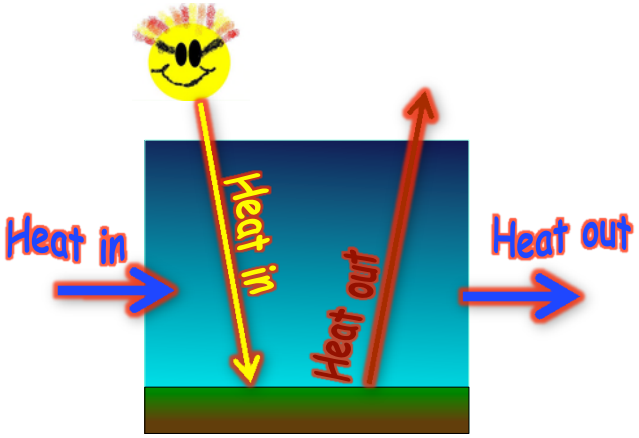
Climate Change:
Simple, Serious, Solvable

Scott Denning
Director of Education, CMMAP
Atmospheric Science, CSU
Email Scott.Denning@ColoState.edu for a copy of this presentation

Simple

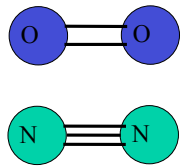
- Day is warmer than night
- Summer is warmer than winter
- Miami is warmer than Minneapolis

Heat Budgets



Dancing Molecules and Heat Rays!

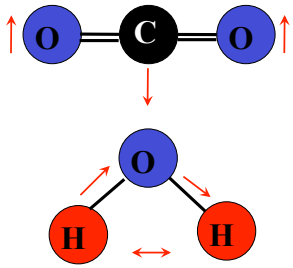
- Nearly all of the air is made of oxygen (O_2) and nitrogen (N_2) in which two atoms of the same element share electrons
- Infrared (heat) energy radiated up from the surface can be absorbed by these molecules, but not very well



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

Dancing Molecules and Heat Rays!

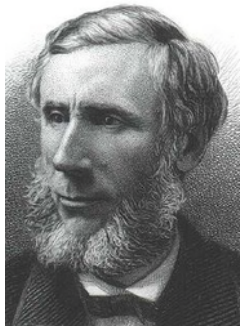
- Carbon dioxide (CO_2) and water vapor (H_2O) are different!
- They have many more ways to vibrate and rotate, so they are very good at absorbing and emitting infrared (heat) radiation



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

Absorption spectrum of CO2 was measured by John Tyndall in 1863

Common Sense

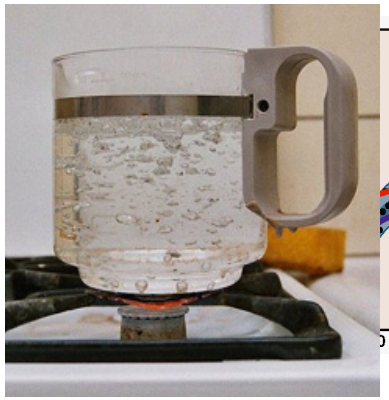


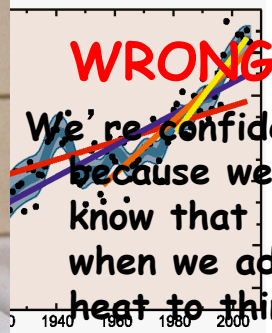
John Tyndall, January 1863

- Doubling CO_2 would add 4 watts to every square meter of the surface of the Earth, 24/7
- Doing that would make the surface warmer
- This was known before light bulbs were invented!

Common Myth #1

"Scientists confident about climate change because it's been warming up recently"

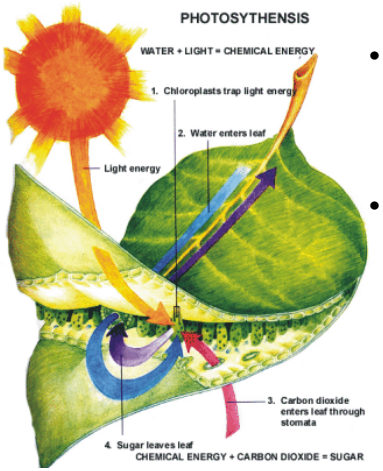




WRONG!

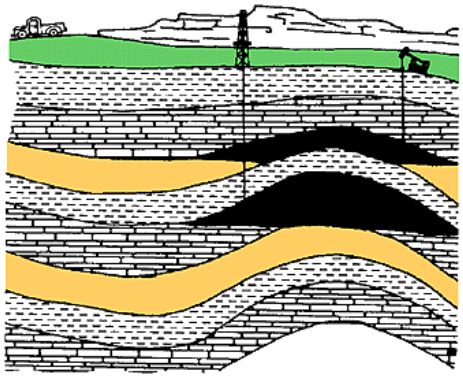
We're confident because we know that when we add heat to things, they warm up

Carbon, Life, and Energy



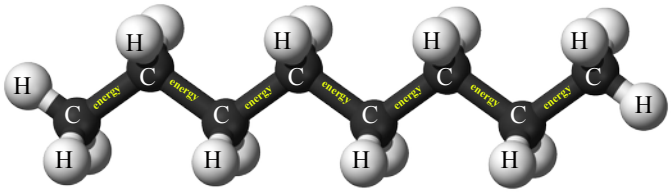
- Photosynthesis uses energy from the sun to **convert inorganic air (CO_2) to living biomass!**
- Most of this energy is **released through respiration (back to CO_2)** when plants are eaten by animals, bacteria, people

Fossil Fuels

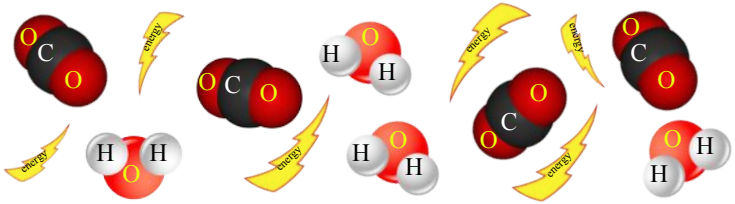


Some of the stored solar energy in biomass can be **preserved in fossilized remains**

Hydrocarbons, Energy, and CO_2



We dig this stuff ("fossil fuels") up and **burn it**, **harvesting the stored energy** to power civilization



Serious

The "Kaya Identity"

CO_2: CO_2 emissions resulting from human activities E: Primary energy consumption G: GDP P: Population

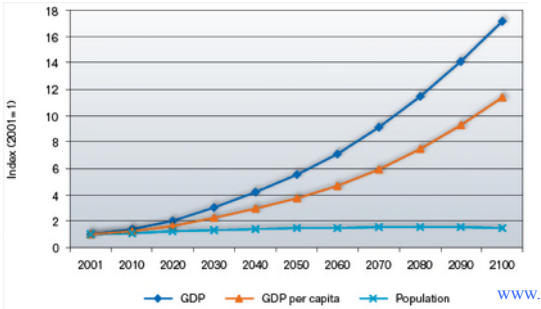
Kaya Identity: Formula that represents the relationship between human activities and CO_2 emissions

$$CO_2 = \frac{CO_2}{E} \times \frac{E}{G} \times \frac{G}{P} \times P$$

$\frac{CO_2}{E}$: CO_2 emissions per unit energy consumption; $\frac{E}{G}$: Energy efficiency of economic activities; $\frac{G}{P}$: Economic level per capita

- **Four factors determine future emissions:**
  - Population
  - Economic activity
  - Energy efficiency of economy
  - Carbon efficiency of energy

Population is not the driver of future climate!



