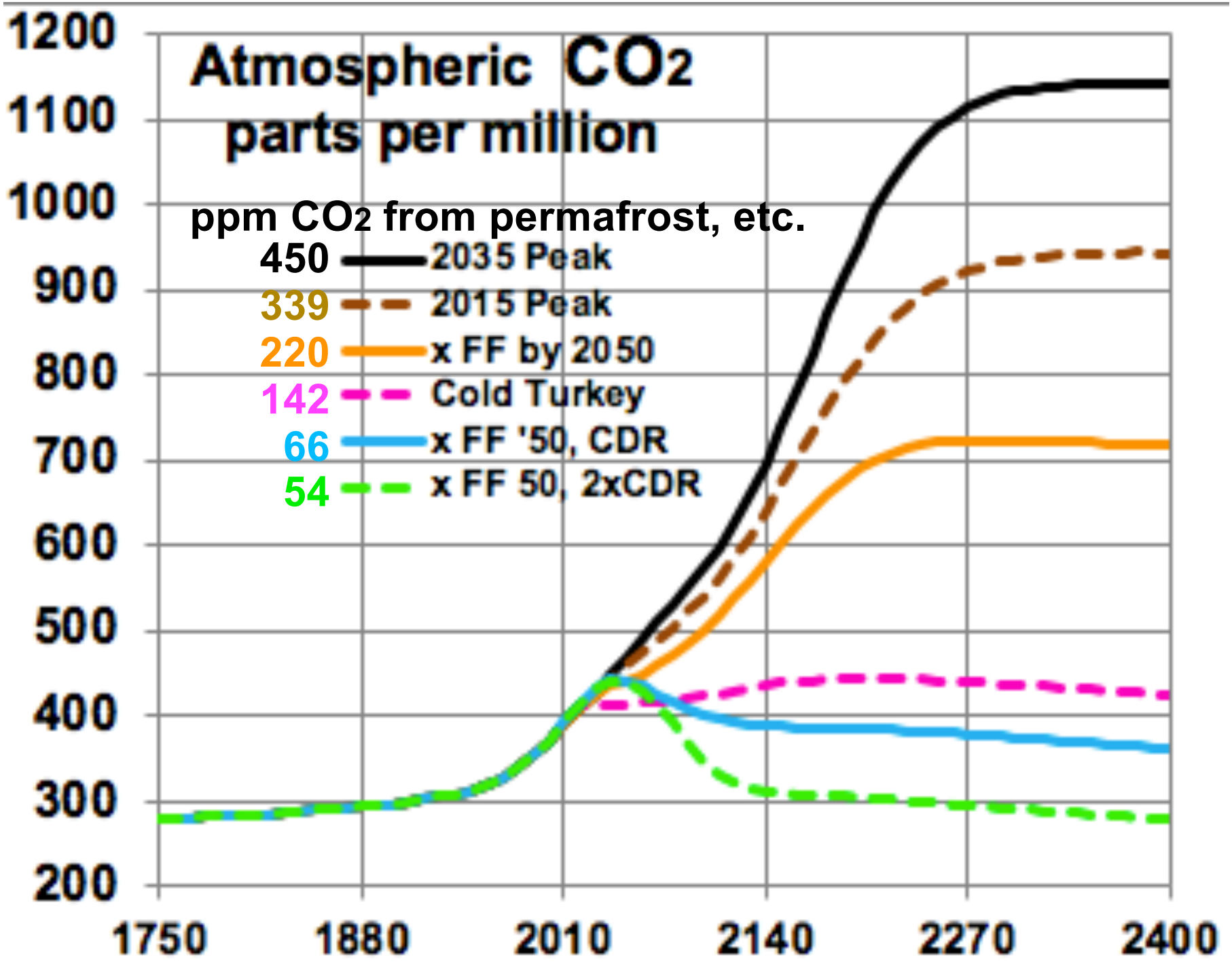
Costs of **Action**: **$9-75** / year / American – CBO, EPA

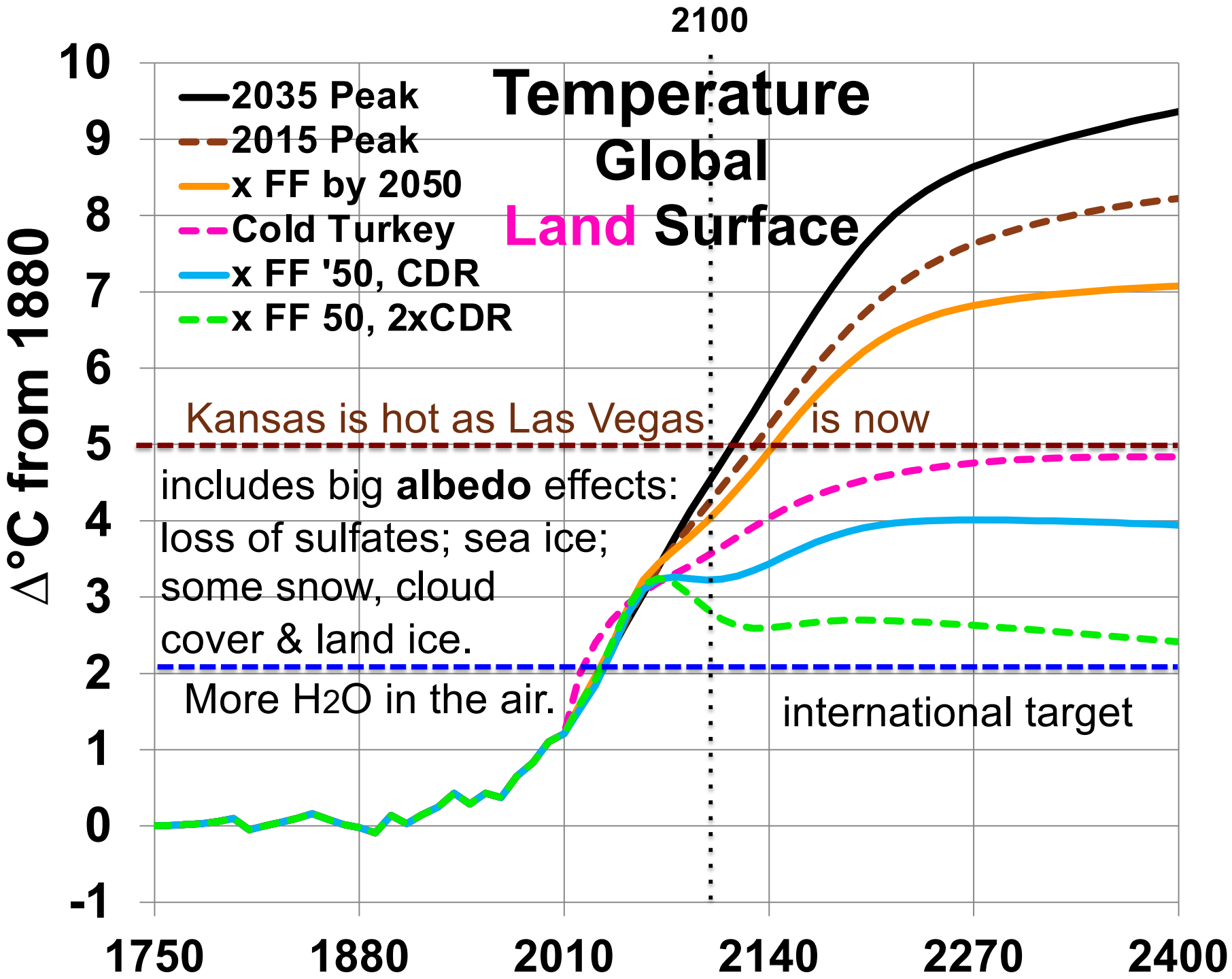
Spend 1% of GWP ($150 billion by US), each year, ± 2%.

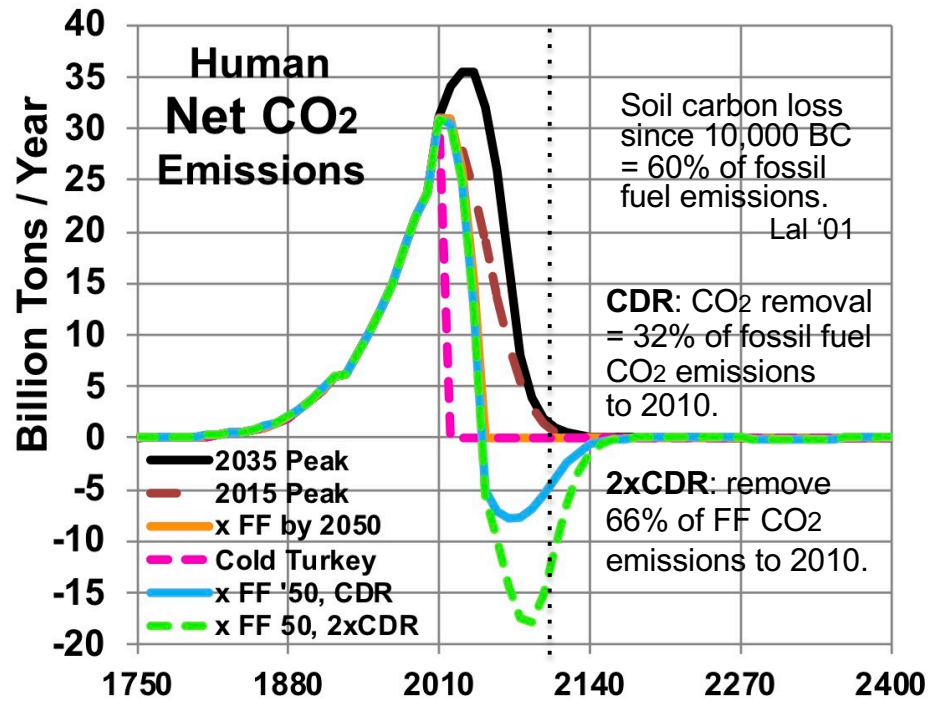
Damages fall to $25 - $30 / Ton of CO_2.

World Savings ~ $2.5 Trillion, net from **each** year's spending.


2100
Human
Net CO2
Emissions
Billion Tons / Year
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
1750
1880
2010
2140
2270
2400
2035 Peak
2015 Peak
x FF by 2050
Cold Turkey
x FF '50, CDR
x FF 50, 2xCDR
Soil carbon loss since 10,000 BC = 60% of fossil fuel emissions.
Lal '01
CDR: CO2 removal = 32% of fossil fuel CO2 emissions to 2010.
2xCDR: remove 65% of FF CO2 emissions to 2010.


Atmospheric CO2
parts per million
ppm CO2 from permafrost, etc.
450 2035 Peak
339 2015 Peak
220 x FF by 2050
142 Cold Turkey
66 x FF '50, CDR
54 x FF 50, 2xCDR
1200
1100
1000
900
800
700
600
500
400
300
200
1750
1880
2010
2140
2270
2400


2100
Temperature
Global
Land Surface
2035 Peak
2015 Peak
x FF by 2050
Cold Turkey
x FF '50, CDR
x FF 50, 2xCDR
Kansas is hot as Las Vegas is now
includes big albedo effects:
loss of sulfates; sea ice;
some snow, cloud
cover & land ice.
More H2O in the air.
international target
Δ°C from 1880
10
9
8
7
6
5
4
3
2
1
0
-1
1750
1880
2010
2140
2270
2400


