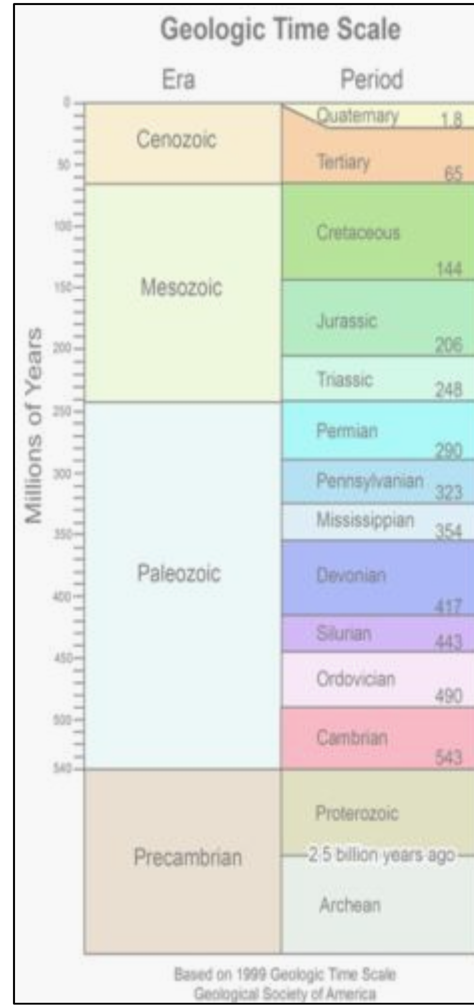
Agenda for this week

The grand picture (Sustainability @ "Anthropocene")

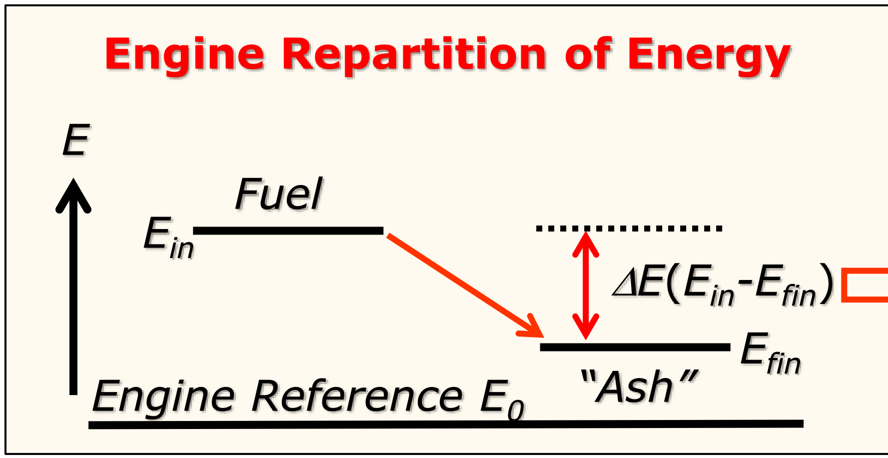
- Human habitat and resources.
- Sustainability of Human Activity & Life on Earth,
  Limit to growth, Club of Rome,
  Socio-economic/ecological network.
- Finite resources: arable land and water for food production, materials for fabrication & construction, fuels for machinery & transportation,
  Human eco-footprint, choices, and dilemmas,
- Energy utilization and environment,
  Energy consumption and human development
  Direct & external costs of energy use,
  Planetary climate, greenhouse effect.
- Stated (aspirational) and actual public policies, mitigation vs. adaptation to environmental & resource challenges.



Human Energy Harvesting: Resource Transformation

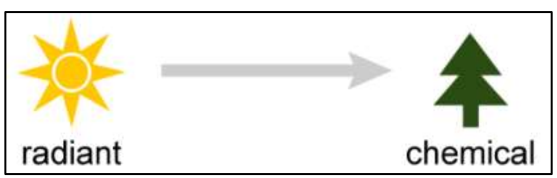
Robert Julius Mayer
1814-1878

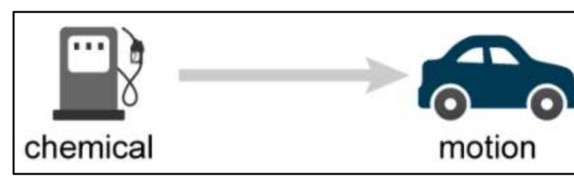
Law of Conservation of Energy: Energy in an isolated system can never be created or destroyed. It can only be transformed. Co-discoverer Robert Mayer. Engines are used for transformation of energy carriers/types.



(*External utilization, with tools*)

