Lecture 7: Climate Change I

ECON7720: Ecological and Environmental Economics

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Semester 2, 2026 | Required reading: Tietenberg & Lewis, Ch. 11

Recap of Lectures 5 and 6

Lecture 5: Air Pollution (T&L Ch. 8)

- Criteria pollutants, $PM_{2.5}$, NAAQS and international standards.
- CAC: technology mandates, nonattainment, cost-effectiveness evidence.
- Market-based: emission charges, the SO_2 Acid Rain Program, ETS worldwide, congestion pricing.

Lecture 6: Water Pollution (T&L Ch. 9)

- Point vs. nonpoint sources, fund vs. stock pollutants, emerging pollutants.
- CAC: CWA, technology-based standards, limited liability and oil spills.
- Market-based: ambient charges, transfer coefficients, watershed trading (Hunter River).

Lecture Outline

1. The science of climate change: greenhouse gases, findings, tipping points
2. Strategies, targets, and timing: mitigation, adaptation, carbon budget, net zero
3. Discount rates and the social cost of carbon: Stern vs Nordhaus

The Science of Climate Change

Unique aspects of greenhouse gases

What makes GHGs different from local pollutants?

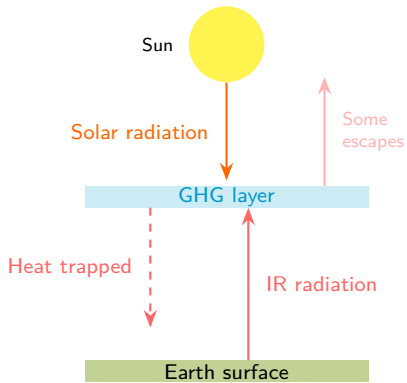
- Involves global, rather than regional or local, pollutants.
- Has an element of irreversibility due to the very long residence time of key GHGs in the atmosphere.
- Has additional uncertainties about key aspects of the threats it poses.
- Global solutions are much more politically complex than national solutions.
- International cooperation is hampered by climate-intensified scarcities (water, food) and expected surge in climate refugees.

Pollutant type

GHGs are global, stock (cumulative), and uniformly mixed pollutants $\Rightarrow$ location of emissions is irrelevant; short-term emission adjustments have little effect on atmospheric concentrations.

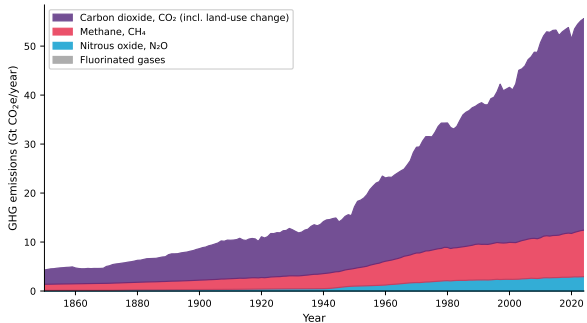
The greenhouse effect

- GHGs absorb infrared radiation re-emitted by the Earth's surface, trapping heat.
- Main GHGs: water vapour, CO_2, CH_4, and N_2O.
- This natural thermal blanket warms the surface to $\sim$15°C (vs. $-$18°C without).
- The problem: human activities enhance this effect by increasing GHG concentrations.



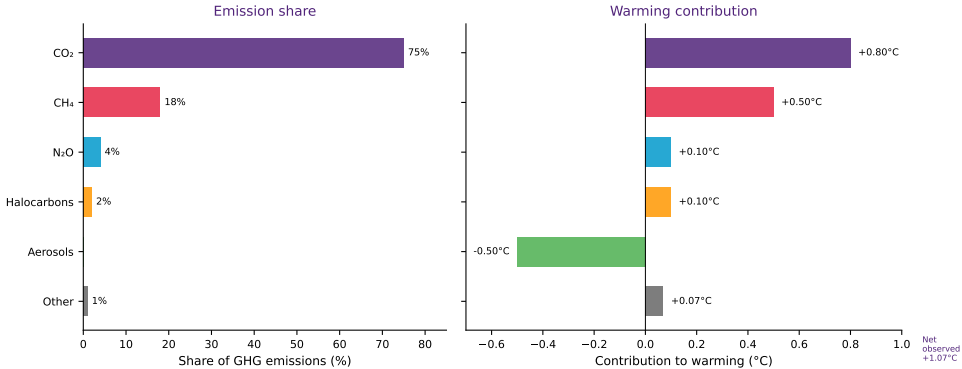
Global GHG emissions by gas

- Total: $\sim$54 Gt CO_2e/year (2024).
- CO_2 dominates ($\sim$75%), but CH_4 causes $\sim$0.5°C of observed warming despite being only $\sim$18% of emissions.
- Comparing gases requires a common unit: CO_2 equivalent (CO_2e), using Global Warming Potentials (GWP).



CO_2 = carbon dioxide (incl. land use); CH_4 = methane; N_2O = nitrous oxide; F-gases = fluorinated gases, a family of synthetic gases including HFCs (refrigeration, air conditioning), PFCs (aluminium smelting, semiconductors), and SF_6 (electrical insulation). Though a small share of total emissions, they are extremely potent (GWPs of 100s to 23,000$\times$ CO_2) and very long-lived (some persist for thousands of years). HFCs replaced ozone-depleting CFCs after the Montreal Protocol but turned out to be powerful GHGs. Source: Our World in Data / Climate Watch (1850–2024).

Emissions vs. warming



Emission shares $\neq$ warming shares, this is why we need **Global Warming Potentials** (GWP) to compare gases on a common scale. Warming contributions (1750–2019) from IPCC AR6 WG I, Ch. 7, Table 7.SM.1 (Forster et al., 2021). Emission shares (2021) from Climate Watch. "Other" includes solar irradiance changes and land-use albedo effects. Net observed warming: +1.07°C above 1850–1900 baseline. Components sum to more than observed because aerosol cooling partially offsets GHG warming.

The major greenhouse gases

Gas	Name	Main anthropogenic sources	GWP_{100}	Atmospheric life
CO_2	Carbon dioxide	Fossil fuels, cement, deforestation	1 (by def.)	100s–1000s yrs
CH_4	Methane	Fossil fuel production, livestock, landfills	28–36	$\sim$12 yrs
N_2O	Nitrous oxide	Agriculture (fertilisers), industry	265–298	$\sim$114 yrs
HFCs	Hydrofluorocarbons	Refrigeration, air conditioning	100s–1000s	1–270 yrs

Global Warming Potential (GWP_{100})

Measures how much energy 1 kg of a gas absorbs over 100 years relative to 1 kg of CO_2.

- CH_4: short-lived ($\sim$12 yrs) but absorbs far more energy per unit of time $\Rightarrow$ GWP of 28–36.
- N_2O: long-lived ($>$100 yrs) and 265–298$\times$ more potent per tonne than CO_2.
- HFCs: designed as ozone-safe substitutes, but powerful GHGs (Kigali Amendment, 2016).

CO_2 equivalent (CO_2e)

- A GWP-weighted sum of GHGs creates a single metric: CO_2e (carbon dioxide equivalent).

$$CO_2e = \sum_i GWP_i \times E_i$$

where E_i is the mass of emissions of gas i.

- Captures the total warming impact of any mixture of emissions.
- Useful for:
  - Comparing the climate impact of emission mixes across countries.
  - Setting emission limits tied to temperature targets.
  - Designing carbon pricing that covers all GHGs with a single price.
- Example: 1 tonne of $CH_4 \approx$ 28–36 tonnes CO_2e.

Natural factors

Natural climate variability (solar cycles, volcanic eruptions, El Niño) also influences climate, but the unambiguous long-term warming trend over the last century cannot be explained by natural factors alone.