UN Reference Scenarios

www.garnautreview.org.au

- Population to grow by 40% in 100 years
- Global **economy to grow by 1600%**

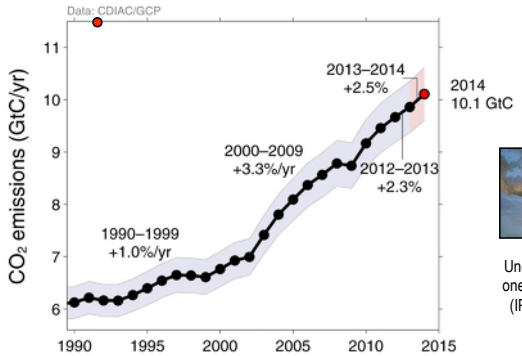
(assumes 2.8% annual GDP growth)

Billions and Billions

Shanghai 1991 and 2012

- Currently 7 billion people on Earth but only 1 billion use lots of energy
- Rapid development to 4 billion energy users over coming decades
- Population growth only 30% but energy growth 300% by 2100

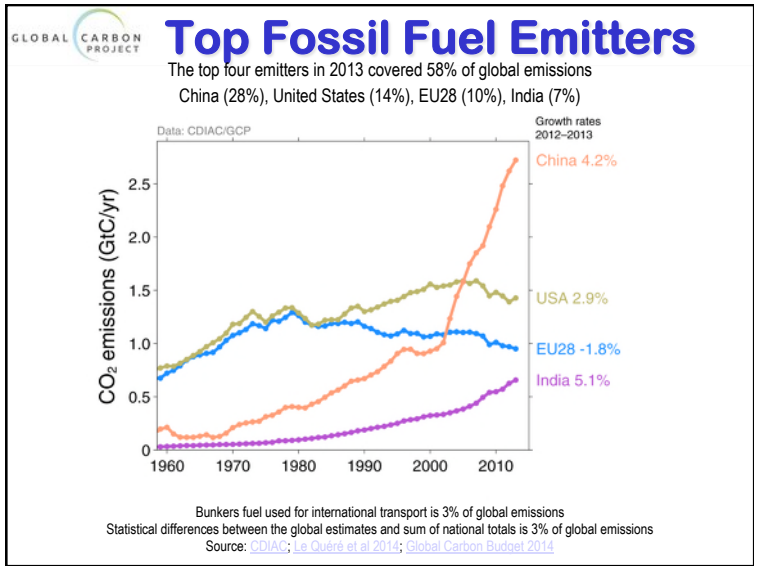
Fossil Fuel Emissions

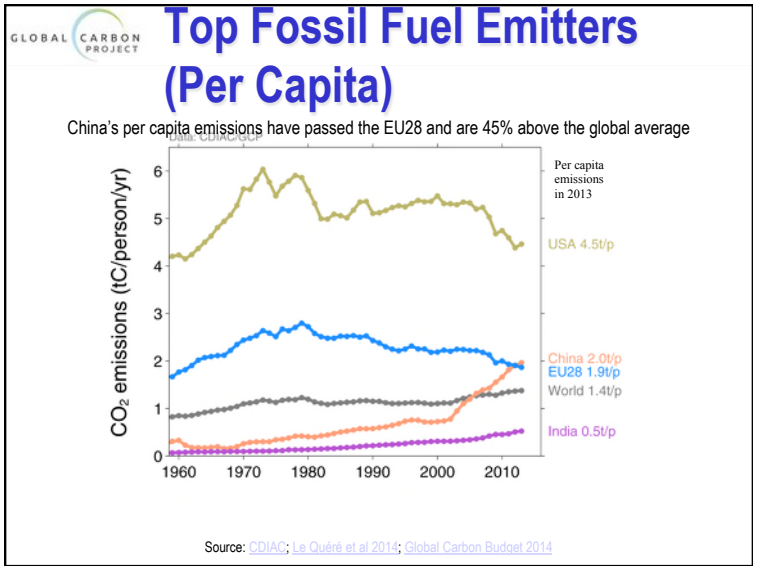


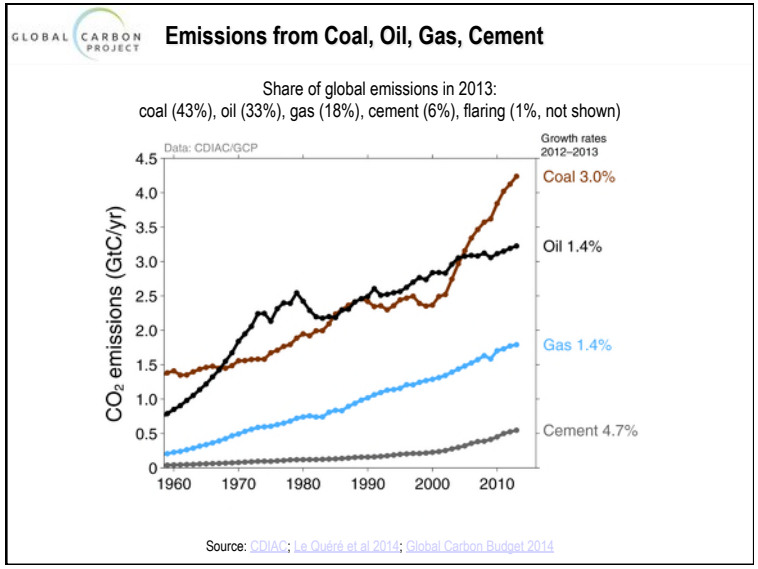
Uncertainty is ±5% for one standard deviation (IPCC "likely" range)

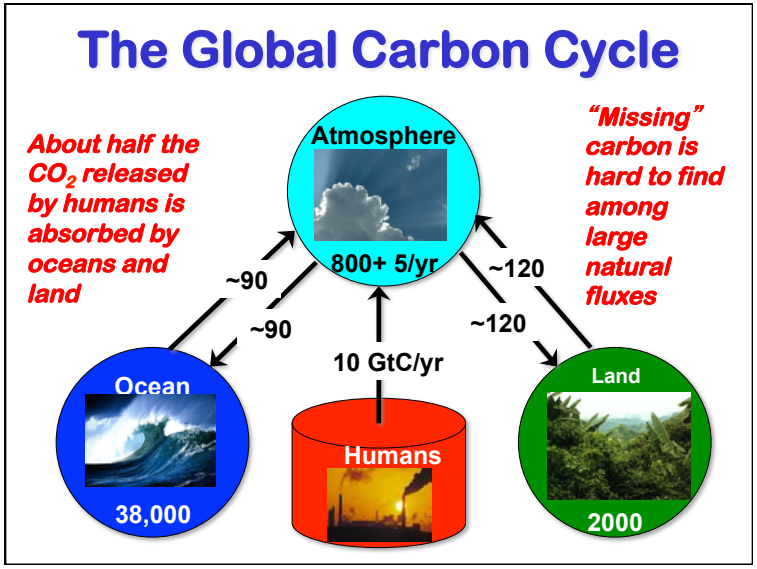
Estimates for 2011, 2012, and 2013 are preliminary

Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014

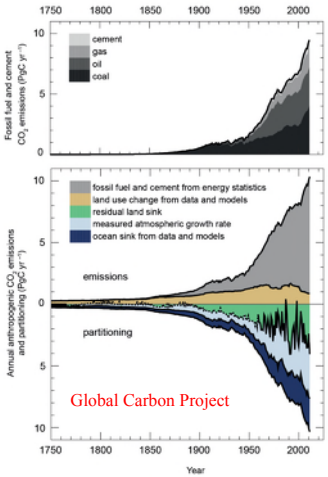

GLOBAL CARBON PROJECT
Top Fossil Fuel Emitters
The top four emitters in 2013 covered 58% of global emissions
China (28%), United States (14%), EU28 (10%), India (7%)
Data: CDIAC/GCP
Growth rates 2012–2013
China 4.2%
USA 2.9%
EU28 -1.8%
India 5.1%
CO2 emissions (GtC/yr)
0
0.5
1.0
1.5
2.0
2.5
1960
1970
1980
1990
2000
2010
Bunkers fuel used for international transport is 3% of global emissions
Statistical differences between the global estimates and sum of national totals is 3% of global emissions
Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014


