universität freiburg

Know your footprint - in High Energy Physics and related fields

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On behalf of the Know-your-footprint team
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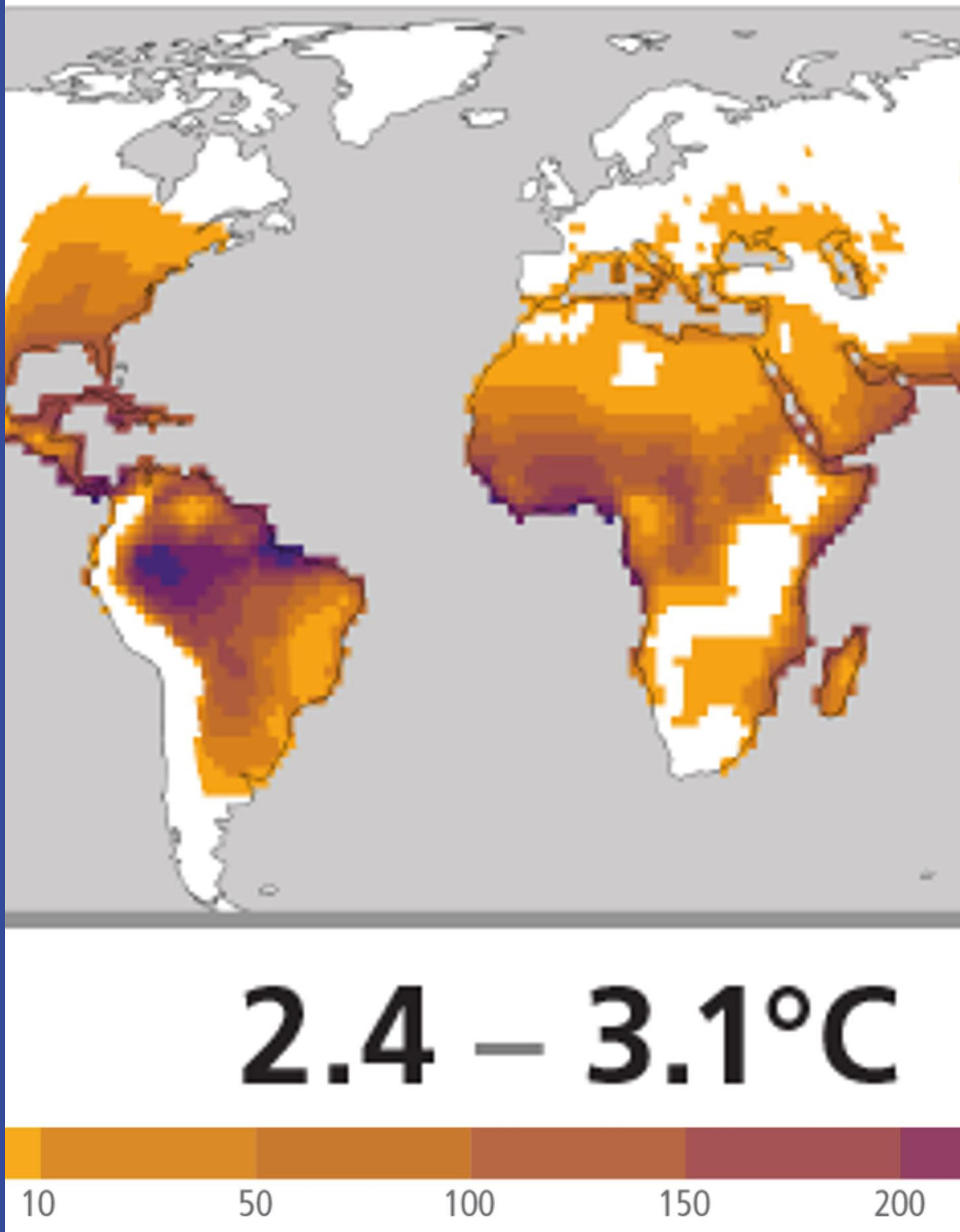
Particle Physics Colloquium
Paul Scherrer Institute, 24 October 2024