Global Warming Potential — formal definition

GWP as a ratio of time-integrated radiative forcing

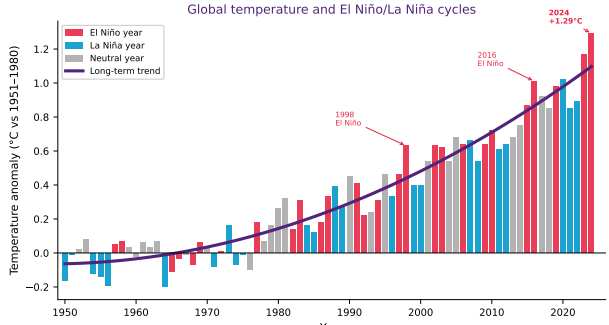
The GWP of gas i over a time horizon H is:

$$\text{GWP}_i^H = \frac{\displaystyle\int_0^H a_i \cdot c_i(t)\, dt}{\displaystyle\int_0^H a_{\text{CO}_2} \cdot c_{\text{CO}_2}(t)\, dt}$$

- a_i: radiative efficiency of gas i ($\text{W m}^{-2}\,\text{kg}^{-1}$), how much additional radiative forcing per unit mass in the atmosphere.
- $c_i(t)$: atmospheric decay function, fraction of a pulse emission remaining at time t.
- The numerator is the cumulative radiative forcing from 1 kg of gas i; the denominator is the same for CO_2.
- The standard horizon is $H = 100$ years (GWP_{100}), but GWP_{20} is also used, it gives more weight to short-lived but potent gases like CH_4.

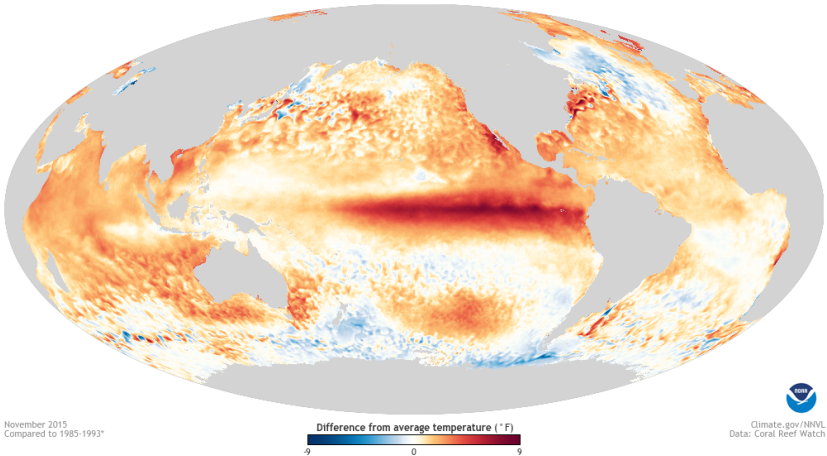
El Niño and climate change

- ENSO: a natural ocean–atmosphere cycle in the tropical Pacific (every 2–7 years).
- El Niño (warm phase) temporarily raises global temperatures by ∼0.1–0.2°C; La Niña (cool phase) lowers them.
- Key distinction: El Niño temporarily *transfers* ocean heat to the atmosphere; GHGs *add* heat by trapping outgoing radiation.



ENSO = El Niño–Southern Oscillation. The 1951–1980 baseline is the NASA GISS standard (well-observed 30-year period); other slides use the IPCC pre-industrial baseline (1850–1900). The choice of baseline shifts the y-axis but does not affect the warming trend or El Niño/La Niña classification. Source: NASA GISS (temperature anomaly); NOAA ONI (ENSO classification).

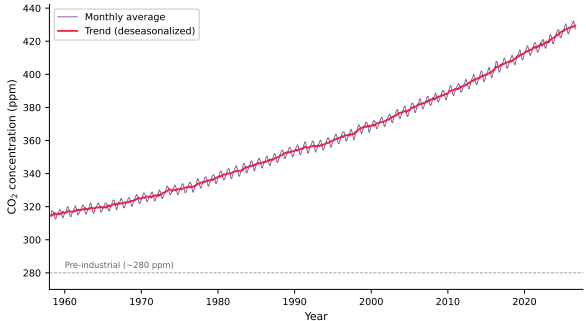
El Niño — sea surface temperature anomaly



Global sea surface temperature anomaly during the 2015–16 El Niño (November 2015, vs. 1985–1993 average). The dark red "warm tongue" across the equatorial Pacific is the signature of El Niño, with SST anomalies exceeding +3°C. El Niño reshuffles global weather patterns: droughts in Australia and SE Asia, floods in South America, and coral bleaching worldwide. The 2015–16 event was one of the three strongest on record (alongside 1997–98 and 1982–83). Source: NOAA Coral Reef Watch / Climate.gov, public domain.

CO_2 over time

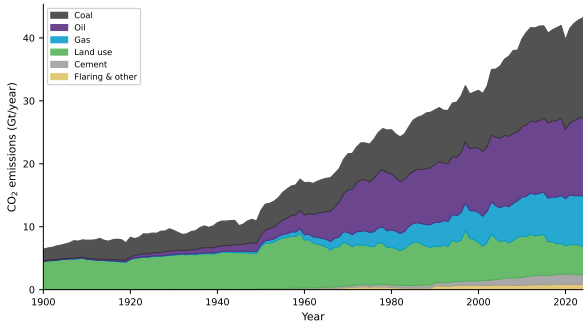
- Pre-industrial: ∼280 ppm. Today: ∼425 ppm (52% increase).
- Highest in at least 800,000 years (ice cores).
- The curve shows:
  - An annual seasonal cycle (vegetation absorbs CO_2 in summer, releases in winter).
  - A relentless upward trend driven by fossil fuels.
- Rate: ∼2.5 ppm/year (accelerating).



Charles David Keeling began continuous CO_2 measurements at Mauna Loa, Hawaii, in 1958.
Source: NOAA GML, Mauna Loa monthly mean CO_2 (1958–2026).

CO_2 sources

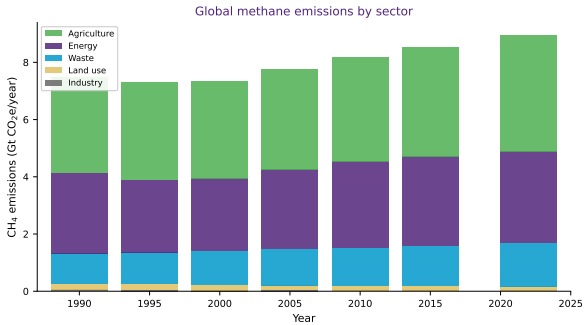
- Coal remains the largest source (37%), followed by oil (29%) and gas (19%).
- Coal: $\sim$95 kg CO_2/GJ vs. $\sim$56 for gas, the most carbon-intensive fossil fuel.
- Land-use change (11%): deforestation releases stored carbon *and* reduces future absorption capacity.
- Total: $\sim$43 Gt CO_2/year (2024).



Emission factors (kg CO_2/GJ): IPCC Guidelines for National Greenhouse Gas Inventories (2006, Vol. 2, Ch. 2). GJ = gigajoule (one billion joules), a standard unit of energy. Source: Global Carbon Project via Our World in Data (1900–2024).

Methane sources

- Agriculture (45%): livestock (enteric fermentation, manure) and rice paddies.
- Energy (36%): methane leaks during extraction, processing, and transport of coal, oil, and gas.
- Waste (17%): landfills and wastewater.
- Global Methane Pledge (COP26, 2021): 150+ countries committed to -30% by 2030.
- Short atmospheric life ($\sim$12 yr) $\Rightarrow$ reducing CH_4 delivers rapid climate benefits.

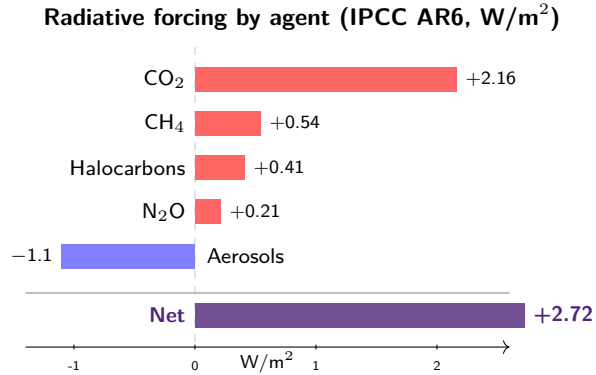


Source: Climate Watch / CAIT via Our World in Data (1990–2022).

