

Global Warming

So What? .

Dr. Gene Fry
January 2023

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

The last times CO₂ exceeded 400 ppm
(~4 and 14 million years ago),
Earth's surface was ~7° and 10°F 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.

WATER

Rainfall becomes more variable.
Wet places get rainier, dry ones grow drier.

Planet-wide, we get a little more rain.

Around the Arctic gets lots more,
mid-latitudes (20-45°) less rain.

Yet in any one place, we get
more hours and days **without rain**.

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

Droughts Worsen.

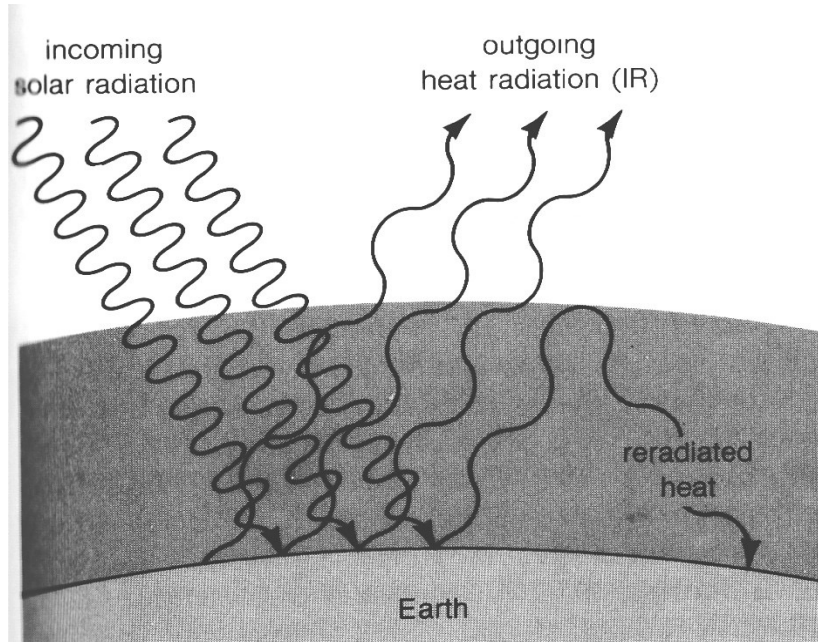
Deserts Spread.



The Culprit?

Evaporation

Greenhouse Effect



Dark Earth absorbs sunlight. Earth **warms** up & 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.

11-yr changes ($\pm 0.08\%$) in sunshine have much smaller effects than GHG changes.

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 33°C (60°F).

Earth's surface would average 0°F without them.

- **Water** vapor (H₂O) does ~ 53% of this warming.

As Earth warms up, evaporation increases H₂O in the air.

This **amplifies** warming from other GHGs (& albedo changes) a lot.

- Of the other GHG warming, carbon dioxide (CO₂) does 52%.

Almost all US CO₂ comes from burning coal, oil & natural gas.

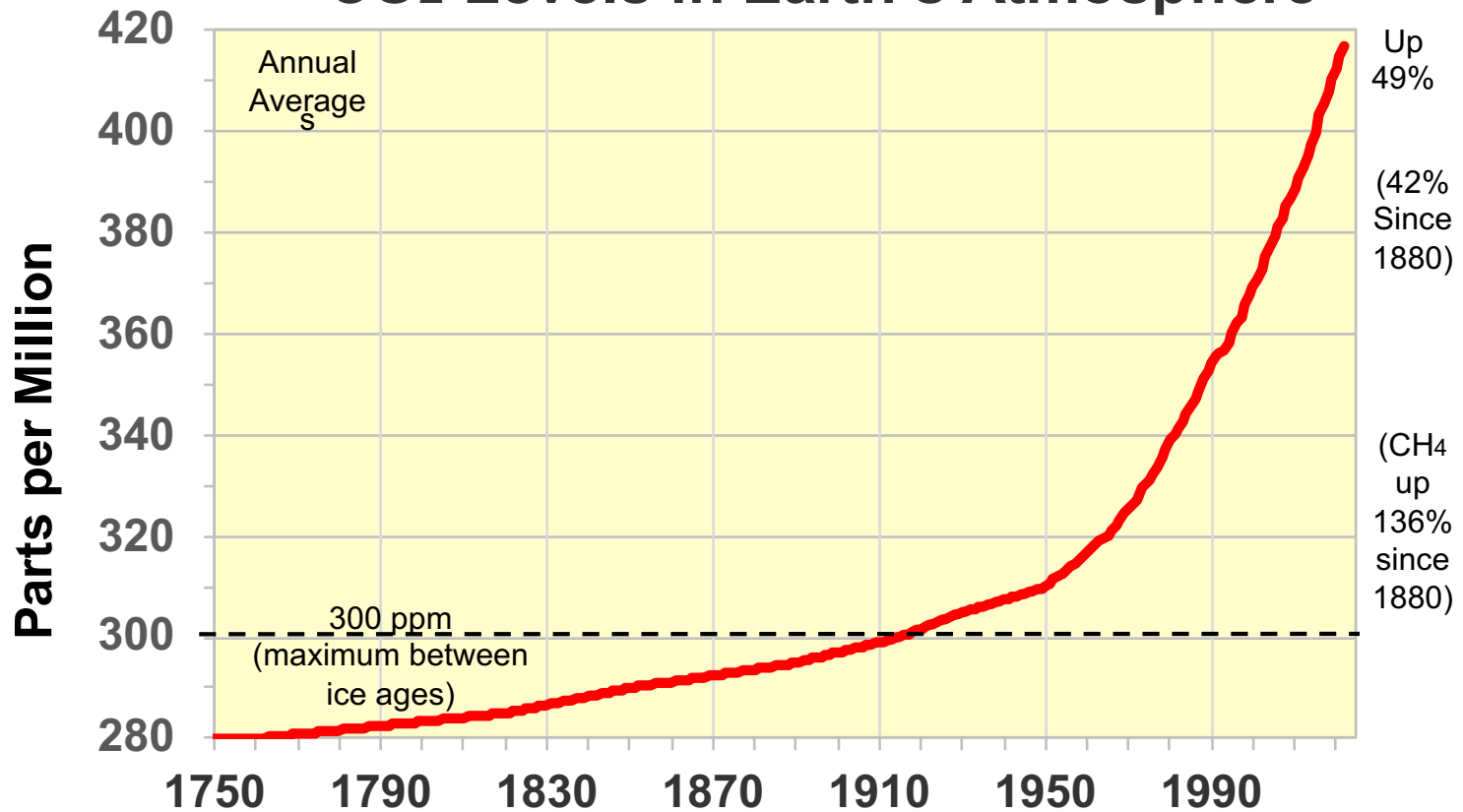
Per unit of energy, coal emits 4 units of CO₂, oil 3, natural gas 2.

- Methane (CH₄, natural gas) does 30% (10% indirect: O₃, H₂O).

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

- CFCs, nitrous oxide, and other factors do the rest.

CO₂ Levels in Earth's Atmosphere



Today's CO₂ 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 6.6°C warmer than now.

Shevenell 2008

Seas then were 25-40 meters higher.

CO₂ levels were **almost** as high (357-405 ppm) 4.0 to 4.2 Million Years ago.

Sea surfaces then were ~ 4°C 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.

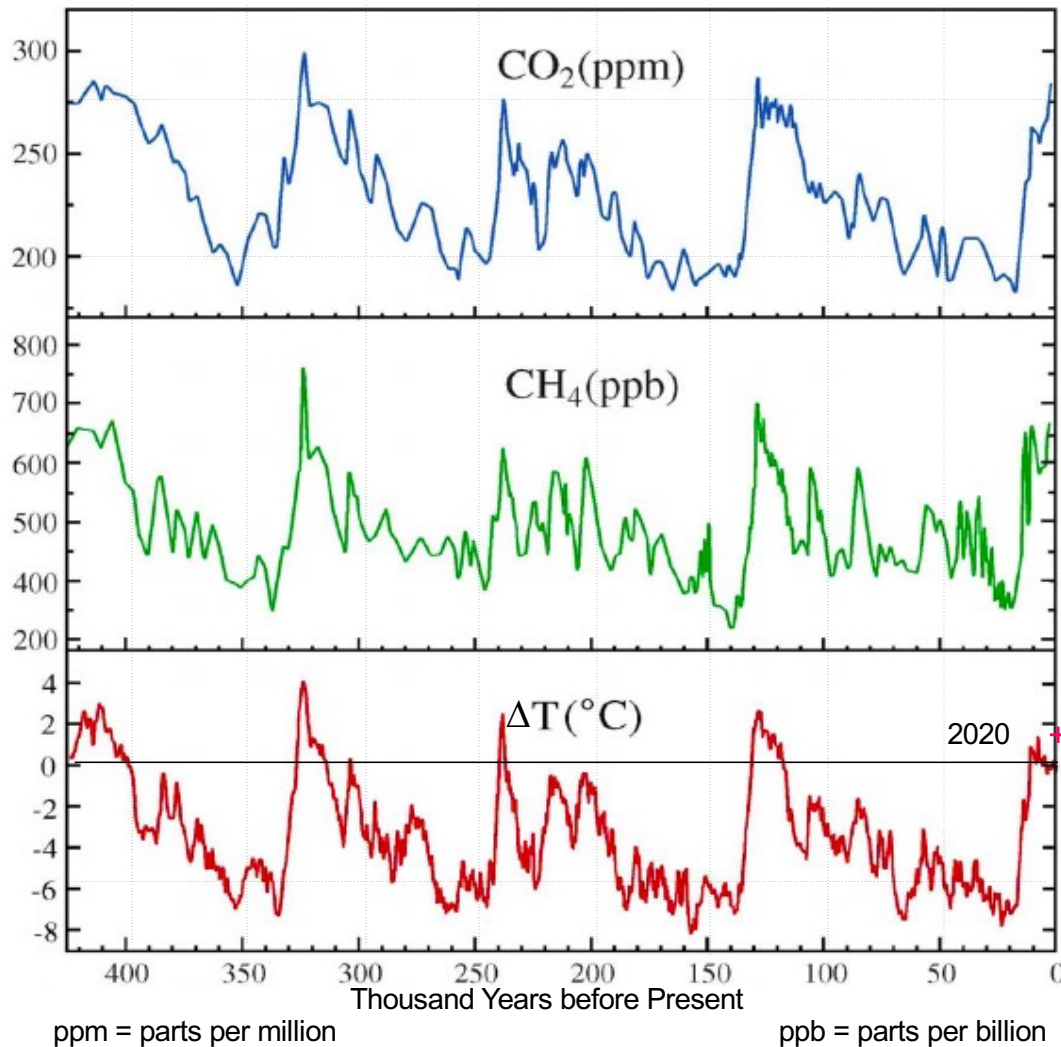
Cook 2013

We face BIG lag effects.

Vostok Ice Core Data

+ 2020 **CH₄** level ~ 1890 ppb

+ 2020 **CO₂** level ~ 414 ppm



For 100s of 1,000s of years, temperatures and levels of GHGs CO₂ and CH₄ in the air have tracked each other closely.

The difference between 190 and 280 ppm of CO₂ was 10°C (18°F) at Vostok and **ice** almost a **mile thick** covering Chicago.

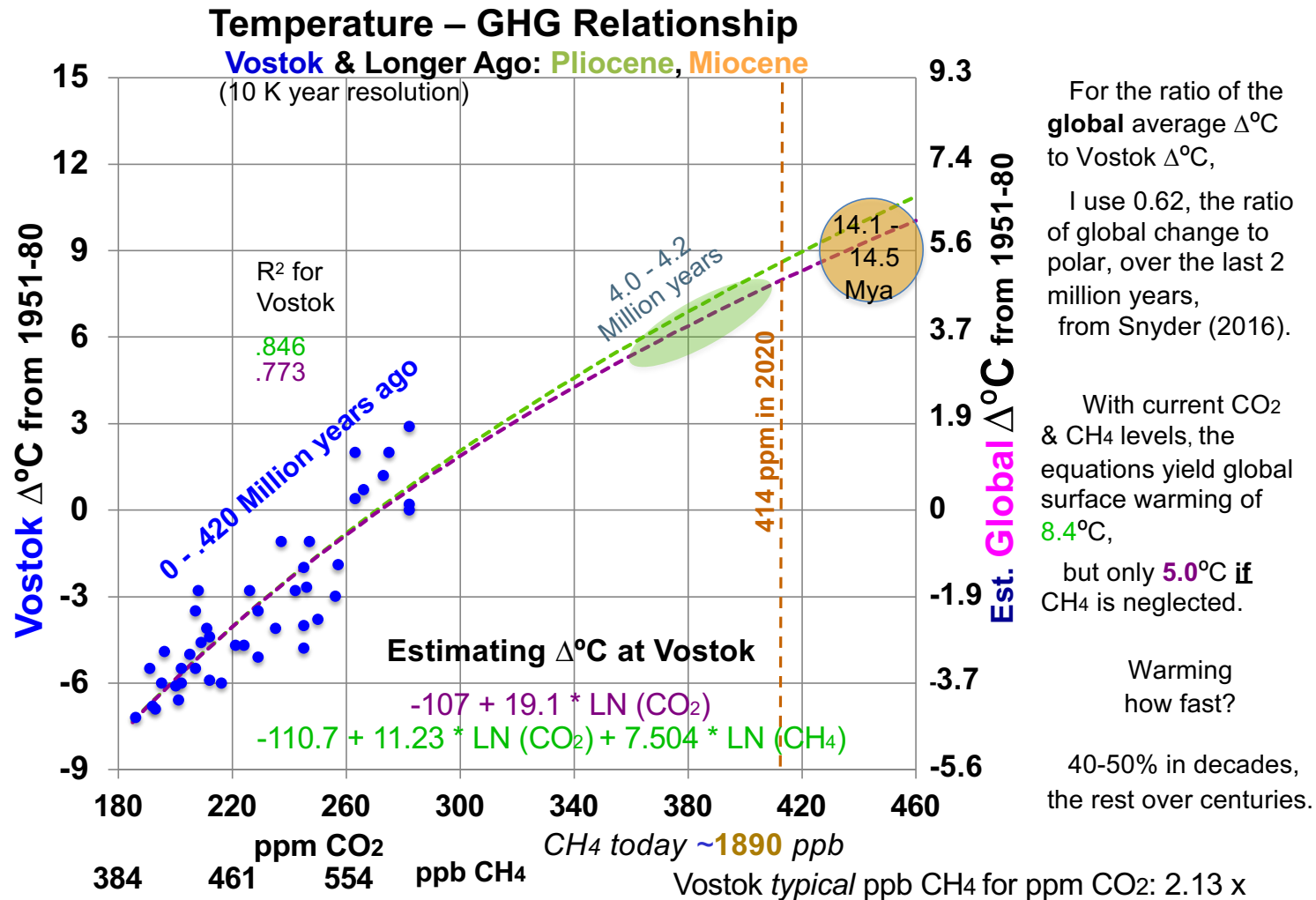
Warming led CO₂ & CH₄ increases by centuries, moving carbon from soil, permafrost and the oceans into the atmosphere.

