Agenda

Summary so far:

Solar influx *S*(ν, λ) is known (Stefan-Boltzmann Law, Sun cycles)

Earth' albedo is measured by satellites

Earth surface temperature is measured → *t* dependence

Atmospheric composition, density and temperature profiles are measured and modeled in detail

Interaction of elm Radiation With Matter

Task: Explain *T*(*t*)

Model radiative forcings due to specific components (CO_2, CH_4,…)

Absorption of atmospheric gas composition as function *f*(ν, λ)

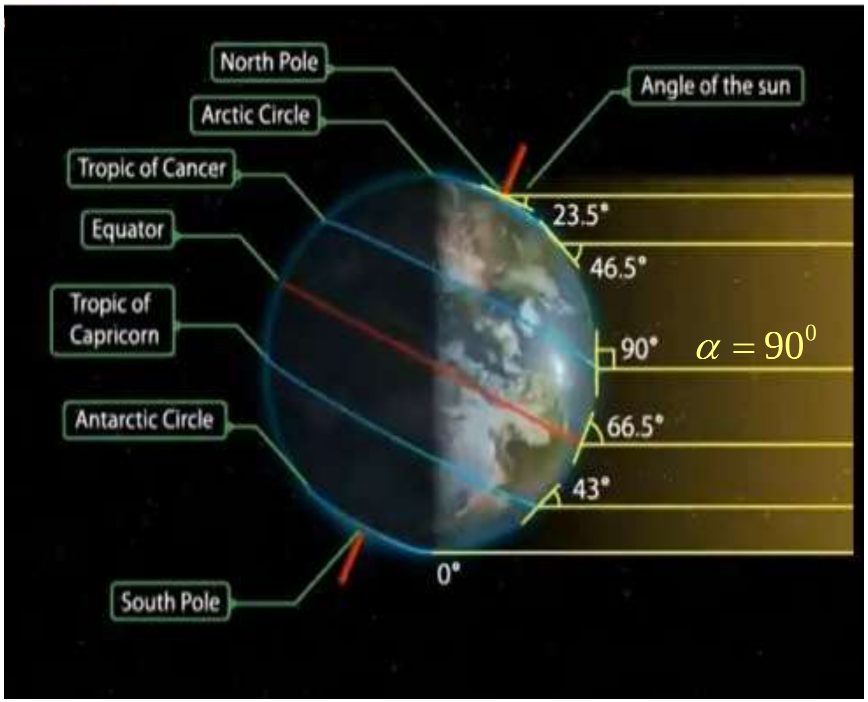
- *Atmospheric absorption of solar radiation → high temps (energies)*
- *Atmospheric absorption of terrestrial radiation→ infrared*

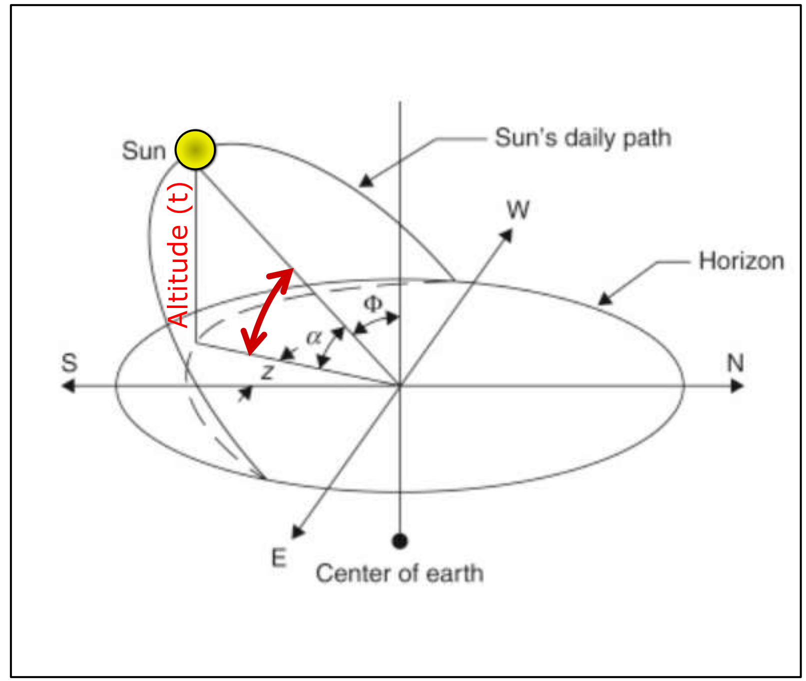
Strategy: Macroscopic absorption → atomic cross section → quantum degrees of freedom → energy spectrum → specific molecular absorption cross section for elm. radiation

Inclination of Sun and Earth

Time averaged over <u>*spinning*</u> *Earth* : $S_{eff}\left(90^0\right)=240W/m^2 \Rightarrow T_0=\left[S_{effective}/\sigma\cdot(4-2f)\right]^{1/4}$

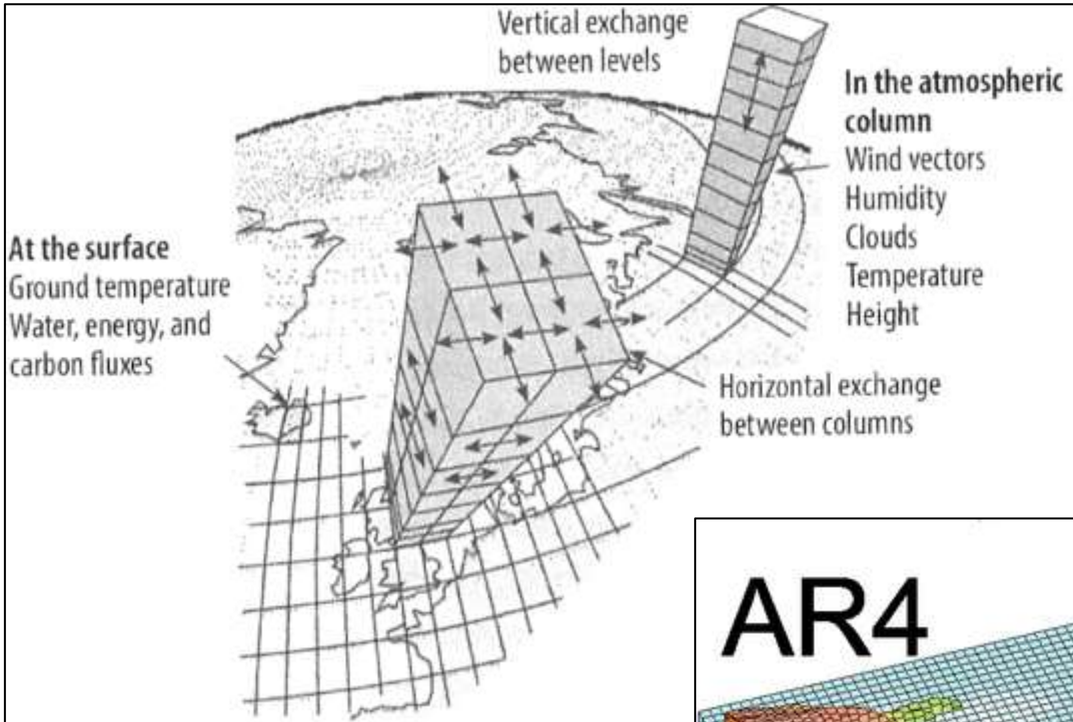
Depends on solar altitude angle α : $S_{eff}(\alpha)=S_{eff}\left(90^0\right)/\sin\alpha(t)$





Effective angle $\alpha \neq 90^0$ of incidence of sunlight onto surface decreases effective insolation S_{eff}, dependent on day in the year, hour in the day. Tabulation and formulas from spherical geometry.