Radiative forcing

The energy imbalance

- Radiative forcing (RF): how much a factor (e.g. CO_2) shifts the Earth's energy balance (W/m^2).
- The common currency for comparing climate drivers: GHGs, aerosols, land use, solar changes.
- CO_2 dominates (∼80% of GHG forcing), but aerosols partially mask warming ($-1.1\,W/m^2$).
- Net: $+2.72\,W/m^2 \Rightarrow$ ∼2.2°C equilibrium warming ($\Delta T \approx \lambda \times RF$).



Bars show effective radiative forcing relative to 1750. Red = warming; blue = cooling. Source: IPCC AR6 WG I (2021), Table 7.SM.1.

Radiative forcing — details

RF is the common currency for comparing climate drivers

- $+2.72\,\mathrm{W/m^2}$ means every square metre of Earth's surface absorbs 2.72 W more than it radiates away, a small LED bulb on *every* m^2 of the planet.
- Seemingly tiny, but summed over Earth's surface ($5.1 \times 10^{14}\,\mathrm{m}^2$) $\Rightarrow$ ∼1,400 terawatts of excess energy, equivalent to ∼75× global electricity consumption.

The link to temperature

$$\Delta T \;\approx\; \lambda \times \mathrm{RF} \qquad \text{where } \lambda \approx 0.8^{\circ}\mathrm{C} \text{ per } \mathrm{W/m^2}$$

- $\Rightarrow +2.72\,\mathrm{W/m^2}$ implies ∼2.2°C equilibrium warming, but we have not reached that yet because ocean thermal inertia creates a lag.
- Warming is "in the pipeline": even if emissions stopped today, temperatures would continue rising for decades.

Recent temperature records

The hottest years on record

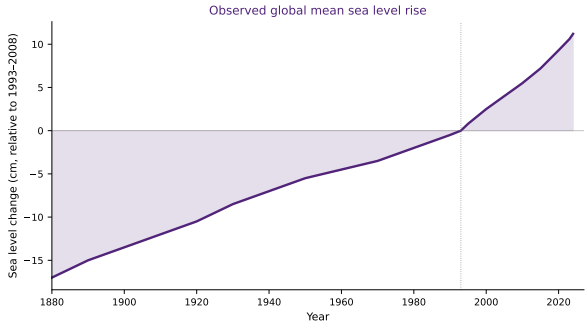
- 2023: confirmed as the hottest year in the instrumental record; global mean temperature 1.48°C above pre-industrial.
- 2024: on track to exceed 2023; multiple months breached the 1.5°C threshold temporarily.
- The 10 warmest years on record have all occurred since 2010.
- Driven by long-term GHG trend + El Niño event in 2023–24.

Does temporary 1.5°C breach mean the Paris target is broken?

- Not yet: the Paris target refers to sustained warming over decades, not individual years.
- But: the remaining carbon budget for staying below 1.5°C is almost exhausted ($\sim$250 Gt CO_2 at 50% chance; current emissions $\sim$40 Gt/yr).

Sea level rise — observed trends

- ∼20 cm rise since 1901; rate accelerating from 1.3 mm/yr (early 20th c.) to 4.5 mm/yr today.
- Main drivers: thermal expansion (∼50%), glacier melt (∼22%), ice sheets (∼20%).
- IPCC AR6 projections may be conservative: ice sheet contributions are tracking the upper end (Fox-Kemper et al., 2021).



Negative values do not mean sea levels were falling, they are relative to the 1993–2008 baseline (the zero line). Sea levels have been rising throughout this period; earlier years were simply lower than the reference average. Source: Church & White (2011) tide gauges; NASA GSFC satellite altimetry. Rates from Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) WG I and WMO (2024).

Sea level rise — projections and economic impacts

IPCC AR6 projections by 2100

Scenario	Likely	Max
SSP1-2.6 (low)	0.32–0.62 m	0.9 m
SSP2-4.5 (mid)	0.44–0.76 m	1.0 m
SSP5-8.5 (high)	0.63–1.01 m	1.6 m

SSP = Shared Socioeconomic Pathways (standardised emission scenarios).

- Irreversible: thermal expansion and ice melt continue even if warming stops.
- Hinkel et al. (2014): US$1.4T/yr flood damages by 2100.
- Kulp & Strauss (2019): under high emissions, land home to 630M people falls below projected high-tide lines by 2100.

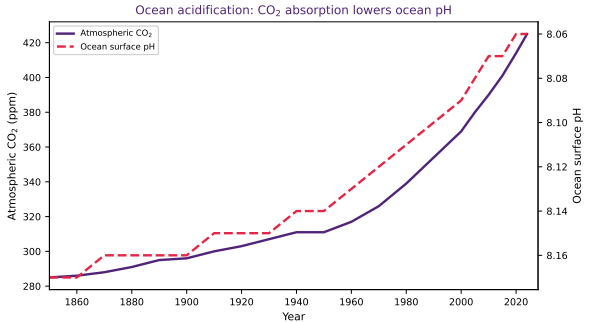


Tuvalu Land Reclamation Project (2025): a Pacific Island nation building new land to survive rising seas, a visible example of climate adaptation. Tuvalu's highest point is just 4.6 m above sea level. Photo: Wikimedia Commons, CC BY-SA 4.0.

Adaptation costs: US$30–70B/yr by 2050 (World Bank, 2021).

Ocean acidification

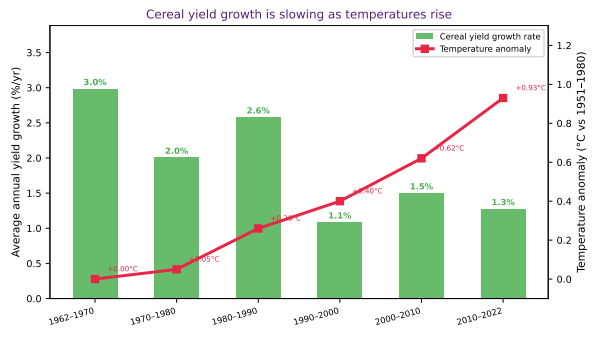
- Oceans absorb ∼25% of CO_2 emissions; $CO_2 + H_2O \rightarrow$ carbonic acid $\Rightarrow$ ocean pH declines.
- pH has fallen from 8.17 to 8.06, a 29% rise in acidity. Irreversible on human timescales.
- Coral reefs: Great Barrier Reef has had 6 mass bleaching events since 1998.
- Shellfish: reduced calcium carbonate formation threatens oysters, mussels, and plankton.



The right y-axis (pH) is inverted so that both curves rise together visually: more $CO_2 \rightarrow$ lower pH (more acidic). Mass bleaching occurs when warm water causes corals to expel symbiotic algae, turning white and often dying. Fsh are affected indirectly through habitat and food web collapse. Source: IPCC AR6 WG I Ch. 5; Jiang et al. (2023); NOAA GML.

Climate change and food security

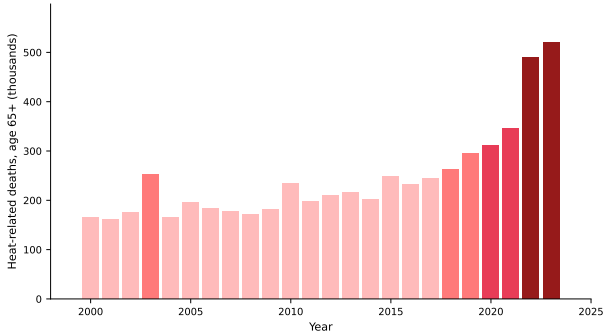
- Agricultural productivity growth reduced by ∼21% since 1961 (Ortiz-Bobea et al., 2021).
- Maize yields decline ∼7% per 1°C; CO_2 fertilisation provides some offset but is outweighed by heat stress and drought.
- Food price volatility from extreme weather disproportionately harms the poorest households.



Source: FAO/World Bank (cereal yields); NASA GISS (temperature anomaly).