Human
Net CO2
Emissions
Billion Tons / Year
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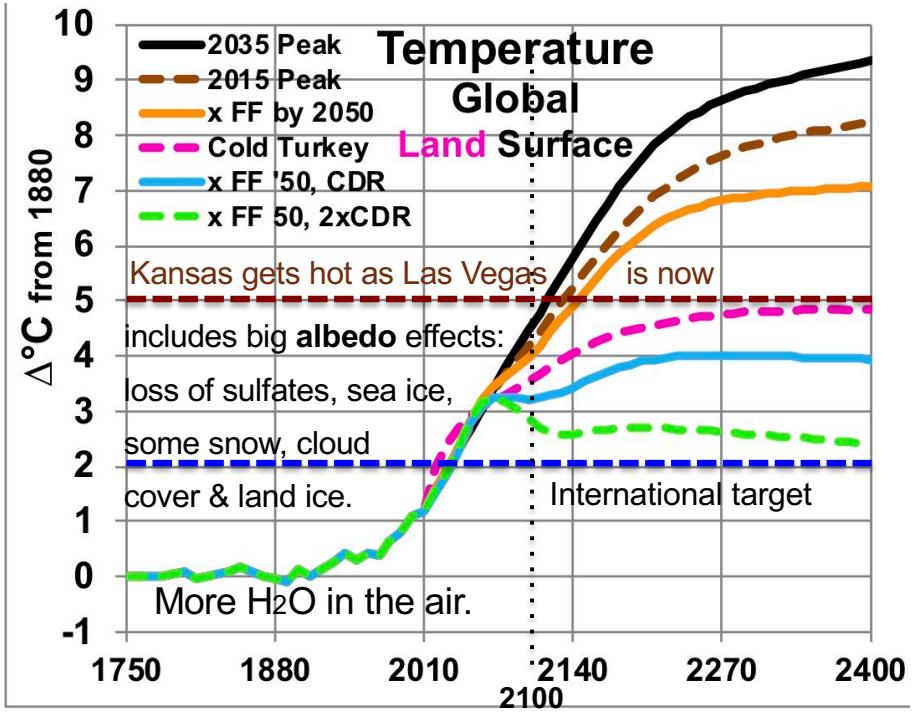
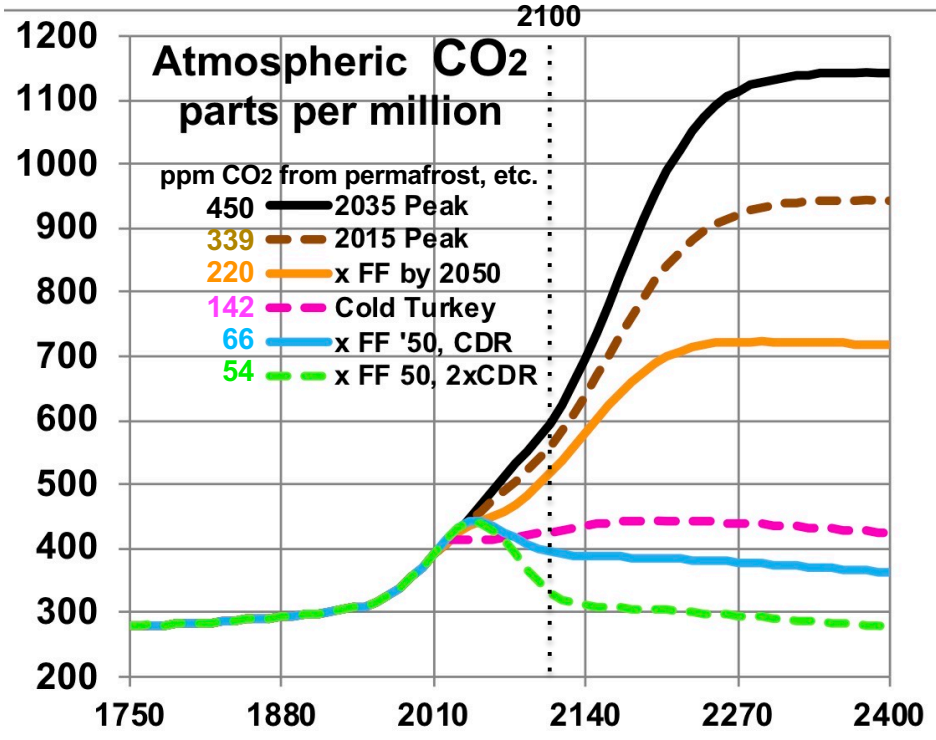
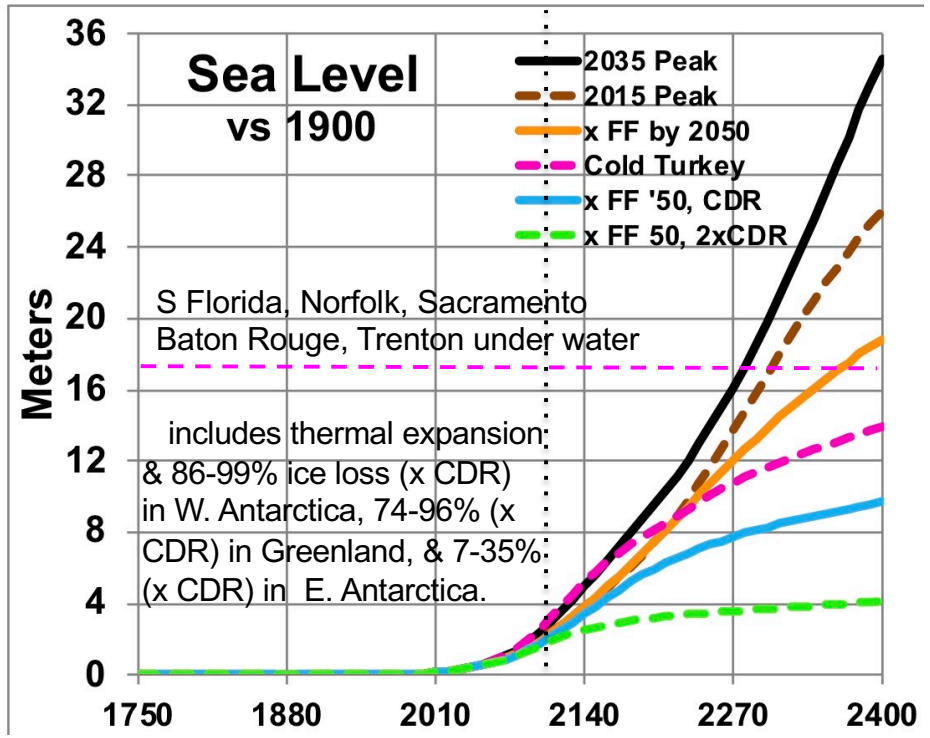
2035 Peak
2015 Peak
x FF by 2050
Cold Turkey
x FF '50, CDR
x FF 50, 2xCDR
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
1750
1880
2010
2140
2270
2400


Temperature
Global
Land Surface
Δ°C from 1880
2035 Peak
2015 Peak
x FF by 2050
Cold Turkey
x FF '50, CDR
x FF 50, 2xCDR
Kansas gets hot as Las Vegas is now
includes big albedo effects:
loss of sulfates, sea ice,
some snow, cloud
cover & land ice.
International target
More H2O in the air.
10
9
8
7
6
5
4
3
2
1
0
-1
1750
1880
2010
2140
2270
2400


Atmospheric CO2
parts per million
2100
ppm CO2 from permafrost, etc.
450
339
220
142
66
54
2035 Peak
2015 Peak
x FF by 2050
Cold Turkey
x FF '50, CDR
x FF 50, 2xCDR
1200
1100
1000
900
800
700
600
500
400
300
200
1750
1880
2010
2140
2270
2400


Sea Level
vs 1900
2100
Meters
2035 Peak
2015 Peak
x FF by 2050
Cold Turkey
x FF '50, CDR
x FF 50, 2xCDR
S Florida, Norfolk, Sacramento
Baton Rouge, Trenton under water
includes thermal expansion
& 86-99% ice loss (x CDR)
in W. Antarctica, 74-96% (x
CDR) in Greenland, & 7-35%
(x CDR) in E. Antarctica.
36
32
28
24
20
16
12
8
4
0
1750
1880
2010
2140
2270
2400

Solutions

Stop putting carbon in the air.

Take carbon out of the air,
big time.

Maybe screen out sunshine too, temporarily.

Taking Carbon Out of the Air.

Overview

METHOD	PRO's & HOW's	CON's
Direct Air Capture Sequester in Carbonate	Permanent, easy to measure	High energy use (high $ cost / ton)
Enhanced Rock Weathering	Long-term, plentiful basalt. Improves soil fertility, crop yields	Not so easy to measure effects
Ocean Alkalinization	Long-term, use mine tailings or plentiful olivine. Helps ocean wildlife, farmed shellfish	Hard to measure direct large-scale effects, but acidity levels measurable
Biochar	Long-term, cheap, soil fertility	Limited biomass & land
Fast-Rotation Grazing "Holistic Management"	Cheap, hundreds do it	Short term (~ 2 Decades) may capture no CO_2
Organic Farming - No-till, cover crop, compost, etc.	Cheap, millions do it. Crops more drought resistant, yields may increase.	Short term (~ 2 decades) may capture no CO_2 — just move carbon from 3+ feet down to 1- feet down.
Keep / Expand Forests	Cheap Mangroves are esp. good.	Short-term (1-6 decades), as forest fires accelerate
Farm Oceans (Kelp, seagrass, etc.)	Most ocean is low-nutrient desert. Use nutrient-rich areas near shore. Add iron filings to Southern Ocean.	Biomass won't sink far. Plankton eat, re-emit the CO_2. Net carbon source?

Take Carbon Out of the Air (Part 1 - Inorganic)

1 **Direct Air Capture** of CO_2, in artificial leaves, ceramic honeycombs, etc.

Fans move air over sorbents to adsorb (solid) or absorb (liquid) the CO_2.

Then, move the CO_2-rich material to a different chamber.

Use heat or moisture to un-adsorb & free purified CO_2 for permanent storage.

Pipe the CO_2 & inject it + water into concrete or basalt: carbonate rock in months.

Or put the CO_2 down in oil fields or salt caverns and prevent leaks. Permanent?

Since CO_2 in the air is dilute, removal requires almost 3 **x** the energy

to extract it as we got from burning carbon to **put** it in the air.

Recent cost estimates are $94-600 / ton. Quantity unlimited.

Climeworks, Carbon Engineering, Blue Planet, Global Thermostat, etc.

2 Rocks have **weather**ed for eons, taking 1 GT CO_2 / year from the air.

Increase surface area a lot to speed it up to 5 GT CO_2 / year: 40 ppm by 2100?

Move CO_2 into crushed basalt, olivine, peridotite to make carbonate rock.

Scatter GT / year of olivine dust across the tropics: $5-200 / ton of CO_2 removed?

Add small olivine gravel to farming soil, to fertilize it and remove CO_2.

Spread olivine dust on ocean surface, to capture CO_2 and de-acidify oceans.

Plants Take Carbon Out of the Air. (Part 2)

3 Farming, done right, may add 1.5 - 4.3 GT of carbon (C) / year to soil.

Organic farms may add 1 ton (T) of C / acre / year,
using no-till, cover crops, and compost.

Rebuild soil organic matter (carbon): from 1-3% now, to 6-10% before farming.
Increase humus with fungi network & glomalin, holding water many months.

$15-100 / T of CO_2 removed? However, these methods seem to raise carbon to the top foot of soil, **from** the next 2 feet down. No removal?

Warming soil increases microbe respiration, CO_2 removal not permanent.
turning soils to net carbon sources before too many years.

4 Rebuild **rangelands** with perennial grasses.

Add soil carbon **5 x** faster with **short** rotation cattle grazing, like buffalo.

Deep roots, dung beetles move carbon into soil.
Fungi network holds water, so 75-90% of rain soaks in.

Absorb 1 T of carbon / acre / yr? Cut CO_2 **40** ppm? for 20-40 years?

However, cows burp out 19% of all CH_4 emissions. Solution?

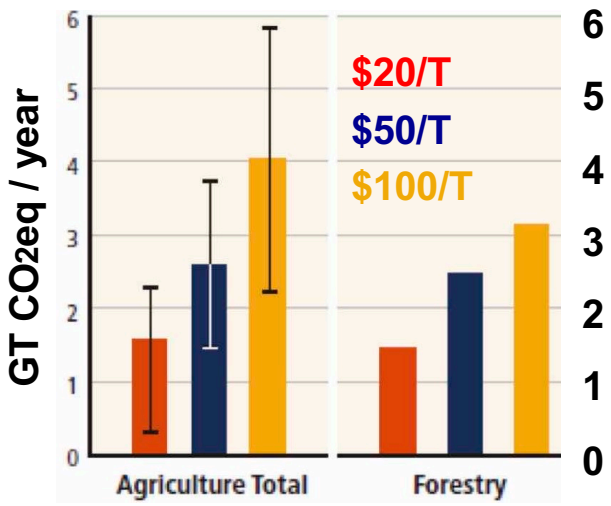
2% of a red algae in feed cuts cow CH_4 burps 70-98%. (13-18% of total CH_4.)

Take Carbon **Out** of the Air, Part 3

5 Bury **biochar** shallow in soils, but don't disrupt fungi networks to do it.
More soil carbon stays eons, holds water.
0.5-2 GT CO_2 / yr by 2050, at $30-120 / ton? Cut CO_2 **5-20** ppm by 2100?

6 Farm the **oceans**: grow algae in pans miles on a side, many inches deep,
Add fertilizer (Fe, N, K, P, etc.) as needed.
Harvest the algae, turn it into biochar (charcoal). Sink it (2+ g / cc).
Or use open ocean, kelp, seagrass, mangrove trees.

7 Plant more **trees** and save our forests. It's a good idea, **but** trees need water.
As the climate warms, stronger evaporation leaves <u>less</u> water in soils.
Droughts hurt, turning forests into carbon sources.
Forest fires soar, few trees regrow, sink turns to source.
Agriculture & forestry can increase soil carbon only for 2-4 decades, before soils warm too much.



Paustian *et al*. 2016. *Nature* 532:49.

8 Cut more **CH_4** emitted: end oil, gas, coal leaks (21%).
Capture and burn all landfill gas, waste (15%)
SRI method grows rice without flooding (4%).