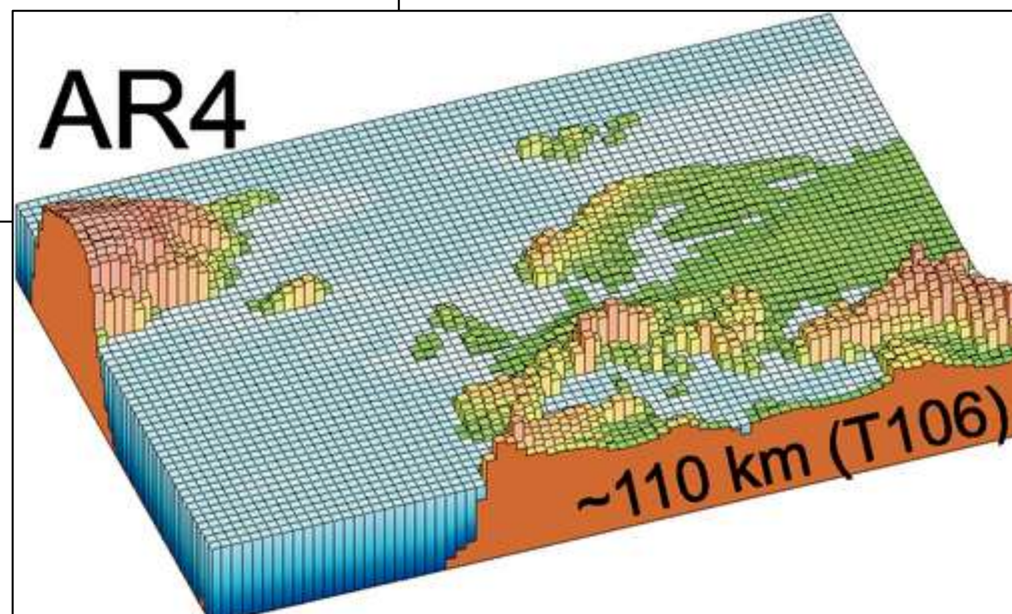
Climate Models: Geographic Resolution



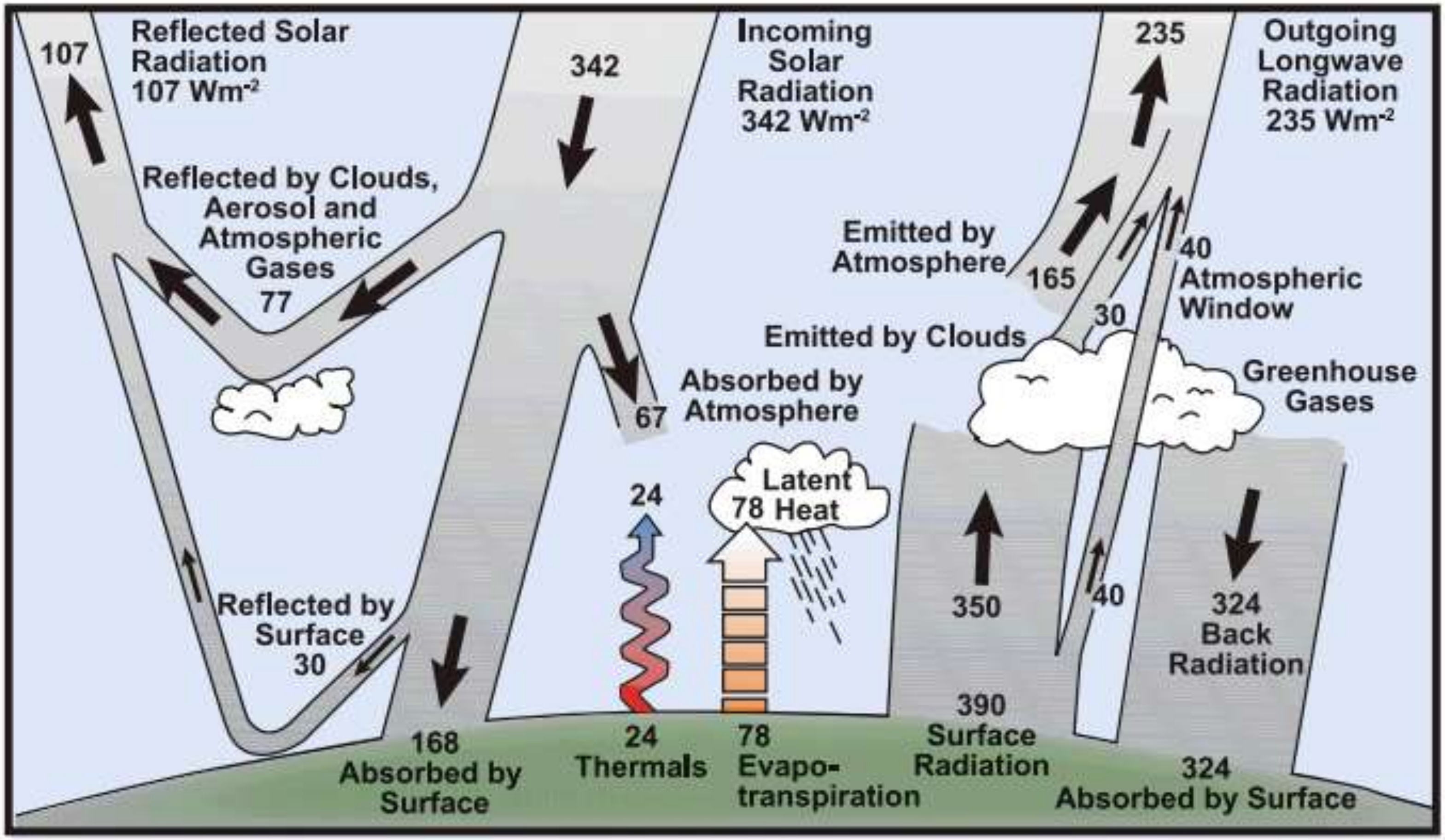
S.E. Koonin, *Unsettled ?*(2021)

Improved spatial resolution of hydrodynamic simulation codes used for extensive IPCC climate models. Require days of Supercomputer power.

AR6 (2020):
lateral resolution 25 km,
vertical resolution
many oceanic and atmospheric layers



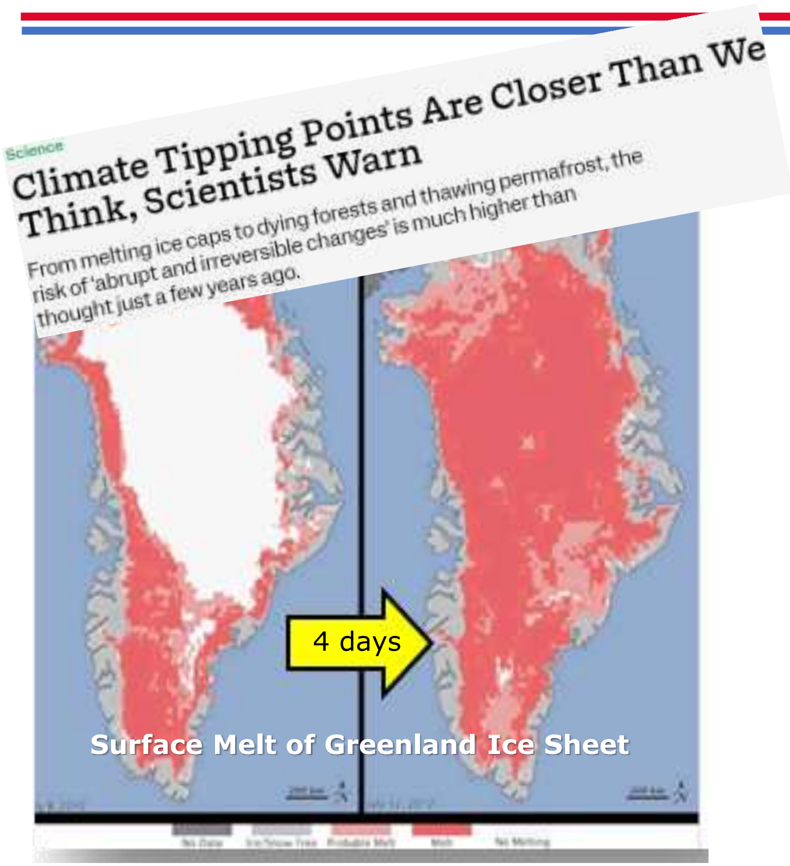
Understanding Earth's Radiation Balance



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).*

From IPCC AR4 Report, assessed Aug. 2012:
http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-chapter1.pdf

Tipping Points in Earth Climate ?



Non-linear and coupled effects in Earth current climate evolution → global warming, melting of sea ice , ice cap, desertification, ocean acidification, sea level rise,……

<u>Historic climate facts:</u>
Earth climate has alternated between Ice ages (little and major) and greenhouse periods. Transition speed?
Do we have time to adapt or change pace?
Mind the fate of planet Venus (NYT 012921)

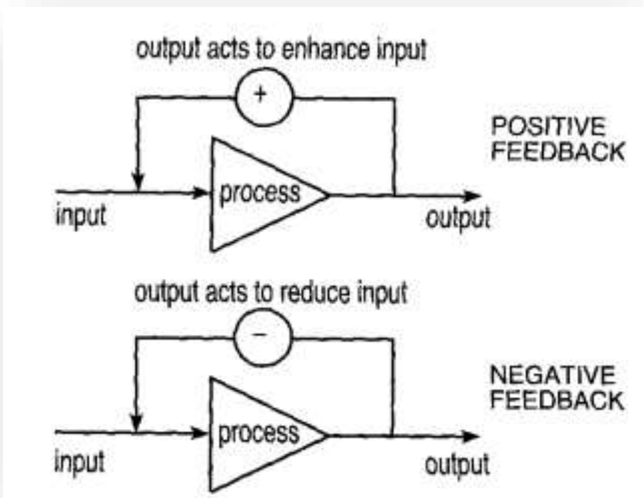
Earth albedo or surface reflectivity ε = important in maintaining radiation balance

Glaciation: increasing ice cover $\Delta\varepsilon > 0 \rightarrow$ *surface temperature change* $\Delta T < 0$

Warming: decreasing ice cover $\Delta\varepsilon < 0 \rightarrow$ *surface temperature change* $\Delta T > 0$

Albedo is non-monotonic function of important driving parameters, has extrema!