Vostok data trends say that 400 ppm CO₂ yields 5.0-8.4°C 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



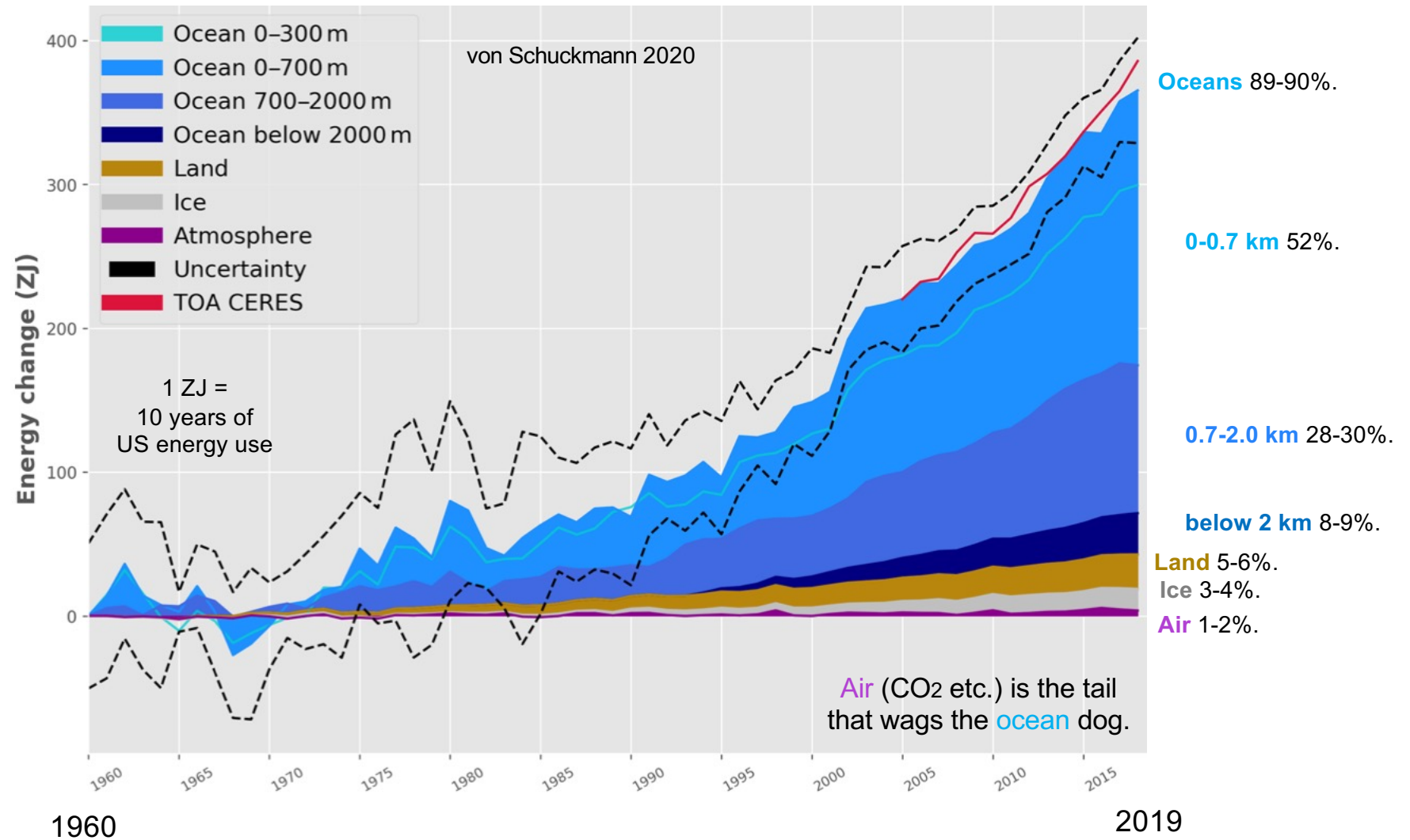
$$\text{Global Surface } \Delta^{\circ}\text{C} = 0.6 * (-110.7 + 11.23 * \text{LN}(\text{CO}_2) + 7.504 * \text{LN}(\text{CH}_4))$$

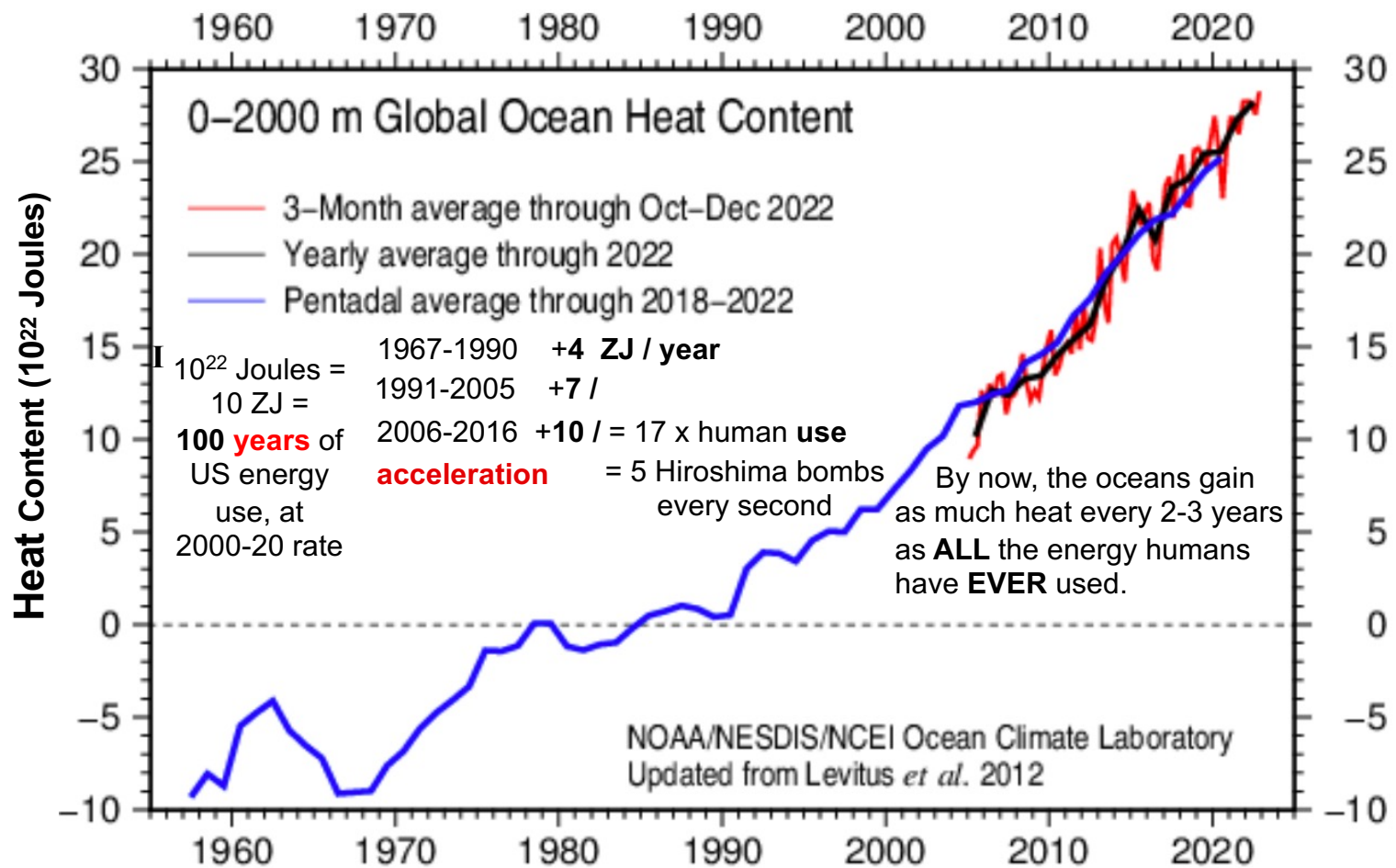
+2°C globally requires (e.g.)
314 ppm CO₂ and
700 ppb CH₄.

This means removing 70-75% of the CO₂
that humans have emitted
+ any future CO₂ emissions
and all of the CH₄.

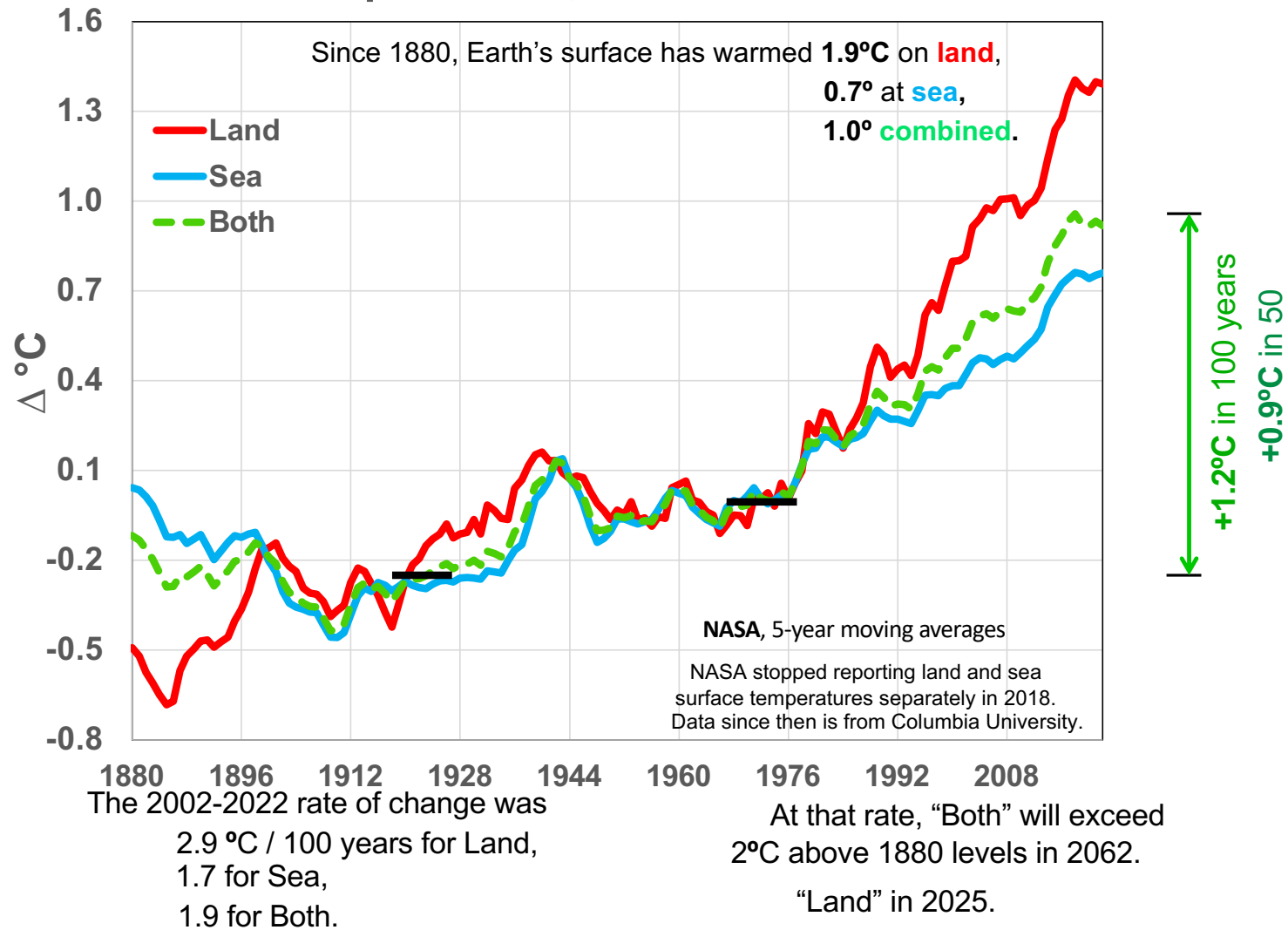
Humanity's remaining carbon budget
for burning fossil fuels is
NEGATIVE 325 GT of carbon.

Global Heat Gain





Temperatures, Global Surface



- **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 H₂O, 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.

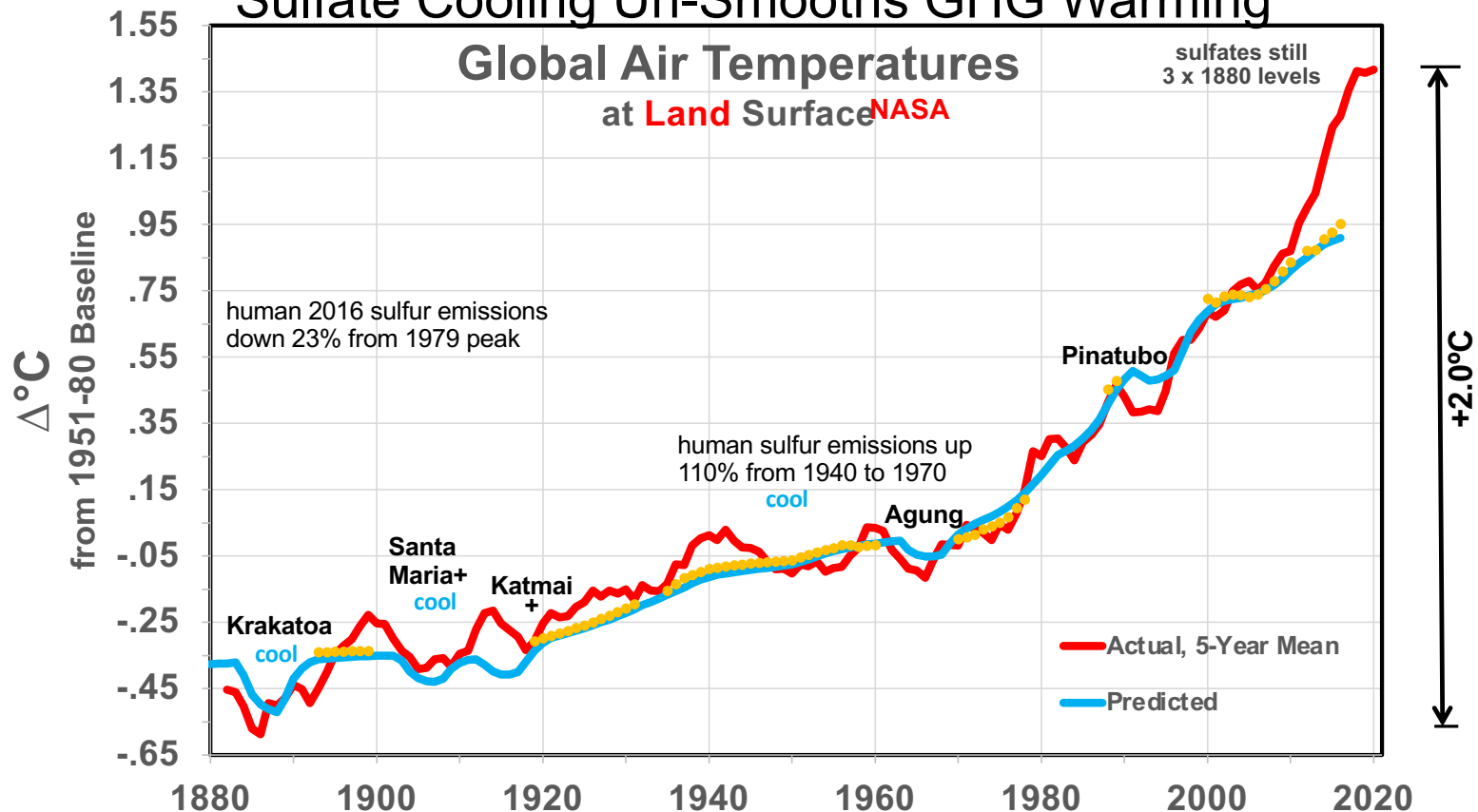
More sulfates = cloudier = **cooler**.

- Most sulfates come from burning coal, some from plankton & volcanos.

SO₂ goes up the smokestacks. It changes to SO₄ (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: 0.4°C.
- As we stop sending up SO₂, warming will catch up.

Sulfate Cooling Un-Smooths GHG Warming



$\text{Predicted } \Delta^{\circ}\text{C} = -20.51 + 2.223 * \text{LN}(\text{CO}_2 \text{ ppm}) + 1.133 * \text{LN}(\text{CH}_4 \text{ ppb}) - .00319 * \text{SO}_4 \text{ ppb}$
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

$\text{Predicted } \Delta^{\circ}\text{C, w/o Volcanos} = -20.48 + 2.089 * \text{LN}(\text{CO}_2 \text{ ppm}) + 1.252 * \text{LN}(\text{CH}_4 \text{ ppb}) - .00393 * \text{SO}_4 \text{ ppb}$
adjusted $R^2 = 98.3\%$. CO_2 , CH_4 & SO_4 (also 5-year averages) are all highly significant ($|t\text{-ratios}| = 6.4$ to 8.7).