Screening Out Sunshine
(Solar Radiation Management)

METHOD	PRO's & HOW's	CON's
Stratospheric Aerosol Injection	Cheap, proven by volcanoes Calcites better than sulfates ~100 flights a day to 7-11 miles up	May disrupt monsoons. Sulfates harm ozone layer & health. Calcites help ozone layer (?).
Marine Cloud Brightening	Spray salt from ship "gun" nozzles to make more cloud condensation nuclei. Effects local. Easy start/stop.	Don't know any
Cirrus Cloud Thinning	Inject ice cloud condensation nuclei. Bigger, fewer nuclei. More infrared radiation escapes to space.	Cooling effect not yet well established.
On Sea, White Mini-spheres	Hollow silicate spheres, sand grain size. Very reflective.	How long do they stay on the surface?
Pump, spray sea water onto sea ice in winter.	Sea ice thickens in winter, so it will last later into spring & summer.	Tough technical challenges on ice floes, for wind turbines. Cloud interaction problems. Winter vs summer radiation
Mirrors	In deserts more controllable than in space. Cooler beneath them.	Weather effects

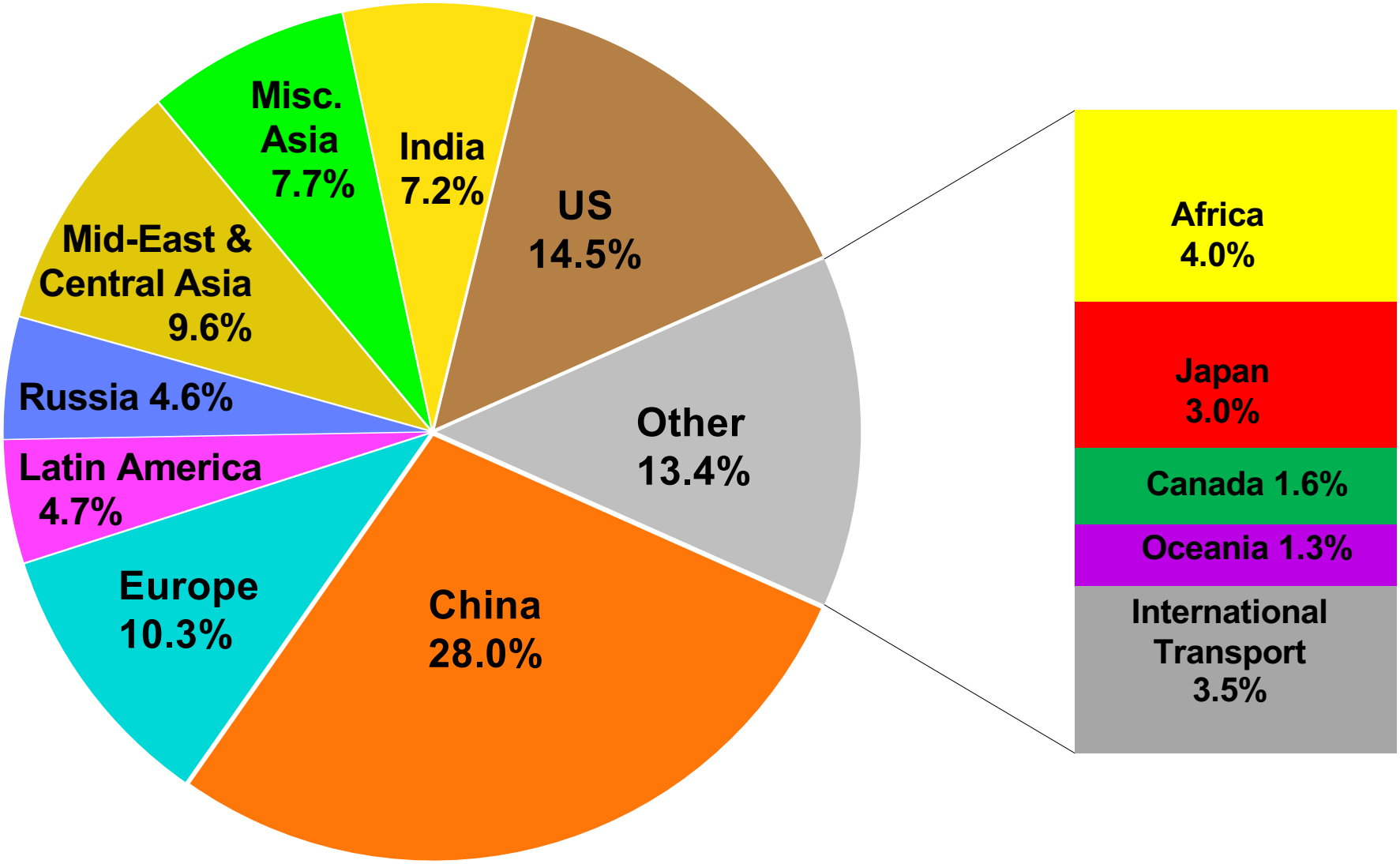
* Misc. = Korea, Indonesia, Thailand, Taiwan, Malaysia, Vietnam, Bangladesh, etc.