Non-Linear Forcings: Feedback Effects



Important feedback forcing mechanisms considered in climate models:

- CO_2 runaway process: Increase [CO_2] → increase T → release additional CO_2 from frozen Tundra →
- Ice – albedo: White Ice surface reflects more radiation, lowers T, more freezing →
- H_2O greenhouse effect: More humidity raises atmospheric IR absorption, higher T, more humidity →
- Cloud effects (dynamical and thermal), complex interaction between radiation, convection, circulation, cloud cover. Albedo effect dominates.

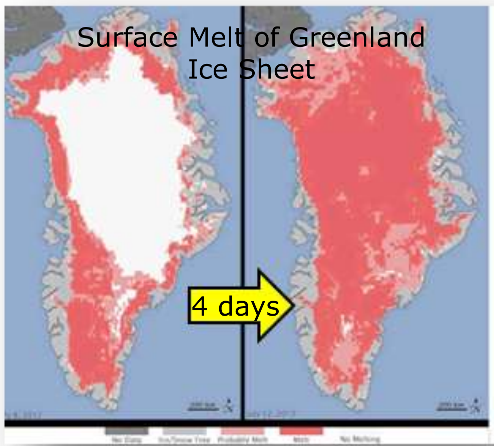
H_2O greenhouse effect looses importance if troposphere is already opaque to IR. Then, it only affects heat convection.

Combination of partially canceling positive and negative feedbacks.
However:
Complex systems have capacity of sudden irregular (chaotic) response to small changes of parameters.

Examples

Non-Linear Climate Forcings

Time dependent Earth albedo, rapid change in Greenland



Thawing Tundra (Area =1.1x Area_of US) → time dependent CO_2/CH_4 emitter

After Taylor (ECP)

$$Earth\ albedo\ a = a\big(T(t)\big) \rightarrow T = T(t) = surface\ temperature$$

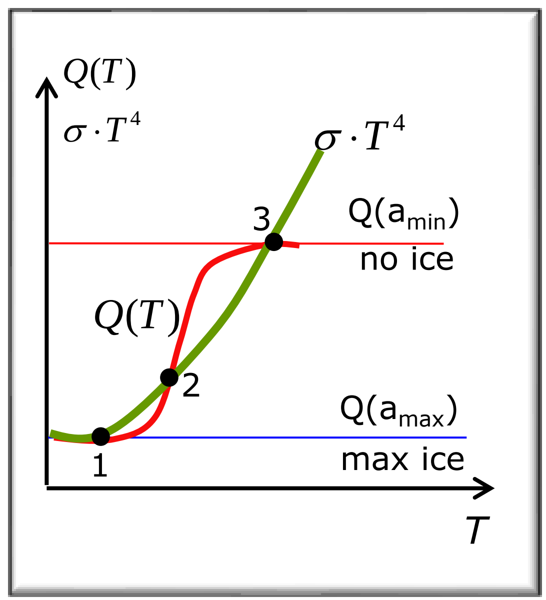
$$C = effective\ surface\ heat\ capacity:\ abs. heat\ energy\ Q = C \cdot T$$

$$Differential\ equation\ for\ T(t)$$

$$C \cdot \frac{d}{dt} T(t) = \big(1 - a(T)\big) \cdot \frac{S}{4} - \sigma \cdot T^4(t) \quad with\ S, \sigma\ constants$$

T increases, and a decreases (more ice melting), as long as

$$\big(1 - a(T)\big) \cdot \frac{S}{4} > \sigma \cdot T^4(t) \ \ or\ \ 1 - 4\frac{\sigma}{S} \cdot T^4(t) > a(T) > 0$$



$Stable\ states: T(t) = const.? \rightarrow$

$dT(t)/dt = 0\ \ at\ \ T = T_i\ \ (i = 1, 2...)$

$$Q(T_i) = \big(1 - a(T_i)\big) \cdot \frac{S}{4} = \sigma \cdot T_i^4$$

$But\ d^2T(t)/dt^2 < 0 \rightarrow\ unstable$

$Assume\ gen.\ dependence\ a(T)$

$a(T) = a_0 + c_1 \cdot T + c_2 \cdot T^2 + ...?$

$T \rightarrow 0 : a \rightarrow a_{max}, T \rightarrow \infty : a \rightarrow a_{min}$

Stable states 1) ice age or 3) ice free. State 2) is meta stable, unstable against small changes in ***a***.

Sudden climate changes !

Speculation: Non-Linear Earth Albedo Model

From history: Albedo ε is non-monotonic function of time, important driving forces.

Combine ε parameter dependence to model *non-linear* dependence on history:

$$\varepsilon(t+\Delta t) = \alpha \cdot \varepsilon(t) - \beta \cdot \varepsilon^2(t) + ...; \quad parameters\ \alpha, \beta = f(CO_2, ...)?$$

$$Since\ \varepsilon(t)\ is\ non-monotonic\ and\ must\ have\ an\ extremum$$

$$\rightarrow sign(\alpha) = sign(\beta),\ choose\ \alpha, \beta > 0$$

$$Adopt\ discrete\ time\ steps\ \Delta t\ \ (days, months, years, ..., centuries) \rightarrow$$

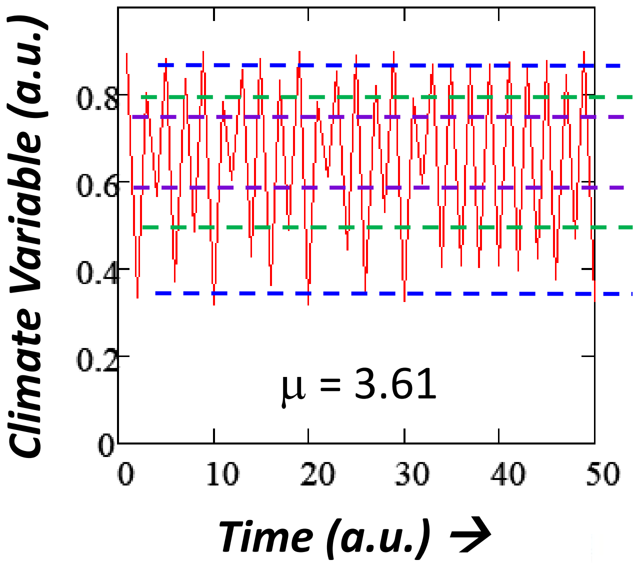
$$\varepsilon_{n+1} = \varepsilon_n(t + n \cdot \Delta t) \approx \alpha \cdot \varepsilon_n - \beta \cdot \varepsilon_n^2 \qquad "Iteration"$$

Variable transformation $\rightarrow$

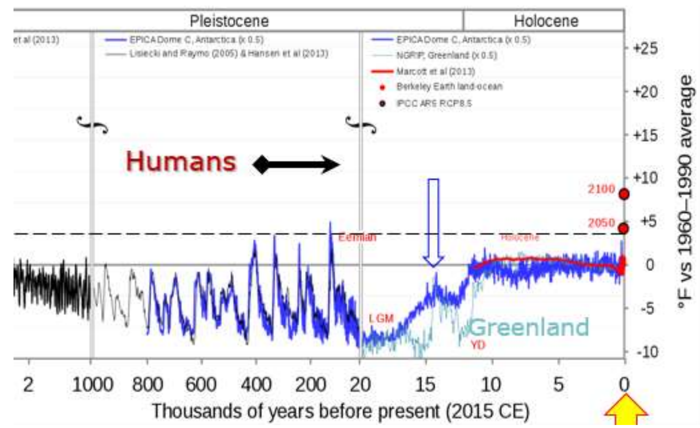
Profile function $f(\varepsilon) = \mu \cdot \varepsilon \cdot (1 - \varepsilon)$ *"Logistic Map"*

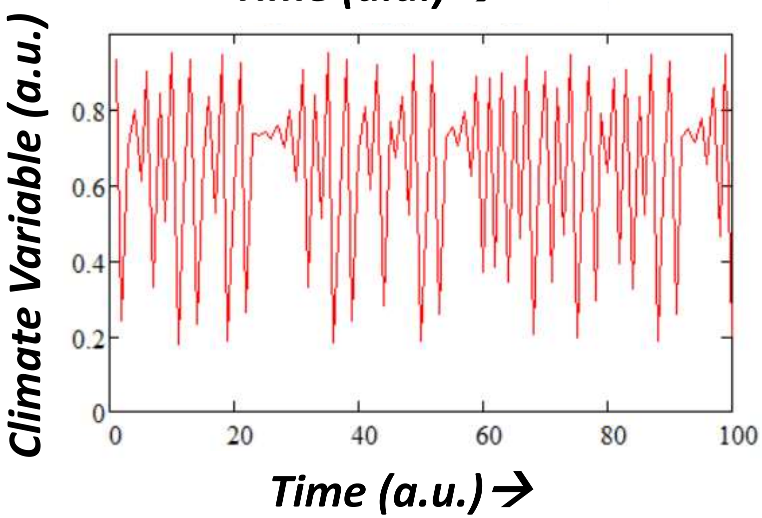
$$\varepsilon_{n+1} = f(\varepsilon_n) = f(f(\varepsilon_{n-1})) = f(f(f(\varepsilon_{n-2}))) = f^3(\varepsilon_{n-2}) \quad Iterative\ Logistic\ Map$$

Speculation: Chaotic Climate Trajectories



Amplification factor $\mu = 3.61$ → Climate variable is unstable, jumps between different extremes at irregular times → chaotic trajectory.