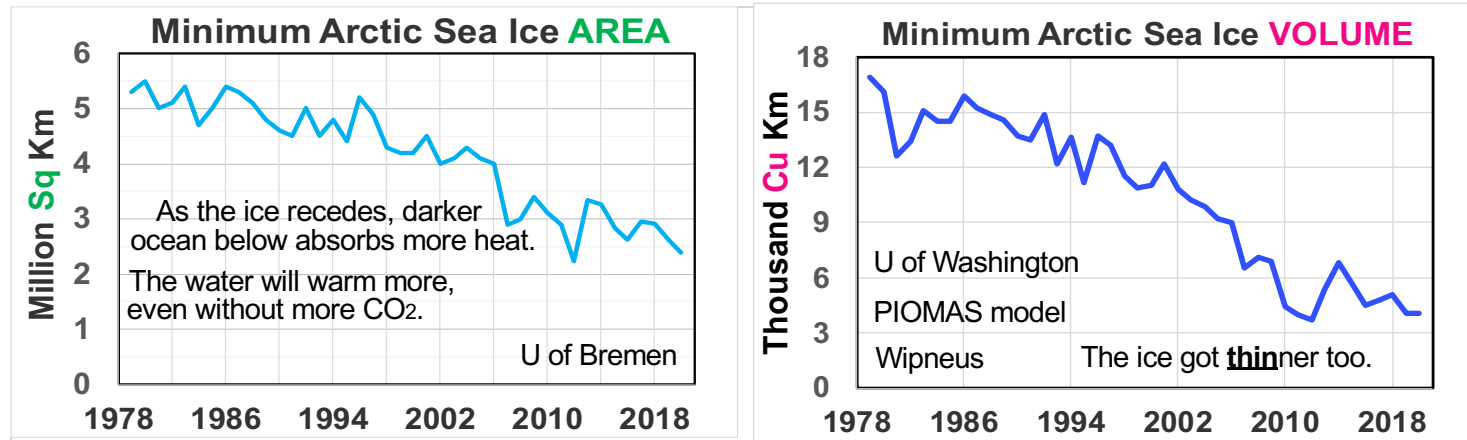
Snow (Timing)

From 1982 thru 2013,
radiative cooling from northern snow cover
decreased by $0.33 \text{ W / sq m / } ^\circ\text{C}$.
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 CO₂.

Quantifying future sea ice albedo effects,
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.

Antarctic sea ice covered a similar area, but it is not clear that its loss has begun yet. It hit record highs in 2013-15, then record lows in 2017-19.

Over 1993-2010, sea level rise (SLR) was 2.8 mm / year.

1.1 came from ocean warming, 0.76 from glaciers outside Greenland & Antarctica, 0.33 from Greenland, 0.27 from Antarctica, and 0.38 from land water storage.

That totals 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, 0.5 meter at 8%, 0.1 meter at 6%.

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

Seas will likely rise 1 to 7 feet more by 2100

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 CO₂ we've added.

How will albedo effects produce so much warming?

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 1°C 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 $.4^{\circ}\text{C}$),

vanishing northern sea ice (about $.4^{\circ}\text{C} = 0.7^{\circ}\text{F}$),

receding northern snow cover ($\sim .4^{\circ}\text{C}$),

vanishing southern sea ice ($\sim .4^{\circ}\text{C}$),

permafrost etc.* ($\sim .4^{\circ}\text{C}$),

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

receding Greenland & Antarctic land ice ($\sim .3^{\circ}\text{C}$),

warming oceans enough so energy out = in ($\sim .2^{\circ}\text{C}$),

more H₂O vapor & less cloud cover (1.7 multiplier).

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

1°C = 1.8°F.

Earth Is Heating Up.

- Earth now **absorbs** 0.33% more energy than it emits –
a **450 million** MW heat gain. (± 60 million MW)

450 million MW = **70** x **global** electric supply = **30** x human energy **use**.

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

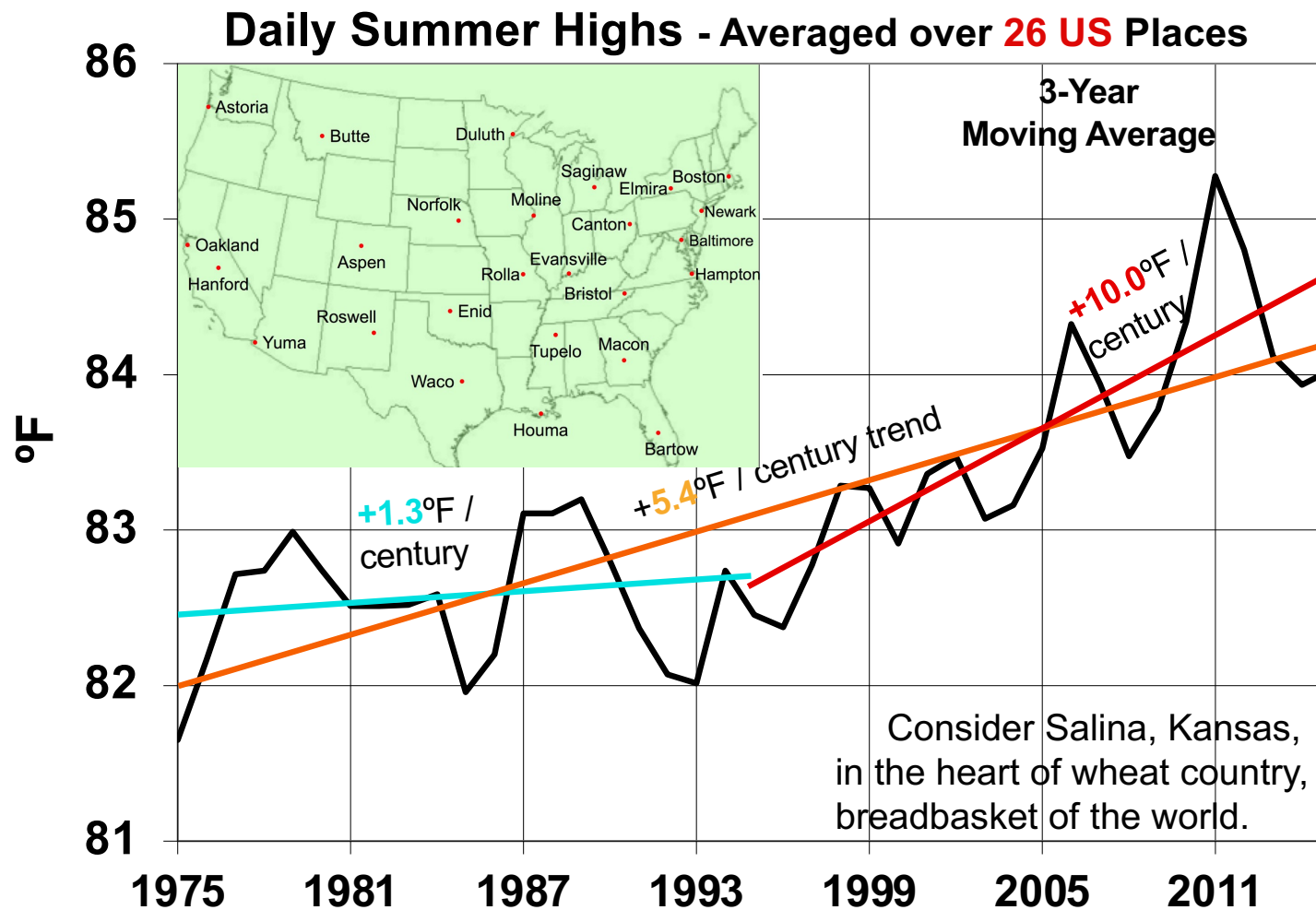
Earth will warm another **0.3°C** or more, so far,
just so it **emits** enough heat to balance absorption.

- Air at the land surface warmed **1.4°C** (5-year average) in 100 years,
1.1°C in the last 50 (**1.5°C** since 1880).
- Air at the sea surface warmed **1.1°C** in 100 years, **0.9°C** 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** > **10** x **more** heat in 40 years
than **ALL** the energy humans have **EVER** used.



At +5.4°F / century, in 2100 summer in Salina would be as hot as Dallas now.
 Warming at 10.0°F / 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:

5.8°F / century over 1975-2015 and 10.5°F / century over 1995-2015.

(Compare to 5.4° and 10.0°F / century for the 26 places.)

Summer warming was **slowest** in the East North Central states.

It was **fastest** 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

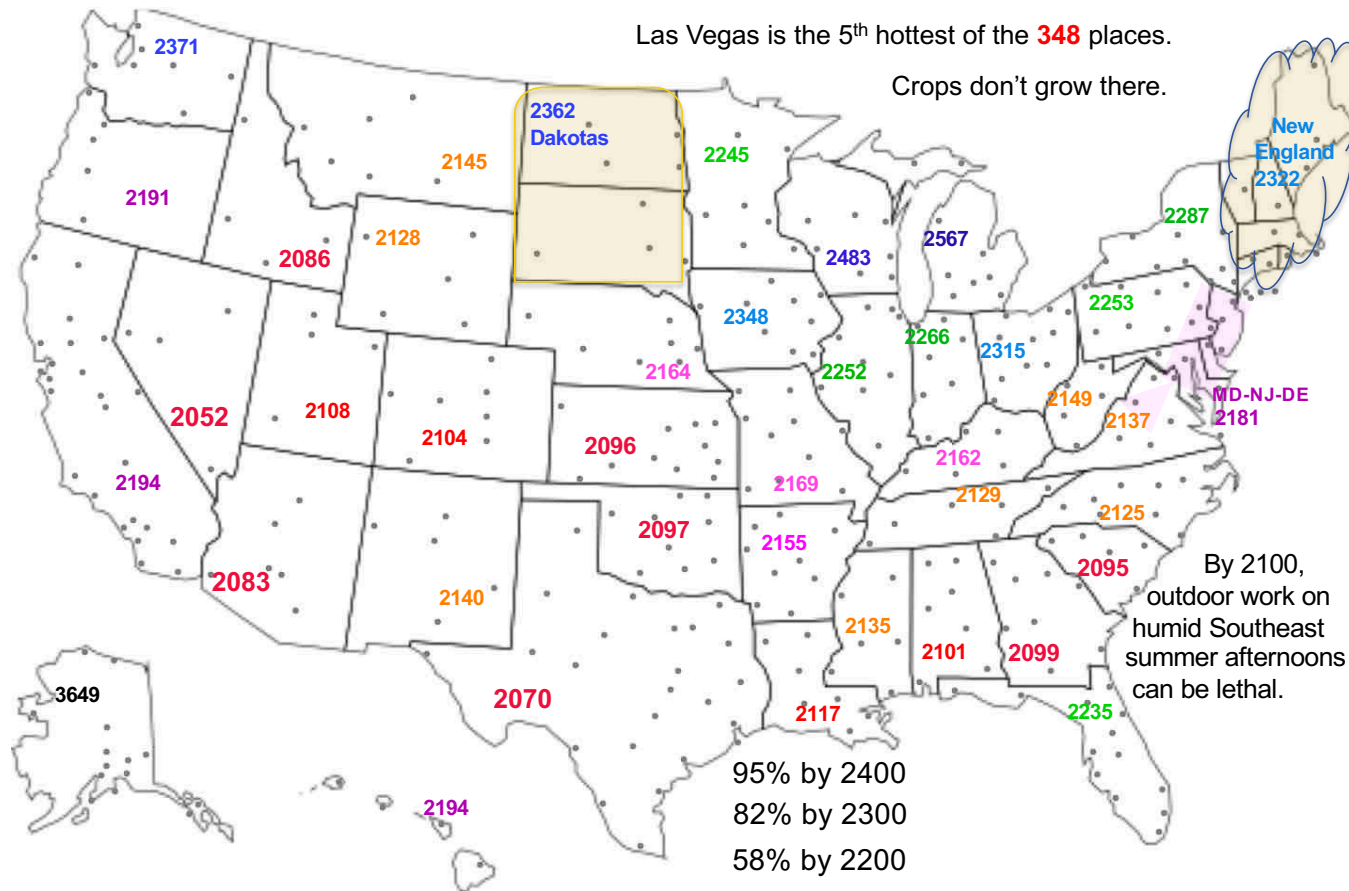
When Do State Summers Become as Hot as Las Vegas Ones Now?

The **average** of daily **highs** in Las Vegas, June 1 thru September 30, 1995-2015, was **100.4°F**
37.8°C.

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.

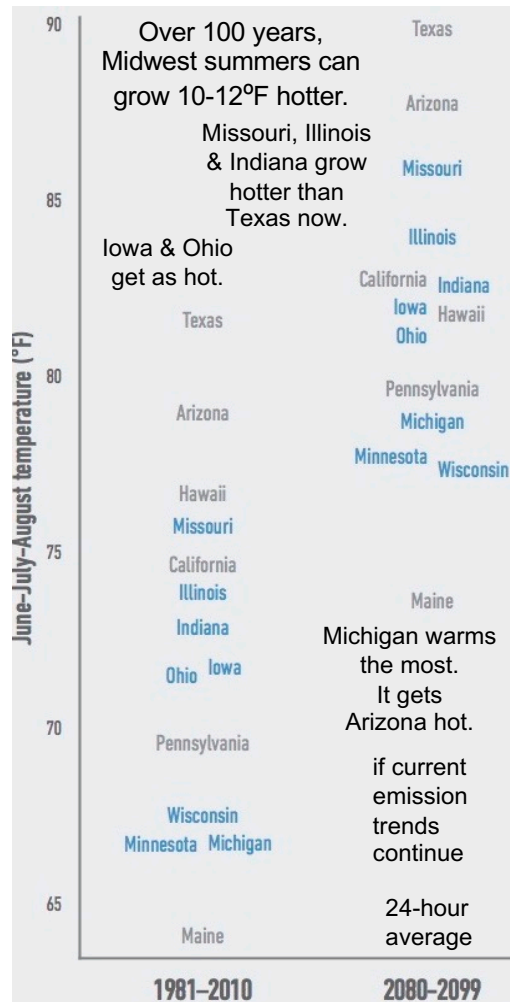
95% by 2400

82% by 2300

58% by 2200

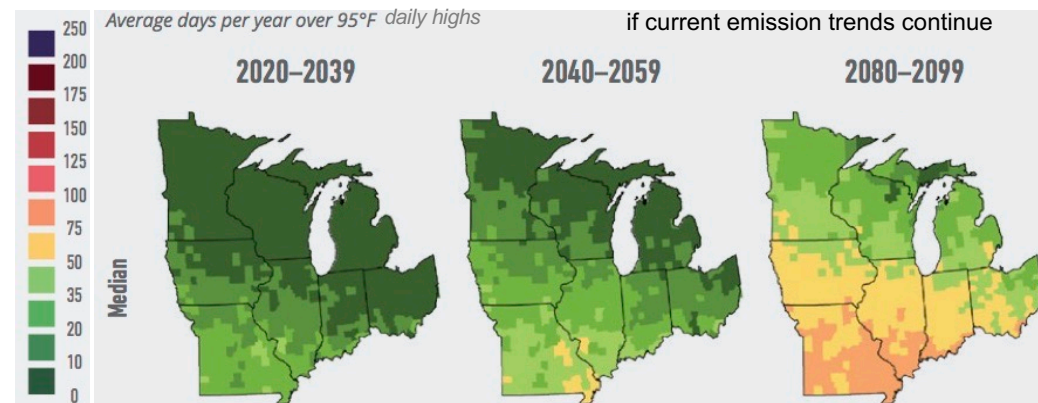
35% by 2150

19% of US population by 2100



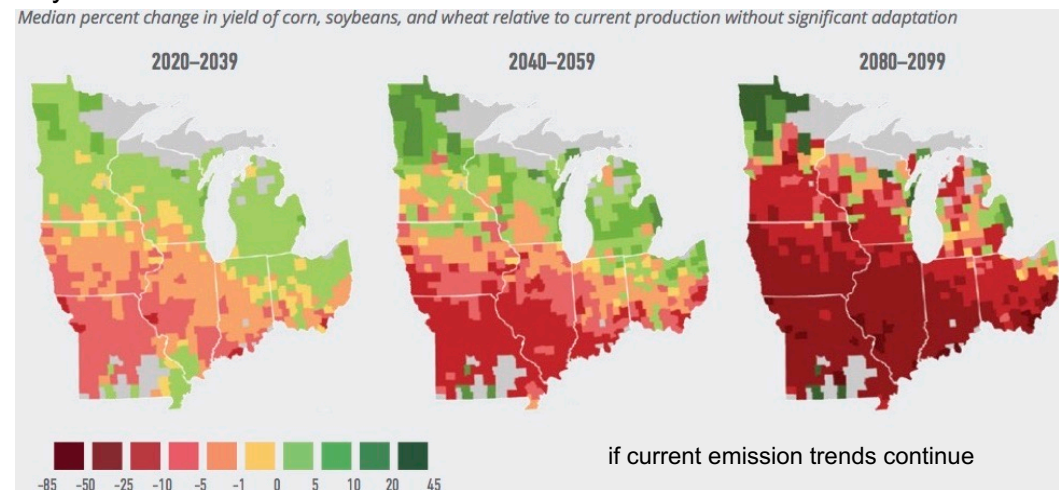
Crop losses of 40-64% by 2100 are likely for corn in the Corn Belt (IA, IL, IN, OH, MO) and 8-38% by 2100 for soybeans in the same states. Winter wheat is barely affected.