Climate change and human health

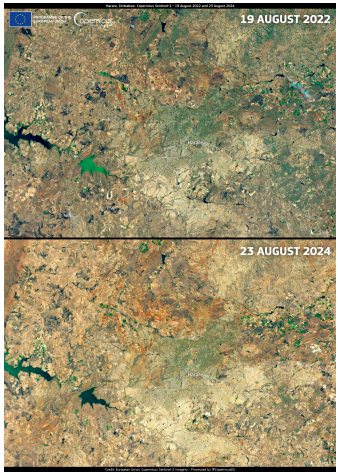
- Heat stress: deadliest weather hazard; 2022 European heatwave: ∼61,000 excess deaths (Ballester et al., 2023).
- Vector-borne diseases: +2B people exposed to dengue by 2070 (Lancet Countdown, 2024).
- Air quality: higher ground-level ozone + wildfire smoke.
- Malnutrition: crop yield losses in sub-Saharan Africa and South Asia (IPCC AR6 WG II).
- WHO (2014): ∼250,000 additional deaths/yr by 2030–2050 (now considered conservative).



Heat-related excess deaths in people aged 65+. Trend: +10,000 deaths/year. Heat mortality has more than tripled since 2000, with 2022–23 far exceeding trend due to record temperatures. Source: Lancet Countdown (2024), Indicator 1.1.2.

Climate refugees and security

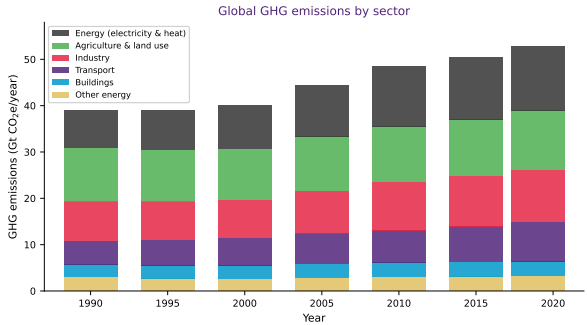
- World Bank: by 2050, 216 million internally displaced by sea level rise, crop failure, and water scarcity.
- Most affected: Sub-Saharan Africa, South Asia, Pacific Islands.
- Climate migration exacerbates conflict over resources.
- Pentagon and NATO: a threat multiplier for geopolitical instability.
- No legal protection: the 1951 Refugee Convention does not cover climate displacement.



Harare, Zimbabwe: El Niño-induced drought (Aug 2024, bottom) vs. normal (Aug 2022, top). 70% of population depends on subsistence agriculture. Source: EU Copernicus Sentinel-2.

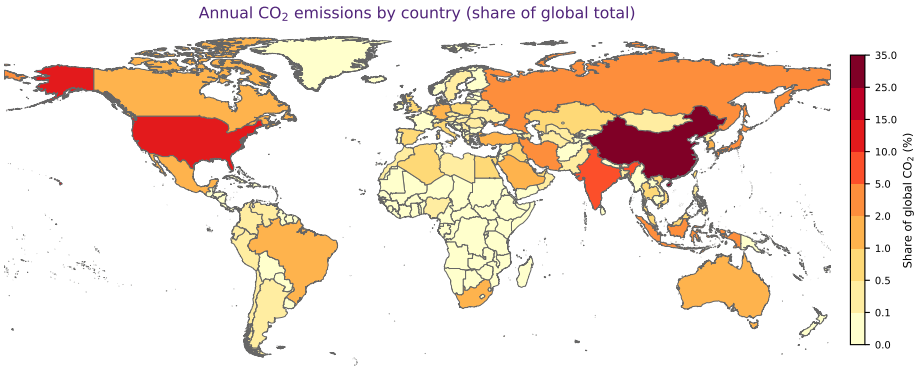
Global emissions by sector

- Energy (electricity & heat, 26%) and industry (21%) dominate and have grown fastest since 2000.
- Agriculture & land use (24%): relatively stable but hard to abate, primary source of CH_4 and N_2O.
- Transport (16%): fastest-growing energy sector; largely oil-dependent.
- The diversity of sources means no single policy can address all emissions, a portfolio of instruments is needed.



Source: Climate Watch / CAIT; IPCC AR6 WG III (2019 data).

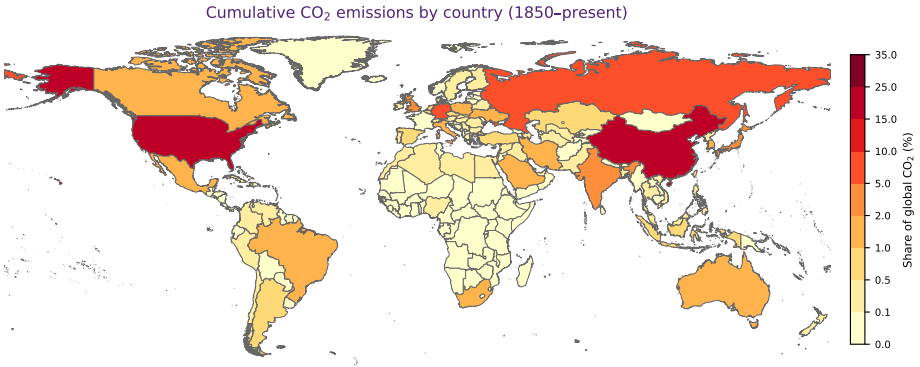
Who emits today?



- China (33%), the US (13%), India (9%), and Russia (5%) account for ∼60% of current annual CO_2 emissions.
- Per capita emissions vary enormously: Australia ∼15 t CO_2/person; India ∼2 t/person.

Source: Global Carbon Project via Our World in Data (latest available year).

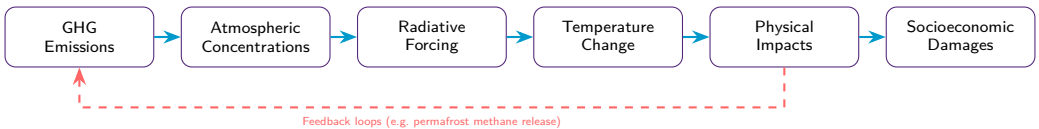
Who is historically responsible?



- The US (24%), China (16%), Russia (7%), and Germany (5%) lead cumulative emissions since 1850.
- Annual vs. cumulative shares differ dramatically—this is central to the equity debate and the principle of common but differentiated responsibilities (UNFCCC).

Source: Global Carbon Project via Our World in Data (cumulative 1850–present).

The causal chain: from emissions to impacts



- Because CO_2 persists for centuries, there is a long lag between emissions and full temperature response.
- Even if emissions stopped today, warming already "locked in" would continue for decades.
- Feedback loops can amplify warming (e.g. melting permafrost releases CH_4, ice loss reduces albedo).

Climate sensitivity and feedback mechanisms

Equilibrium Climate Sensitivity (ECS)

The long-run temperature increase from a doubling of atmospheric CO_2 concentration (from pre-industrial 280 ppm to 560 ppm).

- Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) best estimate: ECS = 3°C (likely range 2.5–4°C).
- This uncertainty is itself a major policy challenge.

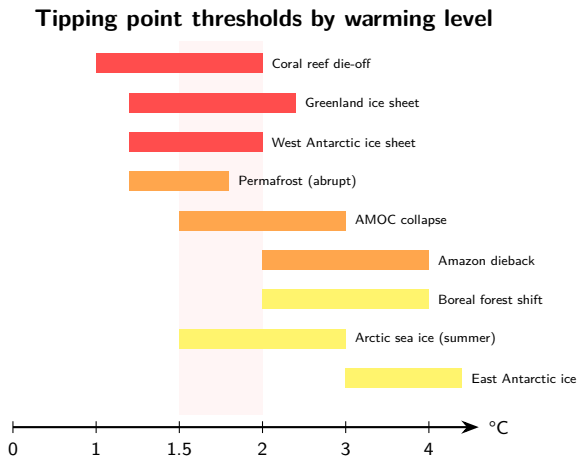
Key feedback mechanisms

- Water vapour feedback (+): warmer air holds more water vapour (itself a GHG) ⇒ amplifies warming.
- Ice-albedo feedback (+): melting ice exposes dark ocean/land, absorbing more heat.
- Cloud feedbacks (±): clouds can both warm (trapping IR) and cool (reflecting sunlight), the largest source of uncertainty in climate models.
- Permafrost-methane feedback (+): thawing releases CH_4 ⇒ further warming (see next slides).