Atmospheric CO_2 vs. ground temperature

First publication on their relationship in 1896, i.e. 128 years ago

- Prof. Svante Arrhenius, *On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground* Philosophical Magazine and Journal of Science Series 5, Volume 41, April **1896**, pages 237-276. (link)

Europe

TABLE VII.—*Variation of Temperature caused by a given Variation of Carbonic Acid.*

Latitude.	Carbonic Acid=0·67.					Carbonic Acid=1·5.					Carbonic Acid=2·0.					Carbonic Acid=2·5.					Carbonic Acid=3·0.				
	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.	Dec.–Feb.	March–May.	June–Aug.	Sept.–Nov.	Mean of the year.
70	−2·9	−3·0	−3·4	−3·1	−3·1	3·3	3·4	3·8	3·6	[illegible]	6·0	6·1	6·0	6·1	6·05	[illegible]	8·0	7·9	8·0	7·95	9·1	9·3	9·4	9·4	9·3
60	−3·0	−3·2	−3·4	−3·3	−3·22	3·4	3·7	3·6	3·8	[illegible]	6·1	6·1	5·8	6·1	6·02	[illegible]	8·0	7·6	7·9	7·87	9·3	9·5	8·9	9·5	9·3
50	−3·2	−3·3	−3·3	−3·4	−3·3	3·7	3·8	3·4	3·7	[illegible]	6·1	6·1	5·5	6·0	5·92	[illegible]	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
40	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
30	−3·3	−3·2	−3·1	−3·1	−3·17	3·5	3·3	3·2	3·5	[illegible]	5·6	5·4	5·0	5·2	5·3	7·2	7·0	6·6	6·7	6·87	8·7	8·3	7·5	7·9	8·1
20	−3·1	−3·1	−3·0	−3·1	−3·07	3·5	3·2	3·1	3·2	[illegible]	5·2	5·0	4·9	5·0	5·02	[illegible]	6·6	6·3	6·6	6·52	7·9	7·5	7·2	7·5	7·52
10	−3·1	−3·0	−3·0	−3·0	−3·02	3·2	3·2	3·1	3·1	[illegible]	5·0	5·0	4·9	4·9	4·95	[illegible]	6·4	6·3	6·4	6·42	7·4	7·3	7·2	7·3	7·3
0	−3·0	−3·0	−3·1	−3·0	−3·02	3·1	3·1	3·2	3·2	[illegible]	4·9	4·9	5·0	5·0	4·95	[illegible]	6·4	6·6	6·6	6·5	7·3	7·3	7·4	7·4	7·35
−10	−3·1	−3·1	−3·2	−3·1	−3·12	3·2	3·2	3·2	3·2	[illegible]	5·0	5·0	5·2	5·1	5·07	[illegible]	6·6	6·7	6·7	6·65	7·4	7·5	8·0	7·6	7·62
−20	−3·1	−3·2	−3·3	−3·2	−3·2	3·2	3·2	3·4	3·3	[illegible]	5·2	5·3	5·5	5·4	5·35	[illegible]	6·8	7·0	7·0	6·87	7·9	8·1	8·6	8·3	8·22
−30	−3·3	−3·3	−3·4	−3·4	−3·35	3·4	3·5	3·7	3·5	[illegible]	5·5	5·6	5·8	5·6	5·62	7·0	7·2	7·7	7·4	7·32	8·6	8·7	9·1	8·8	8·8
−40	−3·4	−3·4	−3·3	−3·4	−3·37	3·6	3·7	3·8	3·7	[illegible]	5·8	6·0	6·0	6·0	5·95	7·7	7·9	7·9	7·9	7·85	9·1	9·2	9·4	9·3	9·25
−50	−3·2	−3·3	—	—	—	3·8	3·7	—	—	—	6·0	6·1	—	—	—	7·9	8·0	—	—	—	9·4	9·5	—	—	—
−60																									

266 Prof. S. Arrhenius on the Influence of Carbonic Acid

→ CO_2 increase by a factor 2: Temperature increase of ~6˚C

→ Surprisingly accurate given coarse understanding at the time

- Confirmed and refined since then in many studies → See e.g. Nobel prize in 2021

Guess the concentration of CO_2 in the atmosphere

What is the current CO_2 content in the atmosphere, given a mean over the last 800k years of around 225 ppm?