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



Las Vegas had 114, 99, and 115 days above 95°F 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**. By 2100, 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? Water

Hurricanes convert ocean heat to powerful winds & heavy rains.
Intense hurricanes are becoming more common.
Higher hurricane energy **closely** tracks sea surface **warming**.

With more carbon, **oceans** have grown more acidic.
So, forming shells is more difficult. They dissolve easier.

Warmer water holds less dissolved oxygen.
Fish & mollusks suffer. Jellyfish prosper.

Sea surfaces warmed 0.15°C over 1997-2004,
so **plankton** absorbed 7% **less** CO₂.

Warming was far strongest in the North Atlantic.
CO₂ uptake there **fell** by **half**.

Ocean **phytoplankton** levels may be down **40%** since the 1950s.
Phytoplankton supply **half** of Earth's **oxygen**.
Phytoplankton levels fell 30% in the Indian Ocean since 1999.

Reservoirs in the Sky

Most mountain glaciers dwindle ever faster:
in the Alps, Andes, Rockies, east & central Himalayas.
30% of Himalayan glacier ice vanished since 1980.

When Himalayan glaciers **vanish**, so could
the Ganges River (& others) in the dry season.

When Andes glaciers vanish, so does
most of the water supply for Lima and La Paz.

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.

Methane Tipping Point?

Thawing Arctic permafrost holds twice as much carbon as our air.

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.

It can add ~100 ppm* of CO₂ to the air by 2100,

and almost 300 more by 2300.

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

Seabed methane hydrates may hold a similar amount,

but so far they are releasing only 20-30% as much carbon.

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

Bio Impacts

To escape heat, species move toward the poles and up mountains.

But some species cannot move fast enough.

Habitat for many 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 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.

Coral bleachings come more often and harder.

Earth's coral reefs vanish.

More acid oceans make it harder from creatures to form shells.

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.

The Mississippi River neared a record low. Lake Michigan-Huron hit one.

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The Mississippi River neared a record low. Again in 2022.

“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

<u>When</u>	<u>Where</u>	<u>How Bad</u>
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.

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).

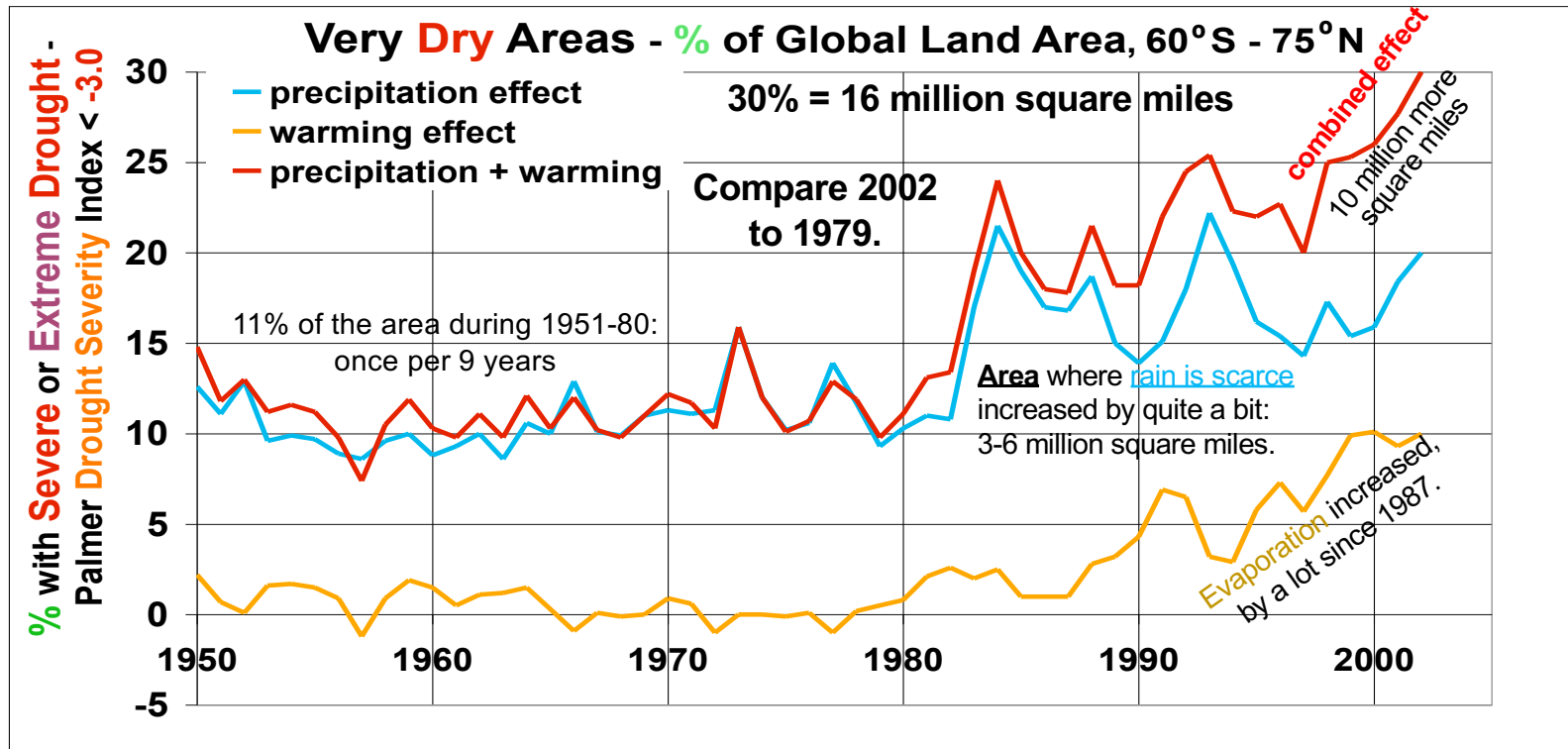
Consider central **Kansas**, heart of wheat country.
330 miles to the SSW lies the area from Amarillo to Oklahoma City.
650 miles to the SSW lies the area around Alpine & Del Rio, TX.

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

No wheat

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.

SUMMARY

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 (+0.5°C)

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.

Extreme Drought Can Clobber Earth

- In 1989, NASA climate models showed, as CO₂ levels rise and Earth warms up, droughts would spread and intensify.
- “Once-per-9-year” droughts would cover 27% of Earth by 2002.
- With business as usual emissions, by 2059 CO₂ levels would **double** pre-industrial levels.
- As a result, Earth would warm 4.2°C [7.5°F] from 1880 levels.
Rain would increase 14%.
- Despite the added rain, increased evaporation would bring extreme “once-a-century” drought to 45% of Earth, & rising.

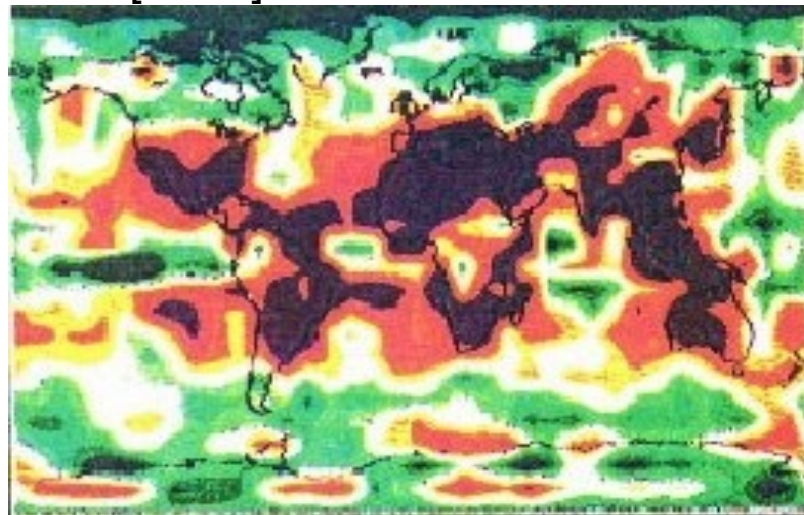
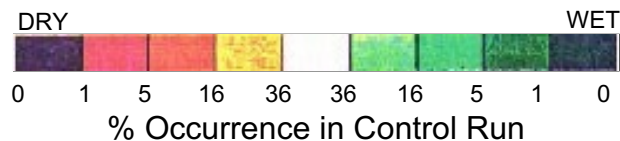


Fig. 1d in David Rind, R. Goldberg, James Hansen, Cynthia Rosenzweig, R. Ruedy, “Potential Evapotranspiration and the Likelihood of Future Droughts,” *Journal of Geophysical Research*, Vol. 95, No. D7, 6/20/1990, 9983-10004.

What Drives Drought?

- The water-holding capacity of air rises exponentially with temperature.
- Air 4°C warmer holds 33% **more** moisture at the **same** relative humidity.

(That's the flip side of “air cools. It holds less H₂O, 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 1°C 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 CO₂ (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 CO₂ - 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.

CO₂ fertilization **not** included

Temperature effects of doubled CO₂ will grow to 4.2 or 4.5°C after 2060, but continue to grow afterward, past 8°C by 2400, as positive feedbacks continue to amplify direct effects.

CO₂ **fertilization** (2 x CO₂) 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 CO₂ fertilization will falter.

Besides, with higher CO₂, 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.

So, with more CO_2 ,

leaves make more carbohydrates, but fewer proteins.

For **wheat, corn & rice**, **photosynthesis** in leaves
slows above 35°C (95°F) and **stops** above 40°C (104°F).

Warming (above 35° or 40°C) **hurts**
warm, tropical areas **harder** & **sooner**.

Over 1992-2003, warming above the norm **cut**
rice yields by 10+% / °C.

Over 1982-98, warming in 618+ US counties **cut**
corn & soybean yields ~17% / °C.

With more CO₂, 2°C warming **cut**
yields 8-38% for irrigated **wheat** in India.

Warmer nights since 1979 **cut**
rice yield growth 10%± in 6 Asian nations.

Warming since 1980 **cut**
wheat yield growth 5.5%, **corn** 3.8%.

With +1°C, weeds & pests constant, US yields fall:
corn 8%, rice 10%, wheat 5-7%, soybeans 3%.

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 29-30°C [84-86°F],
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.

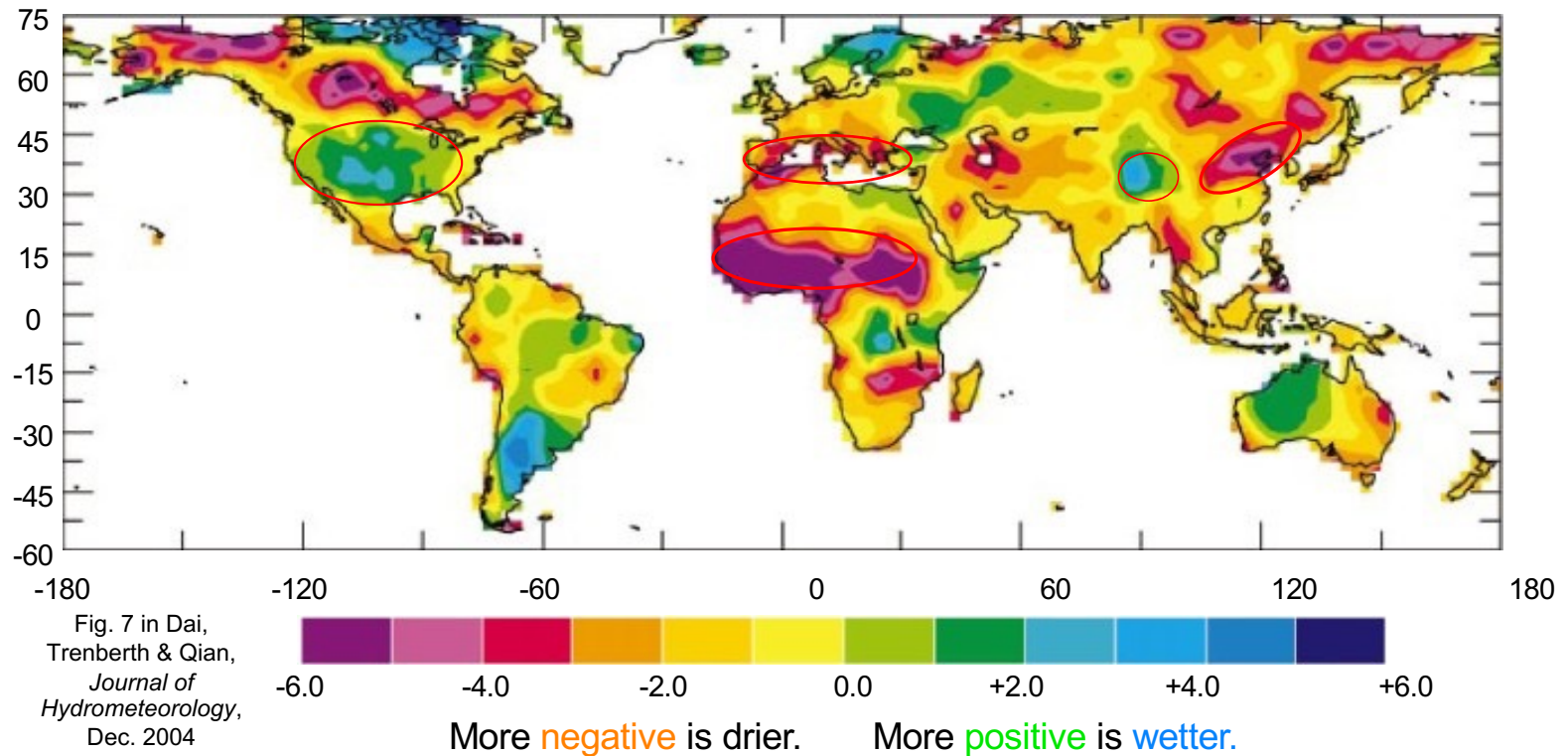
More rain can lessen losses. Plants transpire more water to cool off.

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

- 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**.

Deserts Are Already Spreading.