GLOBAL CARBON PROJECT
Top Fossil Fuel Emitters (Per Capita)
China's per capita emissions have passed the EU28 and are 45% above the global average
Per capita emissions in 2013
USA 4.5t/p
China 2.0t/p
EU28 1.9t/p
World 1.4t/p
India 0.5t/p
CO2 emissions (tC/person/yr)
0
1
2
3
4
5
6
1960
1970
1980
1990
2000
2010
Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014


GLOBAL CARBON PROJECT
Emissions from Coal, Oil, Gas, Cement
Share of global emissions in 2013:
coal (43%), oil (33%), gas (18%), cement (6%), flaring (1%, not shown)
Data: CDIAC/GCP
Growth rates 2012–2013
Coal 3.0%
Oil 1.4%
Gas 1.4%
Cement 4.7%
CO2 emissions (GtC/yr)
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
1960
1970
1980
1990
2000
2010
Source: CDIAC; Le Quéré et al 2014; Global Carbon Budget 2014


The Global Carbon Cycle
About half the CO2 released by humans is absorbed by oceans and land
"Missing" carbon is hard to find among large natural fluxes
Atmosphere
800+ 5/yr
~90
~90
~120
~120
10 GtC/yr
Ocean
38,000
Humans
Land
2000

Carbon Sources and Sinks



- Half the carbon from fossil fuels remains in the atmosphere
- The other half goes into land and oceans
- Land sink was unexpected is very noisy, and remains unreliable in future
- Future of carbon sinks is much harder to predict than temperatures

Where Has All the Carbon Gone?

- Into the oceans
  - **Solubility pump** (CO_2 very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow "rain" of organic debris)
- Into the land
  - **CO_2 Fertilization** (plants eat CO2 … is more better?)
  - **Nutrient fertilization** (N-deposition and fertilizers)
  - **Land-use change** (forest regrowth, fire suppression, woody encroachment … but what about Wal-Marts?)
  - Response to **changing climate** (e.g., Boreal warming)

Carbonate Equilibria in Solution

Three equations (equilibria) in five unknowns

$$CO_2(gas) \longleftrightarrow CO_2(dissolved) \qquad [CO_2(aq)] = K_0 pCO_2$$

$$[CO_2(aq)] + H_2O \longleftrightarrow [H^+] + [HCO_3^-] \qquad K_1 = [H^+][HCO_3^-]/[CO_2(aq)]$$

$$[HCO_3^-] \longleftrightarrow [H^+] + [CO_3^{2-}] \qquad K_2 = [H^+][CO_3^{2-}]/[HCO_3^-]$$

Add two more constraints

$$TA = [HCO_3^-] + 2[CO_3^{2-}] + [B(OH)_4^-] + [NO_3^-] + [OH^-] - [H^+] \pm \text{minor species}$$

(Titration Alkalinity)

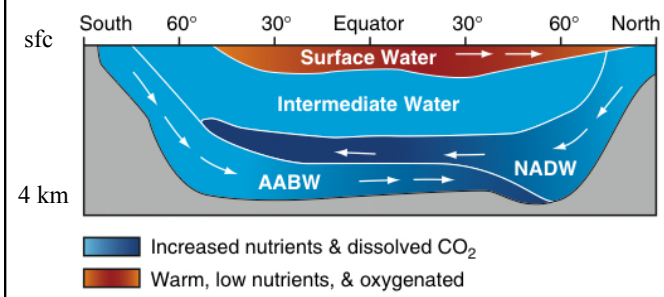
$$B(OH)_3 + H_2O \leftrightarrow H^+ + B(OH)_4^-, \qquad K_b = [H^+][B(OH)_4^-]/[B(OH)_3]$$

(Boric acid dissociation)

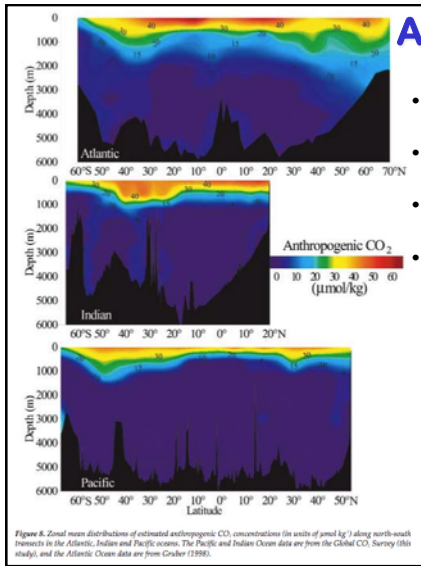
$$\Sigma B = 1.179 \times 10^{-5} S \text{ mol/kg}$$

(Salinity)

Vertical Structure of the Oceans

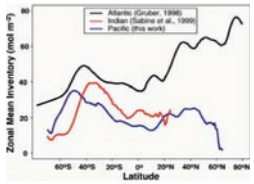


- Warm buoyant "raft" floats at surface
- Cold deep water is only "formed" at high latitudes
- Very stable, hard to mix, takes ~ 1000 years!
- Icy cold, inky black, most of the ocean doesn't know we're here yet!



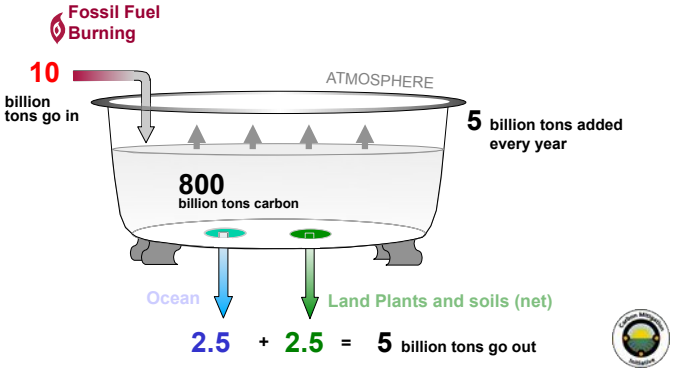
Anthropogenic DIC

- Estimated from total observed DIC using stoichiometry
- Most anthropogenic DIC confined to top few 100 m
- "Shoaling" in tropics, convection at higher latitudes
- Some "contamination" of bottom water in Atlantic (both hemispheres)

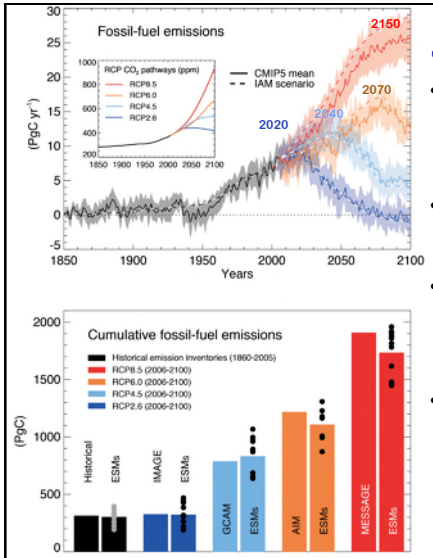


(Feeley et al, 2001)