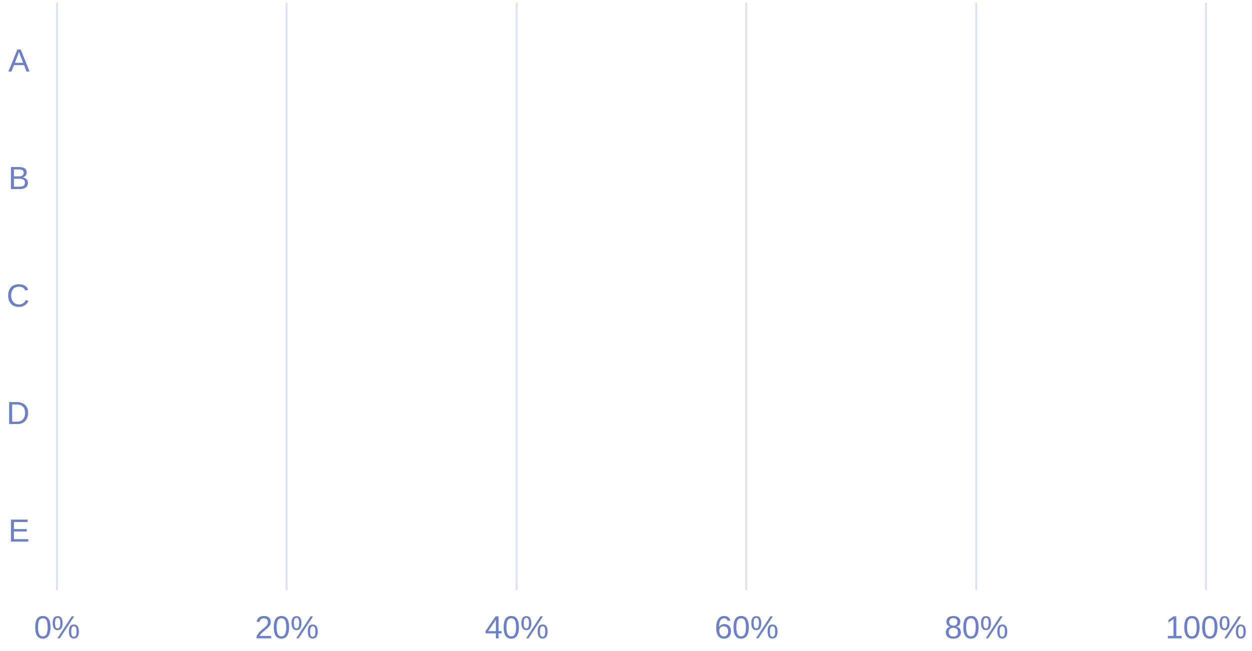
A) Between 250-300 ppm

B) Between 300-350 ppm

C) Between 350-400 ppm

D) Between 400-450 ppm

E) Above 450ppm



Or go to www.vote.ac and type my email address

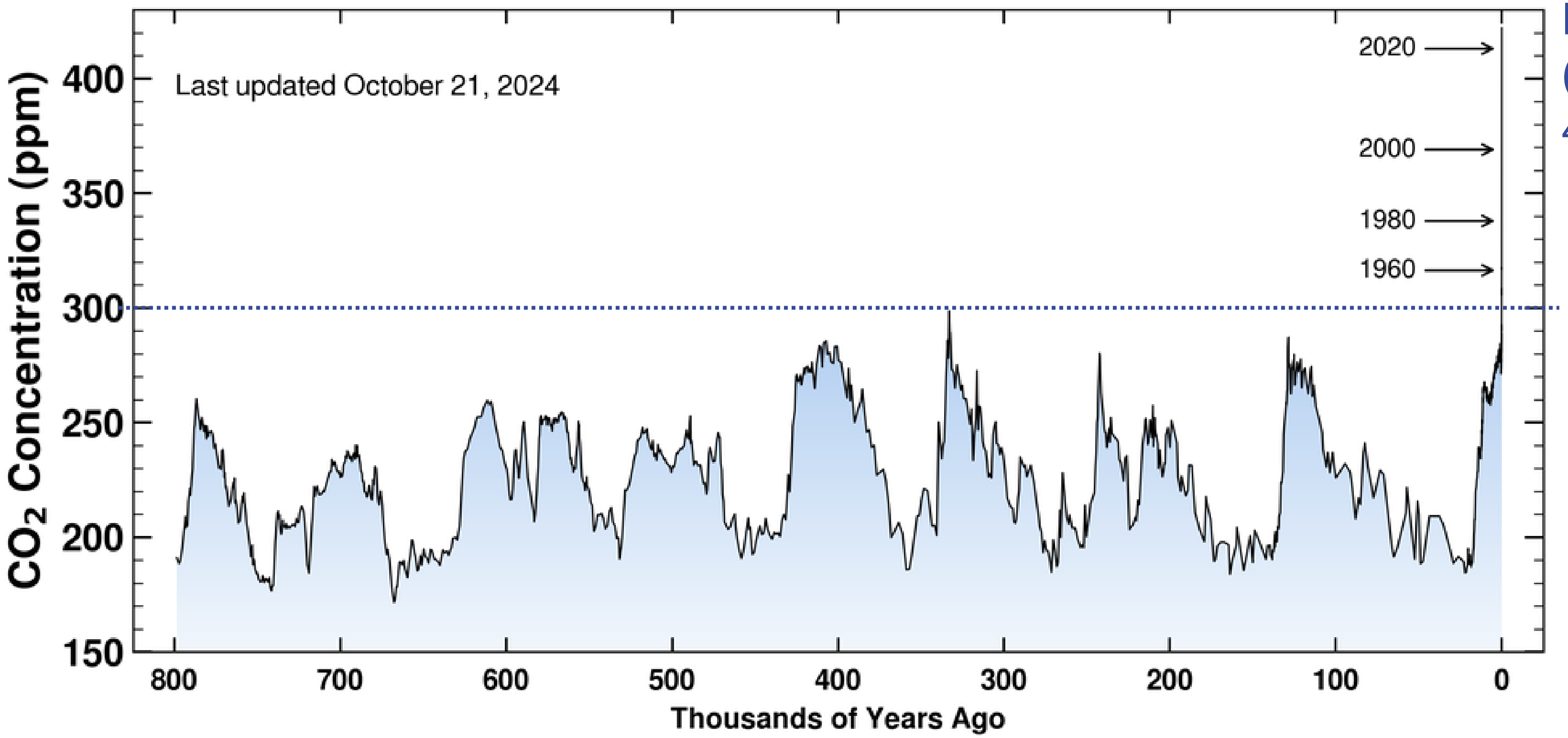
Start Vote

ID = valerie.lang@physik.uni-freiburg.de
Vote has not been started yet

Where are we now? – In terms of CO_2 in atmosphere

Measurements over the last ~70 years at Mauna Loa Observatory → Keeling curve

- Combined with data from ice cores over last 800k years → Composition of air trapped in ice from Antarctica