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

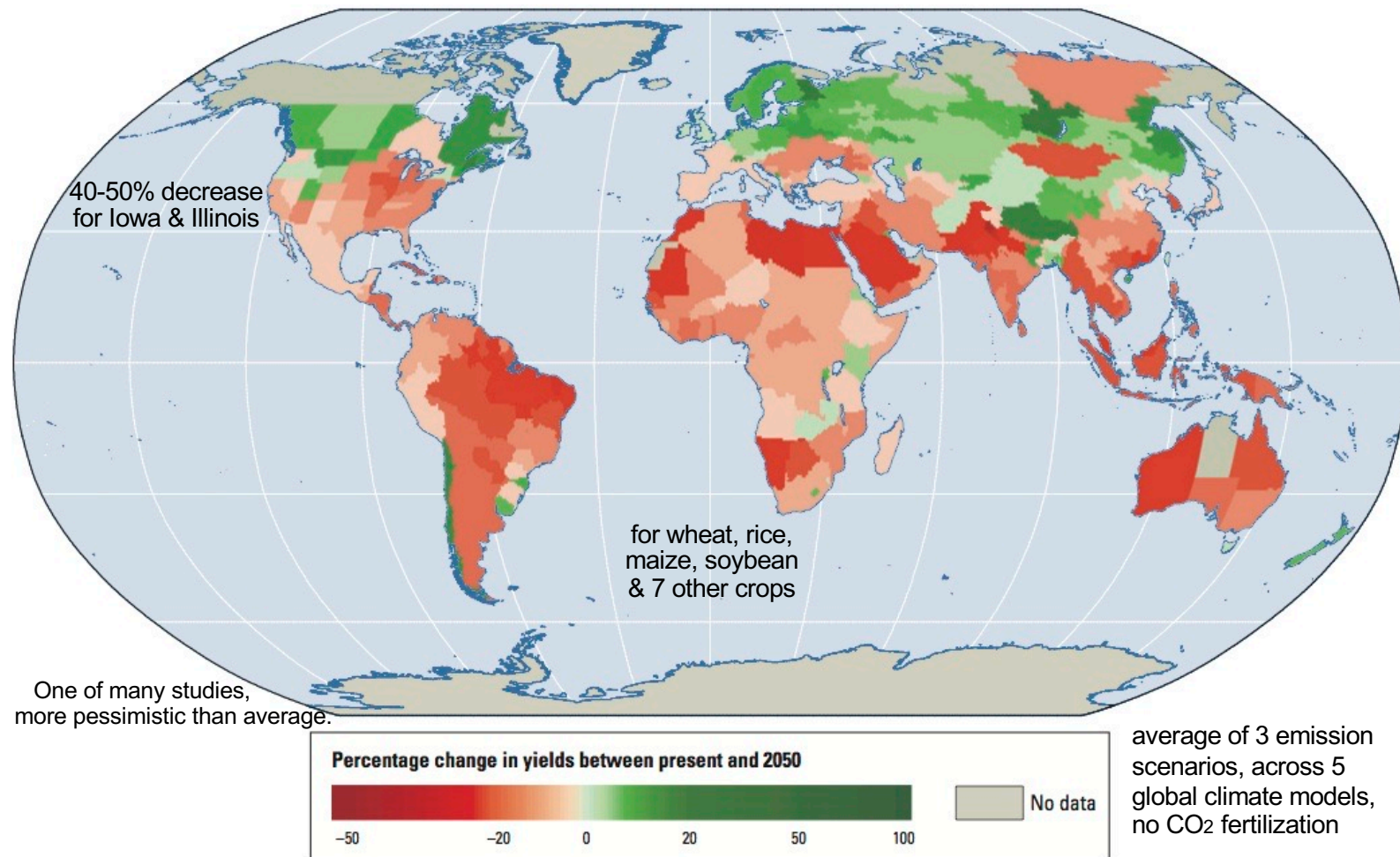


The Sahara Desert is spreading south, into Darfur & the Sahel. See Spain, Italy, Greece.

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.

Estimated Impact of +3°C on Crop Yields by 2050



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

1.1°C **warming** is here. 3-5°C more is in the pipeline. **Emissions** continue.

2°C warming is unavoidable, absent **MASSIVE** CO₂ removal.

Holding warming to 2°C, not 4°, **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**

4°C warming **threatens civilization itself**. 5°C is **worse**.

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

2°C 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** CO₂ 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.
- Crop yields rise nowhere, fall in the tropics.
- Greenland icecap collapse becomes irreversible.
- The Ocean begins its invasion of Bangladesh.

3°C Warming

Stern Review +
World is on this pace for 2100.

additional damages – may be delayed or avoided with MASSIVE CO₂ 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.
- Tropical diseases (malaria, etc.) spread farther & faster.
- 15-50% of species face **extinction**.

4°C Warming.

further damages - **avoidable**

Stern Review

- **Water** shortages afflict almost all people.
- **Crop** yields **fall** in **ALL** regions, by **1/3** in many.
- Entire regions **cease** agriculture altogether.
- Water wars, refugee crises, & terrorism become intense.
- **Methane** release from **permafrost** accelerates more.
- The **Gulf Stream** slows a lot, **monsoons** sometimes fail.
- West Antarctic **ice sheet** collapse speeds up.
- In US SE, at times it's too hot & humid to survive long outside.

5°C Warming

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

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

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

Other species fare worse.

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 said “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

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

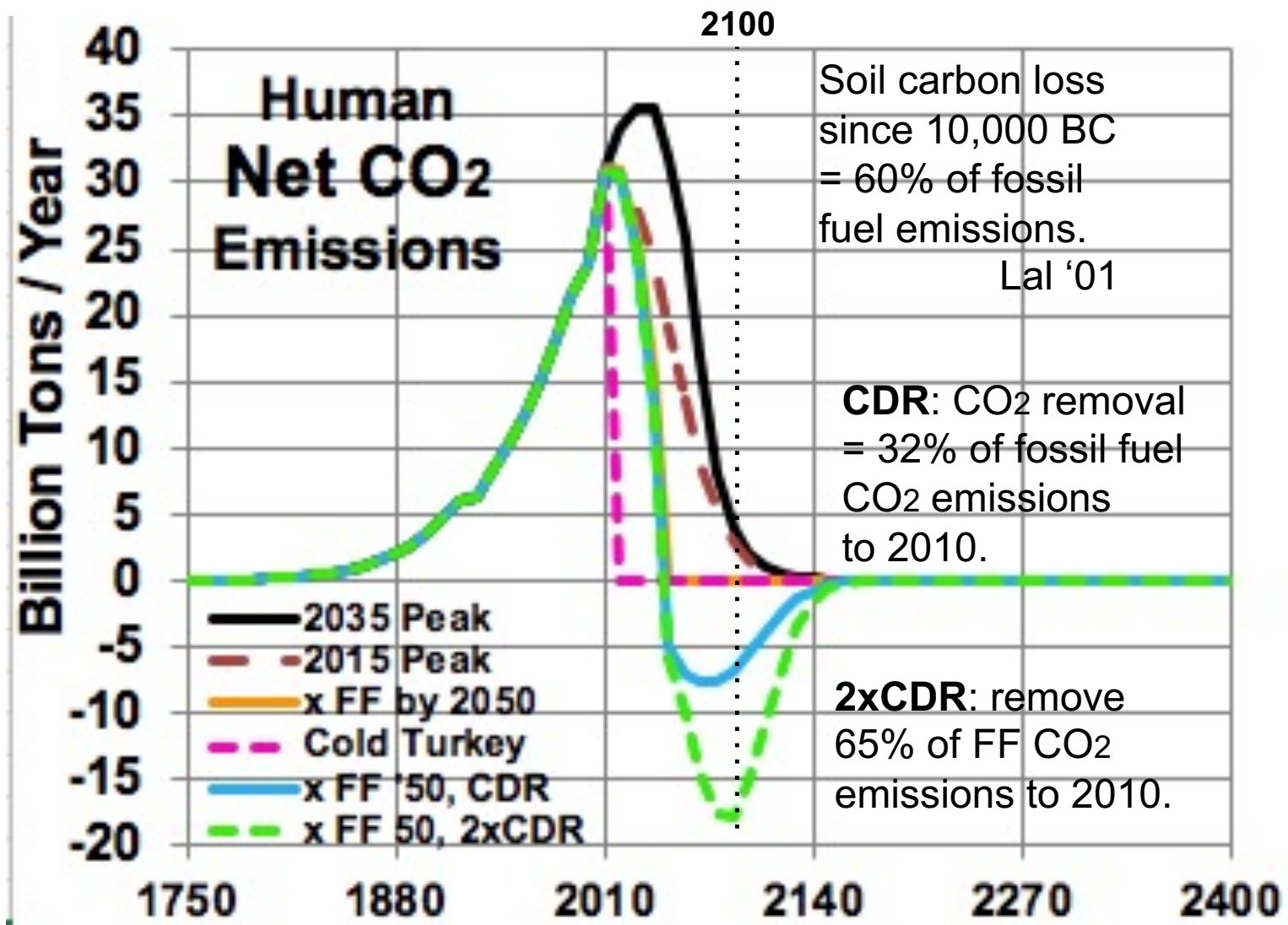
a **HUGE** hidden **TAX: \$50,000** / American
\$85 / Ton of CO₂

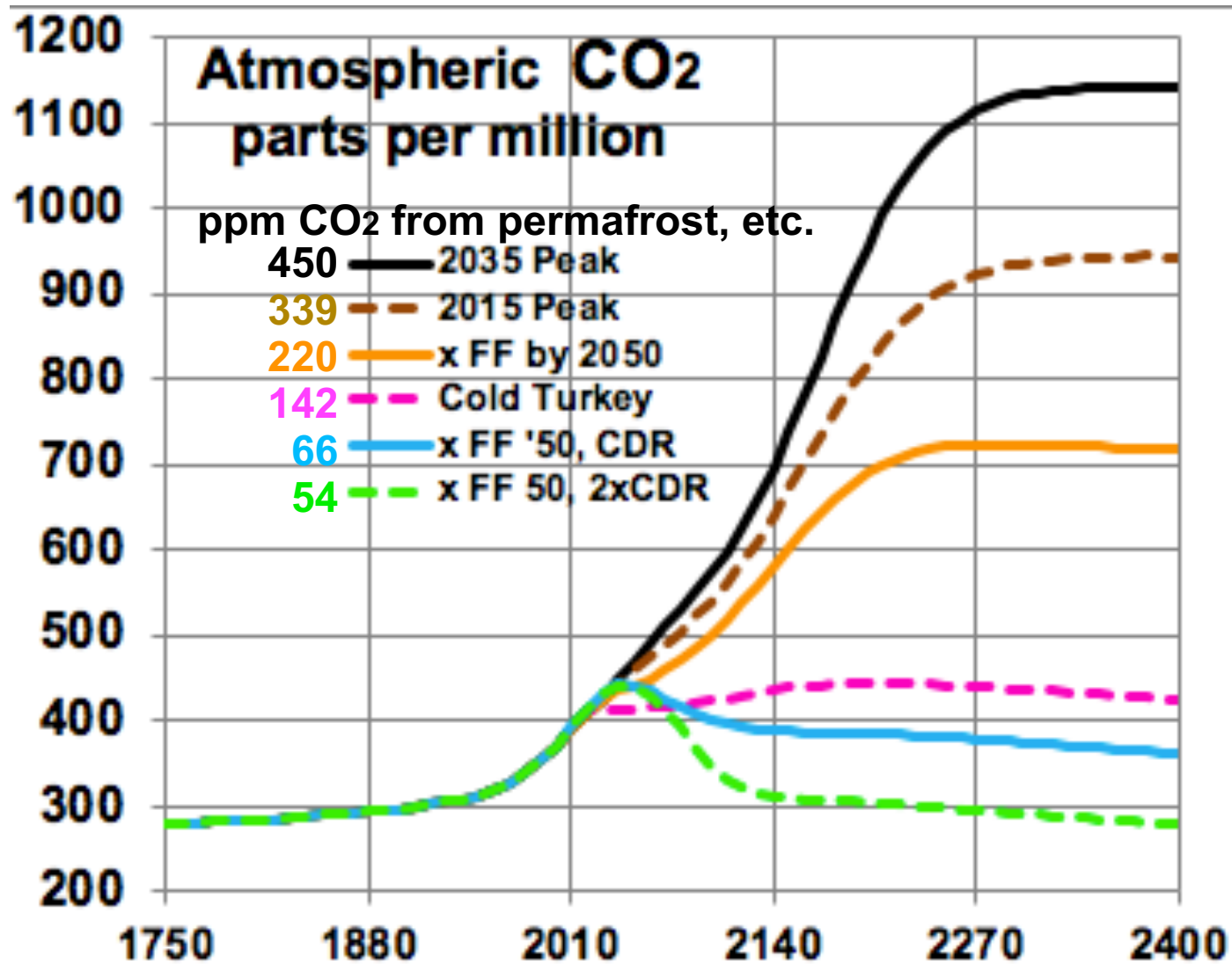
Costs of **Action**: **\$9-75** / year / American – CBO, EPA

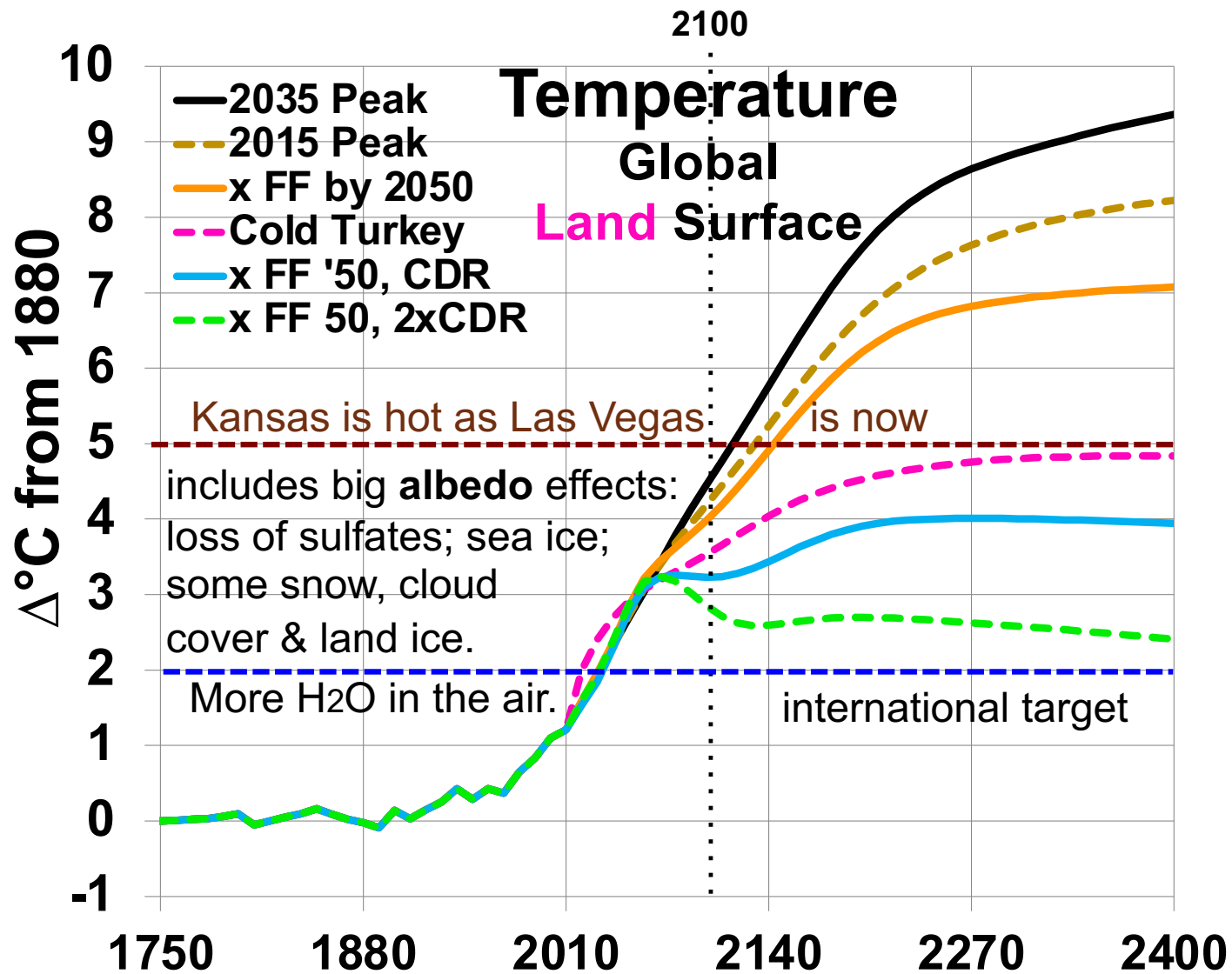
Spend **1%** of **GWP** (\$150 billion by US), each year, **± 2%**.