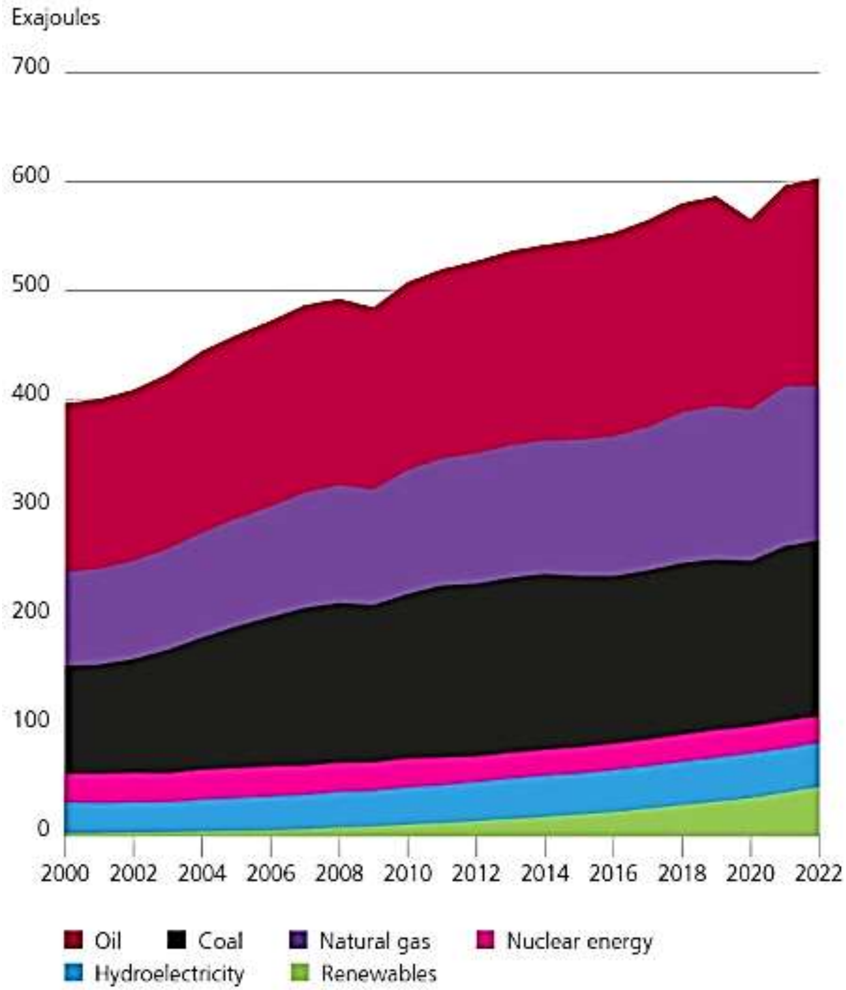
Examples For Energy Conversion



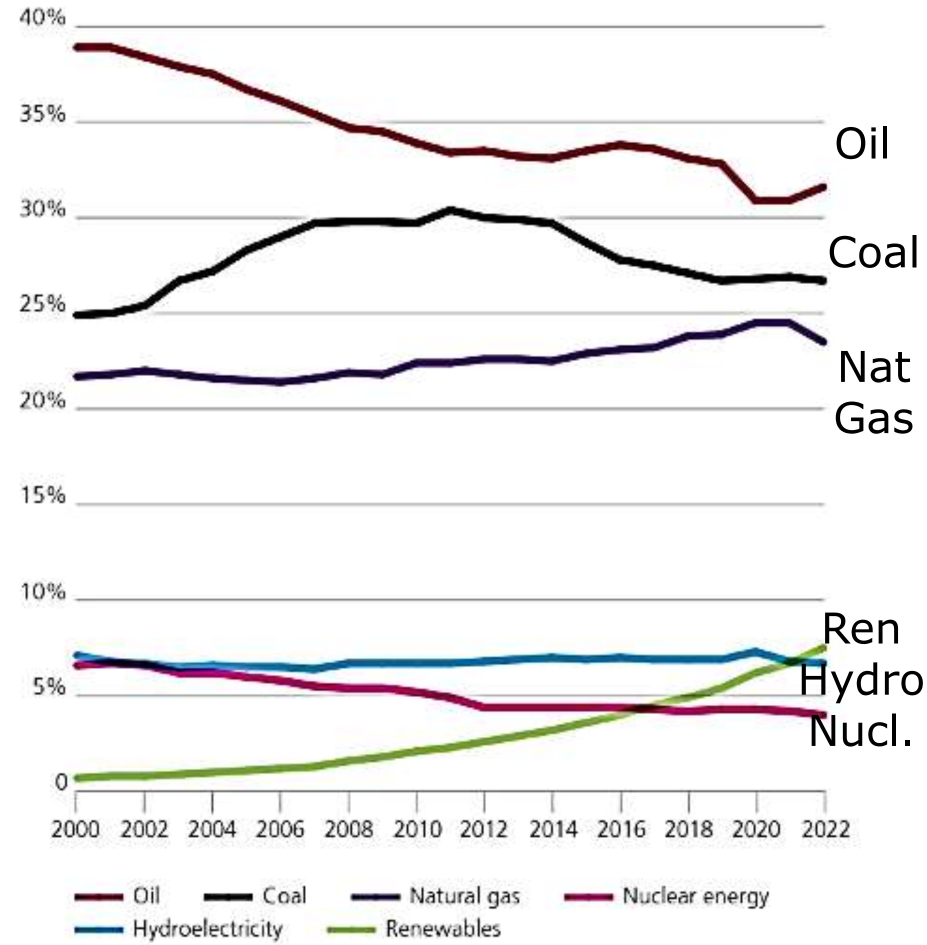


World Energy Consumption per Year

World consumption Trend: $\Delta E/a \sim +2.5\%$

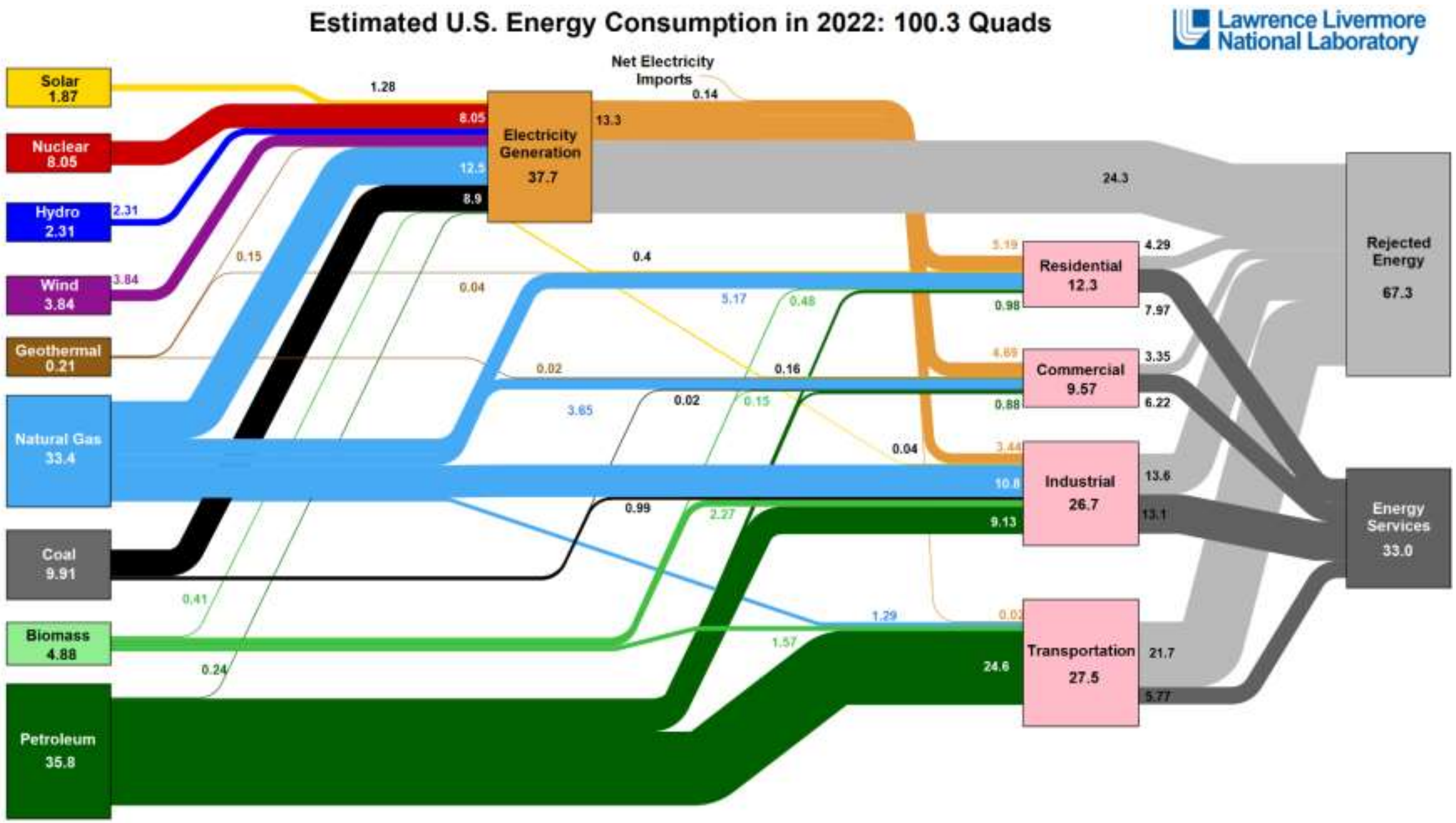


Share of global primary energy



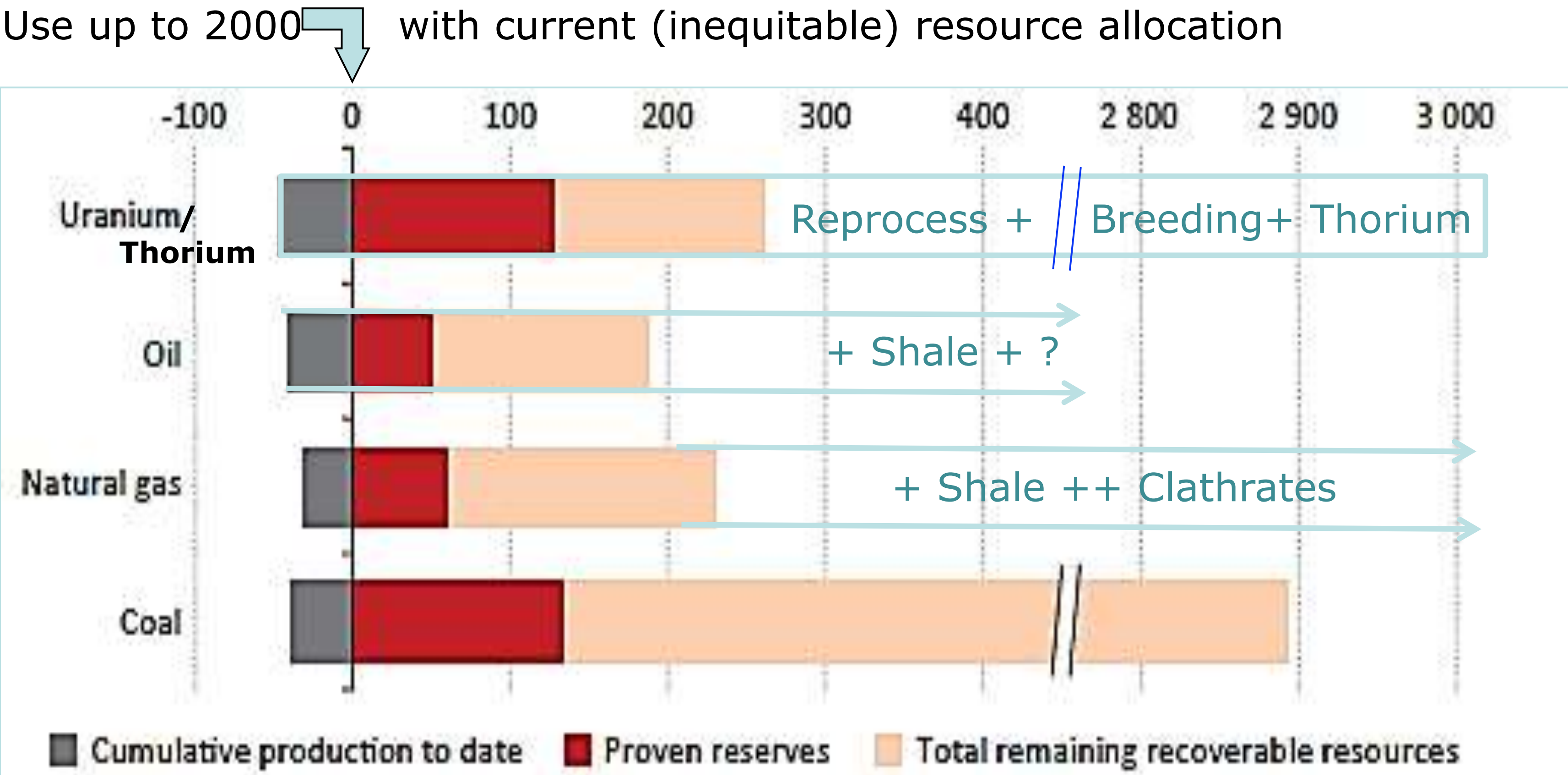
US Energy Consumption in 2022

2015-2018 → + 3.7 Quads *(EJ)* → 2021:-2.8 Quads (EJ)→2022:+3.0 Quads



World Primary Energy Resources/Constant Use

Use up to 2000 with current (inequitable) resource allocation



Modified after IEA World Outlook 2014, in light lettering: use reprocessing + U-238 breeding, Th 232 fertile fuel,

unconventional gas (fracking) + clathrates in frozen environments.

Neglect losses in reprocessing and breeding. Assumed present rate of consumption in future.

Direct (Internal) vs. Indirect (External) Energy Costs

The real direct costs of energy production in a given power plant :

"Levelized cost of electricity (energy)" per kWh, averaged over 1 year. What consumer have to pay for 1 kWh from that provider

$$LEC = \frac{annuity_N \cdot C_{capital} + \left(Operations + Maintenance\right)_{fixed}}{8760 \cdot Capacity - Factor} + \left(Operations + Maintenance\right)_{variable} + fuel$$

Annuity: break-even return on the capital after N years of operation. Estimates are based on Life Cycle Analysis ("from cradle to grave").

Long neglected, but potentially much more significant, and harder to estimate in terms of $$:

→ → "External Costs of Energy"

External Costs of Energy Production/Consumption

Direct and indirect costs and effects that are typically not included in price of primary energy carriers

- Pollution: reduced air and water quality → public health, economic cost.
- Reduction of water quantity → agriculture, public health (food).
- Physiological & aesthetic (audio, visual) effects → quality of life.

- Destruction of arable and wet land, forests→ lasting economic cost
- Ocean acidification, changes marine bio environment, food chain
- Destruction of animal/fish habitat
- Ecological effects from accidental (coal, oil, nuclear,..) spills & waste release
-

- Limits to energy security: Susceptibility to external political pressure from energy producers.
- Accessing foreign energy resources may require military action.

- Addition of heat-trapping gases (GHG) to atmosphere → large changes climate/environment, large economic costs.

Direct External Costs of Energy Production

Direct External Costs of Energy: Fire Hazards

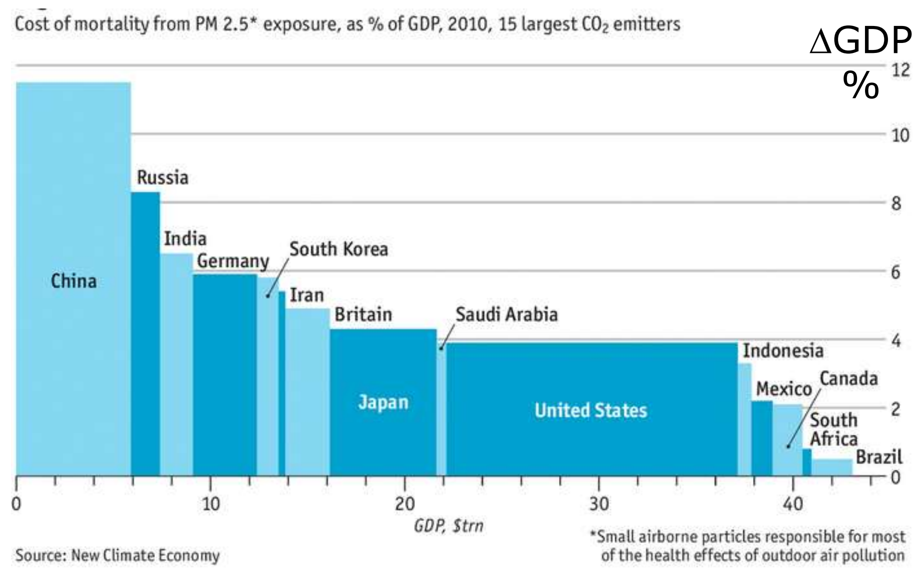
Irvine, California: Two fires began early morning of October 26, 2020, which quickly spread over 30,000 acres in 48 hours.