Tipping points

A threshold where a small additional change pushes a system into a completely new state, potentially irreversibly.

- Small emissions changes can trigger large, long-term consequences.
- Changes can be accelerated and/or irreversible.
- Armstrong McKay et al. (2022, *Science*): at 1.5°C, 5 tipping points are already at risk; at 2°C, several more are likely triggered.
- Current trajectory (∼2.7°C) risks triggering a cascade of interacting tipping points.



Each bar shows the temperature range at which a tipping point could be triggered: left edge = lowest plausible threshold, right edge = upper bound. Several bars begin within the Paris range (pink shading), meaning these tipping points are already at risk at current warming. Source: Armstrong McKay et al. (2022), *Science*.

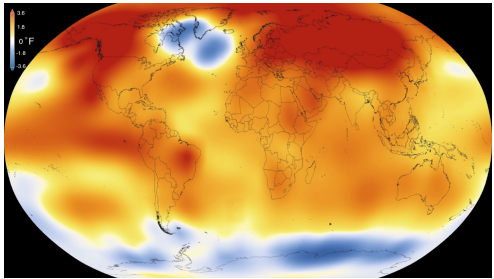
Tipping points — consequences

Tipping element	Threshold	Consequence
Coral reef die-off	>1.5°C	Ecosystem collapse; fisheries loss
Greenland ice sheet	1–2°C	+7 m sea level (over centuries)
West Antarctic ice sheet	1–1.5°C	+3–5 m sea level
Permafrost thaw	1–2°C	CH_4 ⇒ positive feedback
AMOC slowdown	1.5–3°C	Disrupted weather, European cooling
Amazon dieback	2–4°C	Massive carbon release, biodiversity loss

- Lenton et al. (2023): some tipping points may interact, creating a cascade, crossing one makes others more likely.
- Dietz et al. (2021, *PNAS*): tipping points add 25% to the social cost of carbon relative to models that ignore them.
- The economic case for staying below 1.5°C is significantly strengthened once tipping risks are priced in.

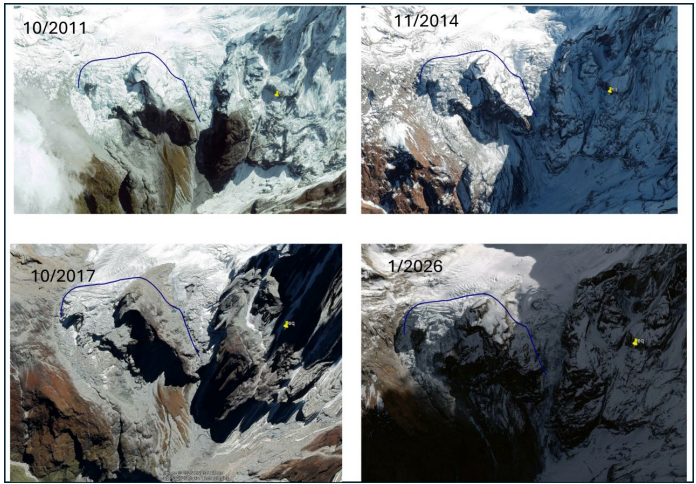
How warming can cause regional cooling

- The AMOC (Atlantic Meridional Overturning Circulation) delivers heat to NW Europe via warm surface currents.
- Warming melts Greenland ice → freshwater dilutes salty water that drives circulation → AMOC weakens (∼15% since mid-20th century; Caesar et al., 2018).
- If AMOC collapses: NW Europe cools by several degrees, regional cooling within a globally warming system.



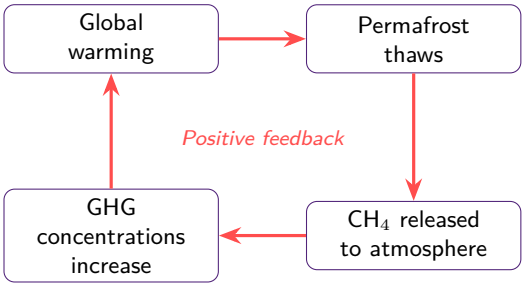
Global temperature anomaly (2015 vs. 1951–1980 baseline). The blue "cold blob" south of Greenland, surrounded by a warming world, is the fingerprint of AMOC weakening: reduced heat transport to the North Atlantic. Source: NASA GISS, public domain.

The 2026 Nepal–Tibet glacier flood



Satellite time series of the Langtang-Lirung glacier (Nepal–Tibet border), 2011–2026. The blue outline tracks the retreating ice mass. By January 2026, the glacier had thinned dramatically; on 26 August 2026 it collapsed, triggering a landslide that dammed the Lhende river. When the dam breached, catastrophic flooding killed 270+ people (1,400+ missing), destroyed hydropower plants and the Gyirong border crossing. The landslide registered as M 5.2 (USGS). Glacial lakes globally have grown 53% since 1990 (Shugar et al., 2020) — the "Third Pole" supplies water to 1.9 billion people.

The methane feedback loop



- Large quantities of CH_4 are trapped in Arctic permafrost.
- As temperatures rise, methane is released, accelerating warming further.



Collapsed permafrost block along the Arctic coast of Alaska. This is one reason why climate models may understate future warming. Photo: USGS, public domain.

Fat tails and the economics of uncertainty

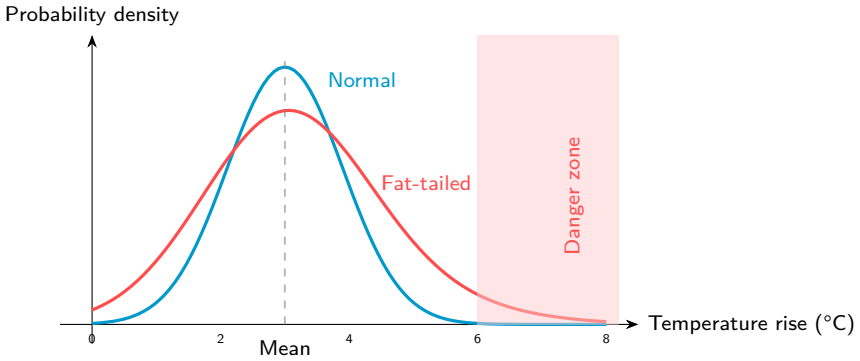
Why the shape of uncertainty matters

- Suppose GHG concentrations double pre-industrial levels; models suggest a mean temperature rise of $\sim$3°C.
- Consider the probability of exceeding a 6°C danger zone:
  - Normal (bell-shaped) distribution: $\sim$2% likelihood.
  - Fat-tailed distribution (reflecting the special uncertainties of climate): $\sim$10% likelihood.
- Models omit some damage types $\Rightarrow$ probability of dangerous thresholds is likely *understated*.

Key insight (Weitzman, 2009)

- High-consequence, low-probability events are not well anticipated by current modelling practices.
- "By the time we learn that a climate-change disaster is impending, it could be too late to do much about it."

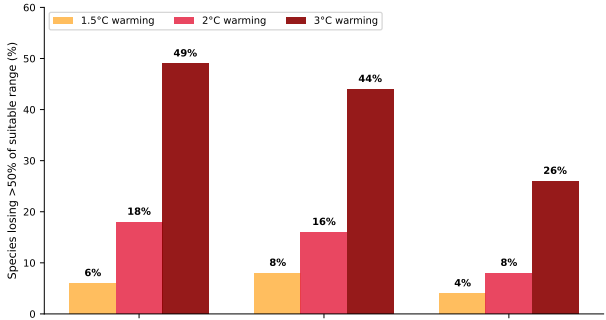
Normal vs. fat-tailed distributions



- The fat tail assigns much more probability mass to extreme outcomes.
- Implication: expected damages are higher under the fat-tailed distribution, even if the mean is the same.
- Even if the probability of catastrophe is "small," the potential damages are so large that aggressive precautionary action is justified (Weitzman, 2009).

