6th IPCC assessment report (AR6)

- Working Group I (physical basis) released in August 2021
  *Summary for Policy Makers is good read*

- Working Group II (impacts) released in February 2022

- Working Group III (mitigation) to be released in April 2022
EQUILIBRIUM CLIMATE OF THE EARTH:
BALANCE BETWEEN SOLAR AND TERRESTRIAL RADIATION

SOLAR RADIATION (visible)

28% reflected by clouds, ice, Deserts, aerosols... (albedo)

TERRESTRIAL RADIATION (infrared)

Emitted radiation flux varies as 4th power of temperature

Effective temperature 255 K (-18°C, 0°F)
Greenhouse gases are transparent to solar radiation but absorb terrestrial infrared radiation and re-emit it both upward and downward.

28% reflected by clouds, ice...

Water, CO₂, methane are the most important greenhouse gases.

Surface temperature: 288 K (15°C, 59°F)
Climate change arises from disruption of radiative equilibrium

\[
\text{Climate equilibrium: } F_{\text{in}} = F_{\text{out}}
\]

\[
\text{Radiative forcing: } \Delta F = F_{\text{in}} - F_{\text{out}} > 0
\]

\[
\Delta X
\]

Positive radiative forcing:
- Warming: \( \Delta T \sim \Delta F \)
- Increase greenhouse gas by \( \Delta X \)

Negative radiative forcing:
- Cooling: \( \Delta T \sim \Delta F \)
- Increase albedo by \( \Delta X \)

Radiative forcing:
\[
\Delta F = F_{\text{in}} - F_{\text{out}} < 0
\]
Radiative forcing of climate change drives cascade of impacts and feedbacks.

External perturbation
- Natural:
  - solar changes
  - volcanoes
- Human:
  - emissions
  - land use change

Temperature change
\[ \Delta T \sim \Delta F \]

Physical impacts
- sea level rise
- ice loss
- precipitation changes
- ecosystem changes…

Societal impacts
- water resources
- agriculture
- fires
- disease…

climate feedbacks amplify \( \Delta T \)
Recent example: glacial-interglacial climate transitions

Fast climate transition driven by water, ice, CO$_2$ feedbacks on an initial solar forcing.
The natural carbon cycle

- Volcanoes
- Erosion

Atmospheric CO₂
- 600 Pg C

Land carbon
- 3,000 Pg C

Ocean carbon
- 40,000 Pg C

Sediment carbon
- 90,000,000 Pg C

Burial
Perturbation of carbon cycle by fossil fuel combustion

Increase in carbon reservoirs since preindustrial time

- Atmospheric CO$_2$: 600 Pg C + 165
- Land carbon: 3000 Pg C + 100
- Ocean carbon: 40,000 Pg C + 120
- Sediment carbon: 90,000,000 PgC

Volcanoes and erosion

Fossil fuel combustion

~ 200 years to take up CO$_2$
CO₂ levels today are higher than in past 800,000 years

418 ppm CO₂ today

Vostok ice core (East Antarctica)
Cooling from large volcanic eruptions

Volcanic aerosol particles reflect solar radiation, increase albedo

Pinatubo eruption (1991) decreased surface temperatures by 0.5°C for 2 years

Soben et al. [2002]
Quantify how human action can disrupt radiative equilibrium

Human action
- emissions
- land use change

Radiative forcing $\Delta F$

Temperature change

Physical impacts
- sea level rise
- ice loss
- precipitation changes
- ecosystem changes...

Societal impacts
- water resources
- agriculture
- fires
- disease...

climate feedbacks amplify $\Delta T$

$\Delta T \sim \Delta F$
Global surface temperature increase since 1880

Global Mean Estimates based on Land and Ocean Data

- Annual Mean
- Lowess Smoothing
- LSAT+SST Uncertainty

Temperature Anomaly w.r.t. 1951-80 (°C)

1880 1900 1920 1940 1960 1980 2000 2020

NASA/GISS/GISTEMP v4

https://data.giss.nasa.gov/gistemp
Can this warming be explained by disruption to climate equilibrium?

**CO₂**:
- 50% increase since preindustrial

**aerosol particles** (air pollution):
- Large increase since preindustrial

**methane**: 3x increase since preindustrial

**Solar radiation**: fluctuations but no long-term trend
Radiative forcing of climate change: $\Delta F = F_{in} - F_{out}$

Disruption of climate equilibrium between energy in ($F_{in}$) and energy out ($F_{out}$)

Climate equilibrium: $F_{in} = F_{out}$

Radiative forcing: $\Delta F = F_{in} - F_{out} > 0$

Positive radiative forcing: warming $\Delta T \sim \Delta F$

Increase greenhouse gas by $\Delta X$

Negative radiative forcing: cooling $\Delta T \sim \Delta F$

Increase aerosol by $\Delta X$
• Relationship of temperature response to radiative forcing is similar for all agents
• Radiative forcing is relatively easy to compute and is standard metric for climate policy (‘CO₂-equivalents’)
• Aerosols cancel about 30% of warming from greenhouse gases
Radiative cooling by aerosols

Earth surface

Aerosols scatter solar radiation back to space, increasing albedo; some aerosols (dust, soot) also absorb solar radiation and have more complicated effects.