Likely causes: Human activities/neglect, downed electrical power lines
Town of Paradise (CA) lost, > 85 fatalities.

Direct External Costs of Energy Consumption

Sulfur, nitrogen oxides, particulates from China's coal-fired power plants → acid rain on Seoul/SK, Tokyo/JP, particulate pollution in Los Angeles (J. Geophys. Res.).

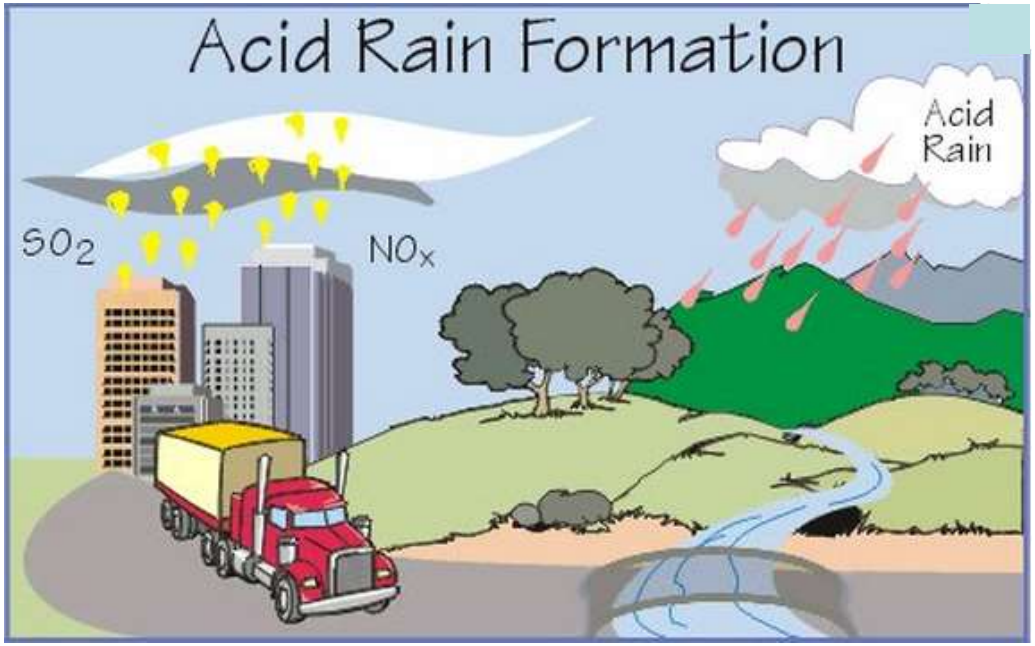
Loss of life & health → economic costs.



New Delhi/India 2021 (l) vs. < 2019(r)

During pandemic lockdown (left), absence of automotive traffic clears air of smog, which is normally present (right panel)

Direct External Costs: Air Pollution, Acid Rain



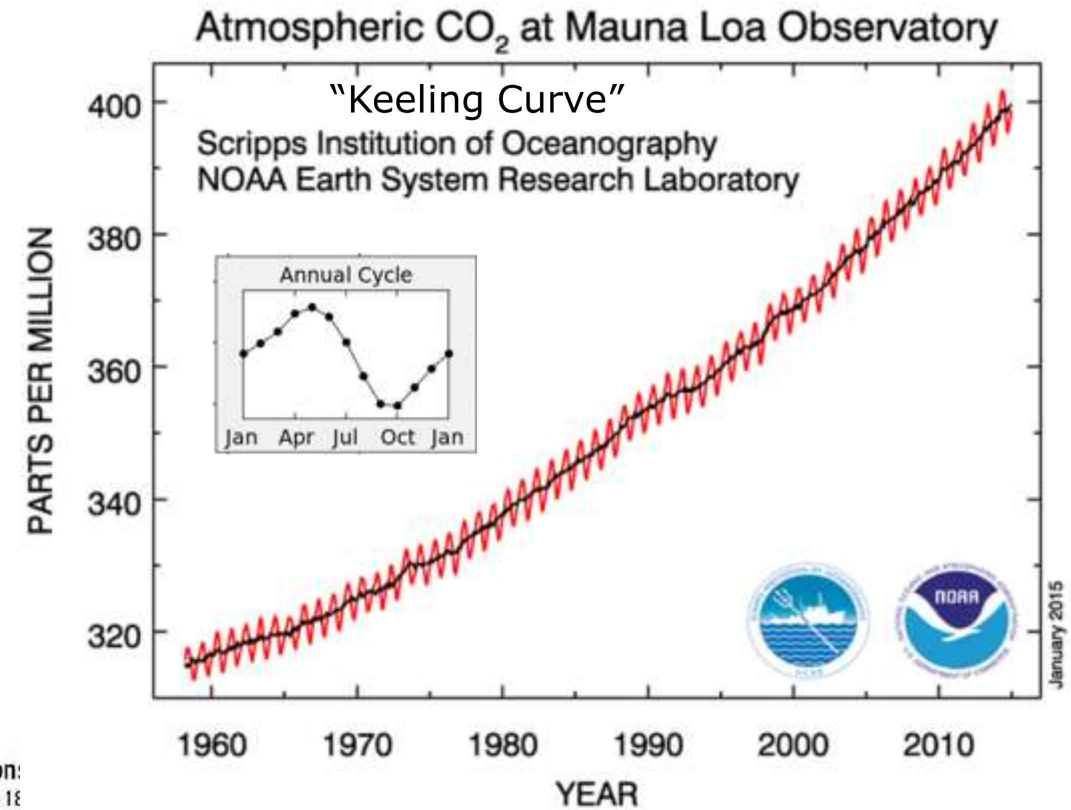
Certain types of coal and oil burn with emission of carbonic, sulfuric, and nitrous oxides

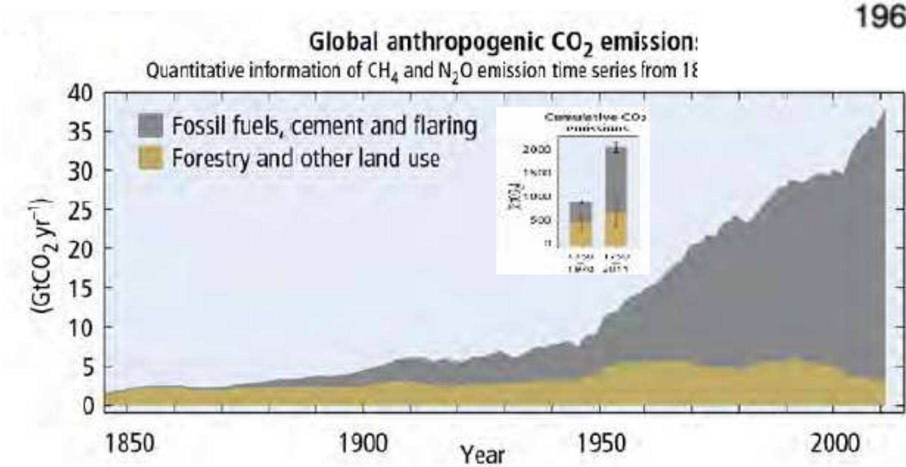
$$SO_2\,(g) + H_2O \leftrightarrow SO_2{\cdot}H_2O$$
$$SO_2{\cdot}H_2O \leftrightarrow H^+ + HSO_3^-$$
$$HSO_3^- \leftrightarrow H^+ + SO_3^{2-}$$

SO_2 in air rains down and pollutes soil and waters, increases the acidity levels of rivers, lakes and seas → kills aquatic life. Taken up in soil → can kill vegetation.

Tracing Atmospheric CO_2

Fossil fuels → 9 GtC/a
2.5 GtC/a → biosphere
2.5 GtC/a → oceans
4 GtC/a → atmosphere