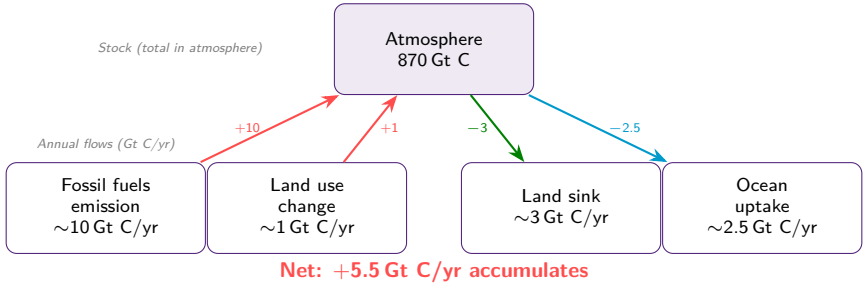
Biodiversity loss from climate change

- Beyond species-range losses, warming above 3°C risks ecosystem collapse (Armstrong McKay et al., 2022).
- Climate, habitat loss, and pollution are synergistic, combined impact exceeds individual effects.
- Ecosystem services valued at US$125–145T/yr (Costanza et al., 2014), largely uncaptured in standard climate–economy models.



Each bar shows the percentage of species projected to lose more than half of their climatically suitable habitat. The key insight is the **non-linearity**: the jump from 1.5°C to 3°C roughly **triples to octuples** the risk, depending on the taxon. Insects are the most affected because they are ectothermic (body temperature tracks the environment) and have narrow thermal tolerances. Since insects underpin pollination and food webs, their loss cascades through entire ecosystems. Source: IPCC AR6 WG II Ch. 2; Warren et al. (2018), *Science*, 360(6390).

The carbon cycle



Source: Friedlingstein et al. (2024), "Global Carbon Budget 2024", *Earth System Science Data*.

- Roughly half of annual CO_2 emissions are absorbed by natural sinks (oceans + land vegetation).
- The other half accumulates in the atmosphere, driving warming.
- Sink capacity is declining (warmer oceans absorb less CO_2; forests under stress) $\Rightarrow$ a larger fraction accumulates $\Rightarrow$ faster warming (positive feedback).

Integrated Assessment Models (IAMs)

Connecting climate science to economics

- IAMs combine:
  - A climate module: emissions → concentrations → temperature.
  - An economic module: GDP, energy use, abatement costs.
  - A damage function: temperature → GDP losses.
- Used to estimate the social cost of carbon (SCC) and optimal carbon tax paths.
- Key IAMs:
  - DICE/RICE: Dynamic Integrated model of Climate and the Economy / Regional (Nordhaus).
  - PAGE: Policy Analysis of the Greenhouse Effect (Hope).
  - FUND: Climate Framework for Uncertainty, Negotiation and Distribution (Tol).

Limitations

- Damage functions are highly uncertain and may omit tipping points, biodiversity loss, and conflict.
- Results are extremely sensitive to the discount rate.
- IAMs are useful frameworks, but should not be treated as precise forecasts.

Recent research on the economics of climate change

Damage estimates are rising

- Bilal & Kähn (2024, *NBER*): 1°C warming reduces world GDP by 12%, 6× larger than DICE. Key insight: previous estimates used *local* temperature variation (partly offset by trade/migration); *global* shocks hit everyone simultaneously with no escape.
- Kotz, Levermann & Wenz (2024, *Nature*): committed damages of US$38 trillion/yr by 2049, even under aggressive mitigation; agricultural and labour productivity hardest hit.
- Rennert et al. (2022, *Nature*): updated social cost of carbon at US$185/tonne (3.5× the US government's prior estimate), incorporating latest climate science and damage functions.

Key insights for policy

- Burke, Hsiang & Miguel (2015, *Nature*): non-linear temperature–GDP relationship; warming benefits cold countries but devastates the tropics, amplifying global inequality.
- Hsiang et al. (2017, *Science*): US county-level damages are highly unequal; poorest counties lose up to 20% of income.

Strategies, Targets, and Timing

Three broad strategies for reducing damages

1. Sequestration
Capture & store atmospheric CO_2

2. Adaptation
Modify systems to reduce harm from impacts

3. Mitigation
Reduce GHG emissions that drive warming

- Sequestration: natural (oceans, forests) and engineered (carbon capture and storage, direct air capture).
- Adaptation: relocate vulnerable infrastructure, prepare health systems, make forests and grids more resilient.
- Mitigation: carbon taxes, cap-and-trade, fuel switching to low-carbon sources, energy efficiency improvements.
- All three are needed simultaneously—they are complements, not substitutes.

Sequestration

Natural carbon sinks

- Oceans absorb ∼25% of annual CO_2 emissions (but capacity is declining; causes ocean acidification).
- Forests and soils absorb ∼30% of emissions.
- Policy: afforestation/reforestation, soil carbon management, protection of existing forests.

Engineered carbon removal

- Carbon Capture and Storage (CCS): capturing CO_2 from power plants/industrial sources and storing in geological formations.
- Direct Air Capture (DAC): chemical processes to extract CO_2 directly from ambient air. Currently very expensive ($250–600/tonne).
- Bioenergy with CCS (BECCS): combining biomass energy with carbon capture for "negative emissions."
- All face challenges of scale and costs.

Geoengineering: last-resort options

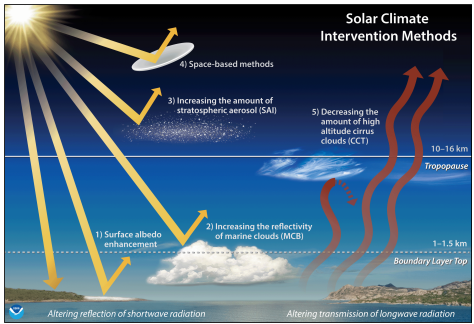
Solar Radiation Management (SRM)

- Reflects sunlight to cool the planet.
- Methods: stratospheric aerosol injection (SAI), marine cloud brightening, space-based reflectors.

Carbon Dioxide Removal (CDR)

- Removes CO_2 directly from the atmosphere.
- Methods: direct air capture (DAC), bioenergy with CCS (BECCS), enhanced weathering, ocean fertilisation.

Both are complements to mitigation, not substitutes.



Solar climate intervention methods: (1) surface albedo enhancement, (2) marine cloud brightening, (3) stratospheric aerosol injection, (4) space-based reflectors, (5) cirrus cloud thinning. Methods 1–4 reflect shortwave radiation; method 5 allows more longwave radiation to escape. Source: NOAA, public domain.

Adaptation strategies

Modifying systems to reduce harm from climate impacts

- Infrastructure: relocate transportation, waste treatment, and coastal development away from sea-level-rise zones; build flood defences, upgrade drainage.
- Public health: prepare for heat-related illness, expanded vector-borne diseases (dengue, malaria), water-borne disease.
- Agriculture: develop drought- and heat-resistant crop varieties; shift planting seasons; improve irrigation efficiency.
- Ecosystems: managed retreats, fire management in forests, coral reef restoration.
- Energy: make the electric grid more resilient to climate-enhanced storms; diversify energy sources.

Key insight

Adaptation reduces the damages from a given temperature rise, but cannot eliminate them entirely. It buys time but is not a substitute for mitigation.

The carbon budget

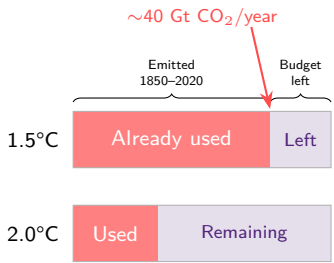
The carbon budget is the total remaining CO_2 that can be emitted while keeping warming below a given target.