California fire plumes

Pollution off U.S. east coast

Dust off West Africa
Aerosols (a.k.a. particulate matter) are decreasing worldwide in response to policies to improve air quality.

Aerosol decrease must be compensated for by more aggressive action on greenhouse gases.

Annual mean fine particulate matter (PM$_{2.5}$) in China

Zhai et al., 2019

Aerosol decrease must be compensated for by more aggressive action on greenhouse gases.

US air quality standards

China
Future projections of CO$_2$ emissions and temperature

Aggressive action is needed if we are to avoid 2 degrees of danger

IPCC [2022]
Recent history of CO$_2$ emission trends is not encouraging

Annual CO$_2$ emissions
Carbon dioxide (CO$_2$) emissions from the burning of fossil fuels for energy and cement production. Land use change is not included.

2020 economic slowdown decreased CO$_2$ emissions but only by a few percent

https://ourworldindata.org/co2-emissions
Methane radiative forcing is amplified by chemistry

• Methane has an atmospheric lifetime of only 9 years (versus ~100 years for CO₂) and produces ozone, water, and CO₂ when oxidized in atmosphere

→ Methane emission is 60% as important as CO₂ in explaining 1750-2019 warming

• The short lifetime of methane has consequences for climate policy:
  → Reducing methane emissions now would have a fast impact on climate
  → It would compensate for the decrease in aerosol pollution
  → It could save us from the ‘2 degrees of danger’ (maybe even 1.5)
  → But methane is largely irrelevant in the long term (~100 years)
  → Methane and CO₂ emissions should not be “equivalent” in climate policy

Current policy accounting of methane emissions as ‘25 CO₂ equivalents’ is based on radiative forcing of methane only and integrated over 100 years—completely flawed!

IPCC [2022]
Increasing attention to methane in climate policy

Biden at COP26 announcing Global Methane Pledge, now signed by 110 countries

Why did he say that methane causes half the warming? He should have said a third…
Methane is a major greenhouse gas, but where does it come from?

Complexity of methane sources

- Wetlands
- Livestock
- Oil/gas
- Waste
- Rice
- Coal mines

Satellite observations hold the key!

- Wetlands: 160
- Fires: 20
- Livestock: 120
- Rice: 40
- Oil/Gas: 70
- Coal: 40
- Waste: 70
- Other: 40

Current emissions in Tg/year (very uncertain!)

Maasakkers et al. [2019]

Uncertainty in current methane emissions makes it challenging to set a 30% reduction target.
Methane has been rising at an accelerated pace since 2007, likely attributable to livestock and fuels— but why?

Observations from NOAA surface network
Observing atmospheric methane from satellites
Satellite observations can now monitor methane hotspots…

…and emission trends

Zhang et al., 2021; Lauvaux et al., 2022
Simple measures can go a long way to decrease methane emissions

Fix leaks detected by satellite or aircraft
Flare excess gas …or use it
Recover gas from landfills

Recover/digest gas from manure ponds, wastewater plants
Upland rice agriculture
Geoengineering methods: CO$_2$ removal, solar radiation management

1. Reflective Aerosols
2. Cloud Seeding
3. Space Mirrors
4. Forestation
5. CO$_2$ Capture from Air plus Storage
6. CO$_2$ Capture from Fossil Fuels plus Storage
7. Ocean Iron Fertilization
8. Carbon Dioxide Removal

Sources: IPCC / Royal Society | More info: www.get2.cc/5e climatecentral.org
Geoengineering as a means to reduce climate risk

- Fossil fuels forever
- Emissions cut to zero
- Carbon removal
- Solar geoengineering
Time

Climate risks

Day of zero net emissions
Peak concentrations

Start large-scale carbon removal

Start solar geoengineering

End solar geoengineering

Start emission cuts

Solar geoengineering
Some key take-aways

- There is no doubt that current climate change is driven by human activity.
- Reducing climate risk requires immediate and strong action on reducing emissions of CO$_2$ and methane.
- Reducing aggressively methane emissions *together* with CO$_2$ emissions can avoid the ‘2 degrees of danger’.
- Although methane emission estimates are uncertain, controlling large point sources identified by satellite data is a ripe strategy for climate action.
- Avoiding 1.5 or 2 degrees of danger may require geoengineering to remove CO$_2$ and (temporarily) decrease solar radiation input.