World CO_2 Emissions

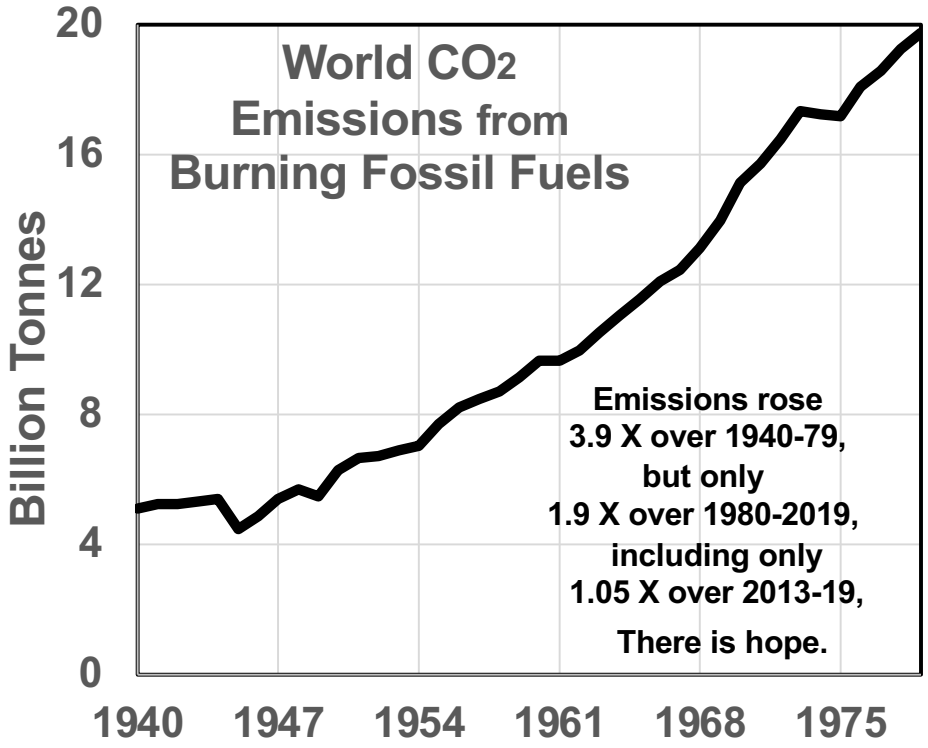
from Fossil Fuels

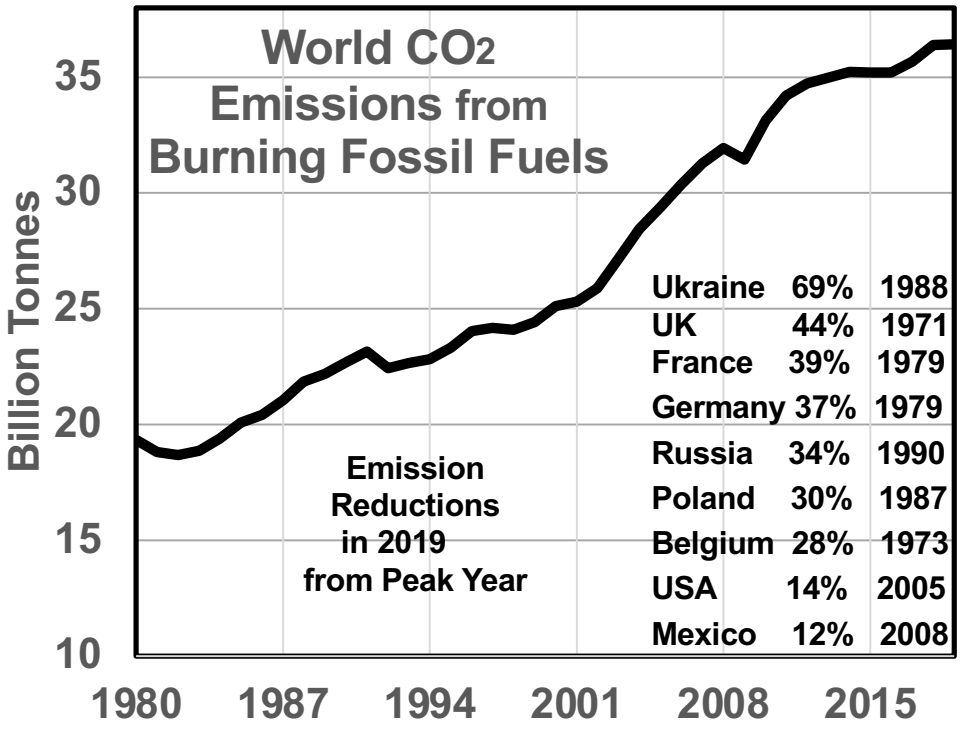
36.4 Billion Tons in 2019

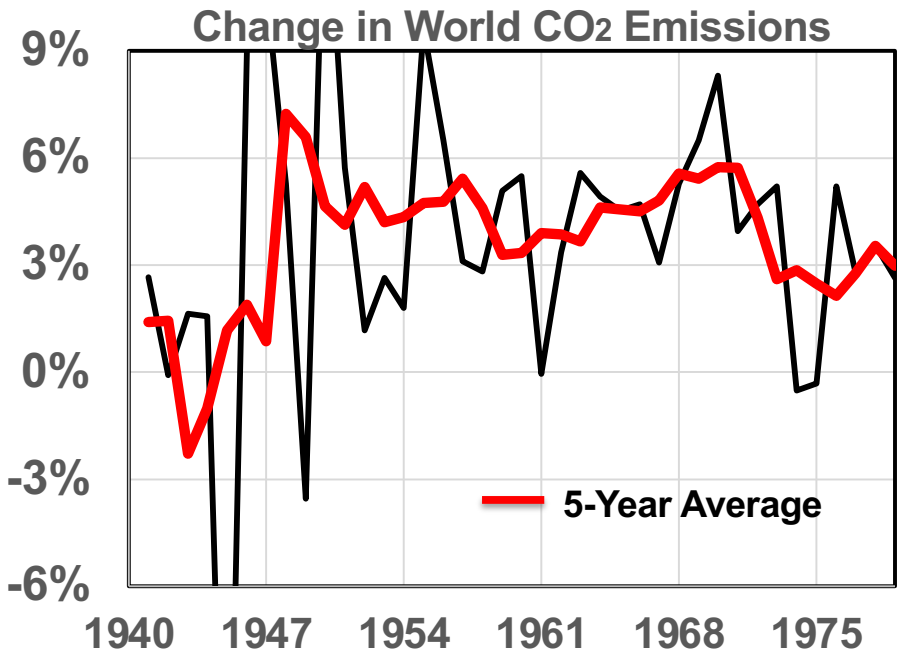
Carbon Tracker

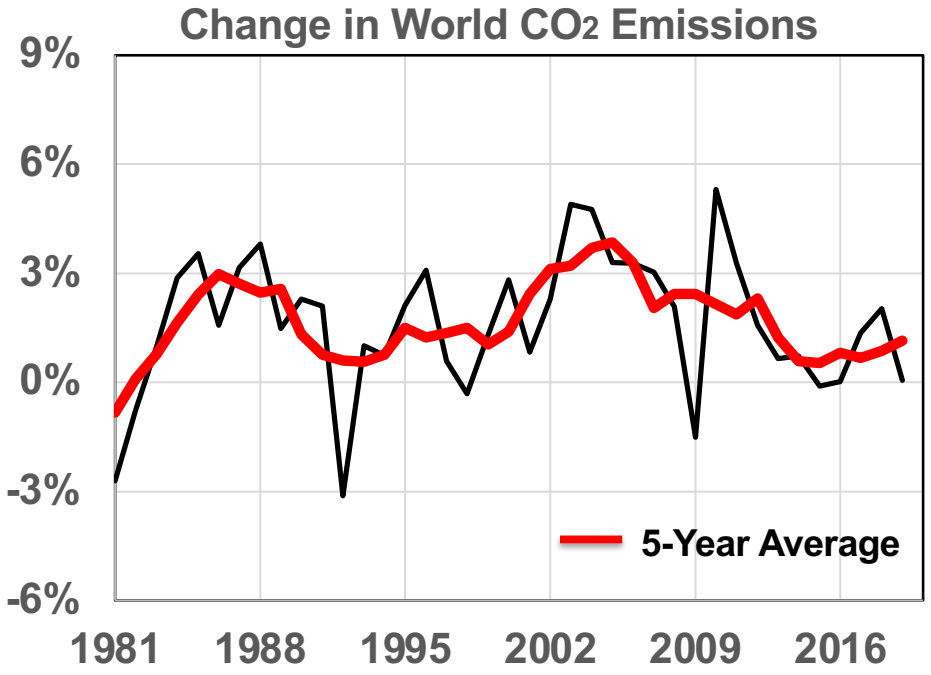


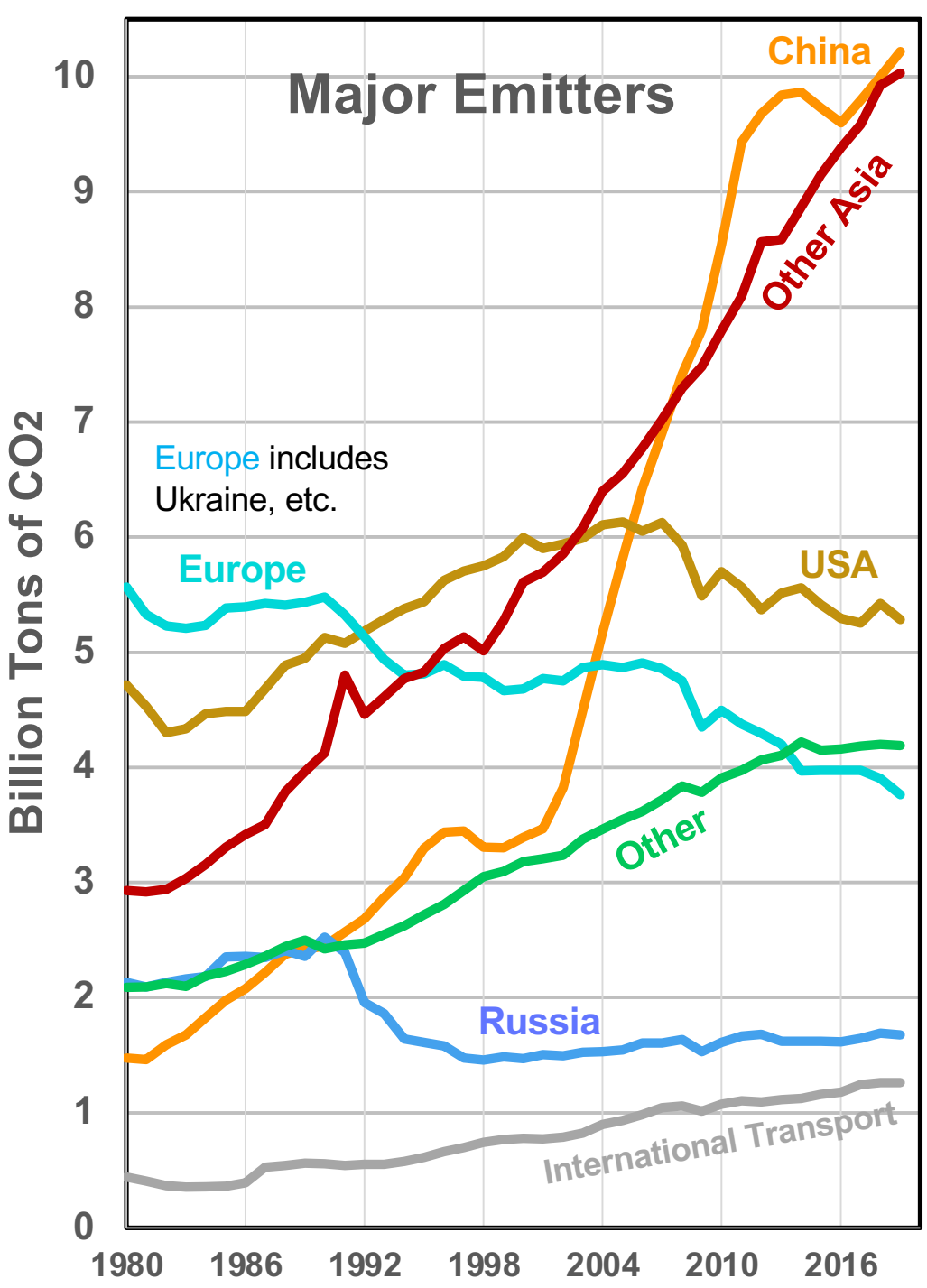
In 2019, US fossil fuel CO_2 came 46% from oil, 33% from natural gas, 21% from coal.
37% came from transportation, 32% from electricity, 20% from industry.

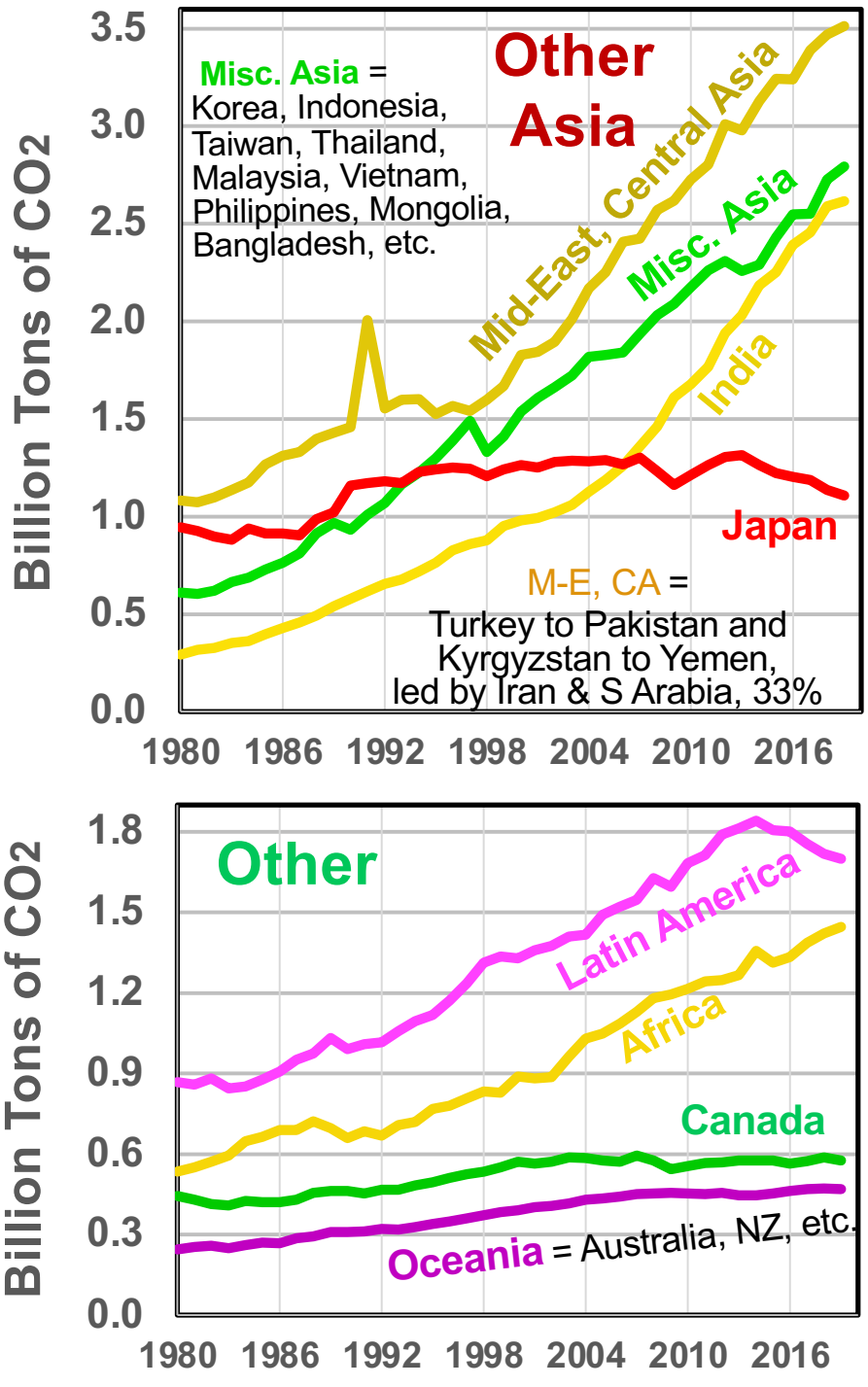

World CO2
Emissions from
Burning Fossil Fuels
Billion Tonnes
20
16
12
8
4
0
1940
1947
1954
1961
1968
1975
Emissions rose
3.9 X over 1940-79,
but only
1.9 X over 1980-2019,
including only
1.05 X over 2013-19,
There is hope.


World CO2
Emissions from
Burning Fossil Fuels
Billion Tonnes
35
30
25
20
15
10
1980
1987
1994
2001
2008
2015
Emission
Reductions
in 2019
from Peak Year
Ukraine 69% 1988
UK 44% 1971
France 39% 1979
Germany 37% 1979
Russia 34% 1990
Poland 30% 1987
Belgium 28% 1973
USA 14% 2005
Mexico 12% 2008

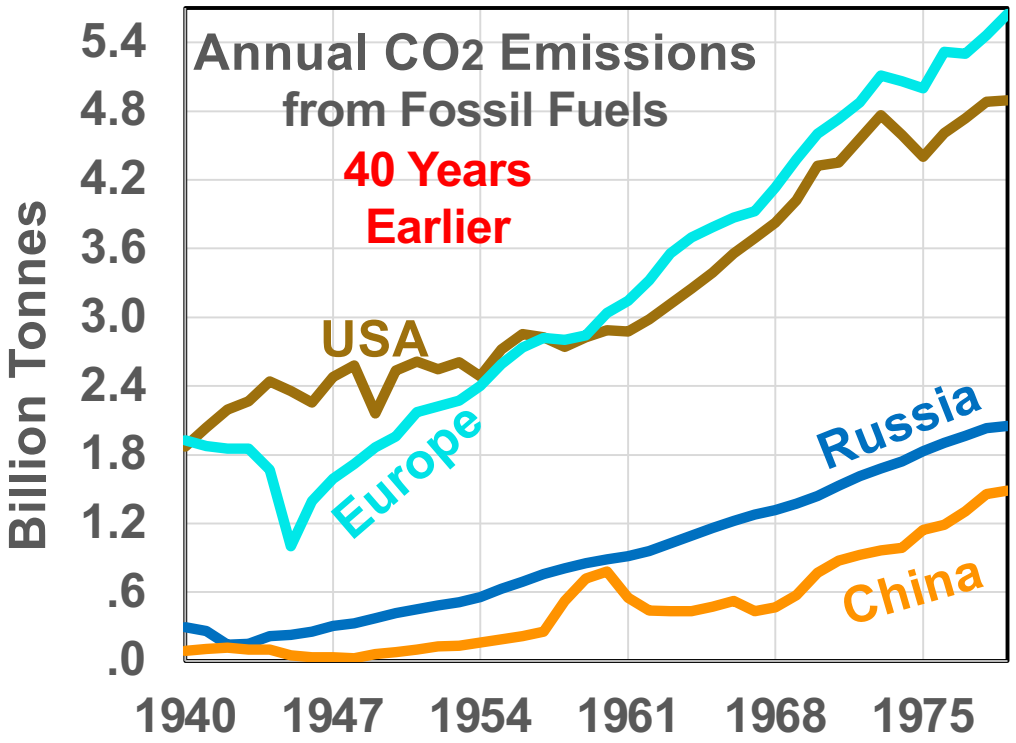

Change in World CO2 Emissions
9%
6%
3%
0%
-3%
-6%
1940
1947
1954
1961
1968
1975
5-Year Average

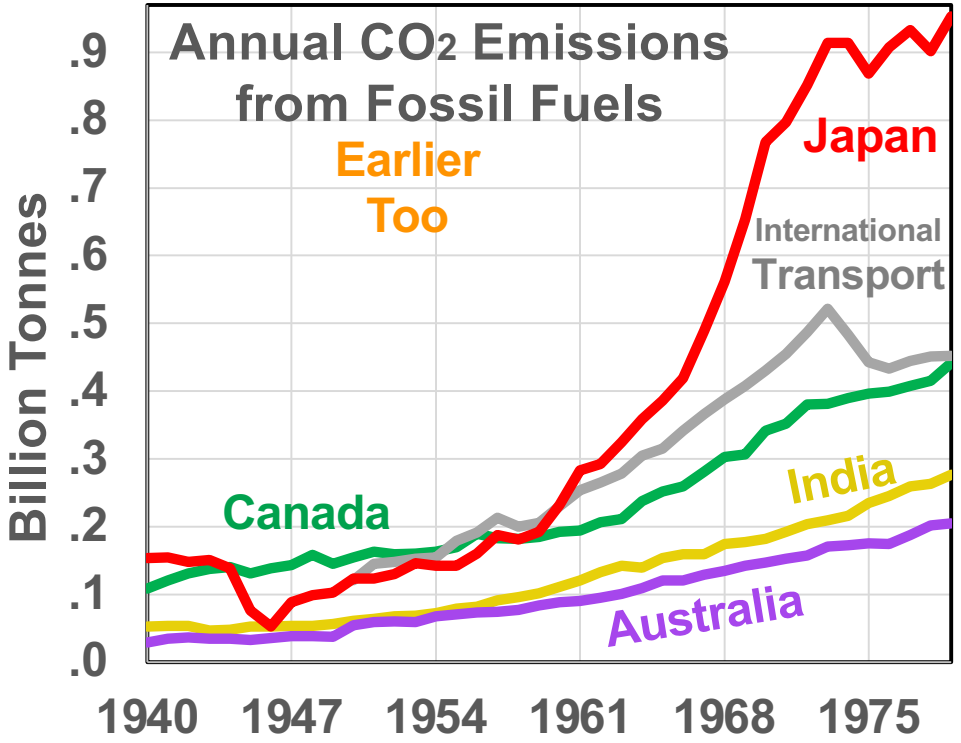

Change in World CO2 Emissions
9%
6%
3%
0%
-3%
-6%
1981
1988
1995
2002
2009
2016
5-Year Average