CO_2 "Budget" of the World



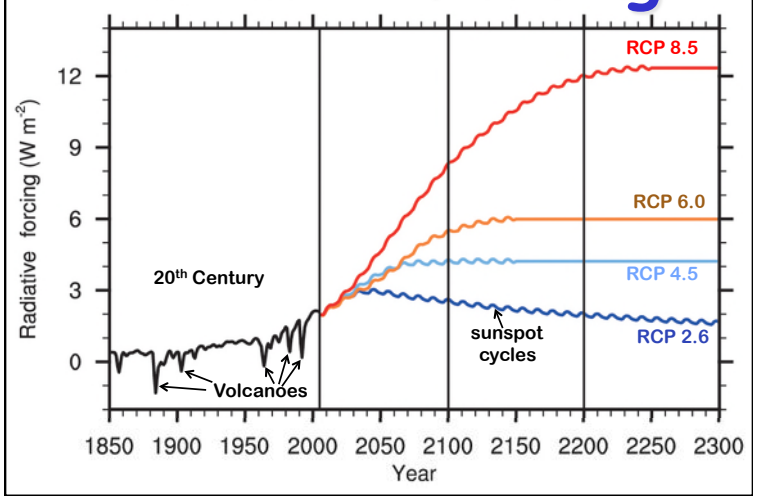
Climate forcing comes from the water, not from the faucet!



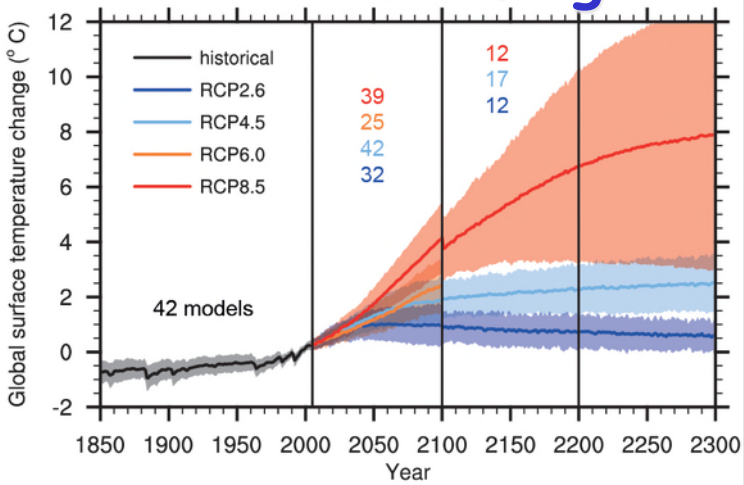
Scenarios

- Not predictions … "what if" experiments
- None are more or less likely
- Depends on economics and policy (politics)
- Emissions peak in
  - 2020 (RCP2.6)
  - 2040 (RCP4.5)
  - 2070 (RCP6.0)
  - 2150 (RCP8.5)

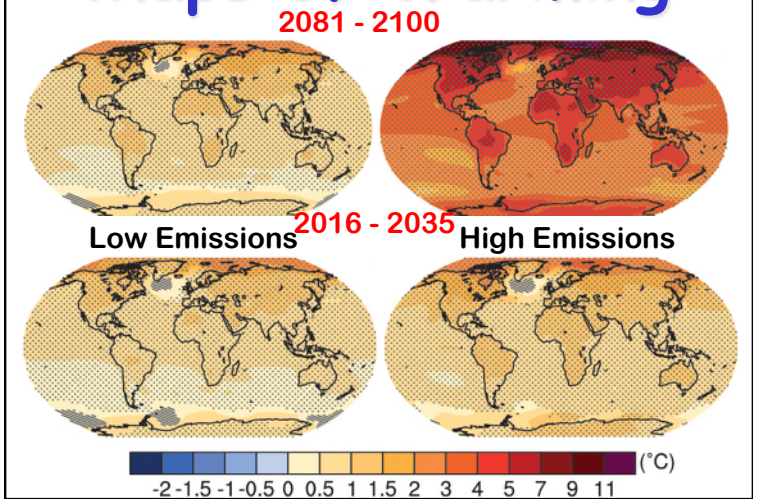
Radiative Forcing



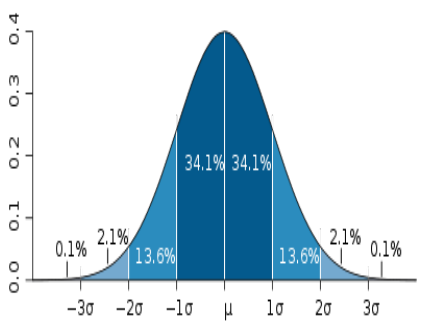
Global Warming



Maps of Warming

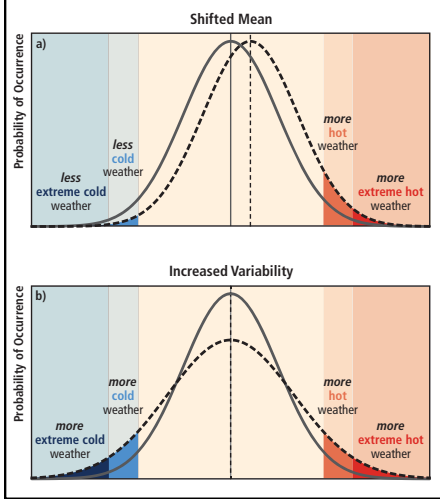


Bell Curves



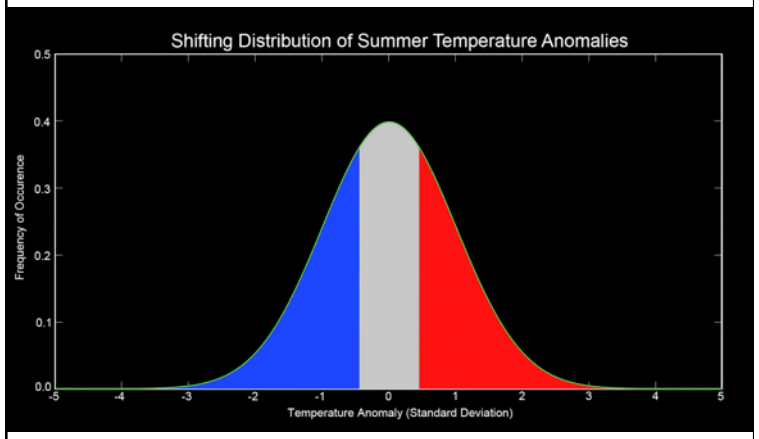
- "Normal distribution" or "Gaussian"
- Average = Mean = Median = Mode
- "Standard deviation" σ measures "width"
  - 68% of values fall within 1σ of mean
  - 95% within 2σ of mean, 99.6% within 3σ

Means & Extremes

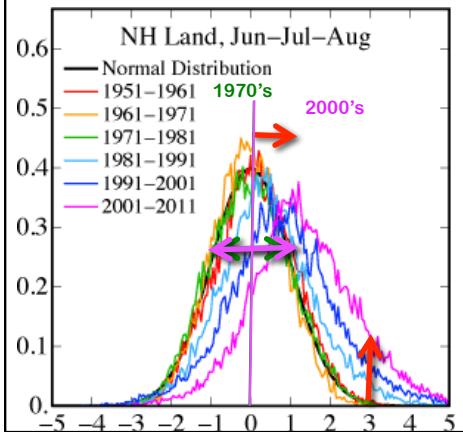


- People care more about extremes (tails) than averages
- Small changes in averages produce large changes in extremes
- Changes in the "spread" also produce changes in extremes