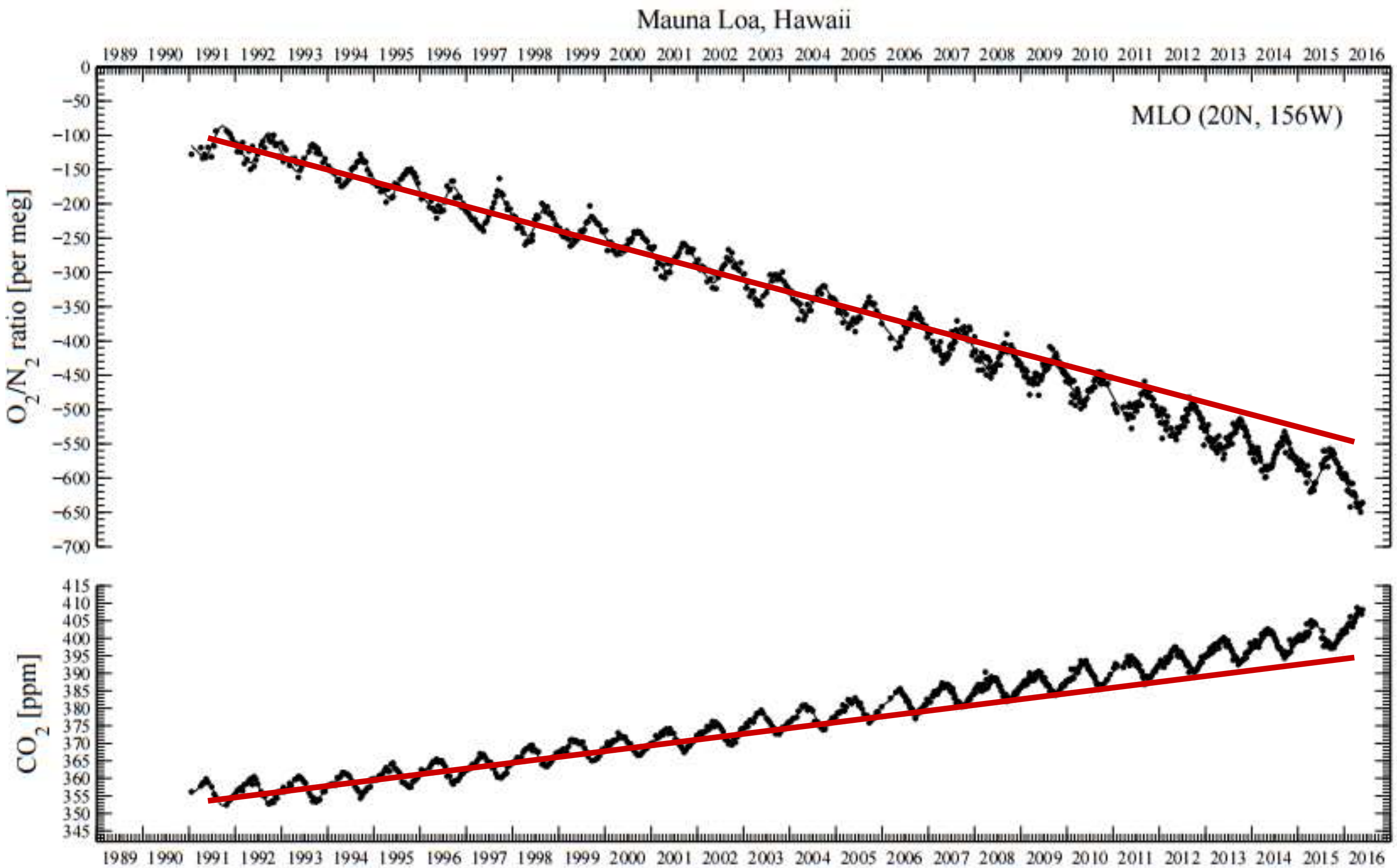


IPCC claim: Anthropogenic emissions are large, have increased and will further increase in future. → Future extent will depend on public policies.

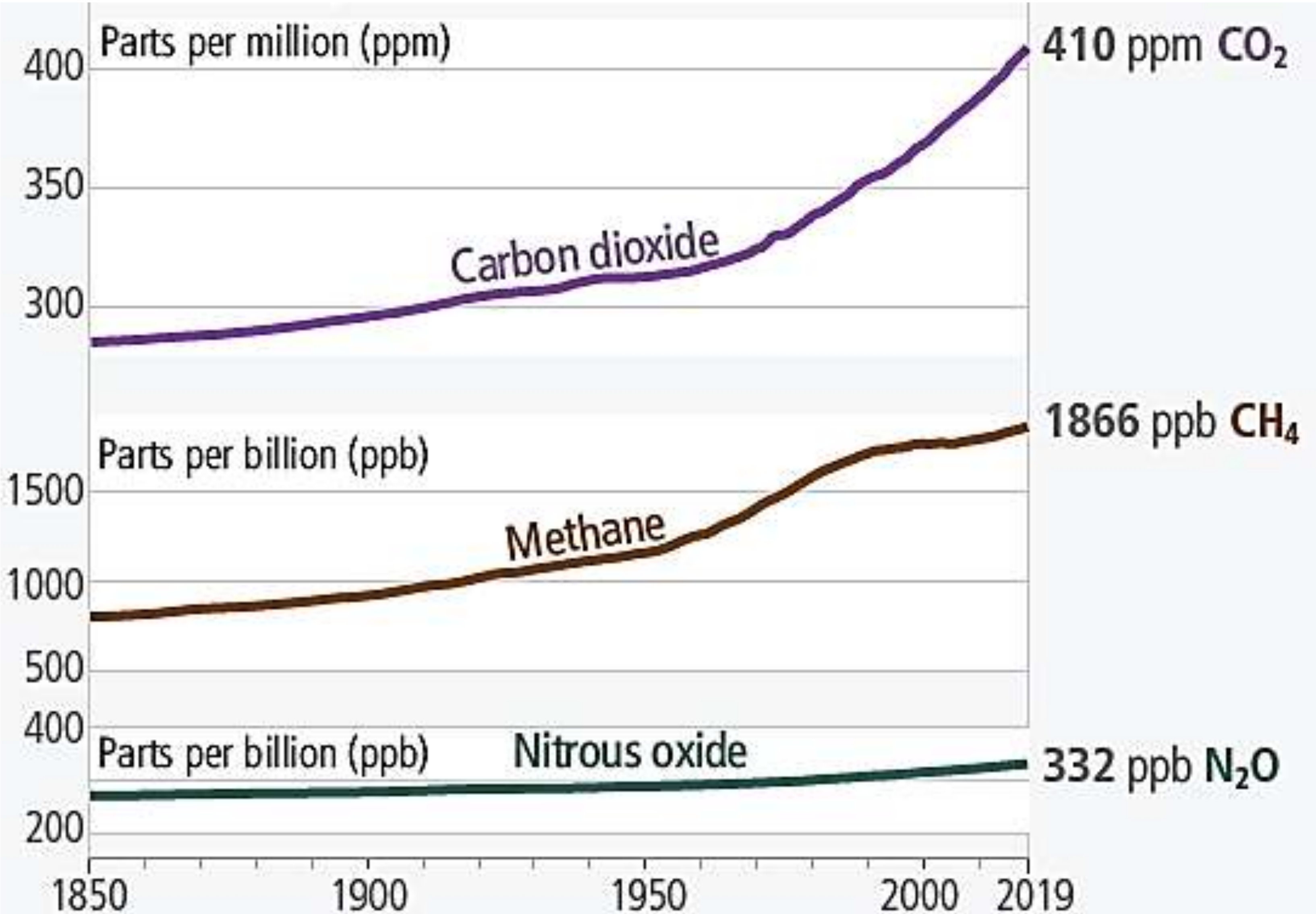
Correlated Changes in Atmospheric Composition

O_2 depletion → correlation with CO_2 ?

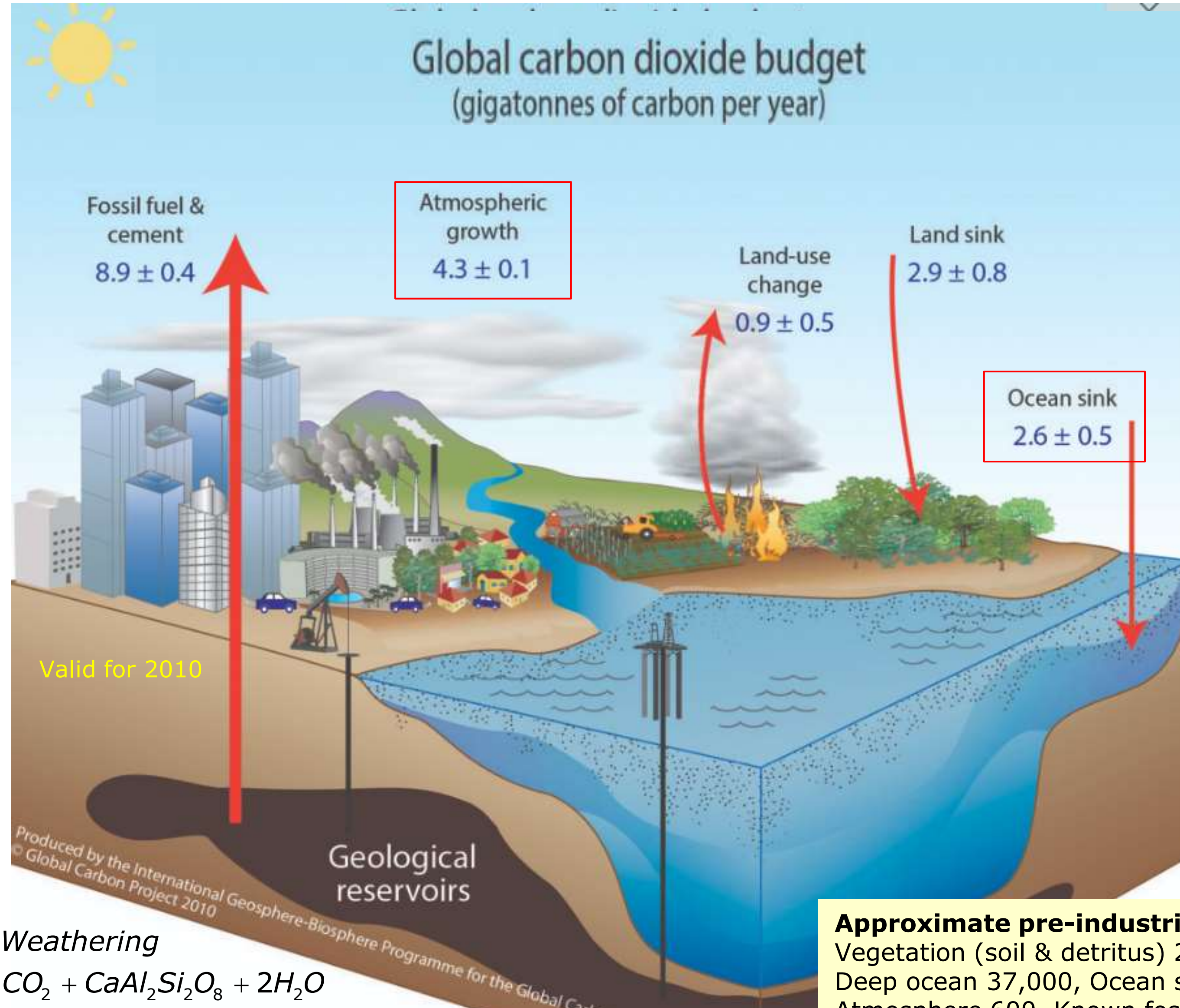
Both have oscillatory pattern, non-linear long-term trends.



Concentration of Greenhouse Gases



Changing a Natural Balance



Man-induced changes in Earth's Carbon Cycle between surface and ocean reservoirs. Anthropogenic changes (+ or -) due to burning fossil fuel, land use,…).

Red up arrows: anthropogenic flows
Zero= pre-industrial flow.
Units:10^9 tons of carbon per year (G*t*C/a).