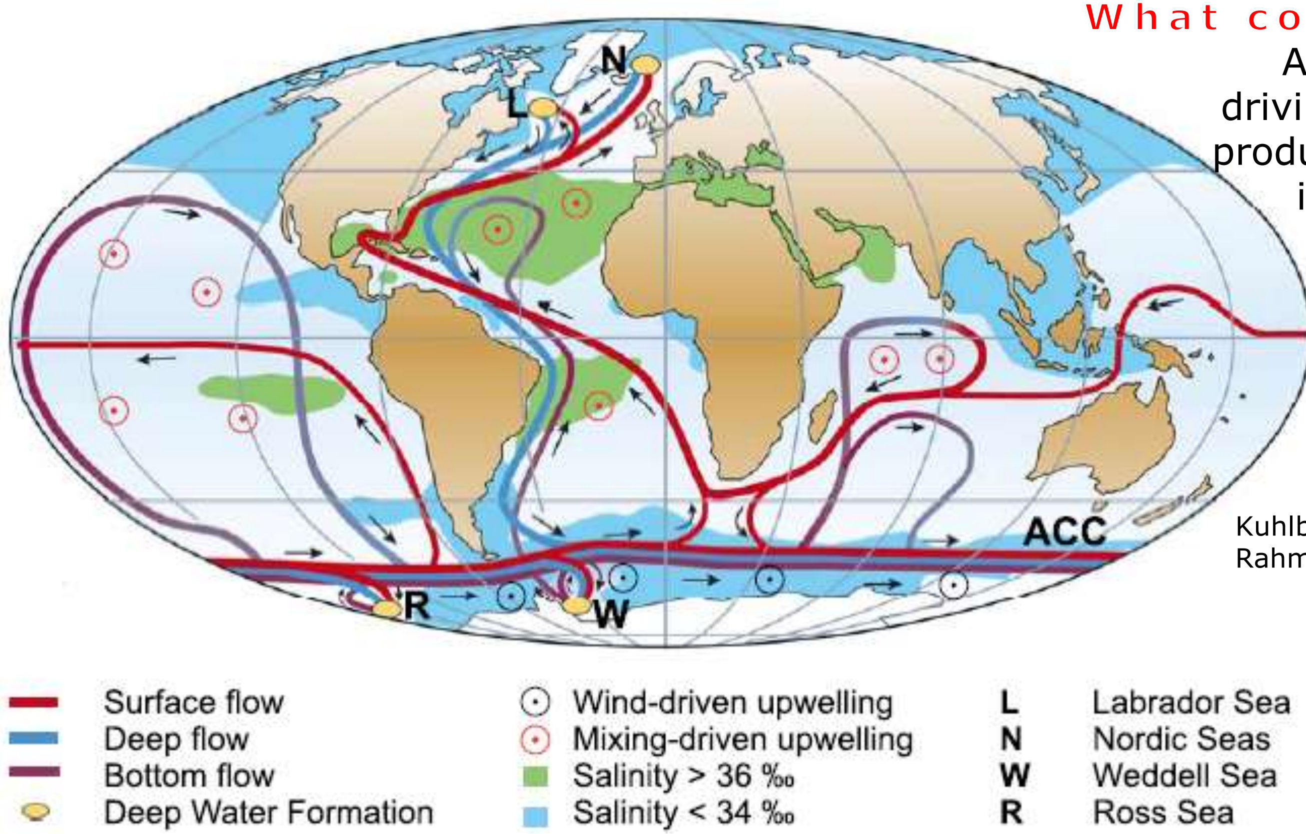


Same example as above for slightly larger amplification factor $\mu = 3.8$ → Climate variable shows similar but not exact similarities, intermittency domains.

Fortunately, actual amplification factor μ are probably small → Climate variable could be stable.

Fragile Thermohaline Ocean Circulation

What could happen with Atlantic "conveyor belt" driving Gulf Stream, which produces moderate climate in Western Europe and North America.



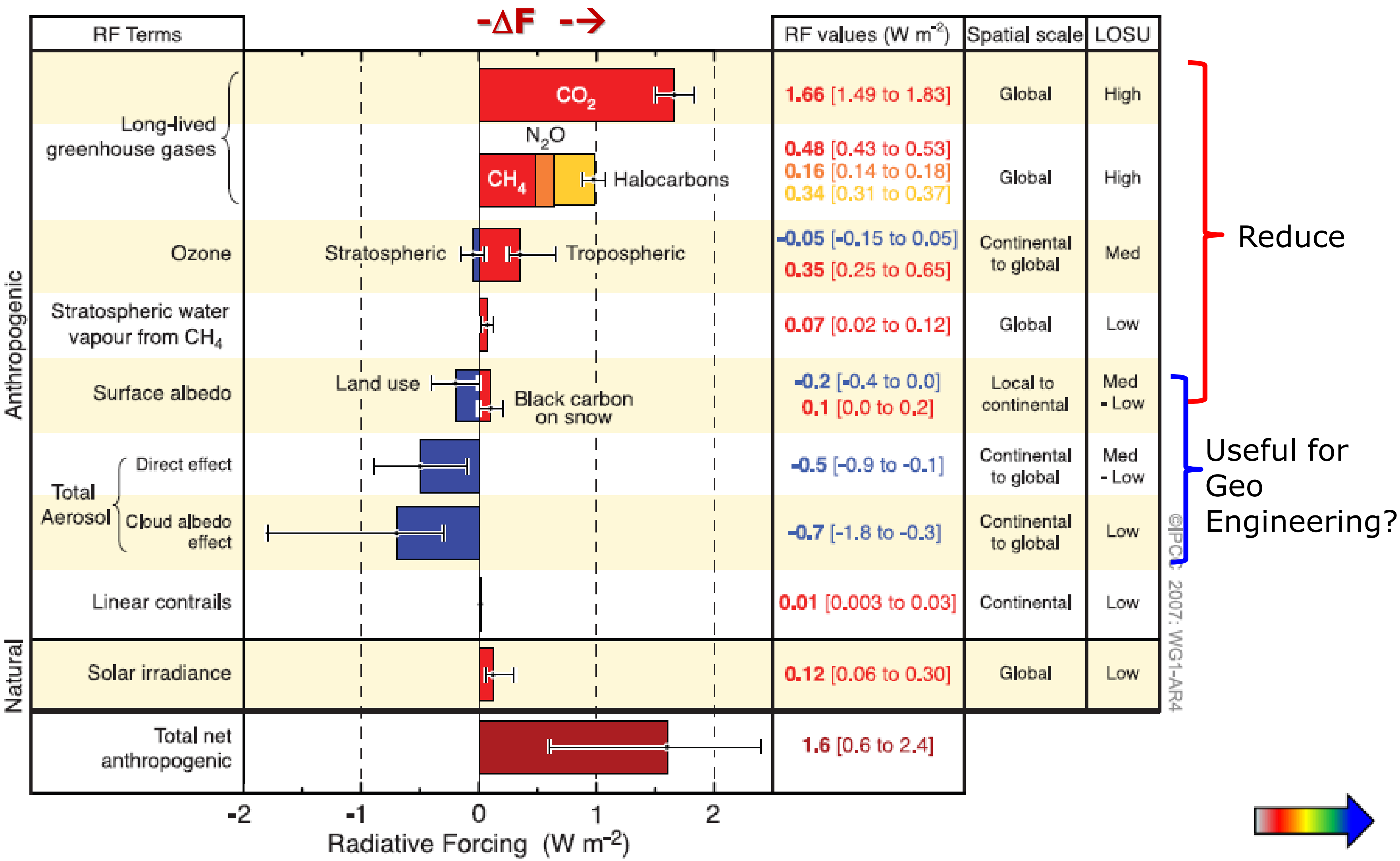
Kuhlbrodt et al., Rahmstorf et al.

Atlantic: Warm saline (sea) water flows north, cools and sinks into deeper waters. Cold saline water returns southward. Possible scenario from glacial ice melting: saline water dilutes with fresh water, which does not sink readily. → backflow to south interrupted, circulation blocked →

stops Gulf Stream: consequences for European and North American climate.