Historic Land Temps



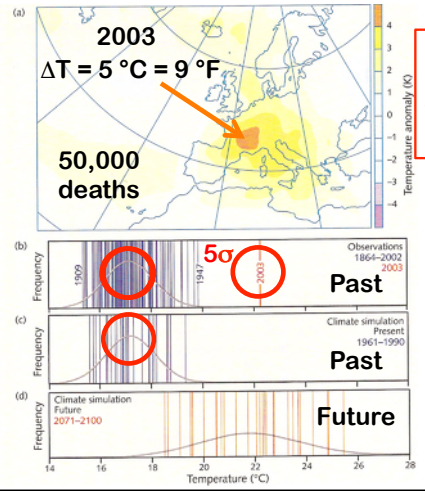
Summer Temperatures



- Shift of mean by about +1 σ
- Increase in variability (σ) as well
- **15-fold increase** in freq of temps that were at 99%-ile in 1970

Heat Wave Statistics

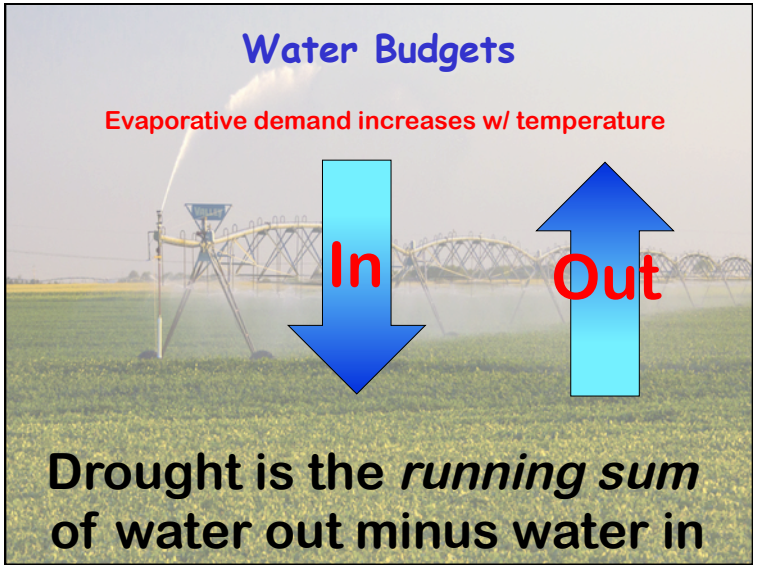
Figure 7.19 Characteristics of the summer 2003 heatwave in Europe. (a) June, July, August (JJA) temperature anomaly with respect to 1961–90; (b) to (d) JJA temperatures for Switzerland; (b) observed during 1864–2003; (c) simulated with a regional model for the period 1961–90; (d) simulated for 2071–2100 under the SRES A2 scenario. The vertical bars in (b) to (d) represent mean summer surface temperature for each year of the time period considered; the fitted Gaussian distribution is indicated in black.



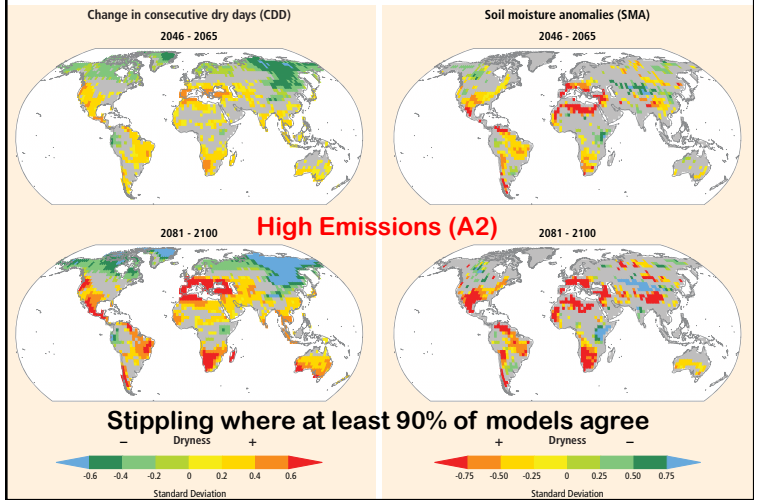
once in 10,000 years

2 years out of 3

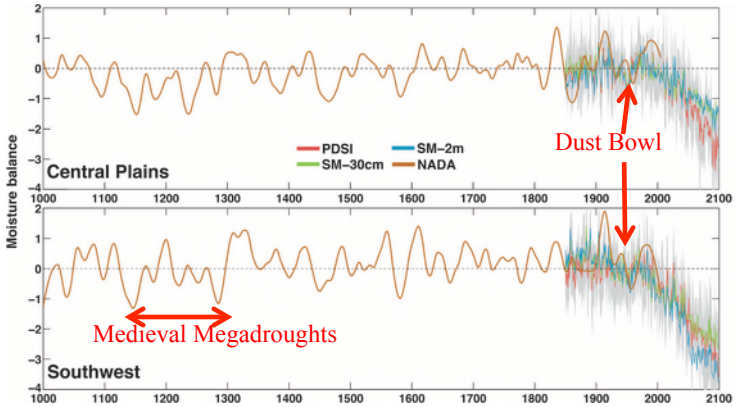
Water Budgets



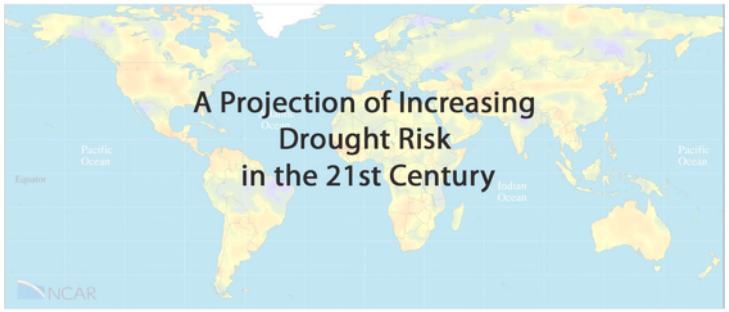
Changes in Drought



Droughts Past & Future



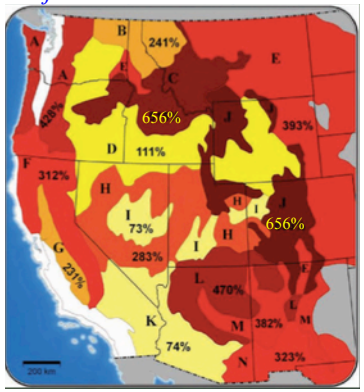
Palmer Drought Severity Index



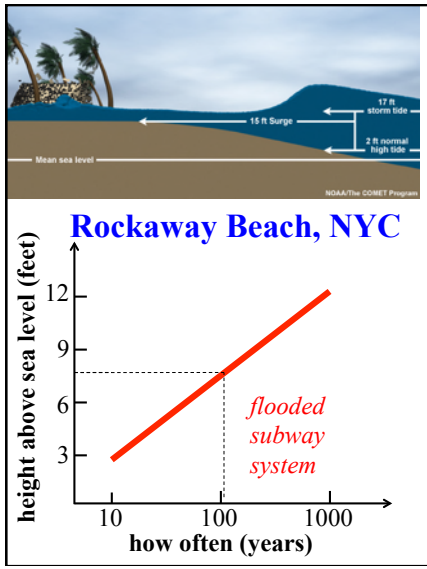
Warming Promotes Wildfire

1. Warmer air increases **evaporative demand** on forests
2. Longer **warm season** depletes soil moisture
3. More frequent extremely **hot, dry, windy days** when fires are uncontrollable