Emissions (2012): +9.6 G*t* C/a = +36.2 G*t* CO_2 equ./a

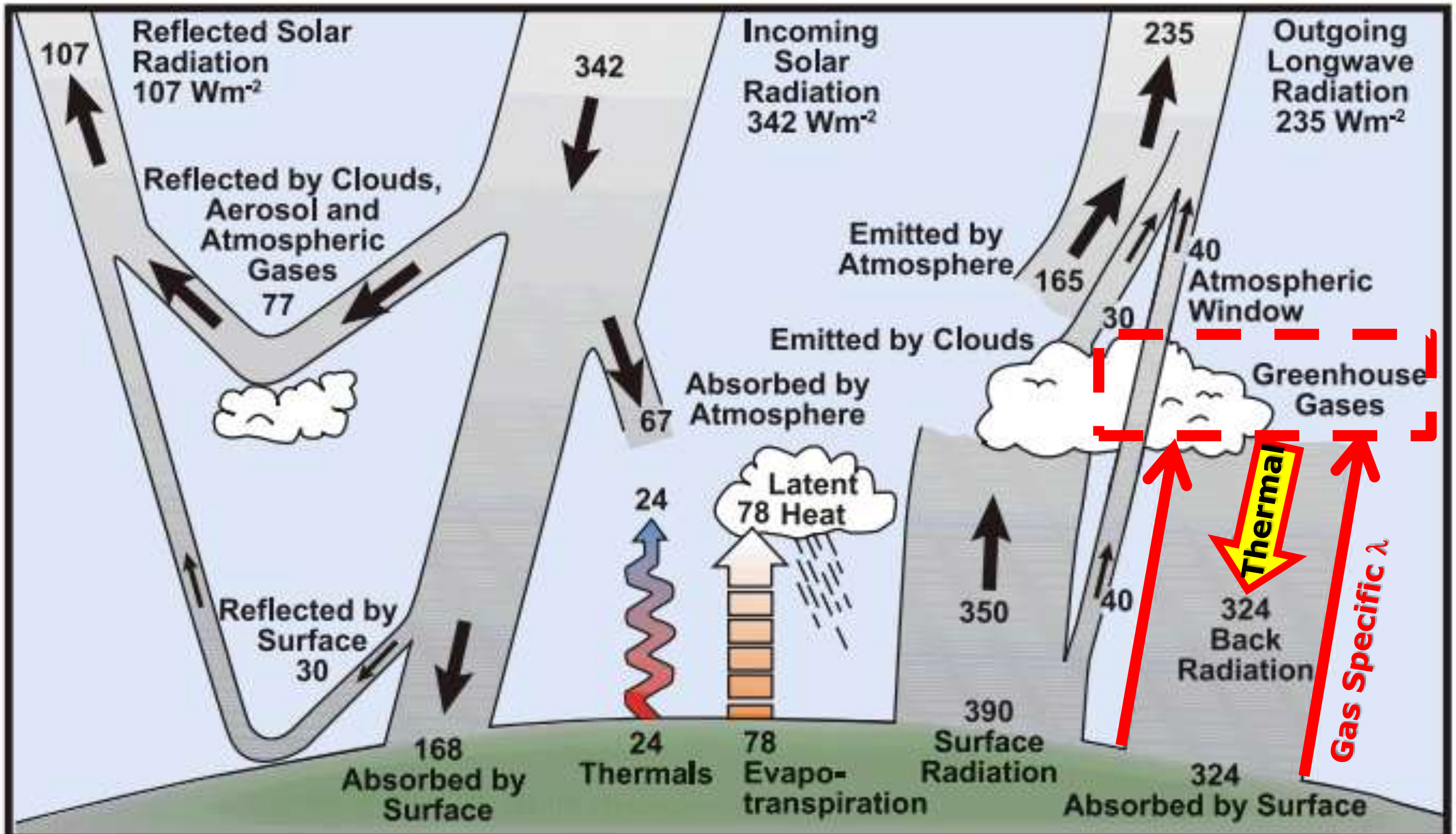
2018:36.7 Gt (NOAA)

Weathering

$$CO_2 + CaAl_2Si_2O_8 + 2H_2O \rightleftharpoons CaCO_3 + Al_2Si_2O_5(OH)_4$$

Approximate pre-industrial inventory carbon (Gt)
Vegetation (soil & detritus) 2,300, Surface oceans 900, Deep ocean 37,000, Ocean sediments 150
Atmosphere 600, Known fossil fuels 3,700

Earth’s Radiation Balance (GH Effect)



FAQ 1.1, Figure 1. *Estimate of the Earth's annual and global mean energy balance. Over the long term, the amount of incoming solar radiation absorbed by the Earth and atmosphere is balanced by the Earth and atmosphere releasing the same amount of outgoing longwave radiation. About half of the incoming solar radiation is absorbed by the Earth's surface. This energy is transferred to the atmosphere by warming the air in contact with the surface (thermals), by evapotranspiration and by longwave radiation that is absorbed by clouds and greenhouse gases. The atmosphere in turn radiates longwave energy back to Earth as well as out to space. Source: Kiehl and Trenberth (1997).*

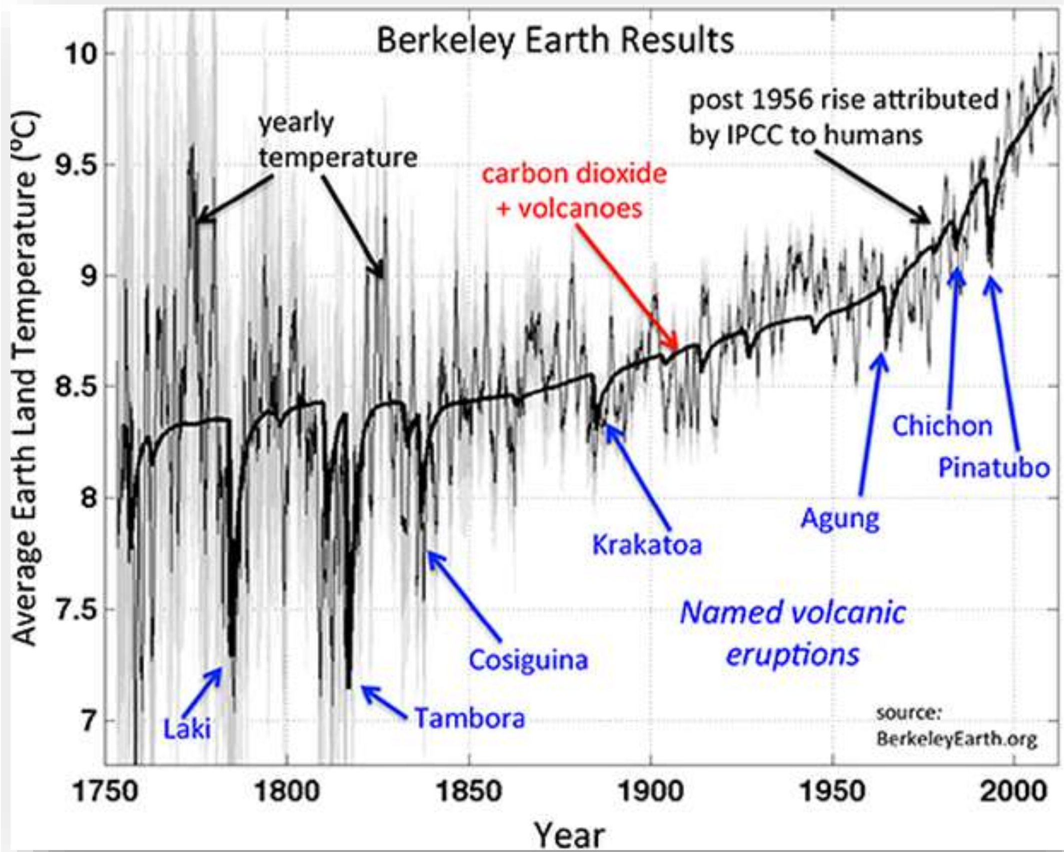
Modified after IPCC AR4 Report:
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter1.pdf

Ominous Correlation: Temperature vs. Atmospheric CO_2

Systematic gradual rise of $\Delta T=1.5^0C$ correlates with experimental record of atmospheric CO_2, as measured from atmospheric samples and air trapped in polar ice.

Solar variation does not seem to impact the *mean* temperature trend.

(Berkeley Earth Surface Temperature study, 2012)



What is Human role in *T* increase?

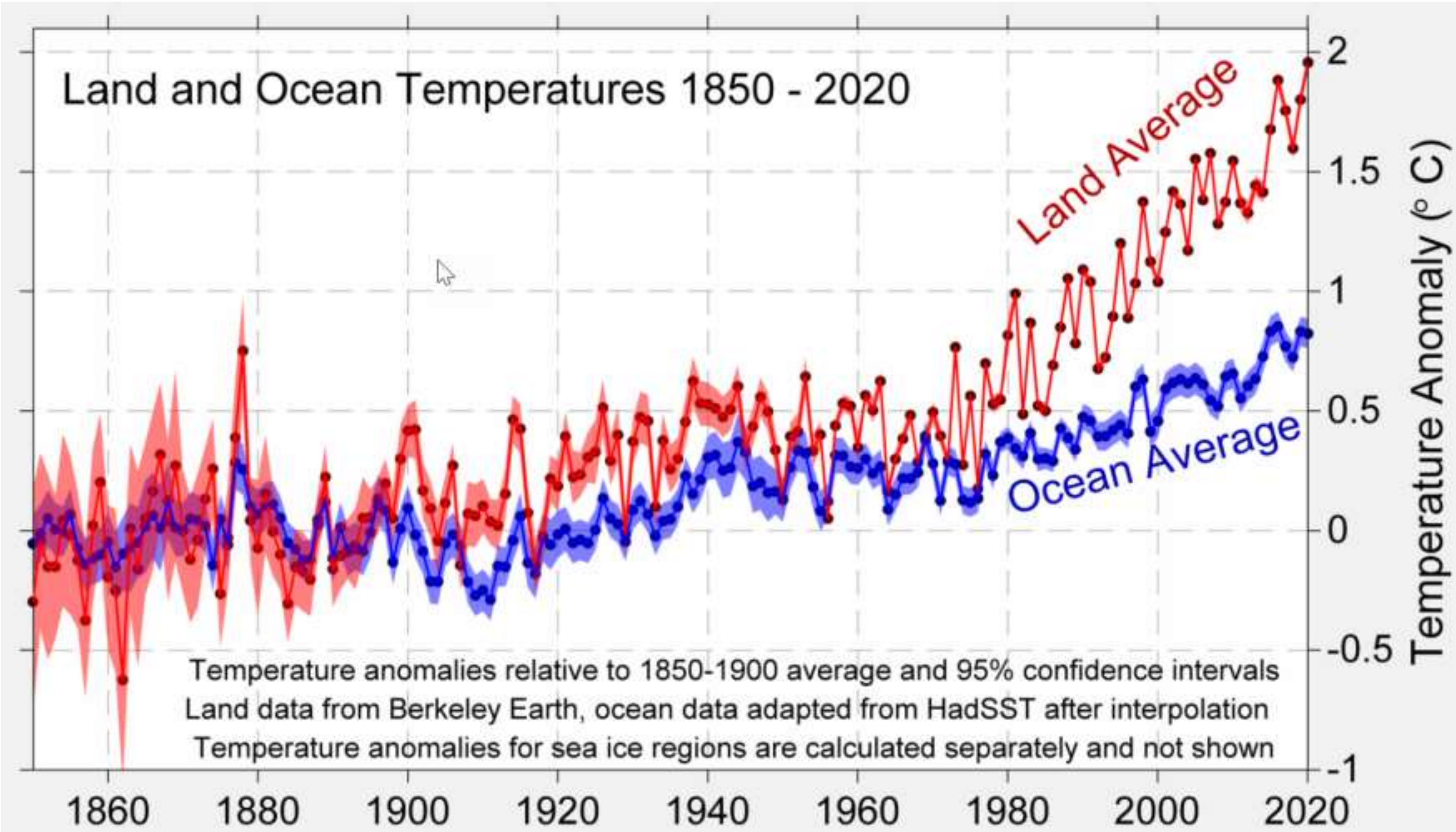
Dips in the observed historic temperature pattern match in time of occurrence and amplitude the emissions of known explosive volcanic eruptions.