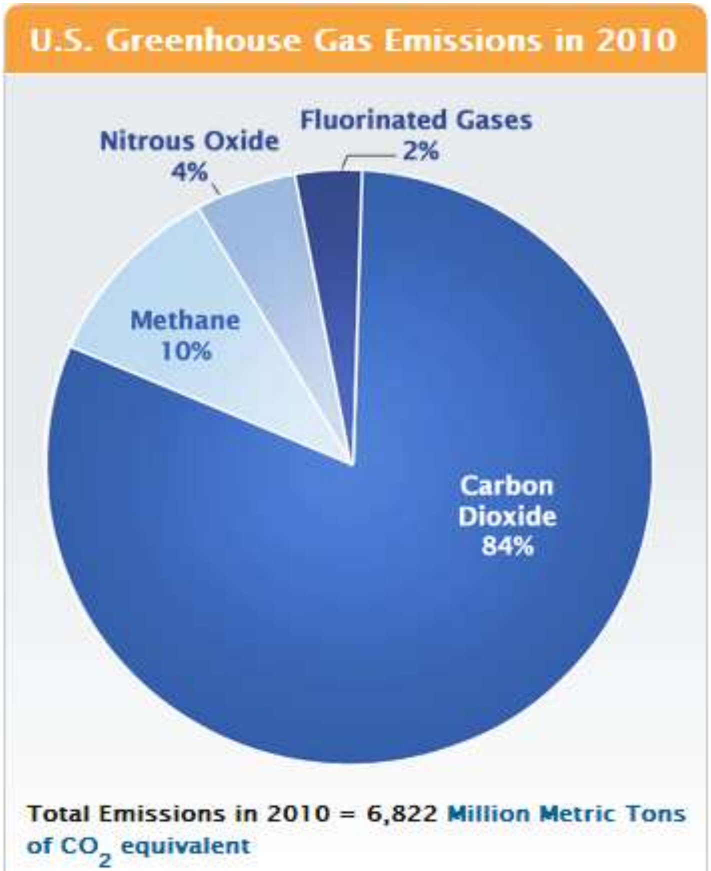
Anthropogenic vs. natural forcings →

Anthropogenic vs. Natural Forcings



Human activities: greenhouse gas (GHG) emissions have significant influence on CC

Greenhouse Gas Emission



EPA Report on Climate Change, GHG
http://www.epa.gov/climatechange/ghgemissions/gases.html

Greenhouse Gases (GHG) = gases that trap heat (IR) in the atmosphere and heat surface.

Carbon dioxide (CO_2) from burning fossil fuels (coal, natural gas, oil), solid waste, biomass (plants, wood, animal products), manufacture of cement. 0.035% in atmosphere.

Methane (CH_4) emitted in production (mining) and transport of coal, natural gas, oil, from livestock, agricultural practices, decay of organic waste in municipal solid waste landfills.

Nitrous oxide (N_2O) from agricultural and industrial activities, combustion of fossil fuels and solid waste.

Fluorinated gases = (HFCs, CFCs, PFCs = hydro/chloro-fluorocarbons, per-fluorocarbons, halon, SF_6) from industrial processes.

→ potent greenhouse gases = High Global Warming Potential gases ("High GWP gases").

Water (H_2O) vapor: >65% responsible for GH effect, but atmospheric content= Humidity is function of *temperature* : Clausius-Clapeyron Law,
H_2O *not directly* affected by anthropogenic activities, but indirectly via CO_2 emission.
Positive feed-back loop T ←→ water-vapor, but clouds stabilize !

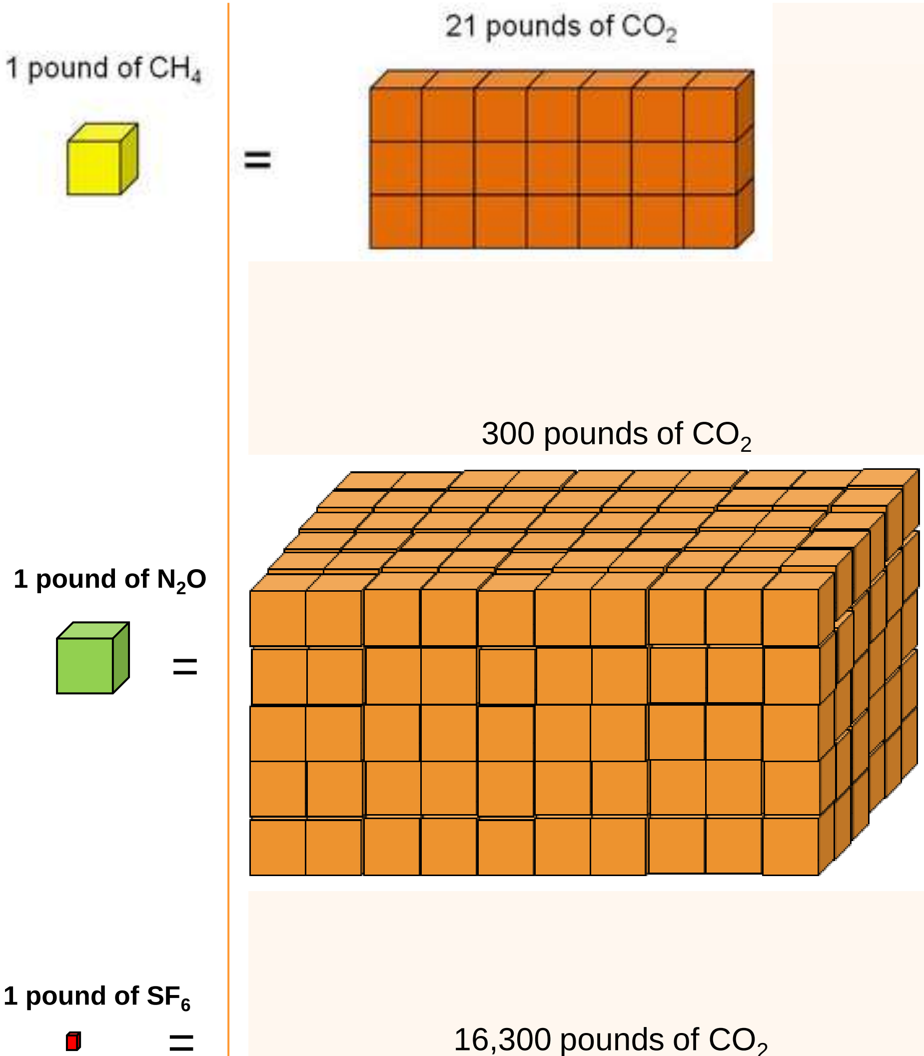
Global Warming Potentials: Data

Species	Chemical formula	Lifetime (years)	Global Warming Potential (Time Horizon)		
			20 years	100 years	500 years
CO_2	CO_2	variable §	1	1	1
Methane *	CH_4	12±3	56	21	6.5
Nitrous oxide	N_2O	120	280	310	170
HFC-23	CHF3	264	9100	11700	9800
HFC-32	CH2F2	5.6	2100	650	200
HFC-41	CH3F	3.7	490	150	45
HFC-43-10mee	C5H2F10	17.1	3000	1300	400
HFC-125	C2HF5	32.6	4600	2800	920
HFC-134	C2H2F4	10.6	2900	1000	310
HFC-134a	CH2FCF3	14.6	3400	1300	420
HFC-152a	C2H4F2	1.5	460	140	42
HFC-143	C2H3F3	3.8	1000	300	94
HFC-143a	C2H3F3	48.3	5000	3800	1400
HFC-227ea	C3HF7	36.5	4300	2900	950
HFC-236fa	C3H2F6	209	5100	6300	4700
HFC-245ca	C3H3F5	6.6	1800	560	170
Sulphur hexafluoride	SF6	3200	16300	23900	34900
Perfluoromethane	CF4	50000	4400	6500	10000
Perfluoroethane	C2F6	10000	6200	9200	14000
Perfluoropropane	C3F8	2600	4800	7000	10100
Perfluorobutane	C4F10	2600	4800	7000	10100
Perfluorocyclobutane	c-C4F8	3200	6000	8700	12700
Perfluoropentane	C5F12	4100	5100	7500	11000
Perfluorohexane	C6F14	3200	5000	7400	10700

United Nations
Framework Convention on Climate Change

http://unfccc.int/ghg_data/items/3825.php

Global Warming Potential (GWP)



Main factors:

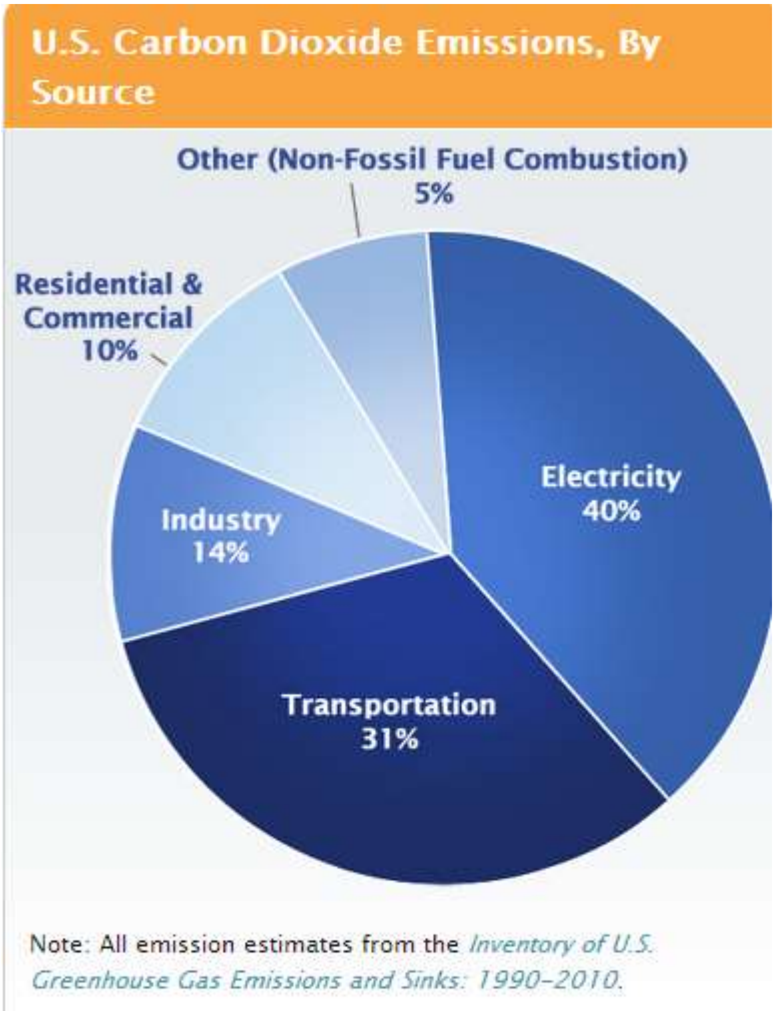
1) Effectiveness to trap heat (GWP#)
2) Abundance in atmosphere
3) Residence/lifetime in atmosphere

CO_2: GWP := 1 (reference).
Lifetime in Earth's atmosphere ~100 a.

CH_4: GWP = 21
Lifetime in Earth's atmosphere ~12 a.

N_2O: GWP = 300
Lifetime in Earth's atmosphere ~120 a.

US GHG Emission Sources (2010)



Electricity (40% of total CO_2, 33% of GHG emission) via combustion of fossil fuels. Coal produces more CO_2 than oil or natural gas.

Transportation (31% of CO_2 , 26% of GHG), via combustion of fossil fuels. This category includes transportation sources such as highway vehicles, air travel, marine transportation, and rail.

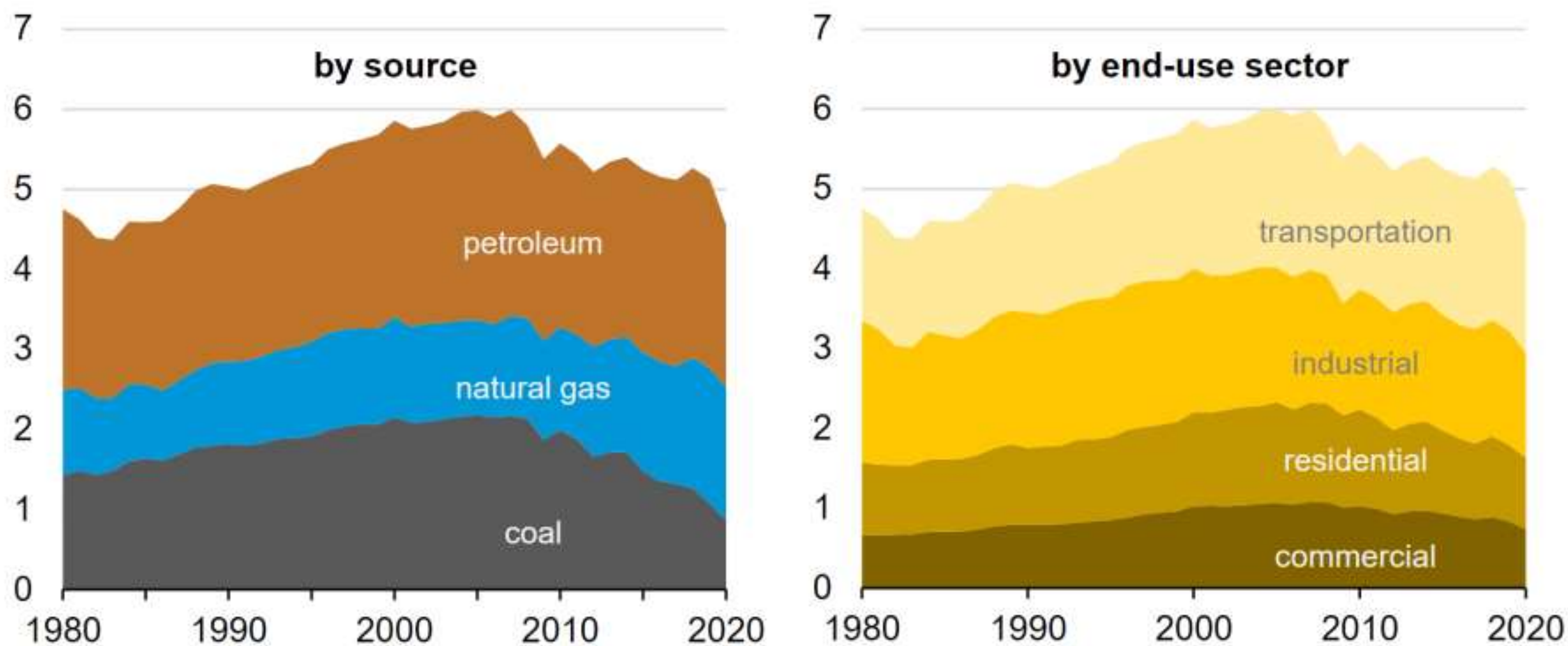
Industry (14% of CO_2 , 20% of GHG) mostly via fossil fuel combustion. Some important processes also produce CO_2 via chemical reactions (not combustion).

Examples: production and consumption of mineral products (e.g., cement), production of metals (e.g., iron, steel, etc.), production of certain chemicals.

Indirect CO_2 production via use of electricity (e.g., aluminum, composites,…).

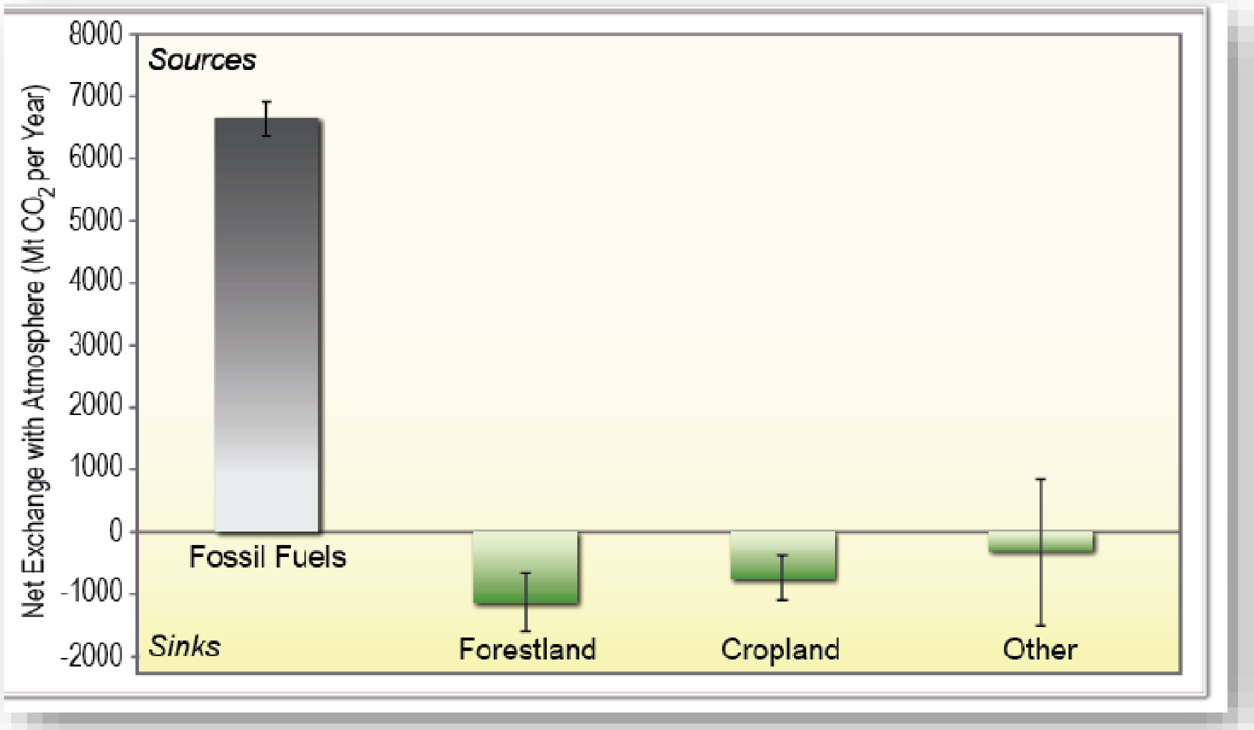
1990-2010: U.S. Trends incresed (5-6 Gt CO_2/a) → contra Kyoto Protocol, decrease!!