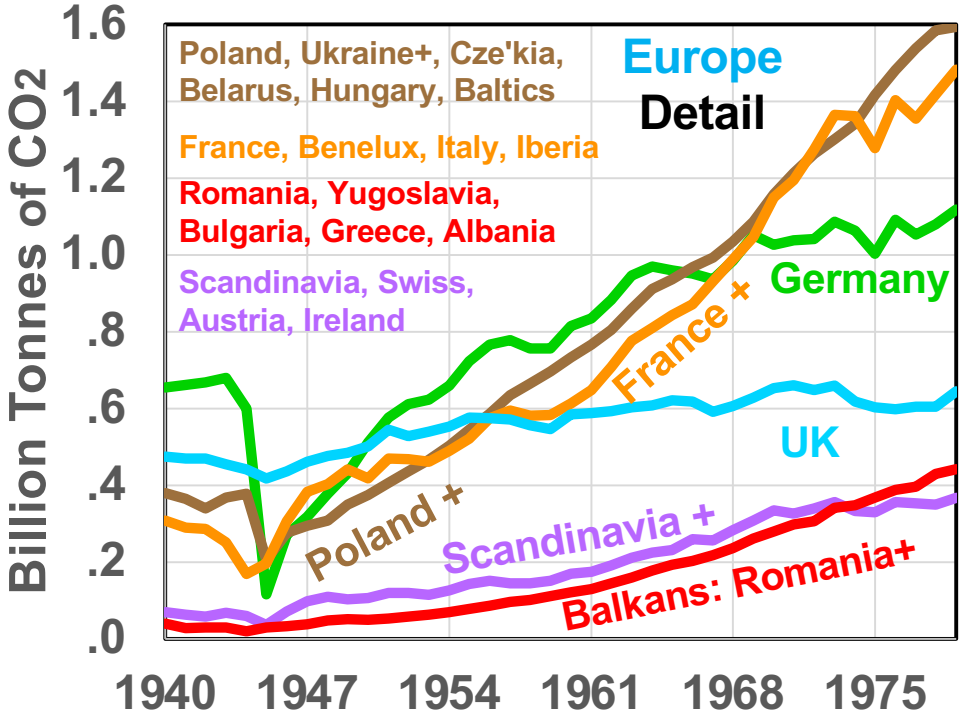

Major Emitters
Billion Tons of CO2
China
Other Asia
USA
Europe
Other
Russia
International Transport
Europe includes
Ukraine, etc.
0
1
2
3
4
5
6
7
8
9
10
1980
1986
1992
1998
2004
2010
2016

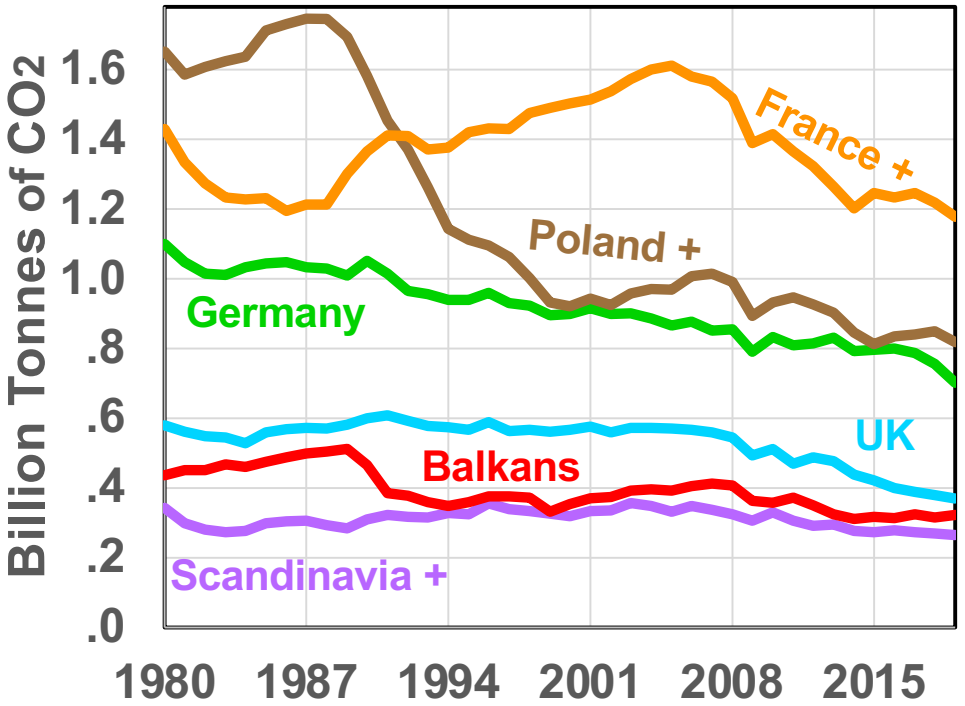

Other
Asia
Misc. Asia =
Korea, Indonesia,
Taiwan, Thailand,
Malaysia, Vietnam,
Philippines, Mongolia,
Bangladesh, etc.
Mid-East, Central Asia
Misc. Asia
India
Japan
M-E, CA =
Turkey to Pakistan and
Kyrgyzstan to Yemen,
led by Iran & S Arabia, 33%
Billion Tons of CO2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
1980
1986
1992
1998
2004
2010
2016

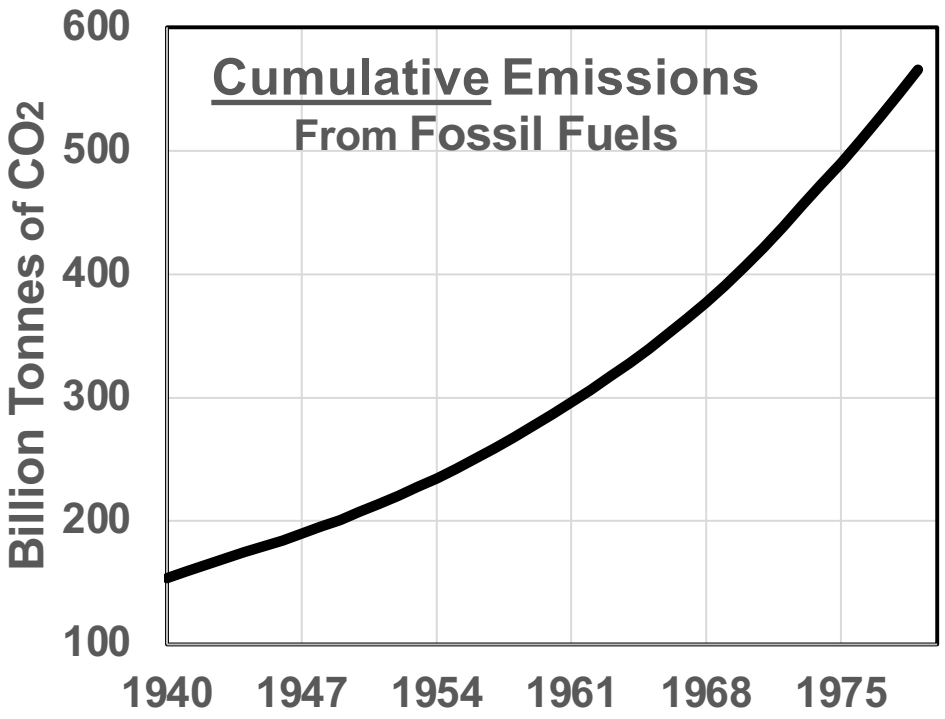
Other
Latin America
Africa
Canada
Oceania = Australia, NZ, etc.
Billion Tons of CO2
0.0
0.3
0.6
0.9
1.2
1.5
1.8
1980
1986
1992
1998
2004
2010
2016

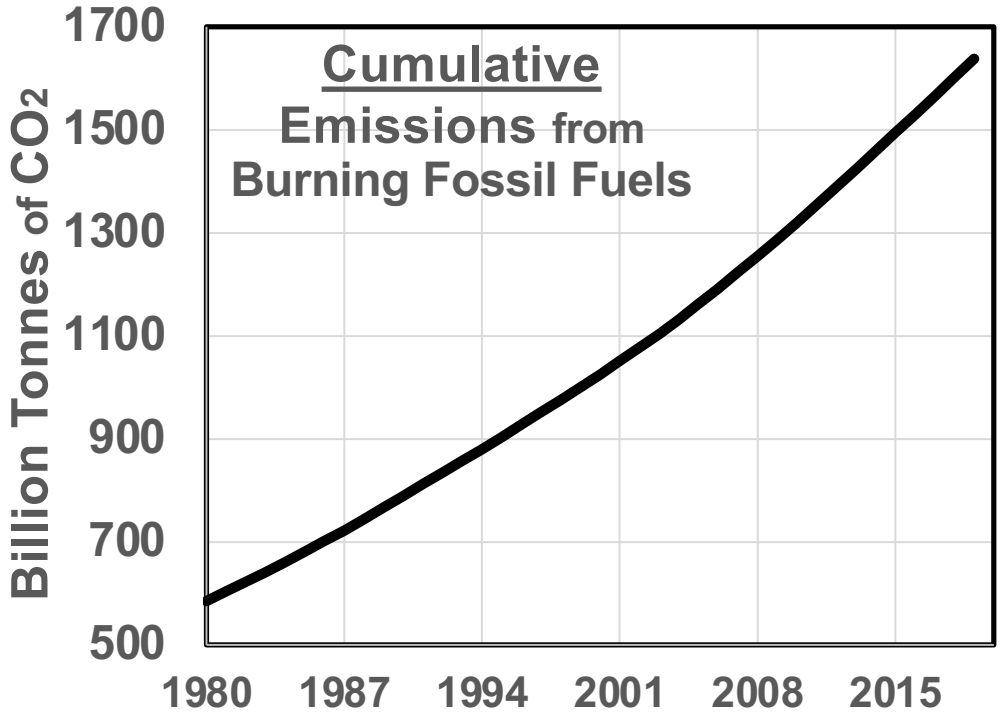

Annual CO2 Emissions
from Fossil Fuels
40 Years
Earlier
Billion Tonnes
5.4
4.8
4.2
3.6
3.0
2.4
1.8
1.2
.6
.0
1940
1947
1954
1961
1968
1975
USA
Europe
Russia
China

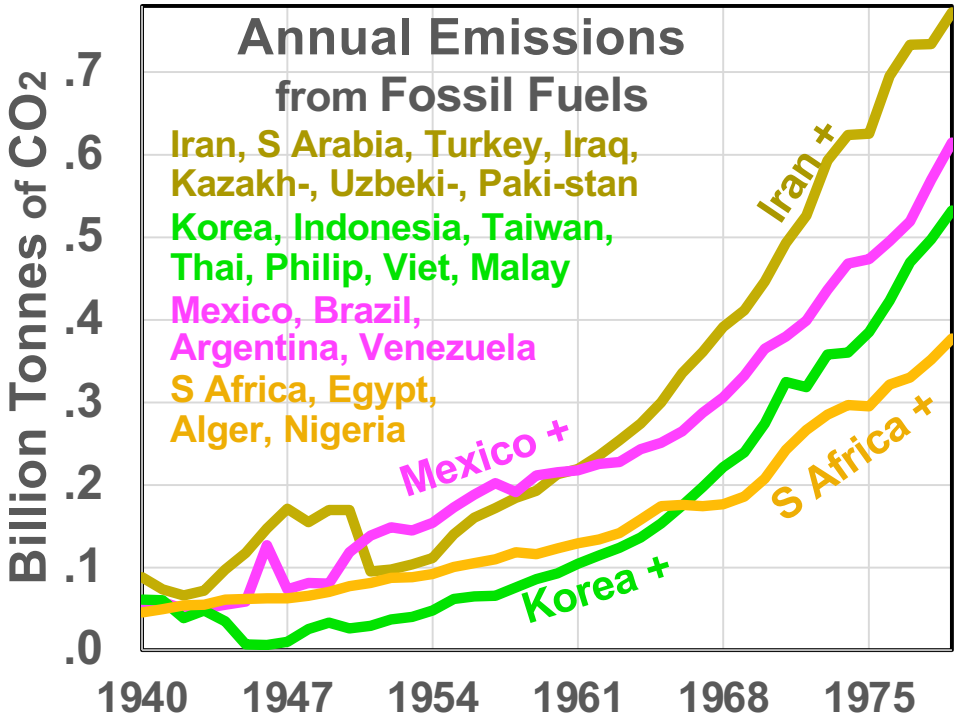

Annual CO2 Emissions
from Fossil Fuels
Earlier
Too
Billion Tonnes
.9
.8
.7
.6
.5
.4
.3
.2
.1
.0
1940
1947
1954
1961
1968
1975
Japan
International
Transport
India
Canada
Australia

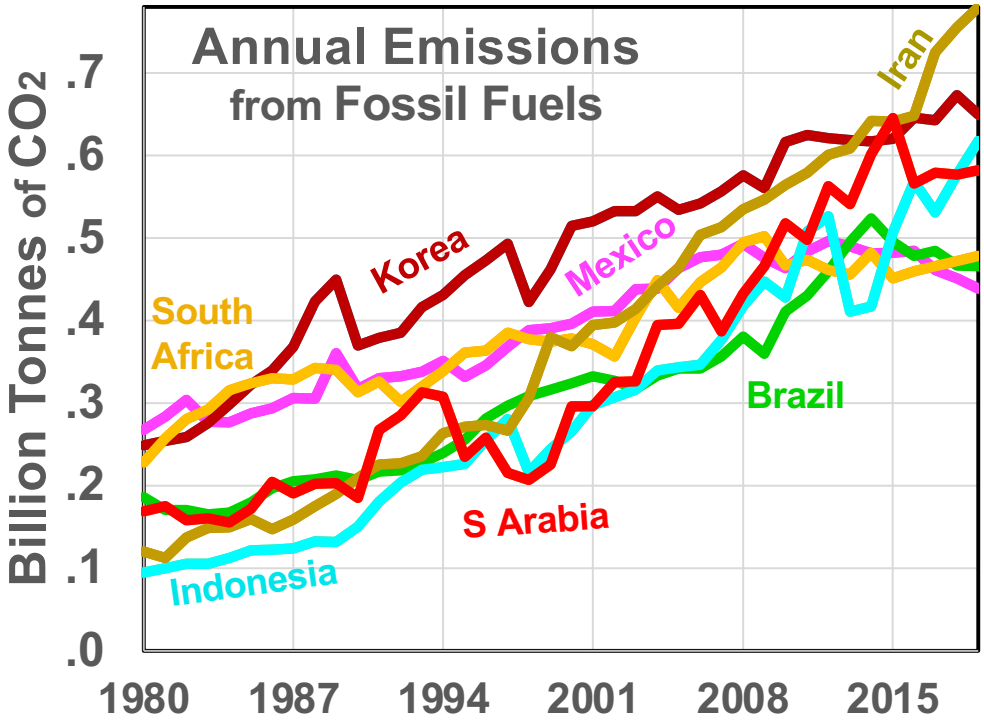

Billion Tonnes of CO2
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
1940
1947
1954
1961
1968
1975
Poland, Ukraine+, Cze'kia,
Belarus, Hungary, Baltics
France, Benelux, Italy, Iberia
Romania, Yugoslavia,
Bulgaria, Greece, Albania
Scandinavia, Swiss,
Austria, Ireland
Europe
Detail
Germany
France +
UK
Poland +
Scandinavia +
Balkans: Romania+