Particulate clouds from volcanic events reflect sunlight and cool the Earth's surface for a few years.

Small rapid variations are attributable to El Nino and other ocean currents such as the Gulf Stream.

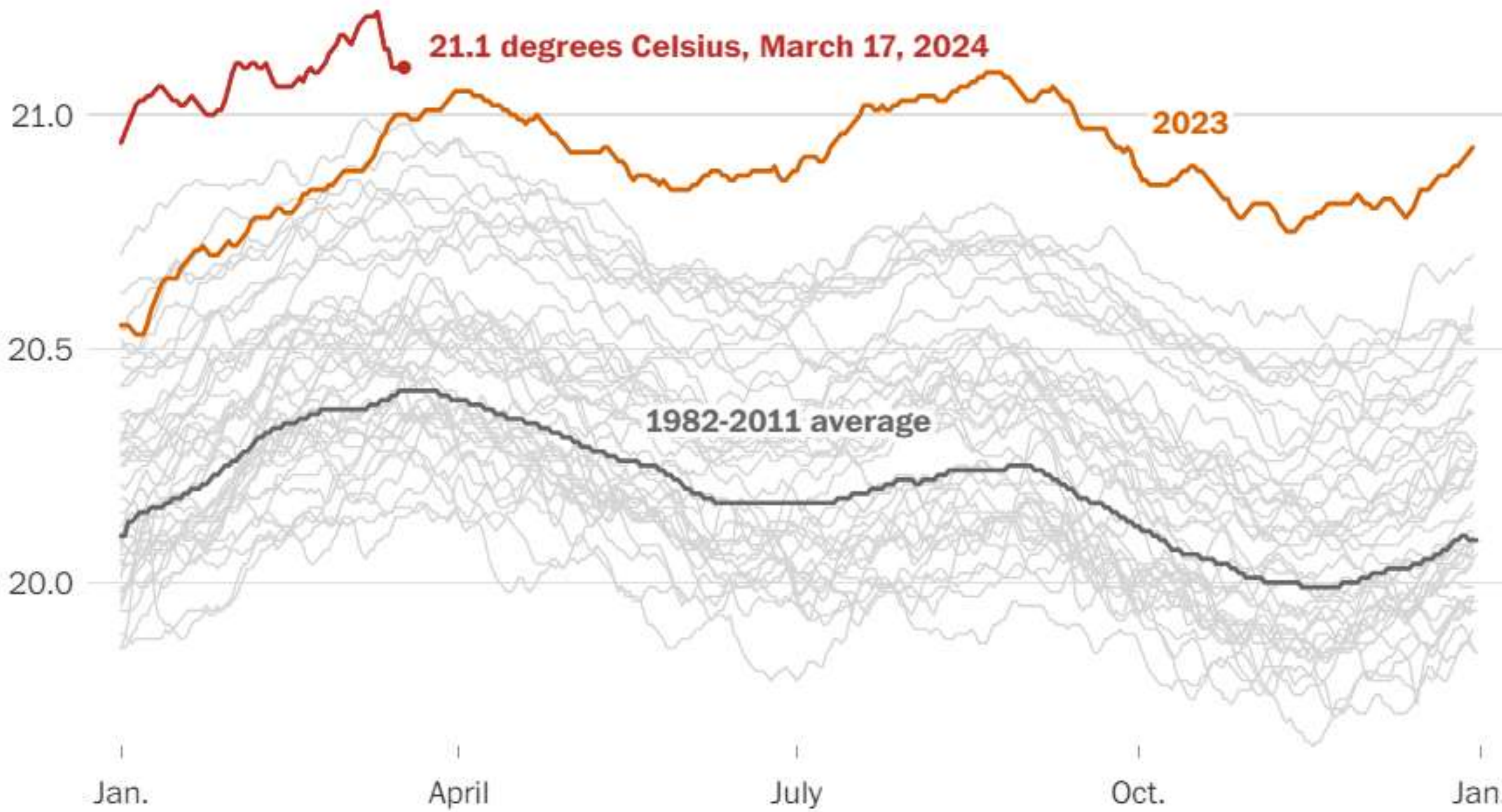
(From BerkelyEarth Project)

Mean Land and Ocean Temperature Trends



http://berkeleyearth.org/global-temperature-report-for-2020/

Trends In Average Global Sea Temperatures

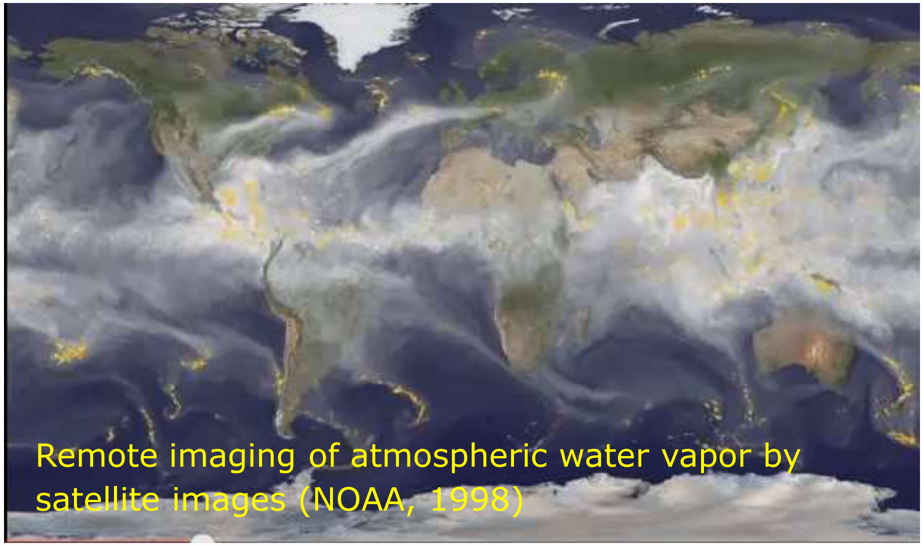


Note: The temperatures shown, in degrees Celsius, include data from 60°S to 60°N across all longitudes.

Source: NOAA OISST v2.1, via ClimateReanalyzer.org, Climate Change Institute, University of Maine.

SCOTT DANCE / THE WASHINGTON POST

Big Data: Weather & Climate Information Sources



Remote imaging of atmospheric water vapor by satellite images (NOAA, 1998)

One of many weather stations (Albany) of US Network.

Ice cores stored in the U.S. Geological Survey **National Ice Core Lab** (NAS 2010)

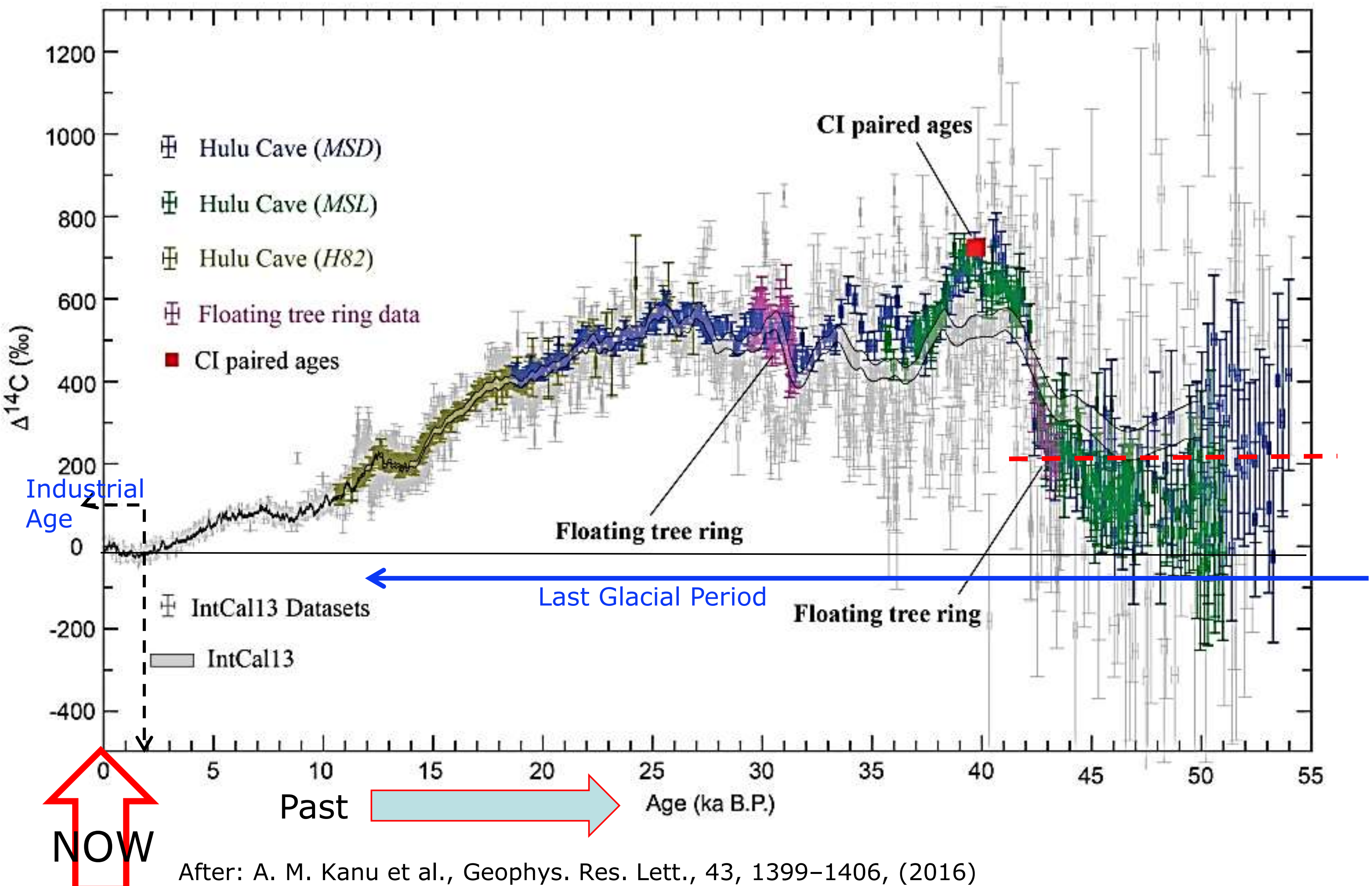
Systematic studies to establish global historic trends require:
Excellent weather/climate information provided by several national/international agencies allows systematic climate evaluation and projection→ Research efforts in Nat'l Labs/Univ.