US CO_2 Emission Trends



Source: U.S. Energy Information Administration, *Monthly Energy Review*

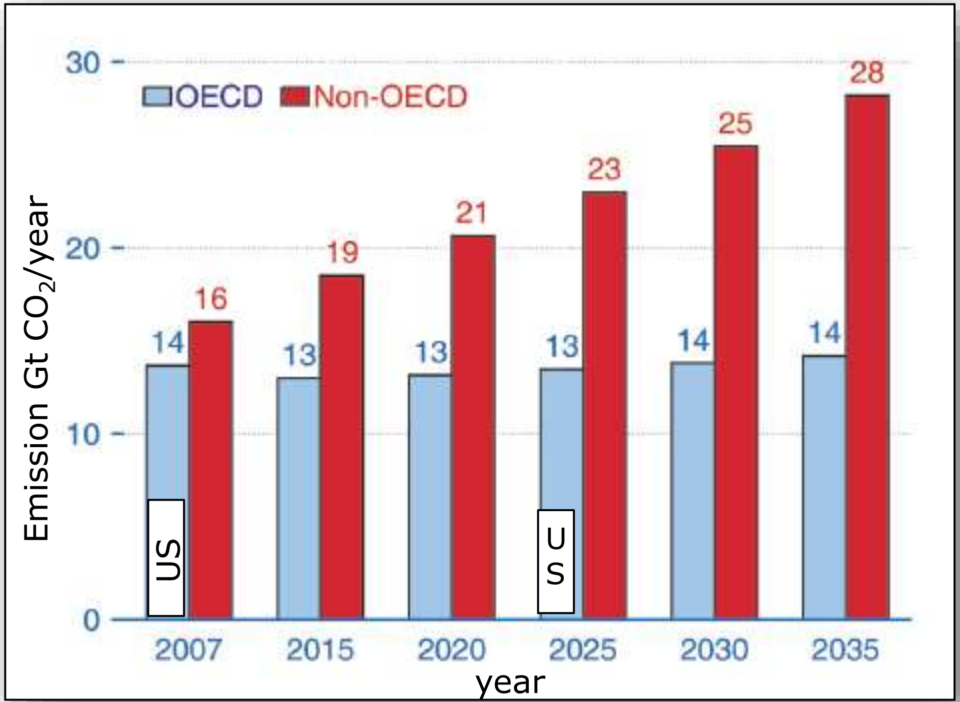
North American CO_2 Sources and Sinks



"At the continental scale, there has been a large and relatively consistent increase in forest carbon stocks over the last two decades (Woodbury et al. 2007), due to recovery of forests from past disturbances, net increases in forest area, and faster growth driven by climate or fertilization by CO_2 and nitrogen (King et al. 2012; Williams et al. 2012). However, emissions of CO_2 from human activities in the U.S. continue to increase and exceed ecosystem CO_2 uptake by more than three times. As a result, North America remains a net source of CO_2 into the atmosphere (King et al. 2012) by a substantial margin."

After NCADAC report 2013

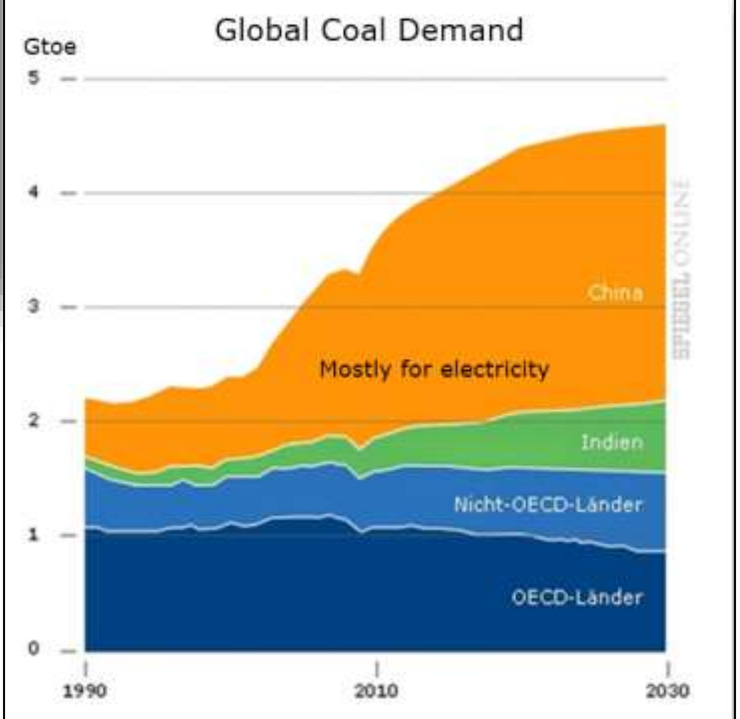
BAU Projections for CO_2 Emissions



Energy Information Administration / International Energy Outlook. 2010

World energy-related CO_2 emission projections (in billion metric tons CO_2), by OECD (Organization for Economic Cooperation and Development) and non-OECD countries over the period 2007-2035.

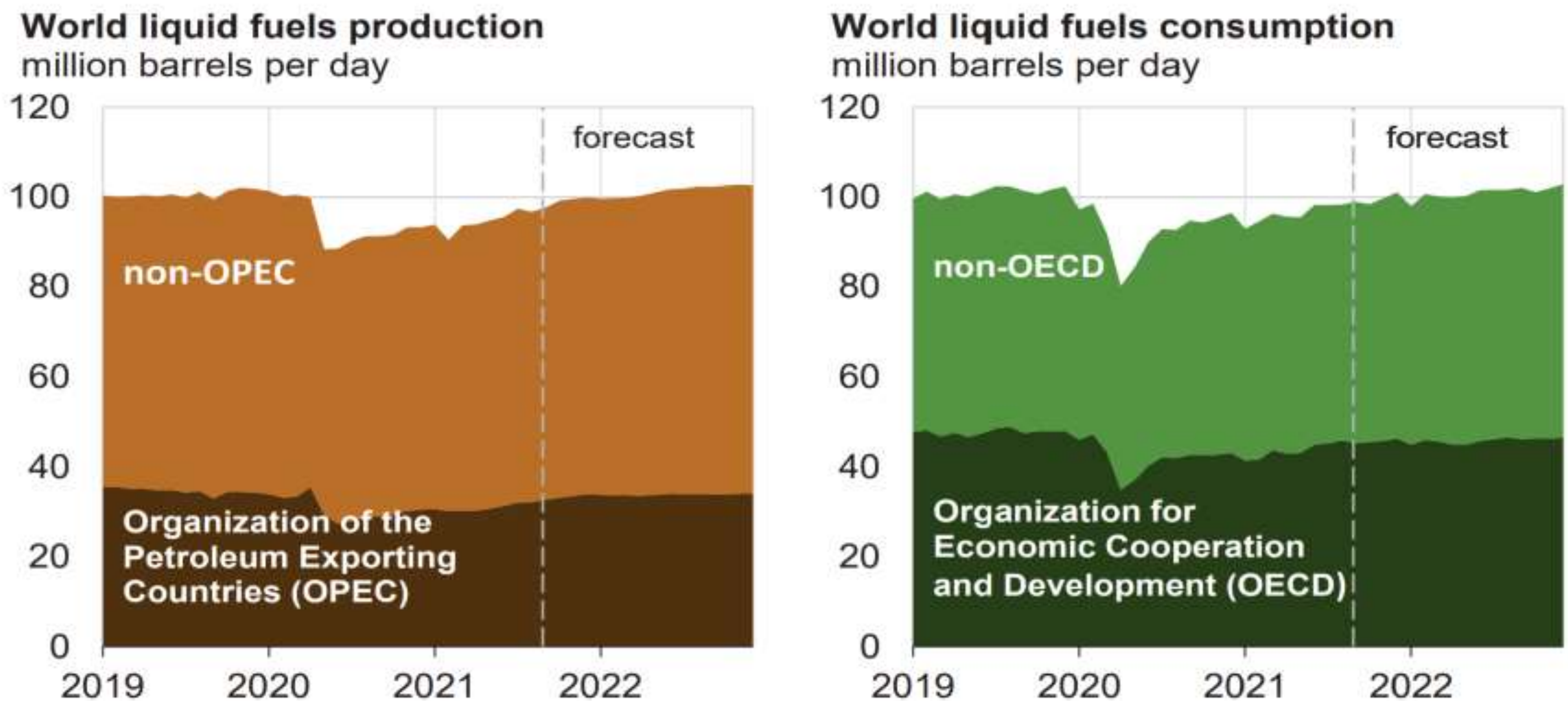
Non-OECD countries include developing, newly industrialized, Eastern European plus former Soviet countries. http://www.oecd.org/countrieslist/.