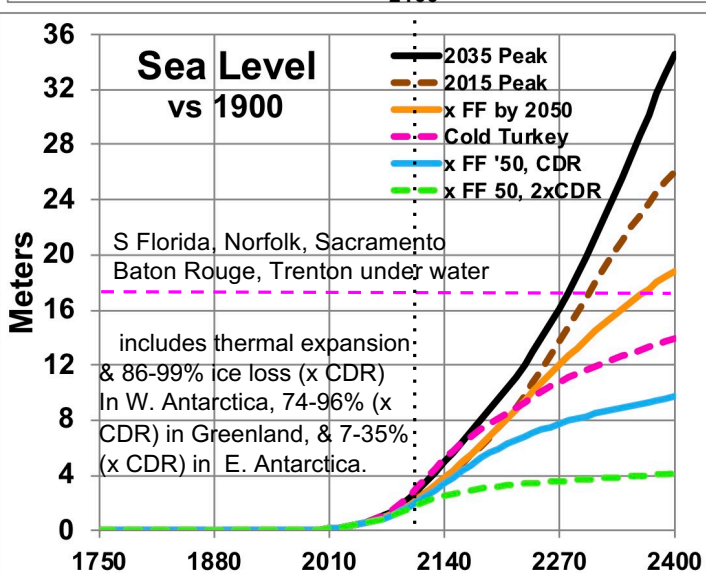
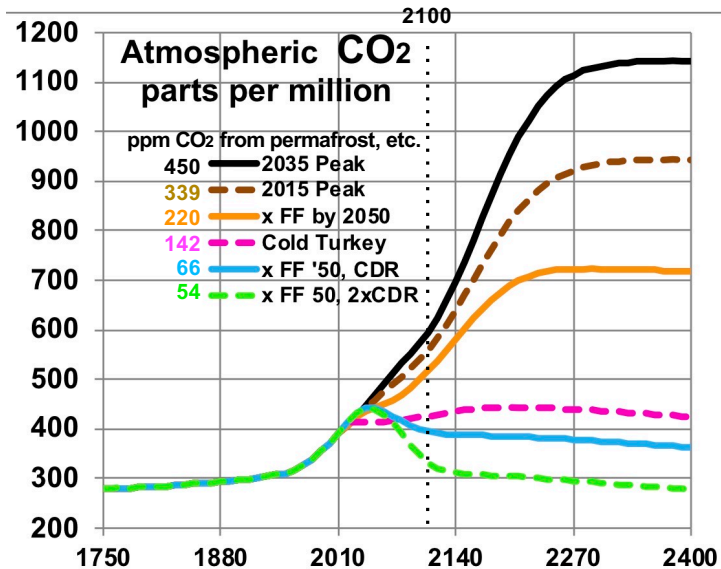
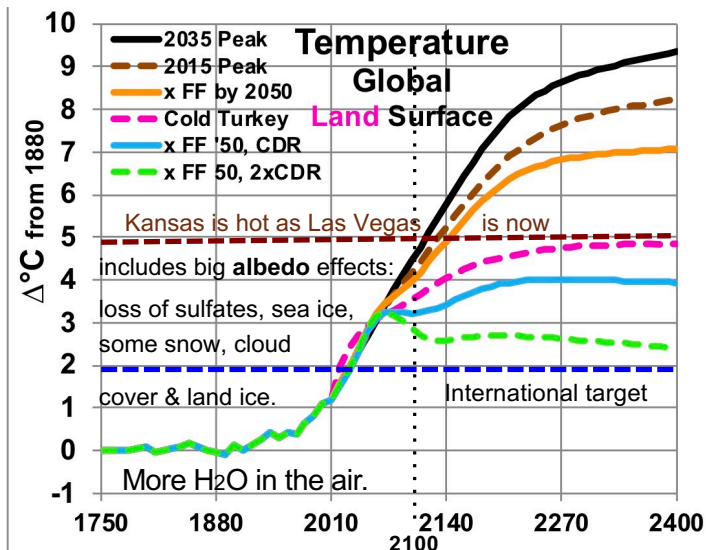
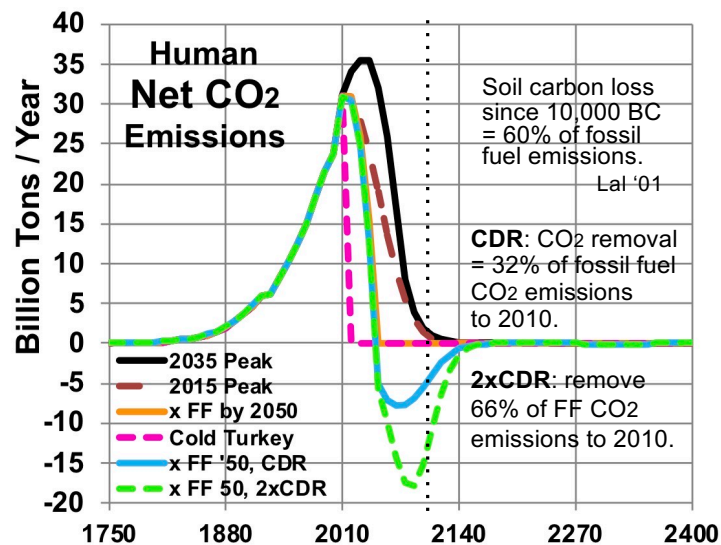
Damages fall to \$25 - \$30 / Ton of CO₂.

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









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 CO₂, in artificial leaves, ceramic honeycombs, etc.

Fans move air over sorbents to adsorb (solid) or absorb (liquid) the CO₂.

Then, move the CO₂-rich material to a different chamber.

Use heat or other methods to un-absorb & free purified CO₂ for permanent storage.

Pipe the CO₂ & inject it into concrete or basalt, making carbonate rock in months.

Or put the CO₂ down in oil fields or salt caverns and prevent leaks.

Since CO₂ in the air is dilute, removal requires almost 3 x the energy to extract the CO₂ as we got from burning carbon to **put** CO₂ in the air.

Recent CO₂ removal cost estimates are \$94-600 / ton. **Unlimited** quantity.

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

2 **Rocks** have **weathered** for eons, taking 1 GT CO₂ / year from the air.

Increase surface area a lot to speed it up to 5 GT CO₂ / year: **40** ppm by 2100?

Move CO₂ into crushed basalt, olivine, peridotite to make carbonate rock.

Scatter GT / year of olivine dust across the tropics: \$5-63 / ton of CO₂ removed?

Add small olivine gravel to farming soils, to fertilize it and remove CO₂.

Spread olivine dust on ocean surface, to capture CO₂ 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 CO₂ removed? However,
these methods raise carbon to the top foot of soil, from the next 2 feet down?

Warming soil increases microbe respiration,
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 / year? Cut CO₂ 40 ppm? for 20-40 years?

However, cows burp out 19% of all CH₄ emissions. Solution?

2% of a red algae in feed cuts cow CH₄ burps 70-98%. (13-18% of total CH₄.)

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 CO₂ / yr by 2050, at \$30-120 / ton? Cut CO₂ **5-20** ppm by 2100?

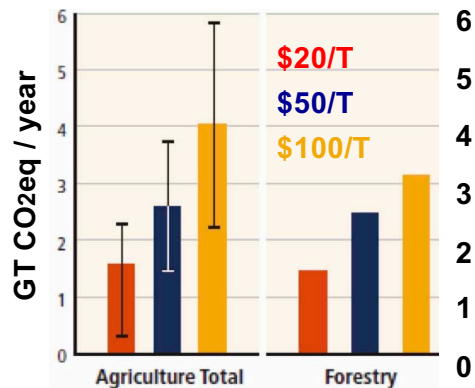
- 6 Farm the **oceans**: grow algae in pans miles on a side, many inches deep,
Add fertilizer (Fe, N, K, P, etc.) as needed.

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 less water in soils.



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

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.

- 8 Cut more **CH₄** emitted: end oil, gas, coal leaks (21%).

Capture and burn all landfill gas, etc. (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 <u>harm</u> ozone layer & health. Calcites <u>help</u> 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

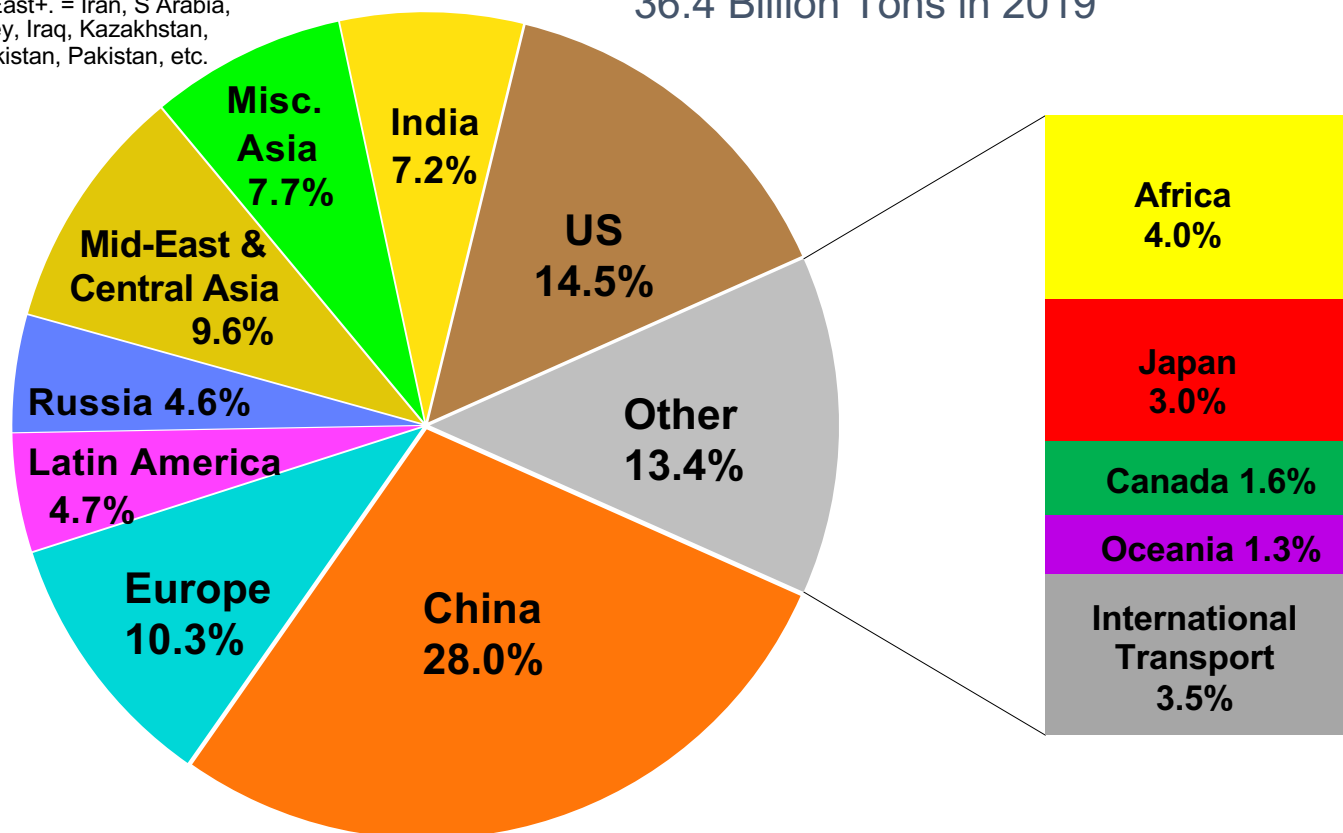
World CO₂ Emissions

Carbon Tracker

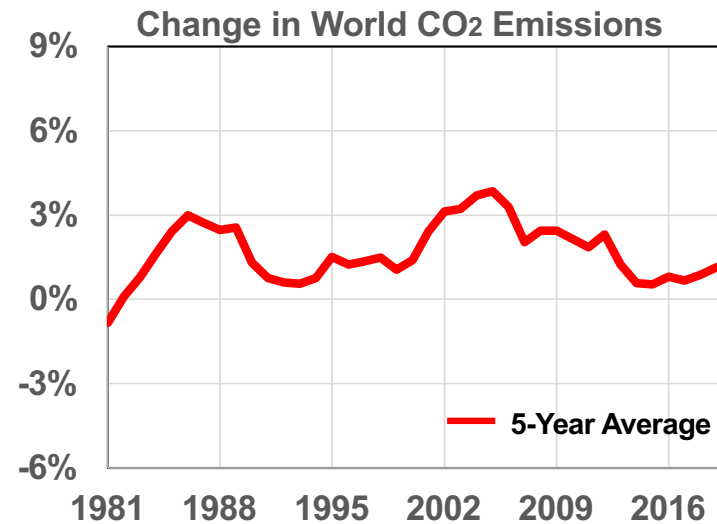
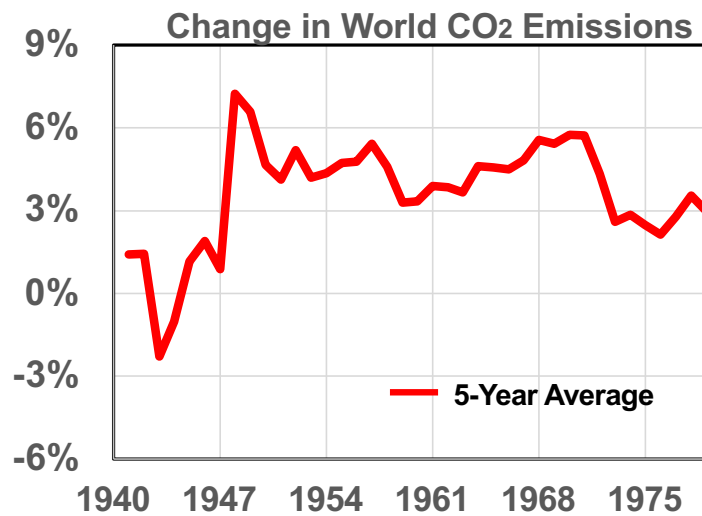
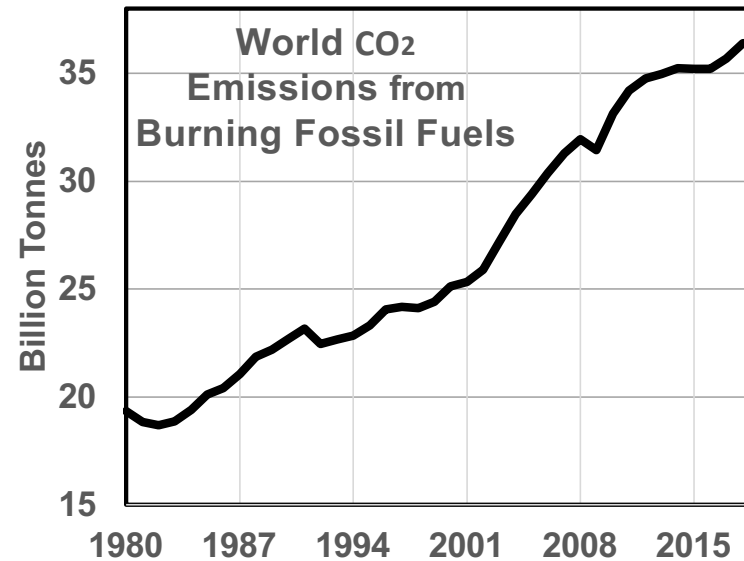
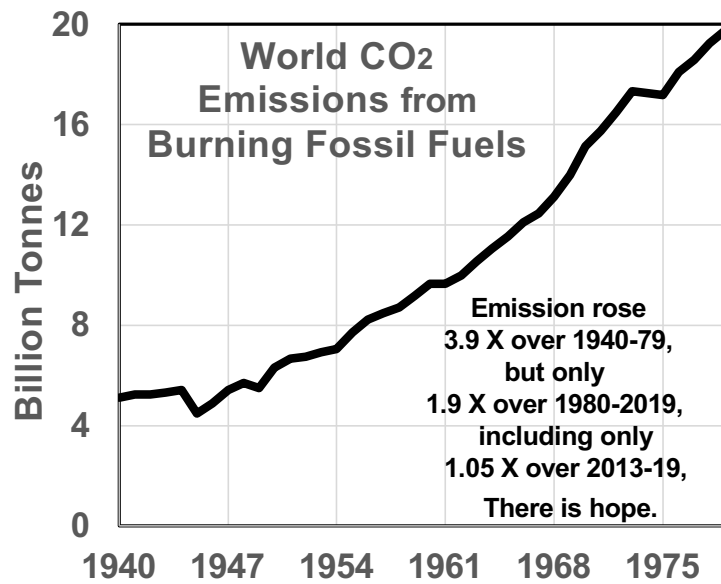
from Fossil Fuels