Projected Increase in Area Burned



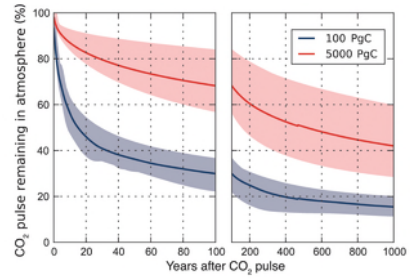
NRC 2011



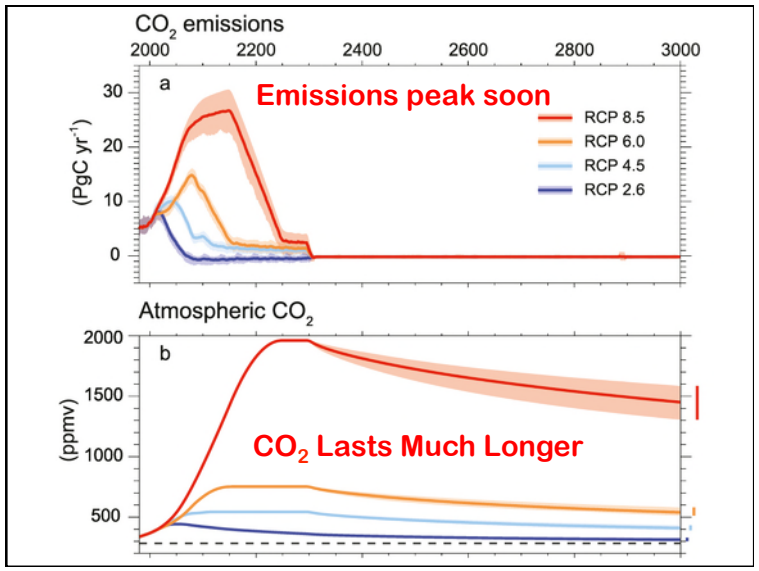
Coastal Flooding

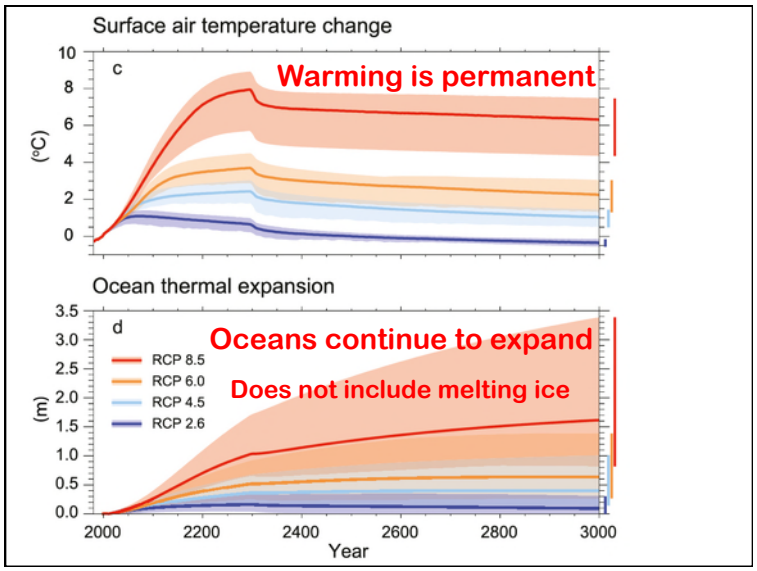
- Small floods are common, big floods are rare
- **Sea level rise shifts the line up**
- **What was a 100-year flood becomes a 10-year flood!**

The Long Tail



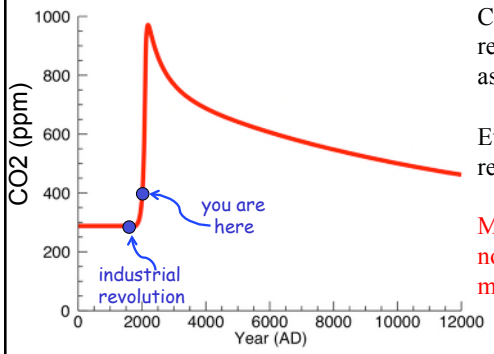
- Fossil CO_2 dissolves into the oceans
- Chemistry limits the amount the oceans can hold
- Mixing with deep oceans is very slow
- Removal of CO_2 depends on how much we add to atmosphere
- For a big pulse, 40% is still in the air after 1000 years





Common Myth #2

"When we reduce or stop the burning of fossil fuel, the CO_2 will go away and things will go back to normal"



CO_2 from fossil fuel will react with oceans, but only as fast as they "mix"

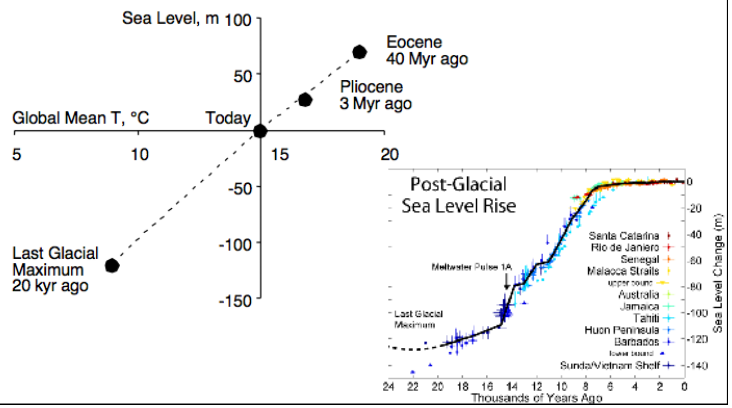
Eventually, fossil CO_2 will react with rocks

Much of the CO2 we emit now will stay in the air for many thousands of years!

Continental Ice Sheets

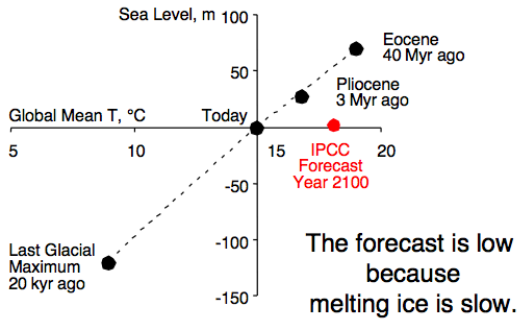
Climate and Sea Levels

Sea Level



Climate and Sea Levels

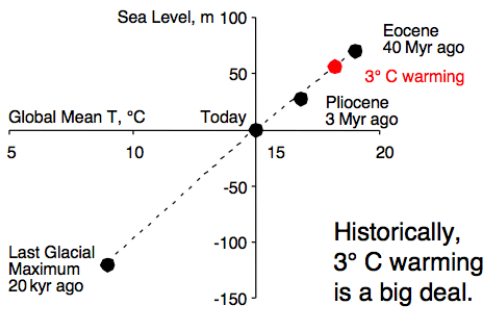
Sea Level



The forecast is low because melting ice is slow.