Target	50% chance	67% chance
1.5°C	∼500 Gt CO_2	∼400 Gt CO_2
2.0°C	∼1,350 Gt CO_2	∼1,150 Gt CO_2

Source: IPCC AR6 WGI, Table SPM.2 (remaining budgets from Jan 2020).

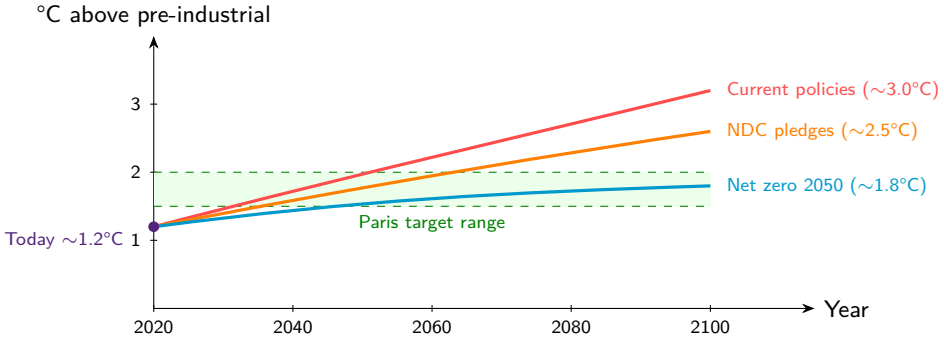
At ∼40 Gt CO_2/year (current rate):

- 1.5°C budget → exhausted in ∼6–7 years from 2025.
- 2.0°C budget → ∼25–30 years, but still requires dramatic reductions.



Every tonne emitted reduces the remaining allowance, the budget makes the urgency quantifiable.

Warming projections under different scenarios



NDCs = Nationally Determined Contributions: each country's self-set climate target under the Paris Agreement (bottom-up, updated every 5 years, procedurally binding but non-enforceable). The gap between NDC pledges and the Paris target is the ambition gap.

Schematic based on UNEP Emissions Gap Report (2024) and Climate Action Tracker (current policies ∼2.7–3.0°C; NDCs ∼2.1–2.5°C); IEA Net Zero by 2050 scenario (∼1.8°C).

Adaptation vs. mitigation: complements, not substitutes



- Without mitigation, adaptation costs escalate beyond manageable levels.
- Without adaptation, even successful mitigation leaves communities exposed to already-locked-in warming.
- The optimal strategy involves both: aggressive mitigation now *and* proactive adaptation.
- IPCC AR6: "Adaptation options that are feasible and effective today will become constrained and less effective with increasing global warming."

Carbon Capture and Storage (CCS) and Direct Air Capture (DAC)

Where are we on engineered carbon removal?

Technology	Current capacity	Cost	Status
CCS (point source)	$\sim$45 Mt CO_2/yr	\$50–120/t	$\sim$30 plants
DAC	$\sim$0.01 Mt CO_2/yr	\$250–600/t	Early stage
BECCS	$\sim$2 Mt CO_2/yr	\$100–200/t	Few projects
Enhanced weathering	Pilot scale	Unknown	Experimental

- Net zero scenarios (IPCC, IEA) require billions of tonnes of CO_2 removal per year by 2050, current capacity is a tiny fraction.
- Carbon removal is not a substitute for emission reduction, it is a necessary complement for residual emissions.

AR6 Working Group III: mitigation pathways

What the IPCC says about solutions (2022)

- Global GHG emissions must peak before 2025 and fall 43% below 2019 levels by 2030 to stay on a 1.5°C pathway.
- Electricity sector: rapid expansion of renewables (solar and wind already cheapest in most regions).
- Transport: shift to EVs, mode shift, demand reduction.
- Industry: energy efficiency, electrification, hydrogen, CCS.
- Buildings: electrification of heating, improved insulation.
- Land use: halt deforestation, restore degraded lands.
- Demand-side measures (behaviour change, reduced consumption, circular economy) could reduce emissions by 40–70% in some sectors by 2050.

Key finding

"The costs of inaction far exceed the costs of mitigation in all assessed scenarios."

Net zero (1)

A transformation of the global energy system

- IEA *Net Zero by 2050* roadmap (2021):
  - No new fossil fuel exploration or development from 2021.
  - Coal phase-out in electricity by 2040 (advanced economies by 2030).
  - 60% of global car sales are EVs by 2030.
  - Renewables supply 90% of electricity by 2050.
  - Heavy industry (steel, cement) decarbonised via hydrogen, CCS.
  - Residual emissions offset by BECCS and DAC.
- This requires ∼US$4 trillion/year in clean energy investment by 2030 (up from ∼$1.7T in 2023).
- No country is currently on track.

Net zero (2)

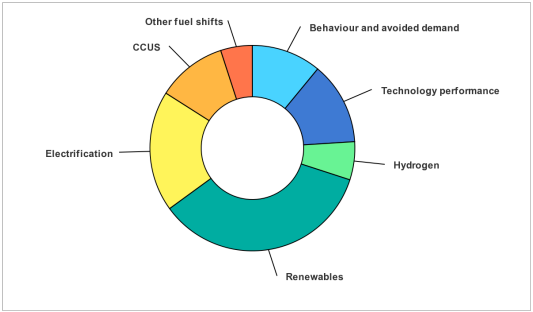
- If fully implemented and enforced, net zero targets could reduce projected warming to 2.0–2.4°C by 2100, bringing Paris goals within reach.
- Compare with:
  - Currently implemented policies: 2.9–3.2°C.
  - Paris pledges (NDCs): 2.4–2.9°C.

Controversies

- Corporate net zero pledges have surged, but the accounting system for carbon absorption is often:
  - Not transparent.
  - Weakly verifiable.
  - Prone to overstated reductions, double counting, or counterproductive offsets.
- Risk: undermining global mitigation efforts by creating an illusion of progress.
- Net zero without gross reductions is insufficient—offsets alone cannot substitute for cutting emissions.

Net zero (3)

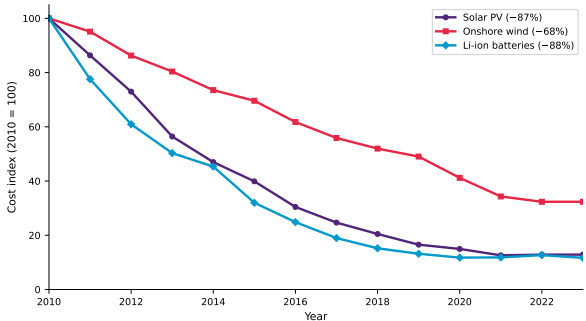
- Some sectors will have residual emissions even in 2050: agriculture (CH_4, N_2O), cement, steel, aviation, shipping.
- "Net zero" = residual emissions offset by negative emission technologies: bioenergy with CCS (BECCS), direct air capture (DAC), afforestation.
- IPCC 1.5°C scenarios require 6–10 Gt CO_2/yr removal by 2050; current capacity $<$0.1 Gt/yr.
- Rapid emission reduction now is essential: the less we cut gross emissions, the more we rely on unproven negative emission technologies.



Cumulative emissions reductions by mitigation measure in the IEA Net Zero Scenario (2021–2050). CCUS (carbon capture, utilisation and storage) plays a supporting role; the bulk comes from renewables, electrification, and efficiency. Source: IEA, *World Energy Outlook* (2023), CC BY 4.0.

The renewable energy transition

- New renewables are now cheaper than new fossil fuels in most countries, even without subsidies.
- In 2023, >80% of new electricity generation capacity worldwide was renewable.
- The economic case for clean energy now reinforces the climate case, a positive feedback for mitigation policy.



Cost index (2010 = 100) for solar PV and onshore wind (levelised cost of electricity, LCOE) and lithium-ion battery packs. Source: IRENA, *Renewable Power Generation Costs in 2023*; BloombergNEF (batteries).

The just transition

Ensuring fairness in the energy transition

- The shift from fossil fuels will create winners (clean energy industries, consumers) and losers (coal mining communities, fossil fuel workers).
- A "just transition" means:
  - Retraining and reskilling displaced workers.
  - Economic diversification in fossil-fuel-dependent regions.
  - Social safety nets (income support, health care) during the transition.
  - Community participation in planning (not top-down imposition).
- Without a just transition, political backlash can derail climate policy entirely.