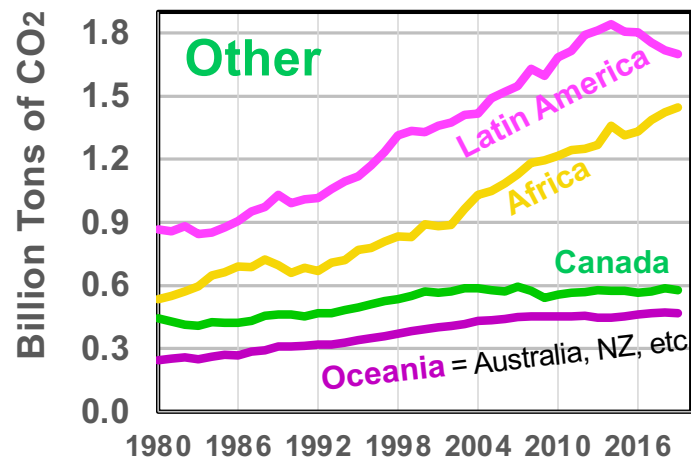
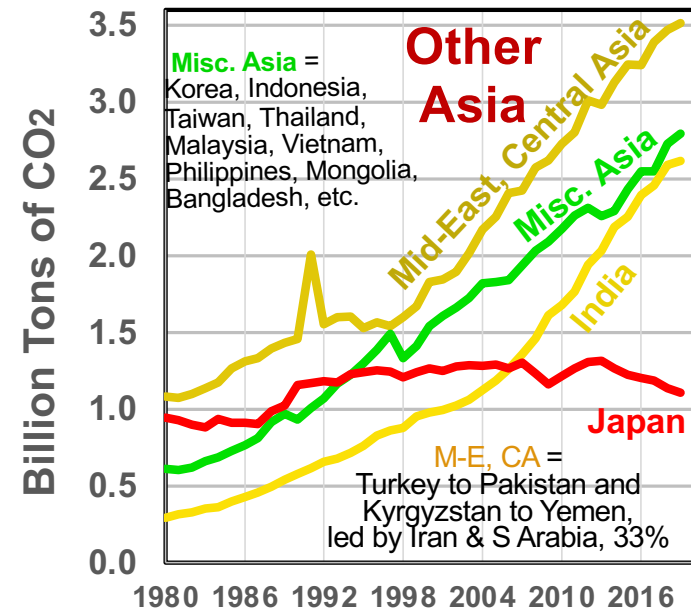
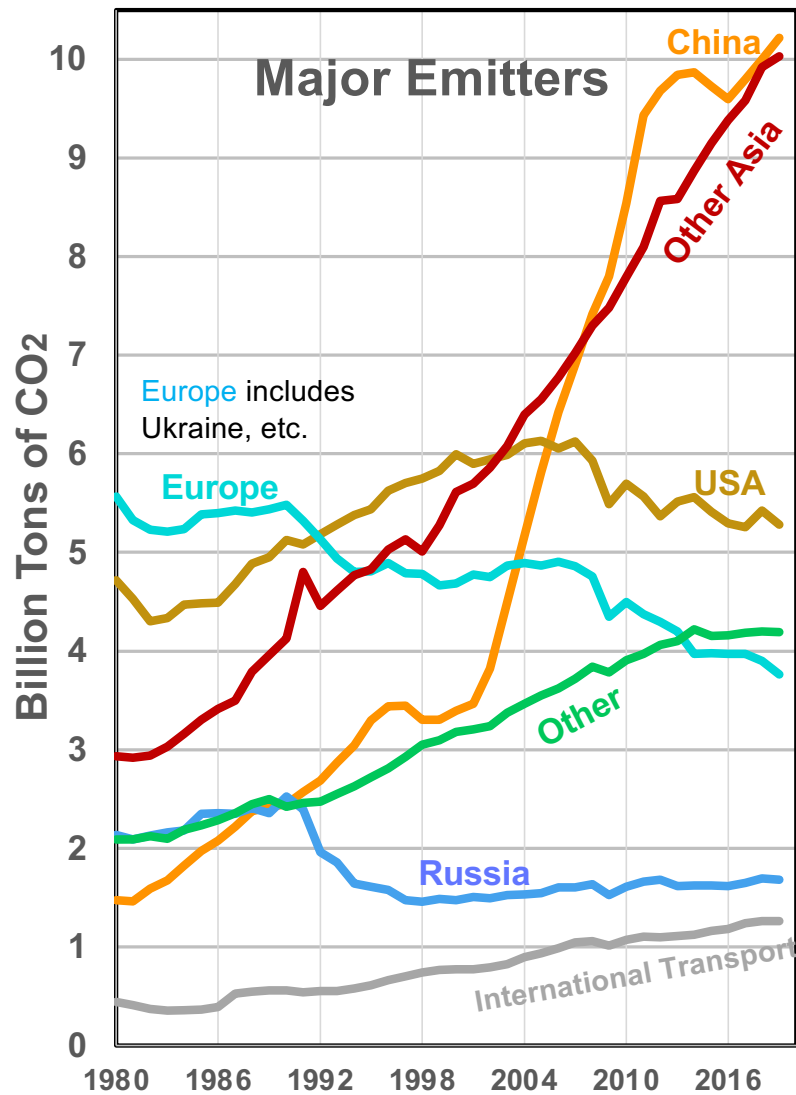
36.4 Billion Tons in 2019

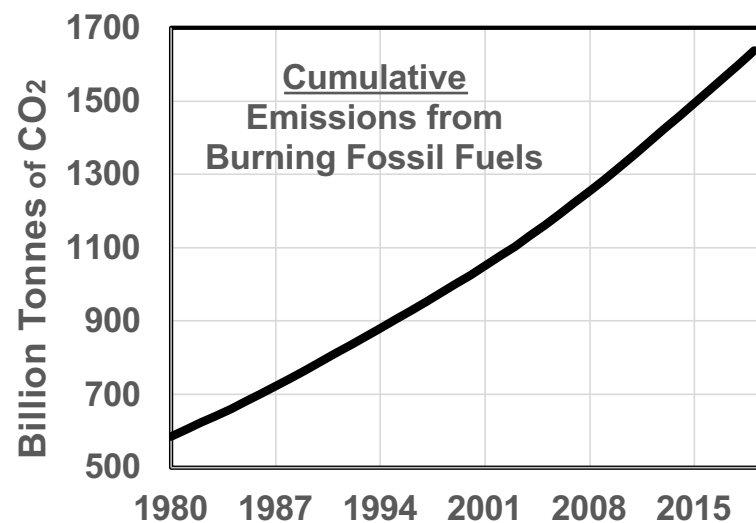
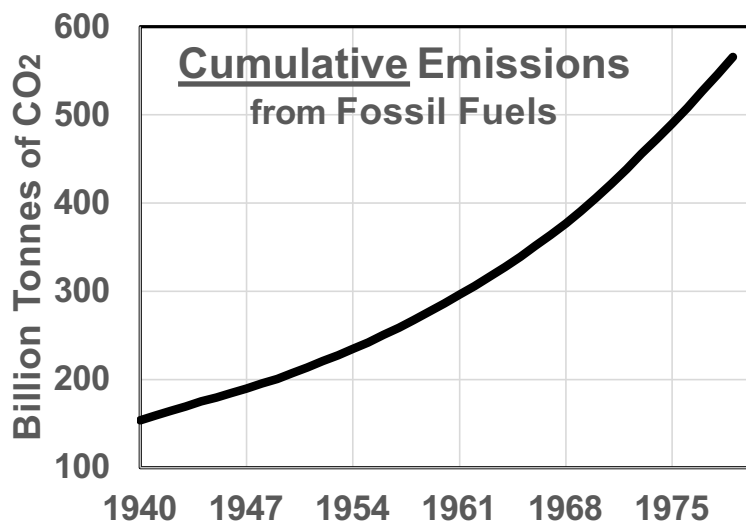
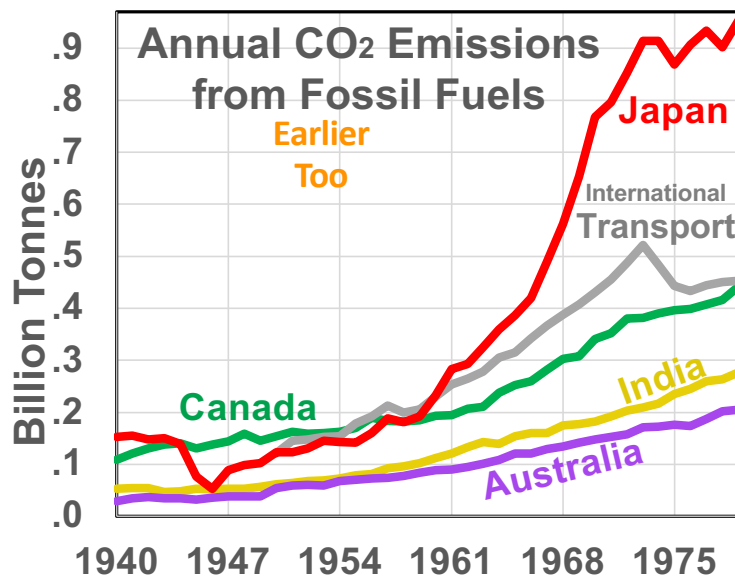
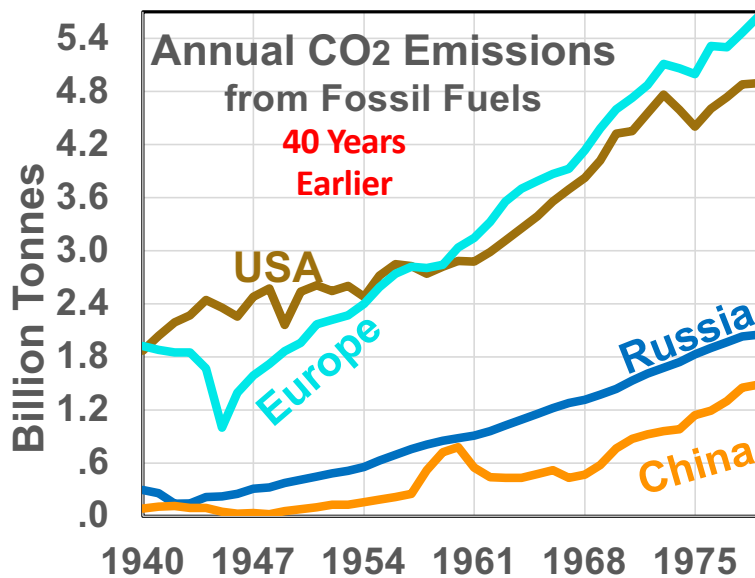
- * **Misc.** = Korea, Indonesia, Thailand, Taiwan, Malaysia, Vietnam, Bangladesh, etc.
- **Mid-East+.** = Iran, S Arabia, Turkey, Iraq, Kazakhstan, Uzbekistan, Pakistan, etc.

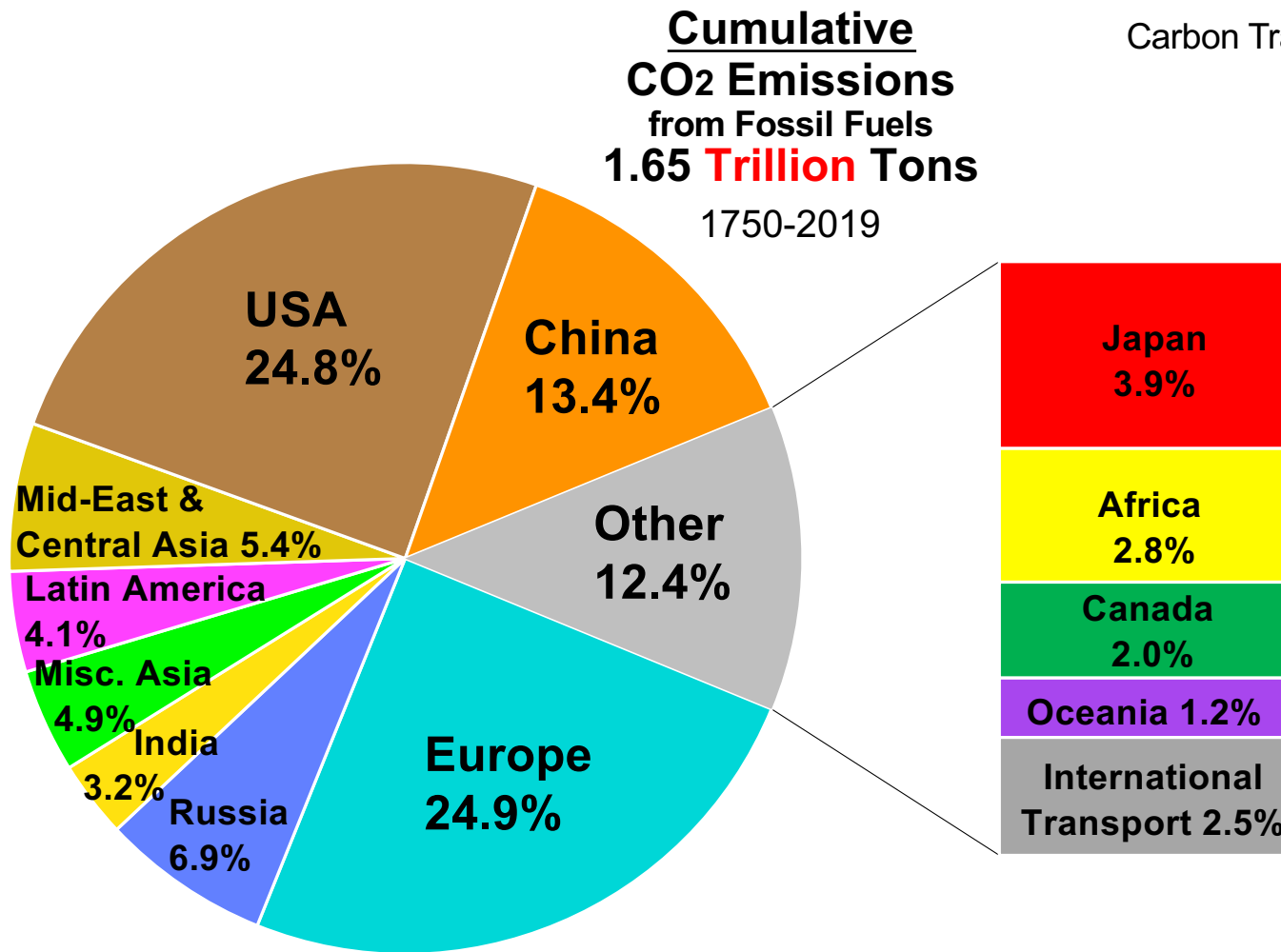


In 2019, US fossil fuel CO₂ came 46% from oil, 33% from natural gas, 21% from coal.
37% came from transportation, 32% from electricity, 20% from industry.