Climate and Sea Levels

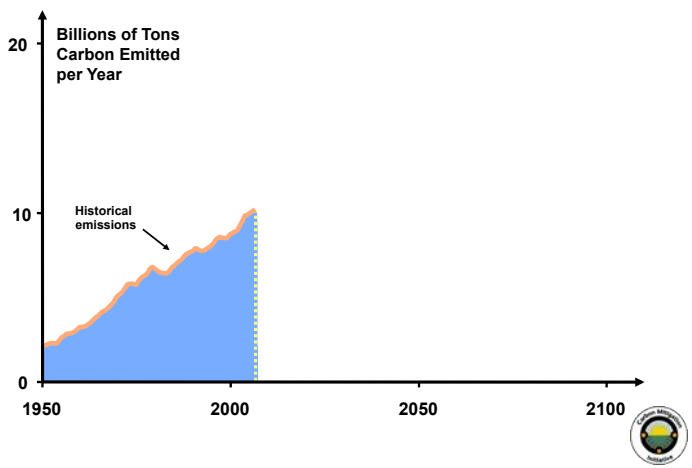
Sea Level



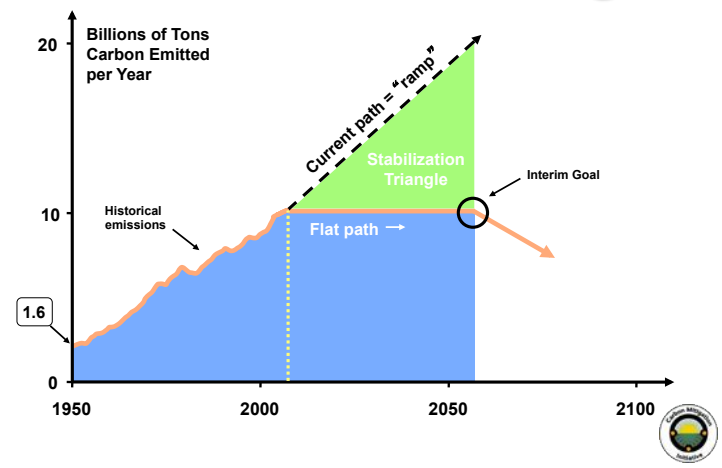
Historically,
3° C warming
is a big deal.

Solvable

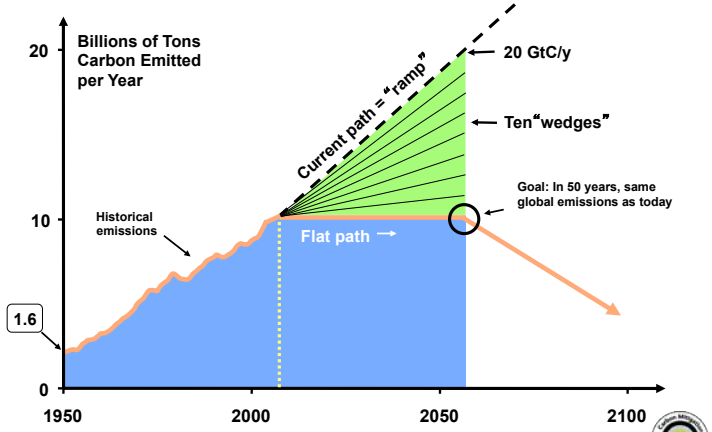
Historical Emissions



"Stabilization Triangle"



"Stabilization Wedges"



http://www.princeton.edu/wedges/

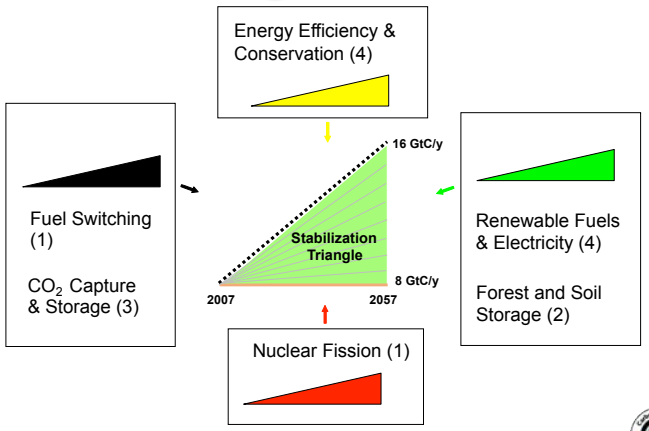
What is a "Wedge"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.

Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

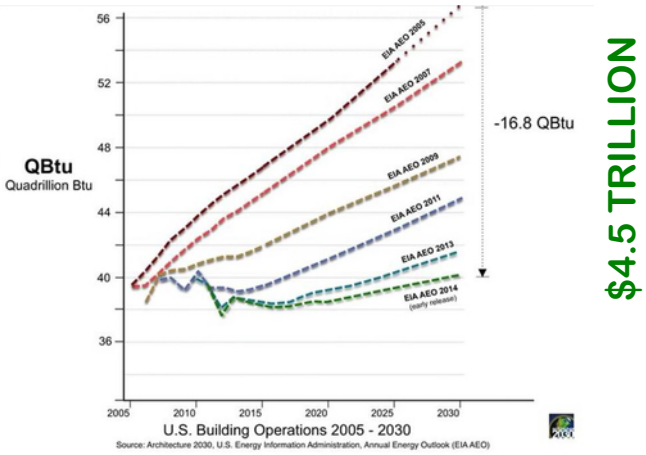
A "solution" to the CO_2 problem should provide at least one wedge.

15 Wedges: Solved!



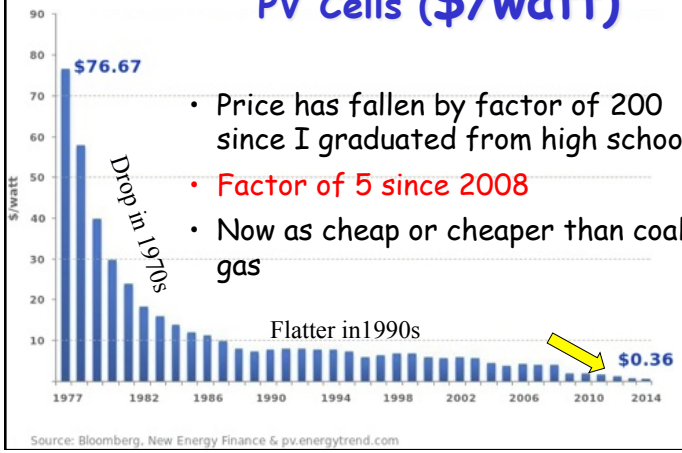
http://www.princeton.edu/wedges/

Efficient Architects!



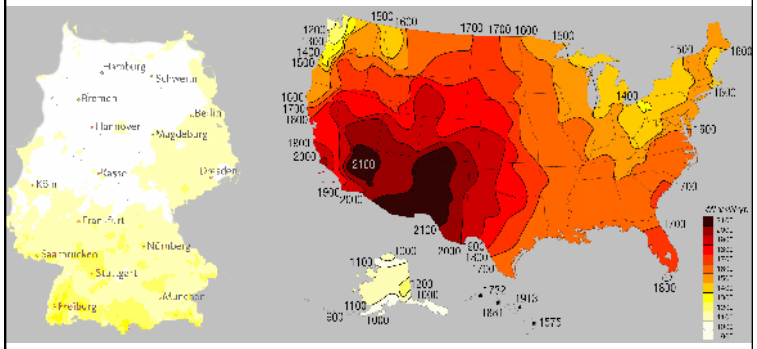
$4.5 TRILLION

Price of Solar PV Cells ($/watt)



- Price has fallen by factor of 200 since I graduated from high school
- Factor of 5 since 2008
- Now as cheap or cheaper than coal or gas