Examples:

1. U.S. *Historical Climatology Network* (USHCN): 1221 observing stations in the 48 contiguous states (Europe equiv).
2. Complex, remote measurements of atmospheric temperatures, composition, flows, ocean temperatures, etc., via many NOAA/NASA/ESA/EUMETSAT satellites.
3. Check theoretical models against known history.

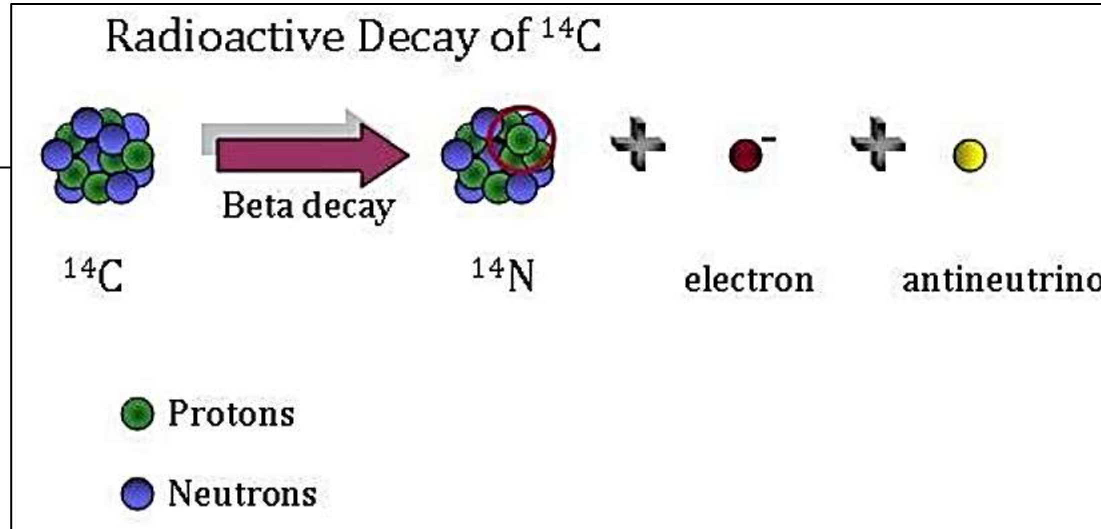
Paleo-climate information: isotope ratios, air bubbles in Greenland or Antarctic ice cores, tree rings, coral reefs, historical records.

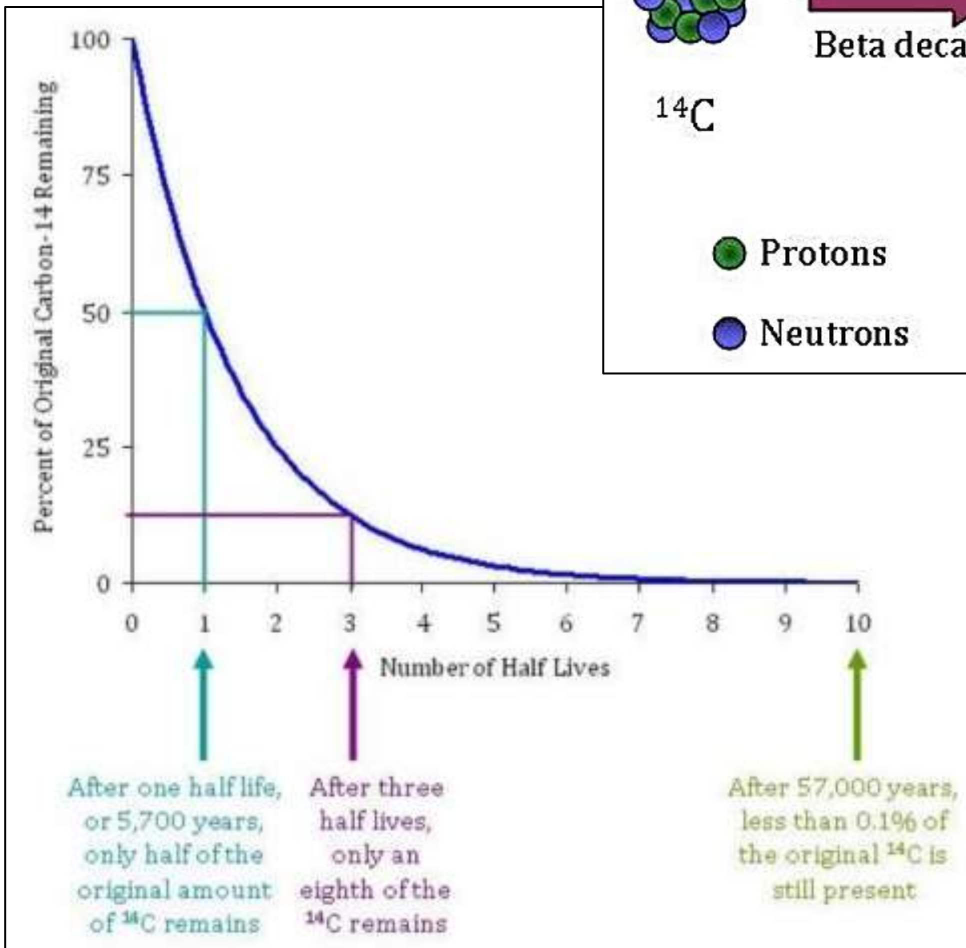
Atmospheric CO_2: Excess Isotope ^{14}C



After: A. M. Kanu et al., Geophys. Res. Lett., 43, 1399–1406, (2016) doi:10.1002/2015GL066921.

Nuclear Isotopes: Time Dependent Fingerprints



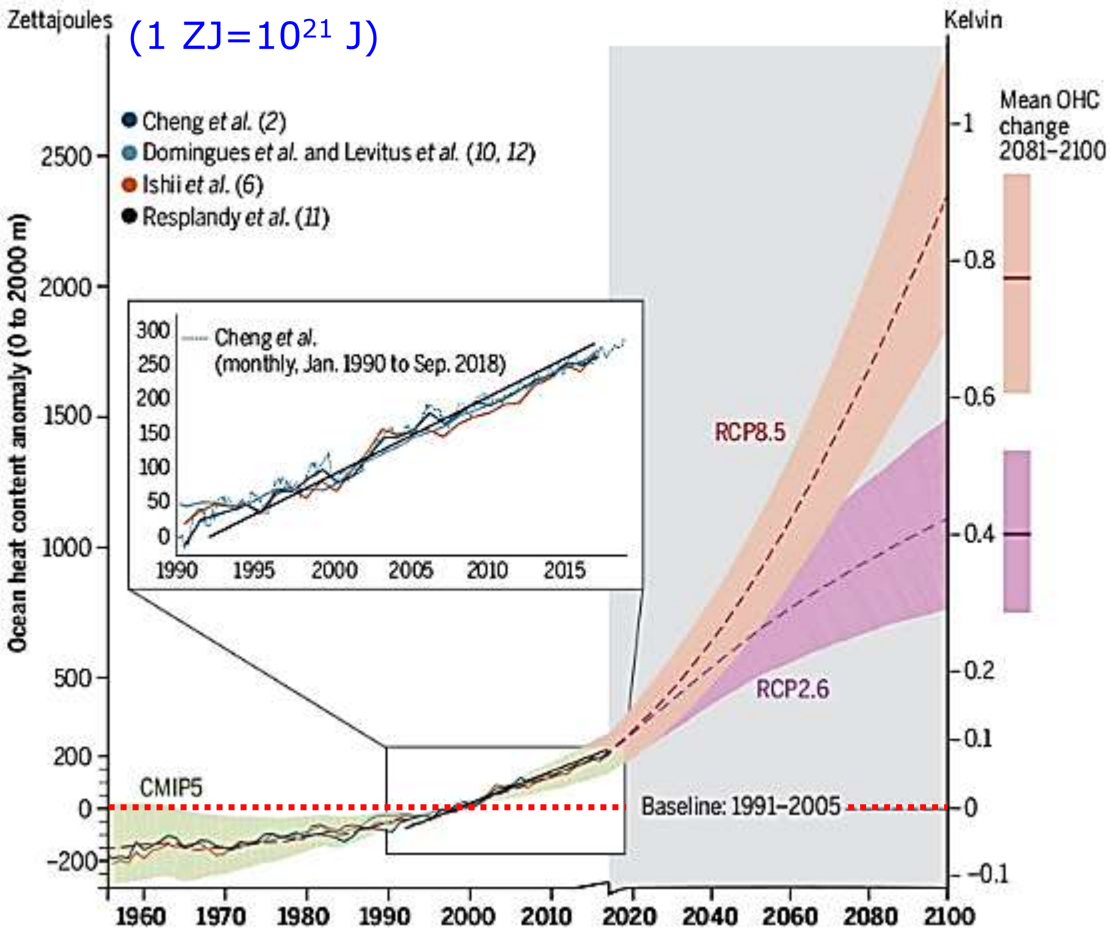


Adapted from NOAA: https://gml.noaa.gov/ccgg/isotopes/decay.html

Ocean Warming Trends

Increased ocean heat content (OHC): 1971-2010: $\Delta P=(0.39\pm0.07)W/cm^2$ for upper 2km ocean.

2018 [Cheng *et al.* (2)], along with the other annual observed values superposed.