After: Spiegel online, Oct. 2012/ Sources BP, IEA

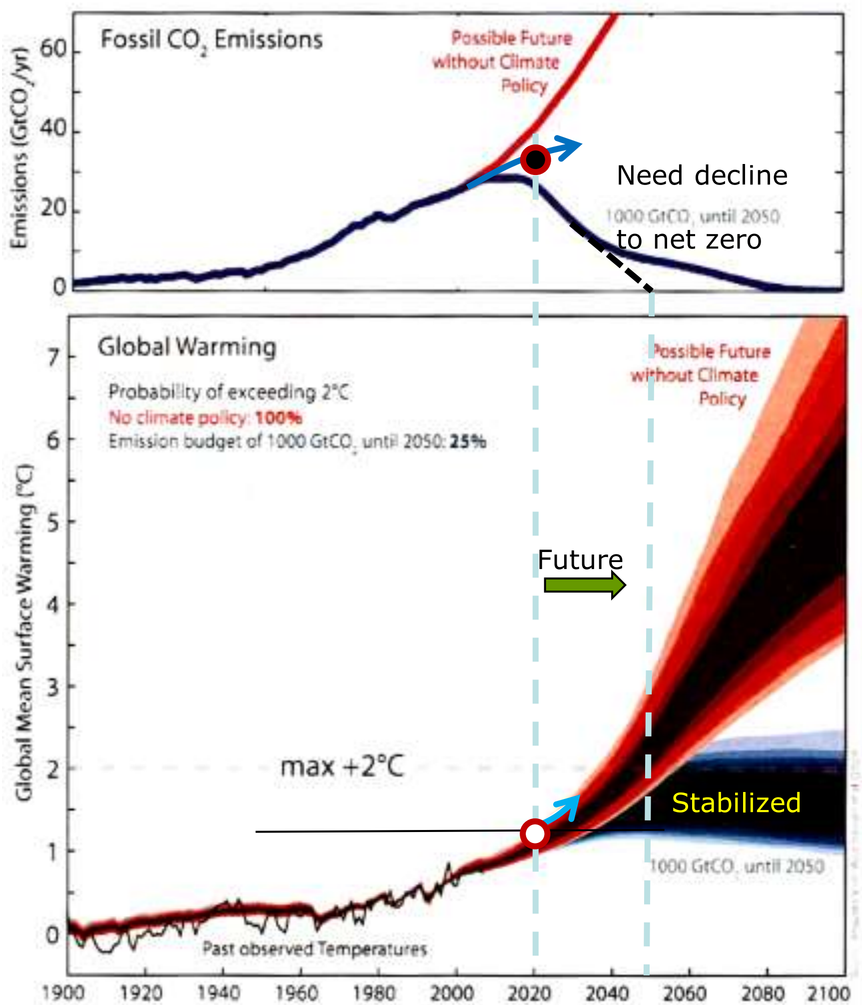
US (5% world population) produce now 20% of global CO_2 emissions.

1 ton of oil equivalent (toe) = 42 GJ =energy released by burning 1 ton of crude oil.



Source: U.S. Energy Information Administration, Short-Term Energy Outlook, September 2021

Possible Climate Futures



Correlated with scenarios of constant, decreased or increased emissions of greenhouse gases.

Changing climate → changes in frequency, intensity, spatial extent, duration, timing of extreme weather and climate events, even produces unprecedented extreme weather and climate events. (NAS report).

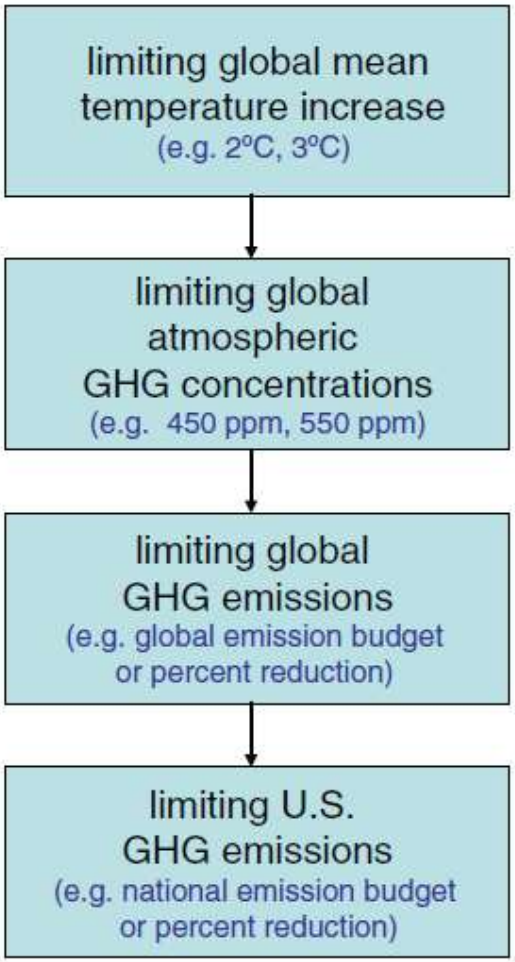
Examples: Extensive heat waves and droughts, super-storms/hurricanes, extreme downpours, flash flooding, coastal flooding due to rising sea levels, atmospheric rain channels, troughs,…. Global: stopping the Gulf Stream.

$\Delta T \leq 2^0C$ until 2050 are probably "relatively well manageable."

Larger temperature increases (4^0-6^0) are likely catastrophic (T, sea level).

We are on a dangerous path !

Mitigation Goals



What is a 'safe' amount of climate change?
Depends on the risks associated with given temperature targets, and decisions about willingness to tolerate these risks

----

How does GHG concentration translate into global temperature change and other impacts?
Depends on climate sensitivity and the strength of other forcing factors (e.g., aerosols)

How does a given level of emissions translate into an atmospheric GHG concentration?
Depends on carbon cycle dynamics and the timing of emission reductions

----

What is a reasonable share of U.S. emission reductions relative to the global targets?
Depends on political, economic, and ethical judgments

Developing nations find requests by the US to limit emissions unjustified because current per-capita emissions and standard of living in the United States and other developed nations are the highest and because US is responsible for largest share of historical increase in atmospheric GHG, and because the US have not yet enacted a restrictive emission policy or ratified Kyoto Protocol.

National Climate Assessment and Development Advisory Committee

Summary Findings (2017, edited). Projections → 2100, Different polit. scenarios:

1) Global climate is changing, apparent in a wide range of observations. The climate change of the past 150 years is due largely to human activities (burning of fossil fuels).

2) Extreme weather and climate events have increased in recent decades; evidence is mounting for human activities as dominant cause (More recently "high confidence"_).

3) Human-induced part of climate change will accelerate significantly if emissions of heat-trapping gases continue to increase.

4) Impacts of climate change, evident in many sectors, become increasingly challenging.

5) Threats to human health and well-being from extreme weather events, wildfire, dangerous air quality, diseases transmitted by insects, food, and water, and threats to mental health.

6) Infrastructure is adversely affected by climate change: sea level rise, storm surge, heavy downpours, extreme heat.

7) Lower reliability of water supplies, affecting ecosystems and livelihoods in many regions: US Southwest, Great Plains, Southeast, Caribbean and Pacific islands, including the state of Hawaii.

8) Adverse impacts to crops and livestock over the next 100 years, increasing disruptions from extreme heat, drought, and heavy downpours.

9) Natural ecosystems directly affected, changes in biodiversity and location of species.

10) Life in the oceans is changing as ocean waters become warmer and more acidic.

11) Planning for adaptation (address and prepare for impacts) and mitigation (reduce emissions) is increasing, but progress with implementation is limited.

→ 12) Large-scale human migration

Literature

F.W. Taylor, *Elementary Climate Physics,* Oxford University Press, Oxford, New York, 2005.

K. McGuffie and A. Henderson-Sellers, *A Climate Modelling Primer*, Wiley, Hoboken, 2005

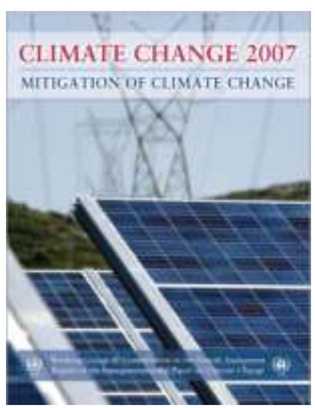
National Academy of Sciences Report on Climate Change (2010) http://nas-sites.org/americasclimatechoices/files/2012/06/19014_cvtx_R1.pdf

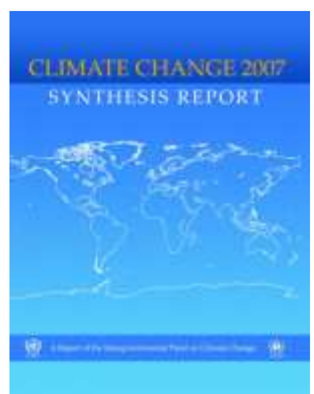
Reports of Working Groups of the Intergovernmental Panel on Climate Change

Climate Change 2007: The Physical Science Basis http://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg1_report_the_physical_science_basis.htm

Climate Change 2007: Mitigation of Climate Change and Synthesis Report
http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4_wg3_full_report.pdf
http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf

National Climate Assessment and Development Advisory Committee, Draft Report 2013, http://ncadac.globalchange.gov/download/NCAJan11-2013-publicreviewdraft-fulldraft.pdf





The End