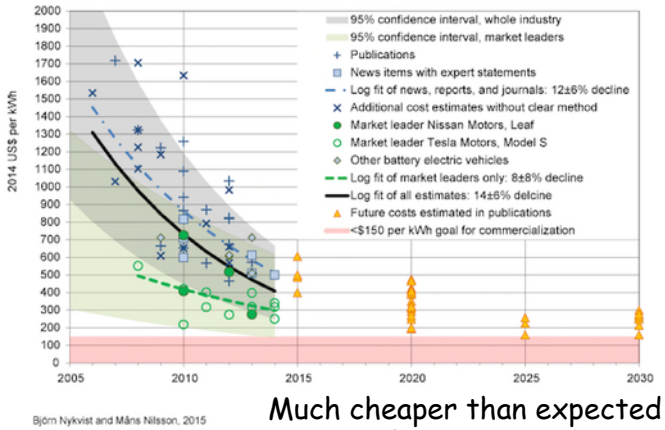
Solar Resources



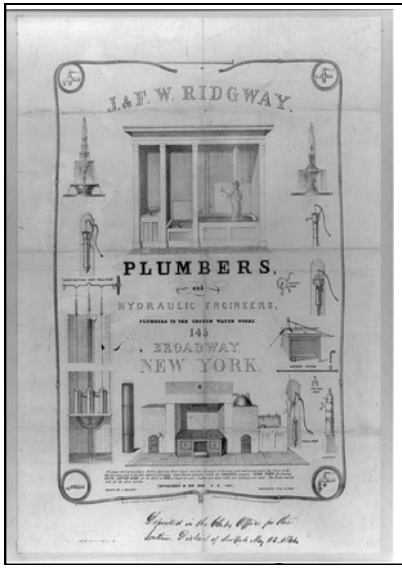
German electricity
- 4% wind & solar in 2000
- 28% wind & solar in 2014

US vs Germany

Lithium-Ion Batteries



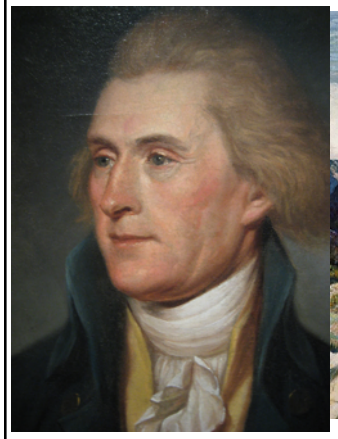
Much cheaper than expected a few years ago!



Costs

- Conversion to 100% noncarbon energy will cost about 1% of GDP
- That's about what it cost to retrofit all the world's cities with indoor plumbing a century ago …
- It was worth it!

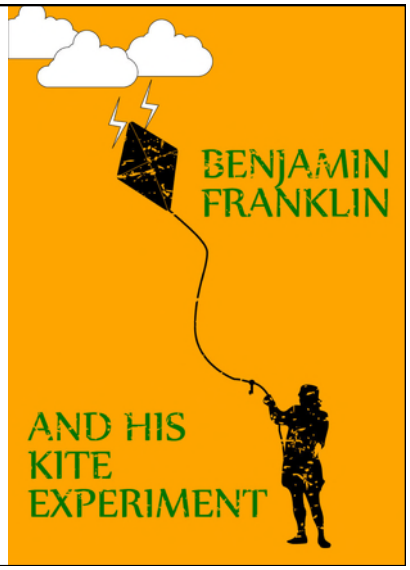
Imagine it's 1800 …



President Thomas Jefferson

Lewis and Clarke with Sacajawea

Imagine it's 1800 …



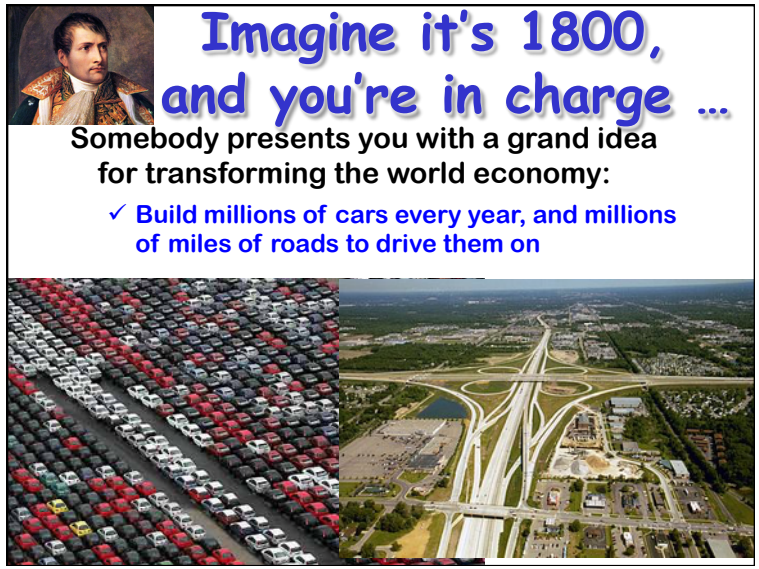
Imagine it's 1800, and you're in charge …

Imagine it's 1800, and you're in charge …

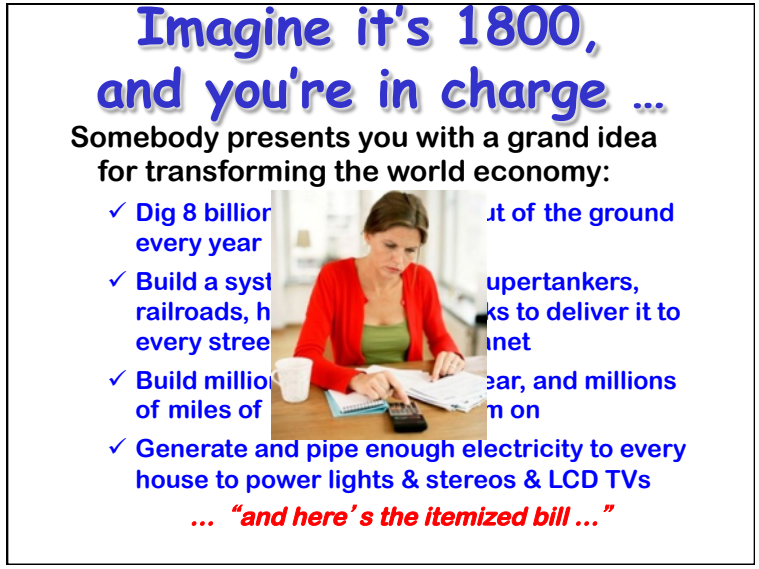
Somebody presents you with a grand idea for transforming the world economy:

- ✓ Dig 8 billion tons of carbon out of the ground every year


Imagine it's 1800,
and you're in charge …
Somebody presents you with a grand idea
for transforming the world economy:
✓ Build a system of pipelines, supertankers, railroads, highways, and trucks to deliver it to every street corner on the planet
GASOLINE
M.STAR


Imagine it's 1800,
and you're in charge …
Somebody presents you with a grand idea
for transforming the world economy:
✓ Build millions of cars every year, and millions of miles of roads to drive them on


Imagine it's 1800,
and you're in charge …
Somebody presents you with a grand idea
for transforming the world economy:
✓ Generate and pipe enough electricity to every house to power lights & stereos & LCD TVs


Imagine it's 1800,
and you're in charge …
Somebody presents you with a grand idea
for transforming the world economy:
✓ Dig 8 billior ut of the ground every year
✓ Build a syst upertankers, railroads, h ks to deliver it to every stree net
✓ Build millio ear, and millions of miles of m on
✓ Generate and pipe enough electricity to every house to power lights & stereos & LCD TVs
… "and here's the itemized bill …"


Who Built That?
• Our ancestors built that very system
• It cost them every dime of global GDP for 200 years (now $78T/yr)
• It created every dime too!
Now our kids get to do it again!


Choose Your Future
Many people think:
"Our well-being is based on stuff we extract from the ground"
When we stop burning coal, will our descendants shiver in the dark?


Choose Your Future
I prefer:
"We create our well-being through creativity, ingenuity, and hard work"
The future is bright!