Billion Tonnes of CO2
1.6
1.4
1.2
1.0
.8
.6
.4
.2
.0
1980
1987
1994
2001
2008
2015
France +
Poland +
Germany
UK
Balkans
Scandinavia +


Cumulative Emissions
From Fossil Fuels
Billion Tonnes of CO_2
600
500
400
300
200
100
1940
1947
1954
1961
1968
1975


Cumulative
Emissions from
Burning Fossil Fuels
Billion Tonnes of CO_2
1700
1500
1300
1100
900
700
500
1980
1987
1994
2001
2008
2015

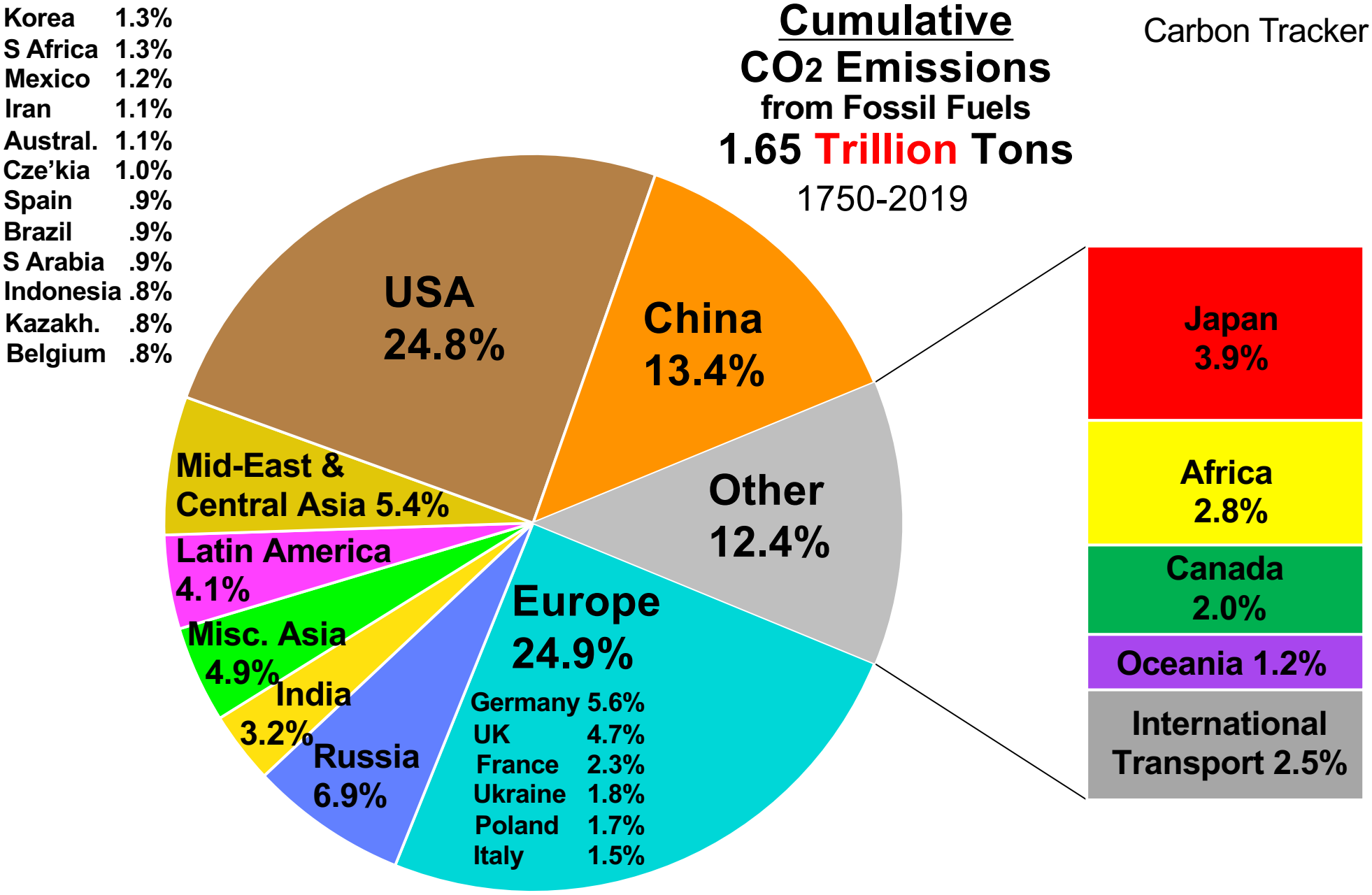

Annual Emissions
from Fossil Fuels
Iran, S Arabia, Turkey, Iraq,
Kazakh-, Uzbeki-, Paki-stan
Korea, Indonesia, Taiwan,
Thai, Philip, Viet, Malay
Mexico, Brazil,
Argentina, Venezuela
S Africa, Egypt,
Alger, Nigeria
Iran +
Mexico +
Korea +
S Africa +
Billion Tonnes of CO_2
.7
.6
.5
.4
.3
.2
.1
.0
1940
1947
1954
1961
1968
1975


Annual Emissions
from Fossil Fuels
Iran
Korea
Mexico
South
Africa
Brazil
S Arabia
Indonesia
Billion Tonnes of CO_2
.7
.6
.5
.4
.3
.2
.1
.0
1980
1987
1994
2001
2008
2015

Cumulative CO_2 Emissions from Fossil Fuels 1.65 Trillion Tons

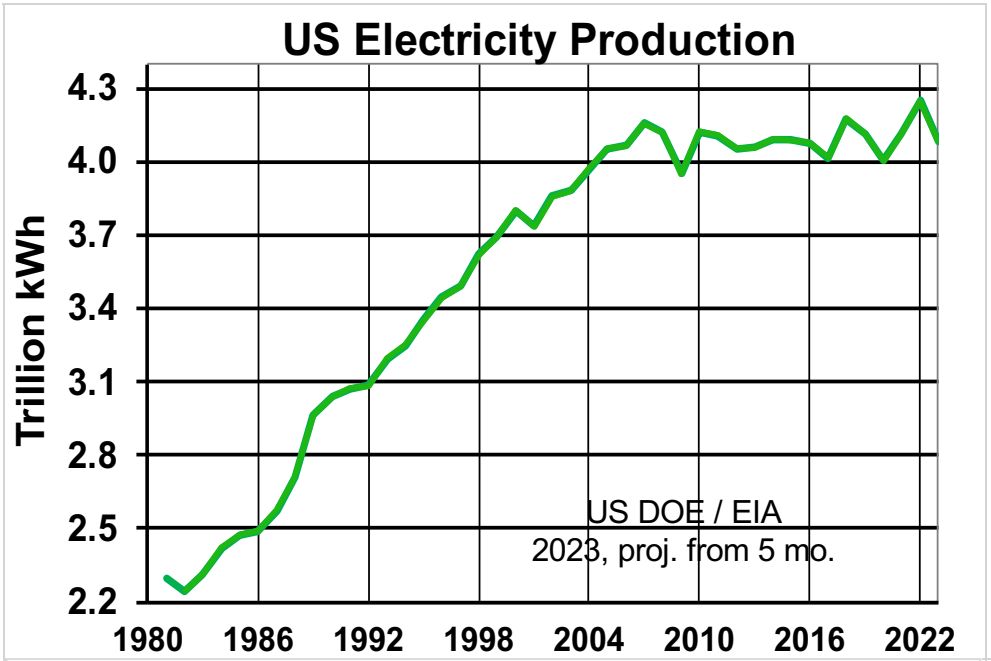
1750-2019

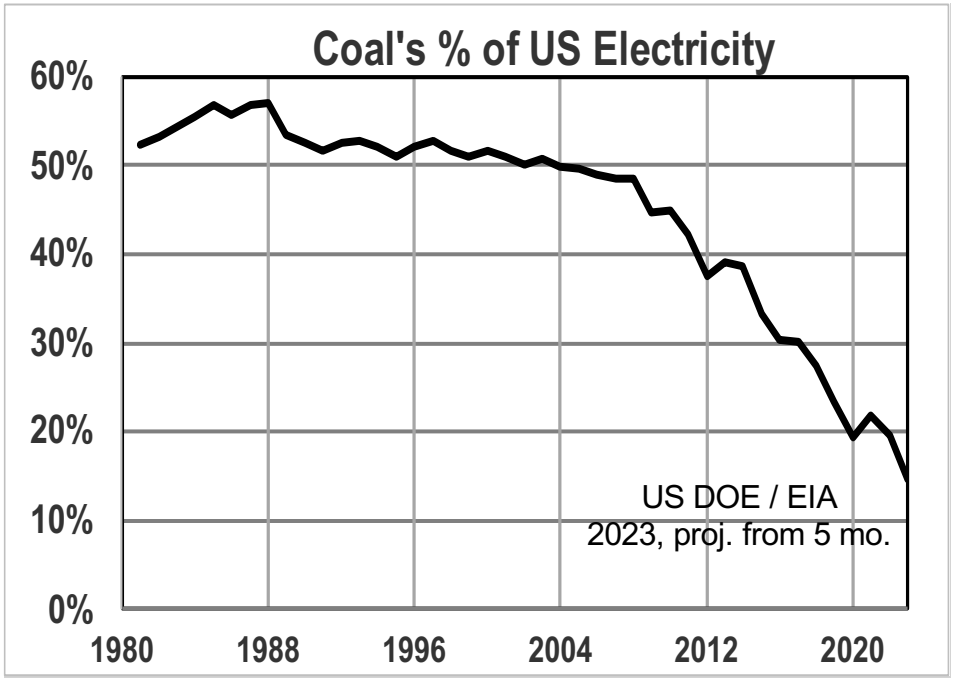
Carbon Tracker

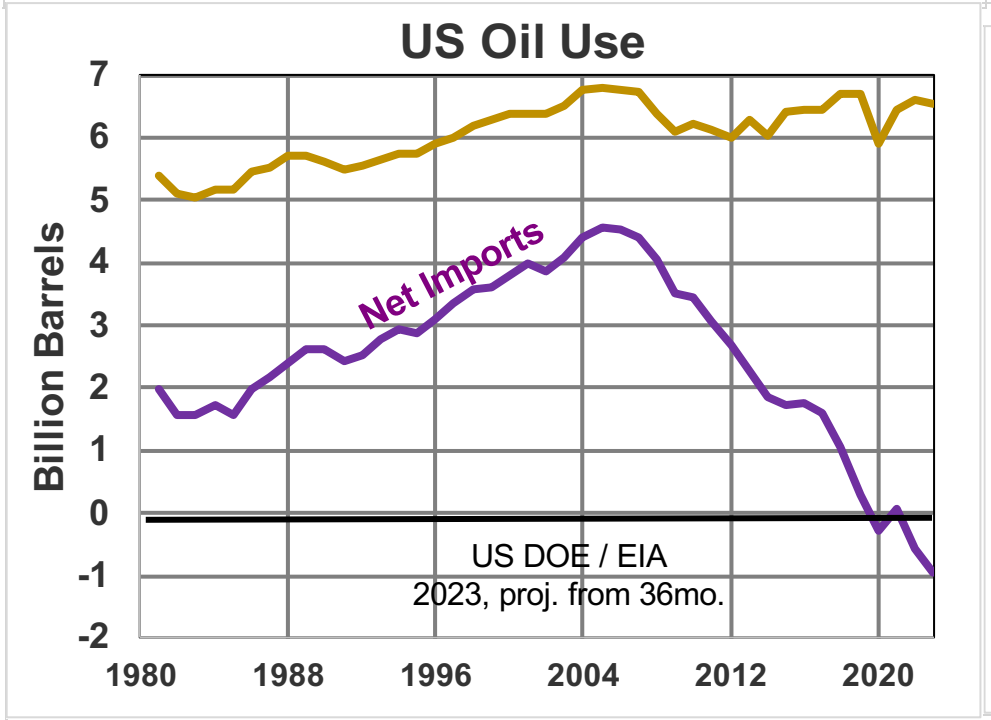


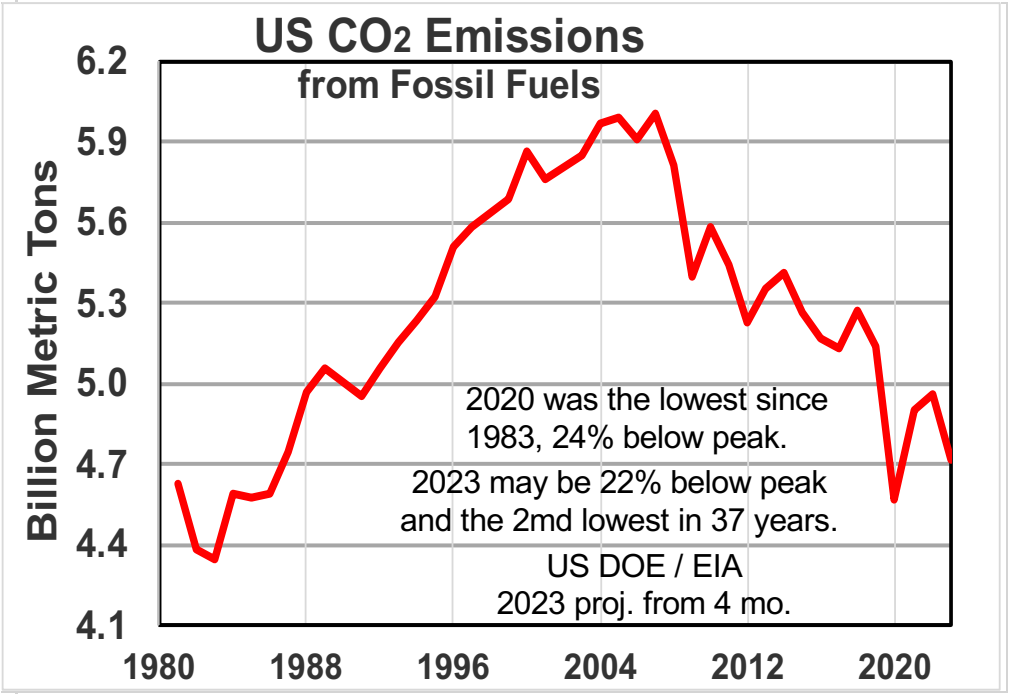
In 2013-14, China began CO_2 cap & trade around its 7 largest cities.
It was extended nationwide for making electricity in 2021.