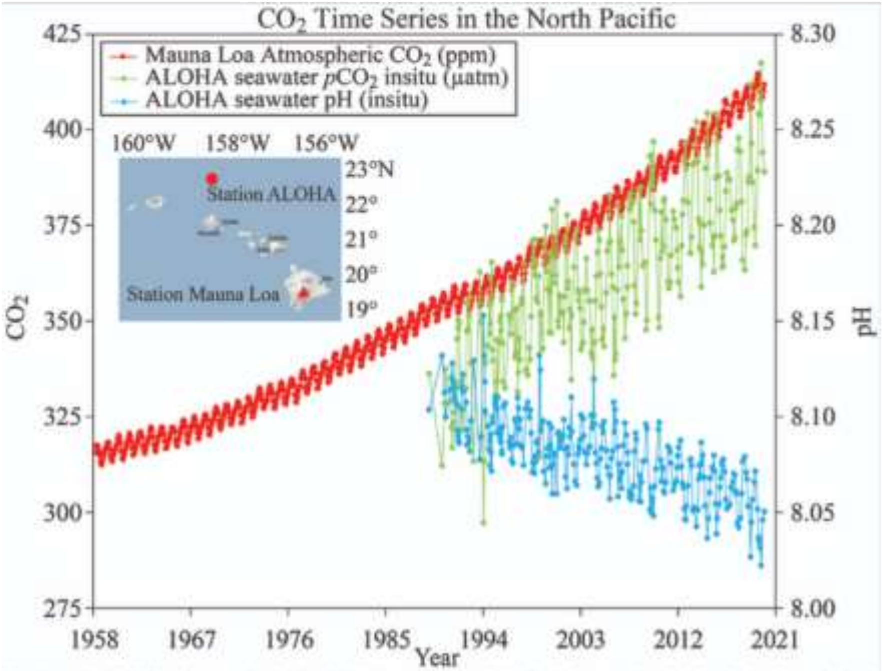
L. Cheng: Science Mag. Jan 11, 2019

Most (>90%) excess heat energy is absorbed by oceans. Many different methods of measurement: Direct contact with floats,…, remotely by satellites.

Predictions: For BAU
ΔE=2300ZJ
ΔT= +0.9 K by 2100.
→ outgassing, sea level rise (by how much?)

Aqueous CO_2 Equilibrium and Consequences

$$CO_2(g) + 2H_2O(\ell) \overset{k_1}{\rightleftharpoons} H_2CO_3(aq) + H_2O \overset{k_2}{\rightleftharpoons} H_3O^+(aq) + HCO_3^-$$



https://www.pmel.noaa.gov/co2/file/Hawaii+Carbon+Dioxide+Time-Series

Henry's Law $p_{CO_2} = k_H(T) \cdot [CO_2]$

Increasing atmospheric concentration of CO_2 → increasing CO_2 solvation in sea water → decreasing pH value (increasing $[H^+]=[H_3O^+]$, complex set of rxns)

NCADAC Report 2013

Shells Dissolve in Acidified Ocean Water

Consequences of ocean acidity

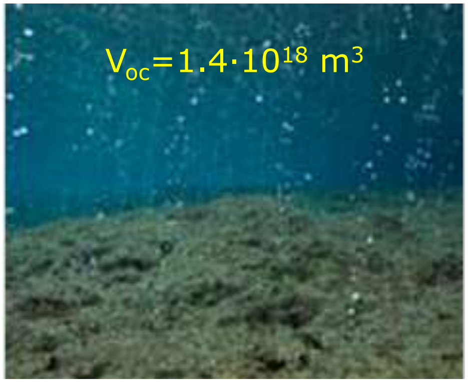
Bleaching of corals,

Dissolution of shells of marine animals

Example: Pteropod, "sea butterfly": Tiny sea creature (size of pea). Pteropods = food for marine species from krill to whales, major food for North Pacific salmon. Shell slowly dissolves after 45 days.

(Photo credit: National Geographic Images)

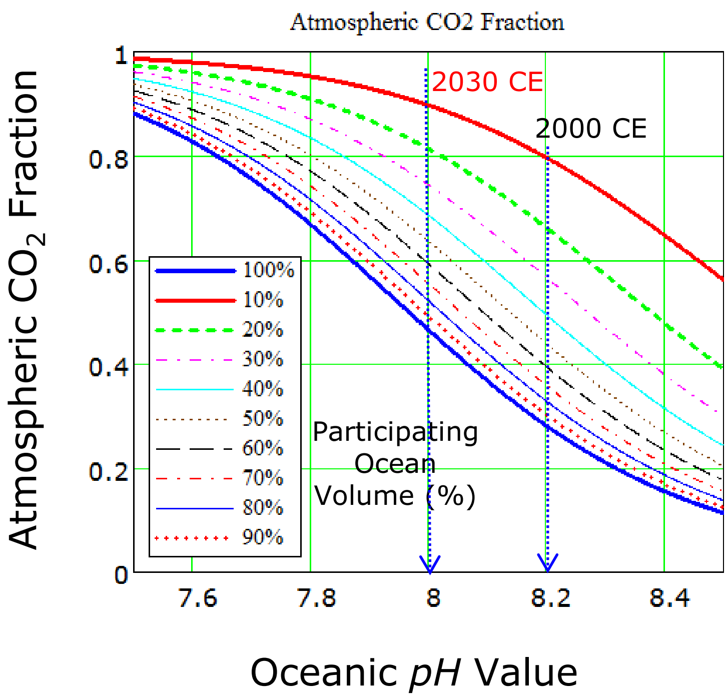
Carbonate Chemistry: Ocean CO_2 Uptake



$$Buffer: CO_2(g) + CO_3^{2-} \xrightarrow[\leftarrow]{H_2O} 2HCO_3^-$$

$$Dissolved\ CO_2: \left[CO_2(aq)\right] = \left[CO_2\cdot H_2O\right] + \left[HCO_3^-\right] + \left[CO_3^{2-}\right]$$

$$\left[CO_2(aq)\right]_{equ} = k_H P_{CO_2}\left(1 + k_1/\left[H^+\right] + k_1k_2/\left[H^+\right]^2\right)$$



Alkaline buffer action of ocean water reduces with increasing acidity (decreasing *pH*)
→ smaller fraction of CO_2 is taken up by ocean.

Average oceanic *pH* has dropped by 0.1 (8.2→8.1) within last 15 years. → Decreased CO_2 uptake: 70% → 50%

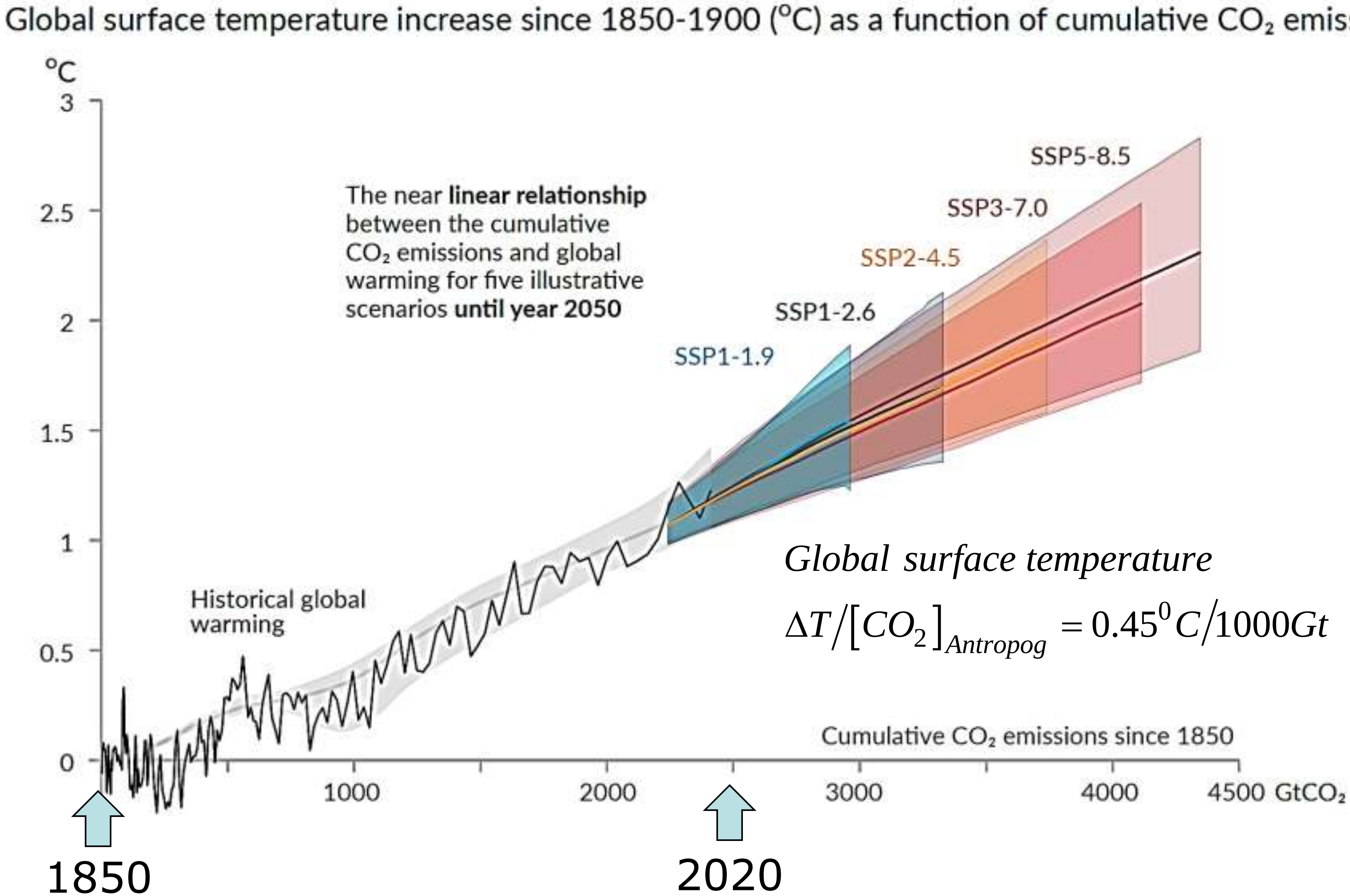
(if 100% of the ocean waters participate, less if only surface layers)

Non-linear positive feedback:
Added CO_2 release decreases uptake by ocean waters.

Complex systems have capacity of sudden irregular (chaotic) response to small changes of parameters.

D.J. Jacob, *Atmospheric Chemistry*, Princeton, 1999

Mean Temperature - GHG Inventory Correlation



Global surface temperature

$$\Delta T / [CO_2]_{Antropog} = 0.45^0 C / 1000 Gt$$