Intergenerational equity

The ethical dimension of discounting

- Climate change is fundamentally an intergenerational problem: current generations emit; future generations bear the damages.
- A positive discount rate ($r > 0$) means future damages are worth less in present-value terms.
- But future generations have no voice in today's decisions $\Rightarrow$ is it ethical to discount their welfare?

Two perspectives

- Equal treatment (Stern): $\delta \approx 0$ (pure time preference near zero); future welfare counts almost equally. Justification: no ethical basis for valuing future people less.
- Growth-based discounting (Nordhaus): future generations will be *richer* due to economic growth $\Rightarrow$ marginal utility of consumption will be lower $\Rightarrow$ the $\eta \cdot g$ term in Ramsey justifies some discounting even if $\delta = 0$.
- Recent trend: declining discount rates for very long-horizon analysis (Weitzman, 2001; UK Green Book).

Declining discount rates

Weitzman (2001): uncertainty justifies lower long-run rates

- If we are uncertain about the correct discount rate, the expected present value of distant future damages is dominated by the *lowest plausible* rate.
- Intuition: in some possible futures, returns are low $\Rightarrow$ future damages loom large. These scenarios dominate the expectation.
- Implication: the effective discount rate should decline over time, even if each individual rate is constant.
- Adopted by the UK Treasury Green Book: 3.5% for 0–30 years, declining to 1% for 300+ years.
- France uses 4% declining to 2% for projects >30 years.
- This approach gives more weight to very long-term impacts (climate change, nuclear waste, biodiversity loss) without abandoning discounting entirely.

Economic insights on targets and timing

The efficient level of control

- Efficiency: $MAC =$ marginal reduction in damages.
- But different assumptions $\Rightarrow$ different optima.
- Two crucial choices:
  - The discount rate.
  - The uncertainty in magnitude and timing of damages.

Discounting climate damages

- Normative discounting: derived from ethical principles about treating future generations $\Rightarrow$ *low* discount rate (e.g. Stern Review: 1.4%).
- Opportunity cost discounting: based on observed returns to capital $\Rightarrow$ *higher* rate (e.g. Nordhaus: $\sim$5%).
- In recent years: convergence toward lower rates.

The Ramsey discount rate

The standard framework for long-run discounting

$$r = \delta + \eta \cdot g$$

- r = social discount rate.
- δ = pure rate of time preference (how much we intrinsically prefer the present over the future).
- η = elasticity of marginal utility of consumption (how fast marginal utility falls as consumption rises).
- g = expected growth rate of per-capita consumption.

Why δ and η matter for climate policy

- Stern: $\delta \approx 0.1\%$, $\eta = 1$, $g = 1.3\% \Rightarrow r \approx 1.4\%$ (future welfare counts almost equally).
- Nordhaus: $\delta \approx 1.5\%$, $\eta = 2$, $g \approx 2\% \Rightarrow r \approx 5.5\%$ (opportunity cost perspective).
- Small differences in δ and η lead to dramatically different policy recommendations.

The Stern–Nordhaus debate

Stern Review (2006)

- Discount rate: $\sim$1.4%.
- Climate change damages = 5–20% of global GDP.
- Stabilisation costs = $\sim$1% of GDP.
- Conclusion: strong, immediate action is urgently needed.
- Based on normative/ethical grounds: future generations' welfare should be weighted nearly equally.

Nordhaus (2007)

- Discount rate: $\sim$5%.
- Lower present value of future damages.
- Conclusion: gradual ramp-up of controls; invest returns at market rates; future generations will be richer.
- Based on opportunity cost of capital: returns from investment could fund future adaptation.

Convergence

Recent literature has trended toward lower discount rates, especially as evidence of tipping points and irreversibility has grown.

The social cost of carbon

- The social cost of carbon (SCC) is the marginal damage from an additional tonne of CO_2e emitted.
- US EPA (2023 update): SCC $\approx$ US\$190/tonne CO_2 (central estimate, 2% discount rate, 2020 dollars).
- If existing carbon prices $<$ SCC $\Rightarrow$ additional action to reduce emissions would increase net benefits.

Are current carbon prices adequate?

- World Bank data shows: carbon prices (taxes or ETS) are typically considerably lower than SCC estimates.
- Only a handful of jurisdictions (Sweden, Switzerland, Liechtenstein) have carbon prices above US\$100/tonne.
- Implication: action is not only scientifically merited, but makes enormous economic sense, additional emissions reductions would increase net benefits.

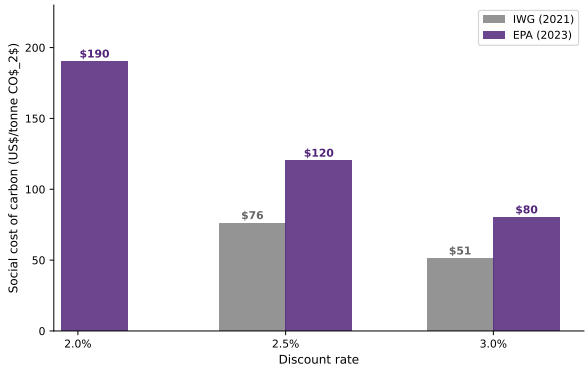
The social cost of carbon: how it is calculated



- The SCC is the present value of all future damages from one additional tonne of CO_2e emitted today.
- Highly sensitive to three inputs:
  1. Climate sensitivity (how much warming per unit of CO_2).
  2. Damage function (relationship between temperature and economic loss).
  3. Discount rate (how much we value future vs. present).
- Estimates range from $\sim$\$50 to $>$\$300/tonne depending on assumptions.
- The "right" SCC is a matter of values (discount rate) as much as science.

The SCC under different discount rates

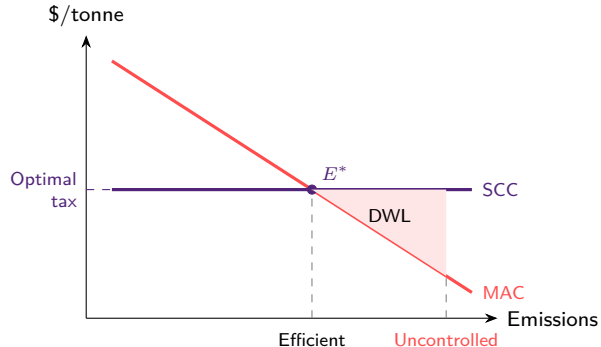
- The discount rate is the single most important driver of SCC estimates.
- Lower rates $\Rightarrow$ future damages weigh more $\Rightarrow$ higher SCC $\Rightarrow$ stronger policy.
- EPA (2023) revised SCC sharply upward from earlier IWG estimates, reflecting updated science on damages and discounting.



IWG = Interagency Working Group on the Social Cost of Greenhouse Gases (2021 estimates). EPA (2023) updated estimates based on Rennert et al. (2022), *Nature*, 610, 687–692. All values in 2020 USD for emissions in 2020.

The efficient level of carbon emissions

- The optimal carbon tax equals the SCC: it internalises the climate externality.
- At the efficient level, the marginal cost of abatement equals the marginal damage (SCC).
- This is the same equimarginal principle from Lectures 3–4, applied to CO_2.
- Current carbon prices (∼\$5–90/t in most ETS) are well below the SCC.



The SCC acts as the marginal damage of CO_2. Since CO_2 is uniformly mixed, a single global carbon price equal to the SCC achieves the efficient outcome.

Appendix

Climate data and monitoring resources

Global temperature and climate indicators

- NASA GISS Surface Temperature
- NOAA Climate at a Glance
- Copernicus Climate Change Service (C3S)

CO_2 and greenhouse gas monitoring

- NOAA Global Monitoring Lab
- Global Carbon Project

Interactive data visualisation

- Our World in Data, CO_2 and GHGs
- Climate Action Tracker
- Climate TRACE (facility-level emissions)

Policy and assessments

- IPCC AR6 Reports
- UNEP Emissions Gap Report

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