America's Low-Carbon Revolution Has Begun









Companies are cashing in on green technologies. *e.g.*,

- Tesla (electric cars, solar, batteries)
- Vestas (wind turbines)
- Orsted (offshore wind farms)
- Aptiv (self-driving EV software)
- Sociedad Química (lithium mining)
- Cree (LED lighting)
- Johnson Controls (energy management systems)
- Entergy (nuclear power plants)
- Magna International (lightweight auto parts)
- Halma (detect water leaks)

- Re-insurers – Lloyd's of London, Swiss Re, and Munich Re – look to cut their losses by urging governments to slow climate change.
- Direct insurers – Allstate, MetLife, etc. – cut coverage in vulnerable areas, *e.g.* Florida.

- Investors (> $20 Trillion in assets) pushed 100+ companies to disclose climate-related risks.

Markets now value high-carbon companies less. Carbon disclosure raises stock prices.

Coal and oil company $ / share prices have fallen a long way, especially coal.

100s of companies have set decarbonization targets, dates ranging from 2025 to 2050.

- In June 2015, 6 European oil majors called for a worldwide carbon price.

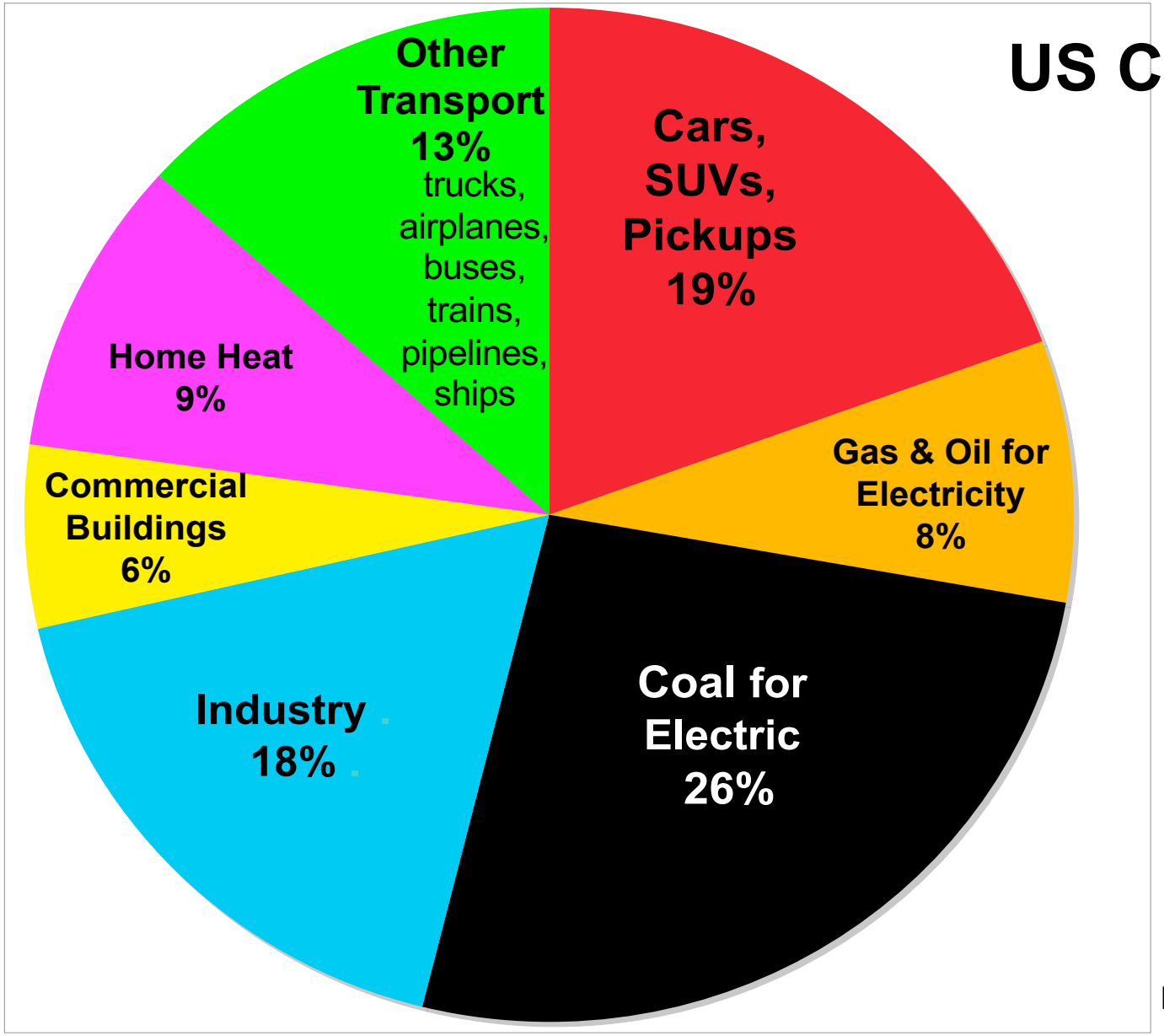
9 oil majors already use shadow CO_2 prices, e.g., $34-80 / ton.

- In 2017, 26 companies, 2 NGOs, & 17 individuals founded the **Climate Leadership Council**.

It called for pricing CO_2 emissions: $40 / ton to start, rising 3-10% / year + inflation.

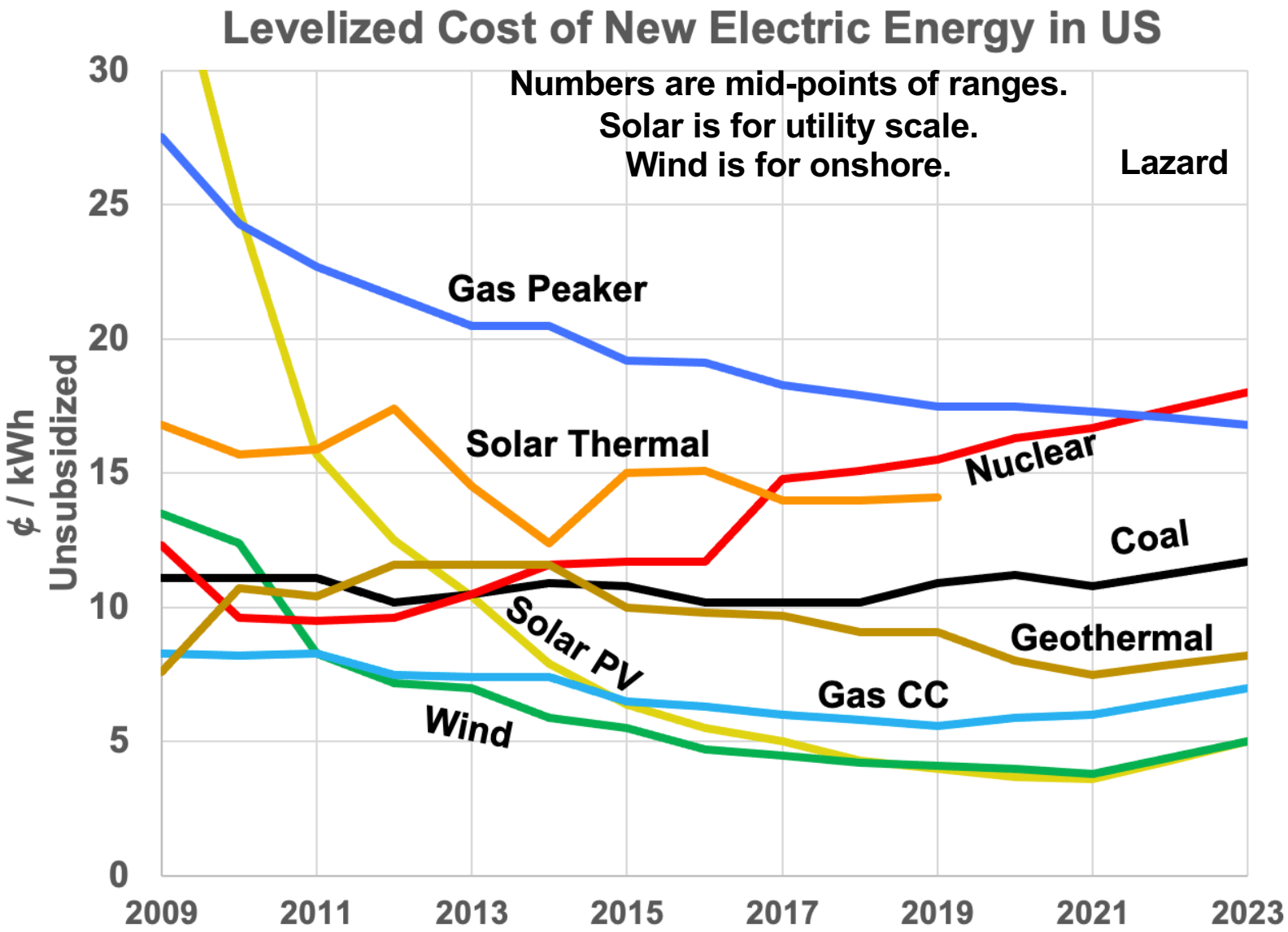
CLC = Shell, BP, Microsoft, GM, Ford, P&G, J&J, MetLife, JP Morgan Chase, IBM, AT&T, Pepsi+ Conoco, WWF, WRI, 2 Fed chairs, 4 Secretaries, Walton, Figueres, Schwab, Mankiw, Feldstein+

US CO_2 Emissions by Use



2012: USDOE - EIA
(US Department of Energy - Energy Information Administration)

Concentrate on the BIG stuff: **coal** for **electricity**
(with a **carbon tax**) & **personal transportation**.

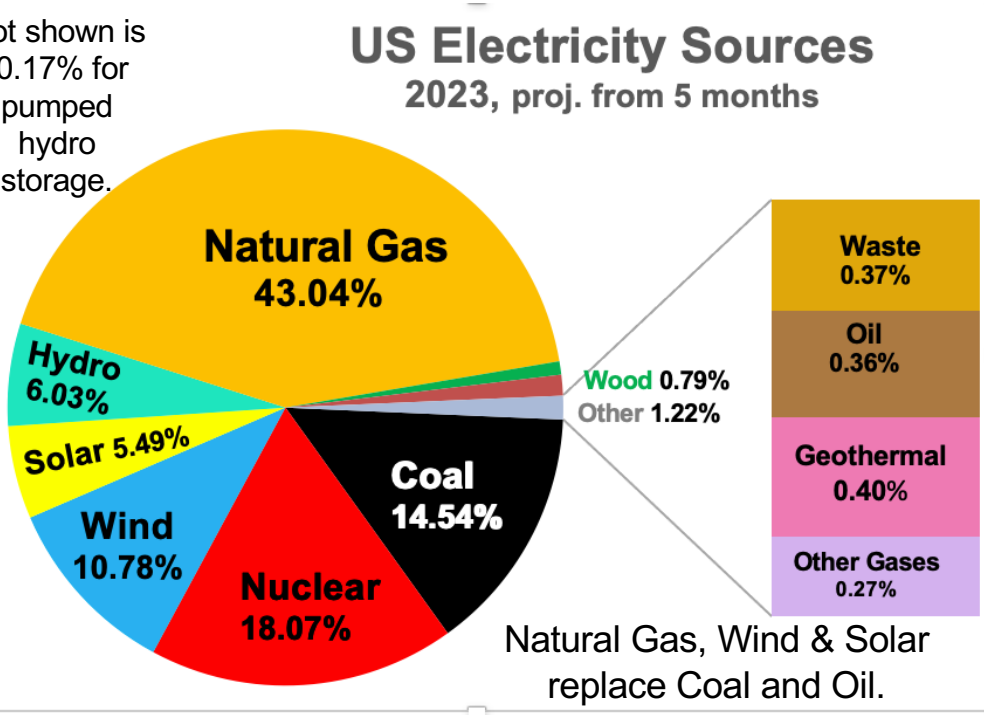


Solar & Wind are now the cheapest US electricity sources.