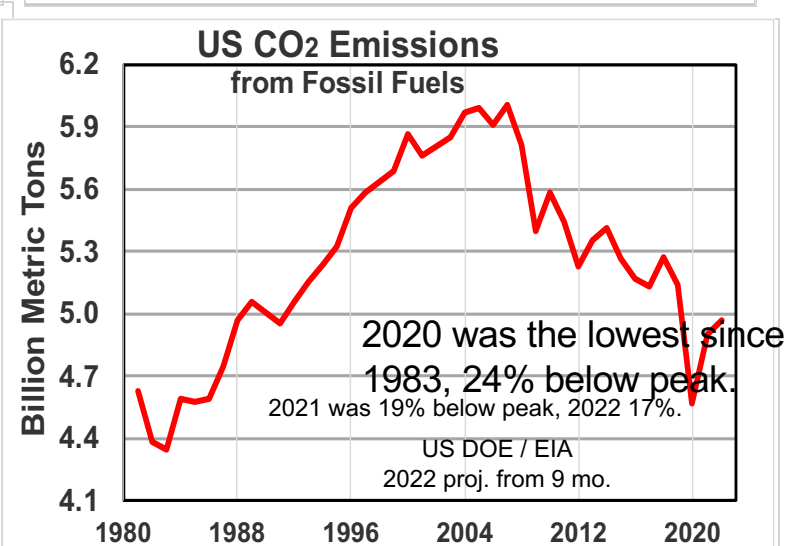
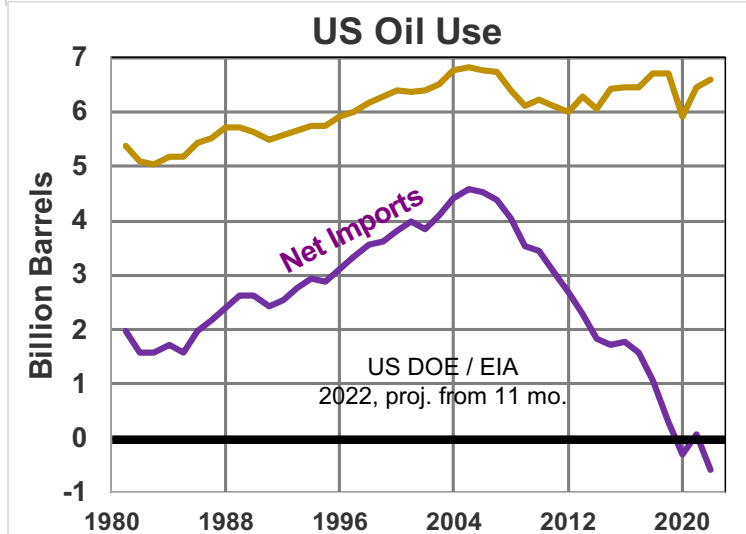
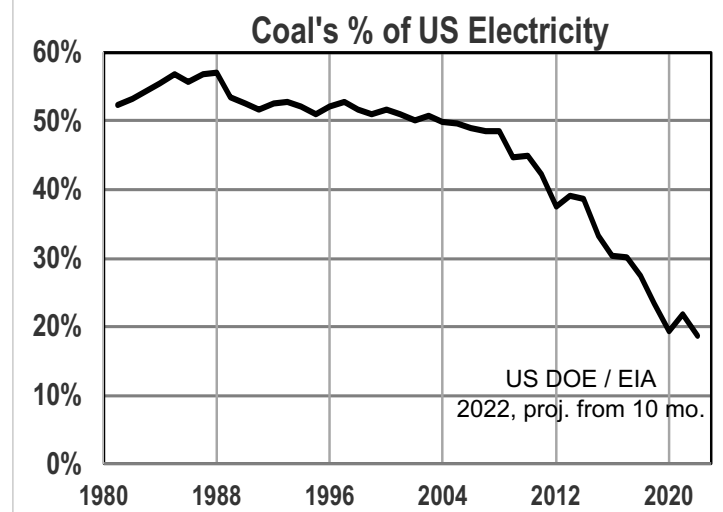
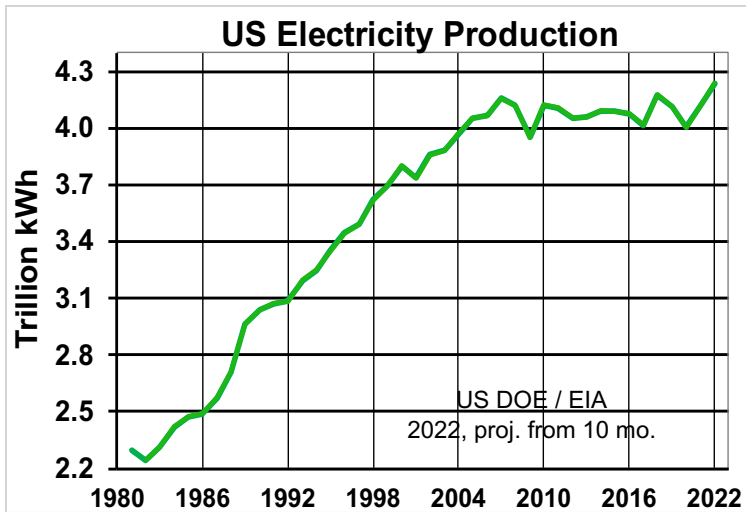






In 2013-14, China began CO₂ cap & trade around its 7 largest cities.
It was extended nationwide for making electricity in 2021.

America's Low-Carbon Revolution Has Begun



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

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

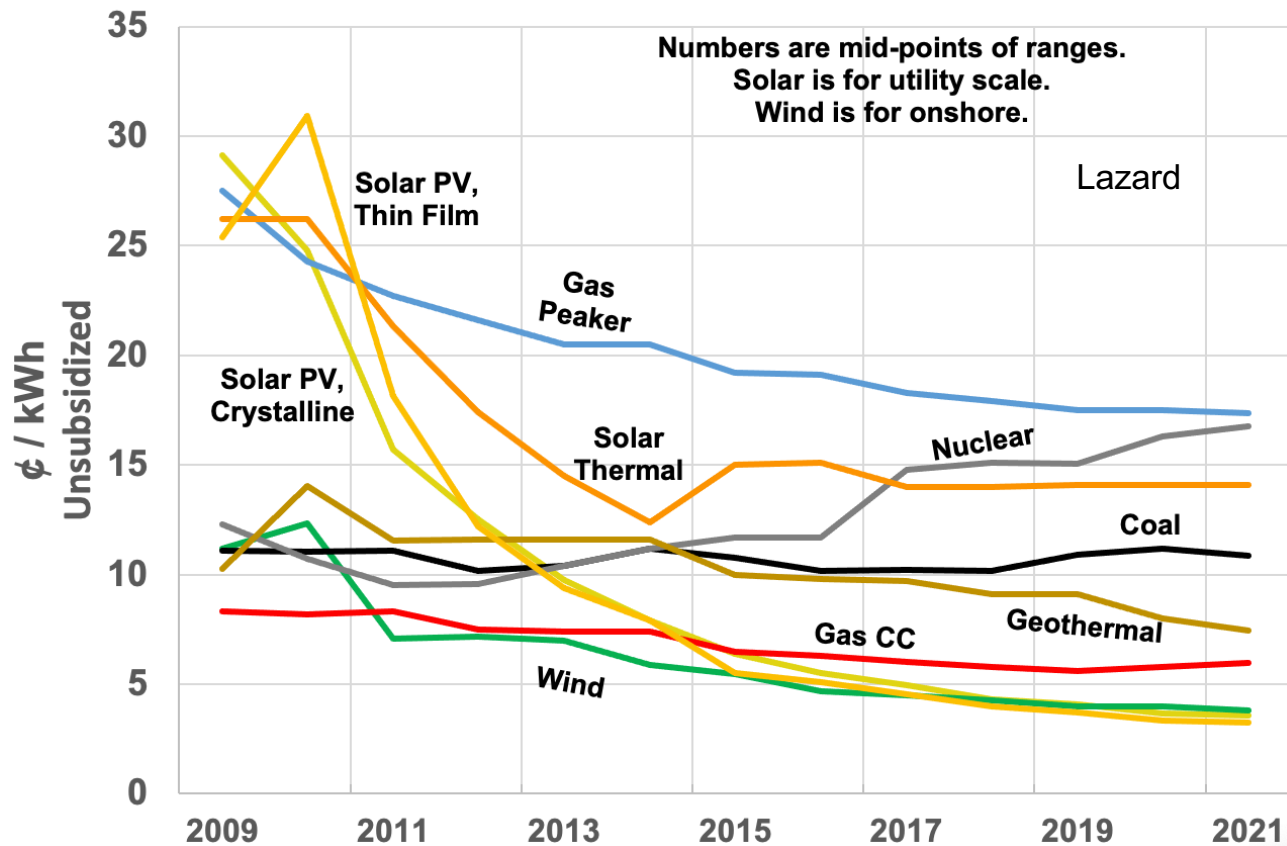
• Investors (> \$20 Trillion in assets) pushed 100+ companies to disclose **climate**-related risks. Markets now value high-carbon companies less. Carbon disclosure raises stock prices. Coal and oil company \$ / share prices have fallen a long way, especially coal. 100s of companies have set **decarbonization 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 CO₂ prices, *e.g.*, \$34-80 / ton.

• In 2017, 26 companies, 2 NGOs, & 17 individuals founded the **Climate Leadership Council**. It called for pricing CO₂ 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 +

Levelized Cost of New Electric Energy

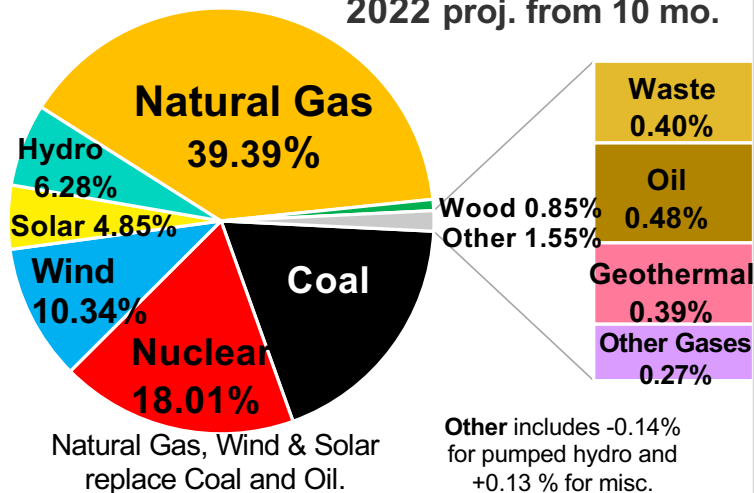


Solar & Wind are now the cheapest US electricity sources.

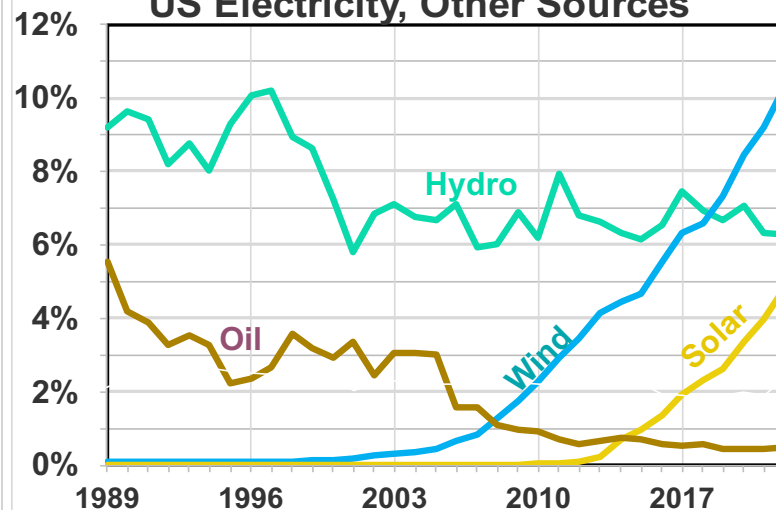
In most of the US, new solar and wind are cheaper than new gas-fired plants and the variable operating costs of coal-fired plants too.

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

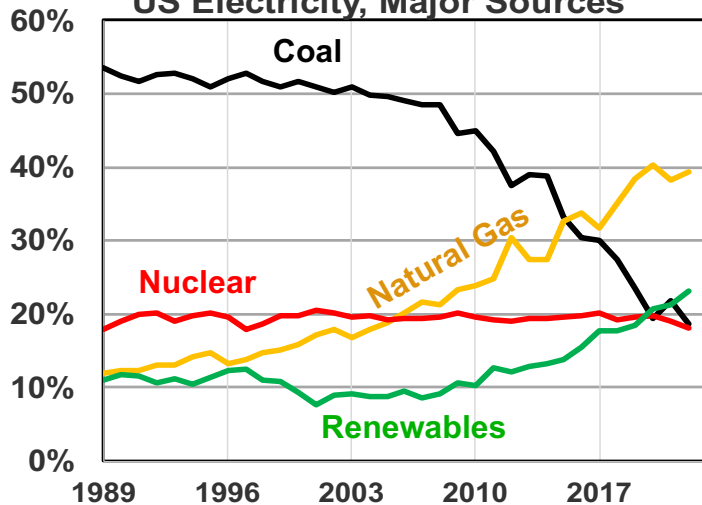
US Electricity Sources
2022 proj. from 10 mo.



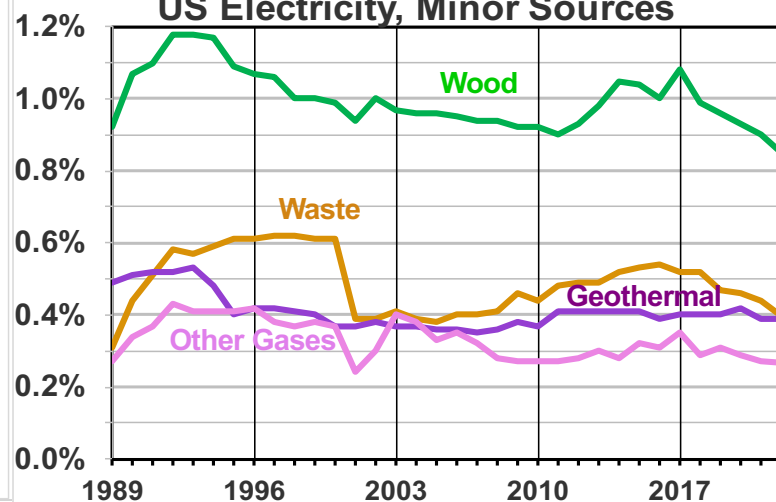
US Electricity, Other Sources



US Electricity, Major Sources



US Electricity, Minor Sources



The US Is Cutting CO₂ 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 CO₂ 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 afternoons.
- **Coal**: Phase it out. Remove CO₂ 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 10 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, 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 micro cogeneration, heat pumps.

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 CO₂ by 50% in 20 years is easy.

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 CO₂ 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 CO₂ emissions before 2050.

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

Include tax credits to **take CO₂ 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 CO₂), rising \$10 / year.

Citizens Climate Lobby

Return net proceeds as equal tax 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