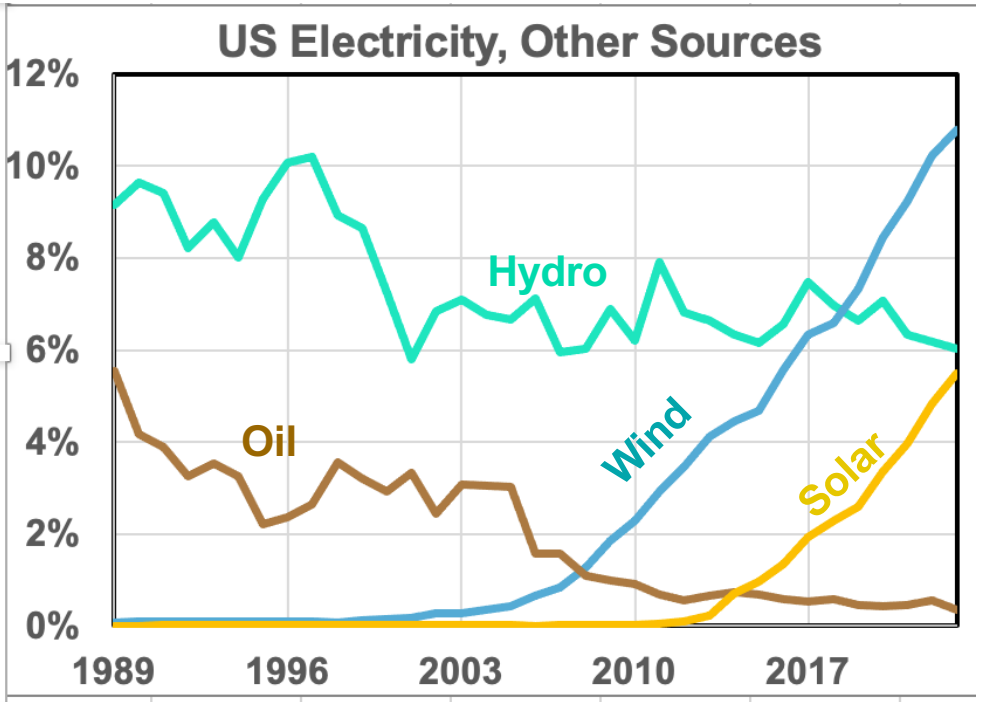
In most of the US, new solar and wind are cheaper than new gas-fired plants and the variable operating costs of coal-fired plants too.

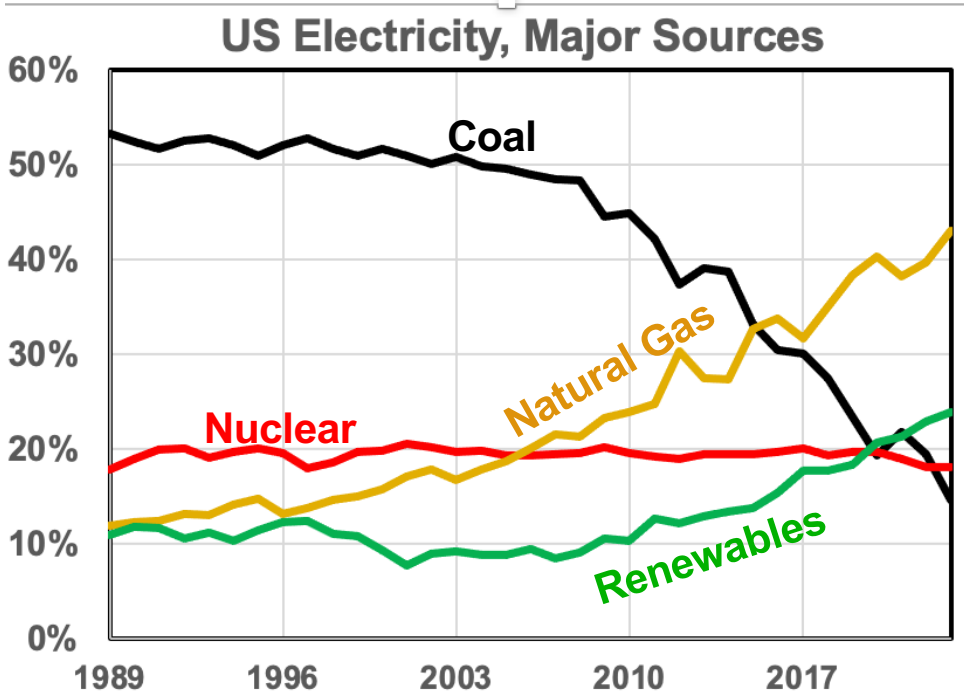
So, their share of electric generation is rising. (next slide)

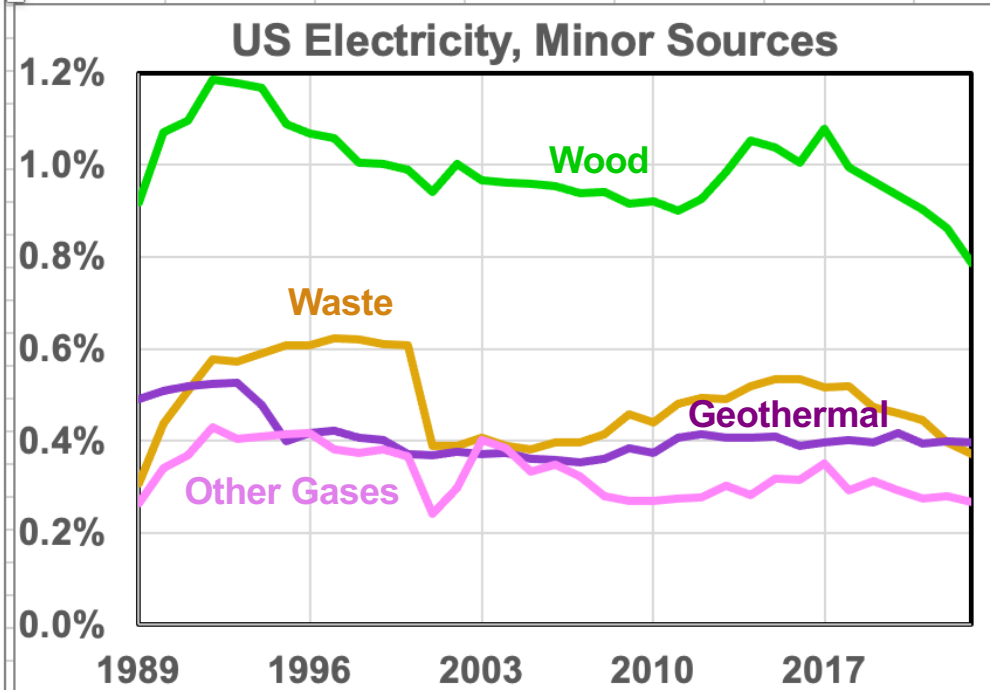
Not shown is -0.17% for pumped hydro storage.



Natural Gas, Wind & Solar replace Coal and Oil.







The US Is Cutting CO_2 Emissions.

Obama pledged 26-28% by 2025. Biden 50-52% by 2030.

Natural gas prices fell steeply in 2011-12 and stayed low.
Cheaper gas has replaced coal - a lot - to make electricity.

EPA's interstate transport rule for SO_x and NO_x makes coal plants operate scrubbers more and use low-sulfur coal.
This makes coal power costlier, so less coal is being used.

Financial markets expect CO_2 to be priced.
Almost all planned coal plants have been cancelled.
Over 2009-16, 14% of coal capacity retired. It's accelerated since.

Trump said new cars & trucks must average 40.4 mpg by 2025.

1,000s of big companies save money by saving energy.
Incandescent light bulbs have mostly phased out.
New standards require ever more efficient appliances.

Solutions - Electricity

- Price it right retail, for everyone: low at night, highest on hot late afternoons.
- **Coal**: Phase it out. Remove CO_2 from smokestacks.
- Natural Gas follows daily load up & down. To follow load, **store** energy in car batteries, flow batteries, water or rocks uphill, compressed air, flywheels, molten salt, hydrogen. Keep methane (& chemicals to groundwater) **leaks** from fracking to **very** low levels.
- Wind - Resource is many x total use: US Plains, coasts - NC to ME, Great Lakes. Growing 12% / year over 5. US prices average 3.8¢/kWh, down 66% in 12 years. Wind turbines off the East Coast could replace all US coal plants.

  Solar - Resource **dwarfs** total use. Output peaks near when cooling needs peak. Growing 28% / year over 5. PV prices average 3.5¢/kWh, down 87% in 12 years. Off-grid in Africa & India: 45¢/day for PV panel, battery, 2 LEDs, phone charger.
- Nuclear - new plants in China, India, Korea. Modular liquid sodium-cooled reactors?
- Water, Wood, Waste - Rivers will dwindle. More forest fires limit growth.
- Geothermal - **big** potential in Ring of Fire, Iceland, Kenya, Caribbean, Hawaii, Italy
- Ocean - tides, waves, currents, thermal difference (surface vs deep)

Solutions - Efficient Buildings +

- At Home - Use **heat pumps**.

  Better lights - compact fluorescents (CFLs) & LEDs. Turn off un-used lights.

  Energy Star appliances - air conditioners, refrigerators, front load clothes washers

  Insulation - high R-value in walls & ceiling, honeycomb window shades, caulking

  Low flow showerheads, microwave ovens, trees, awnings, clotheslines, solar roofs

- Commercial - Use heat pumps, micro cogeneration.

  Don't over-light. Use day-lighting, occupancy sensors, reflectors.

  Use LCD Energy Star computers. Ventilate more with **Variable Speed Drives**.

  Use free cooling (open intakes to night air), green roofs, solar roofs.

  Make ice at night. Melt it during the day - for cold water to cool buildings.

- Industrial - Energy $ impact the bottom line. Check % IRRs.

  Efficiency is generally good already. Facility energy managers do their jobs.

  Case-specific process changes as energy prices rise. Use more cogeneration.

  Replace fossils fuels with electricity for heating materials and fluids.

Solutions - Personal Vehicles

US cars get 25 mpg. Pickups, vans & SUVs get 18. Average 23.

Toyota and VW outsell GM and Ford around the world.

In 2019, **new** US cars, pickups, SUVs, vans averaged only 25 mpg.
In 2008, new cars averaged 37-44 mpg in Europe, 45 in Japan.

To cut US vehicle CO_2 by 50% in 20 years is <u>easy</u>.

For gasoline ones, lighten up, downsize, don't over-power engines.
Use CVTs, start-stop, VVT, hybrid-electric.

Use pickup trucks & vans only for work that requires them.

The **electric vehicle revolution has begun**, even in the US.

EV sales are soaring, up to 148 mpge, and up to 315 mile range.

Electric cars will cost less up front than gasoline ones before 2025.

Store wind on the road, with plug-ins & EVs.
Charge them up noon and night.

Solutions - Other Transportation

- Fuels - Cut CO_2 emissions further with low-carbon fuels?
  - Save ethanol, other biofuels for ships, airplanes.
  - Get ethanol from sugar cane (energy out / in ratio = 8:1).

For biofuels, GHGs from **land use** changes **DWARF** GHG savings.

Hydrogen has low energy density, is hazardous. Limit to ships, airplanes.

- Trains, Planes, and Ships

Use high-speed magnetic levitated railroads (RRs) for passengers.

Shift medium-haul (100 - 800 miles) passengers from airplanes to maglev RRs (fast as bullet trains).

Shift long distance freight to electric RRs and electric trucks.

Big cargo ships use two 2 MW wind turbines, biofuels, nuclear reactors.

Solutions - Personal

Make your home & office efficient. **Don't over-size a house.**

Drive an efficient car. Don't super size a vehicle.

Don't drive much over 55 mph. Combine errands, idle 1 minute tops.

Walk. (Be healthy!) Carpool. Use bus, RR, subway. Bicycle.

Buy things that **last**. Fix them when they break.

Eat less feedlot beef. Less is healthier! 1 calorie = 7-10 of grain.

Garden. Compost. Move carbon from the air into the soil.

Reduce, re-use, recycle. Minimize packaging. Use cloth bags.

Ask Congress to price carbon. End CO_2 emissions before 2050.

Tax carbon 3¢ / lb, rising 2¢ per year.

Include tax credits to **take CO_2 OUT of the air.**

Policy

Tax carbon across fossil fuels, worldwide, in proportion to carbon content. Impose the tax upstream (wellhead, mine mouth, port).

1,000s of the world's leading economists

It should start low, but then rise substantially and briskly, on a pre-set trajectory.

the same

End subsidies for production and use of fossil fuels.

the same

Give carbon tax credits for carbon removal from ambient air, at the same rate carbon emissions are taxed.

Dr. Fry

US$60 / tonne of carbon ($15 / ton CO_2), rising $10 / year.

Citizens Climate Lobby

Return net proceeds as equal monthly dividends to individuals.

This creates jobs and grows GDP, compared to no carbon tax.

We humans must go
carbon negative
big time,
by 2050.

QUESTIONS?

Contact Dr. Gene Fry
for more details, citations & references.

gene.fry@rcn.com

www.globalwarming-sowhat.com

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