Latest reading (Status: 21 October 2024): 422.57ppm

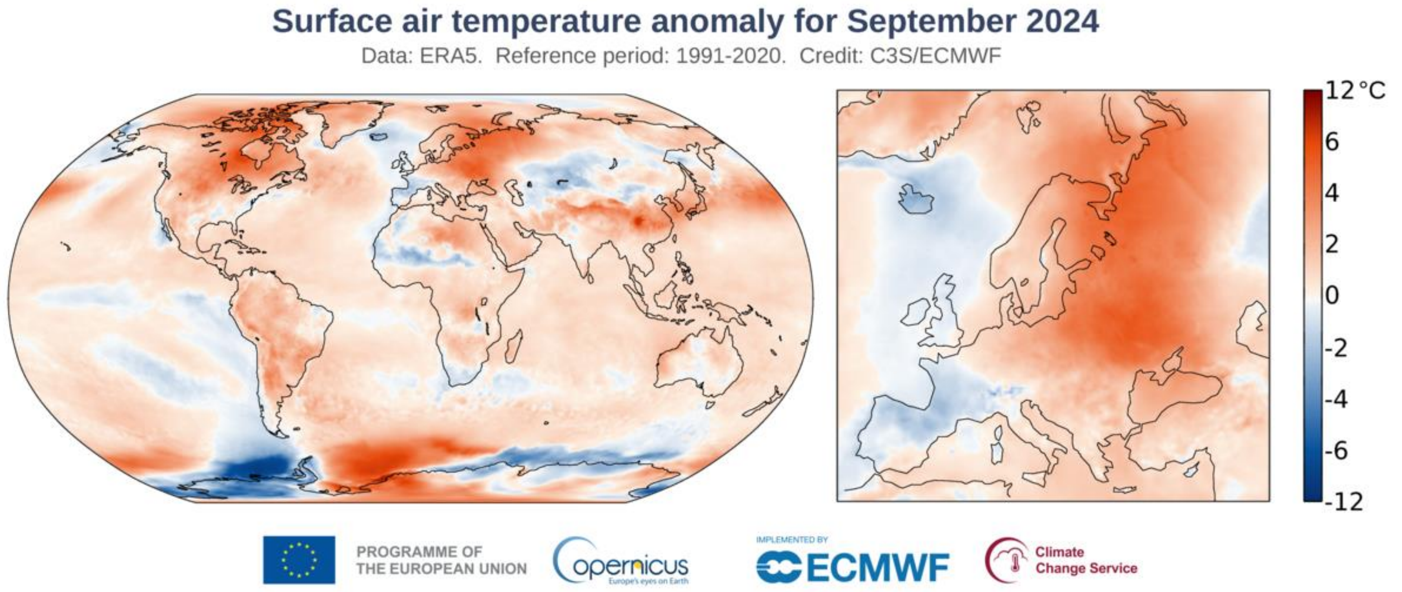
→ Reaching ~40% more than highest point in past 800k years

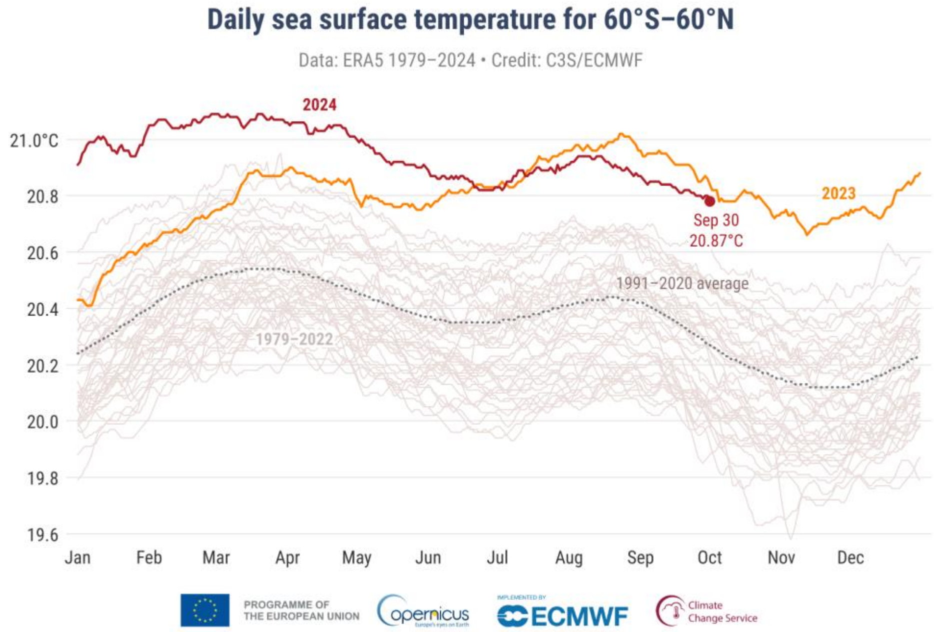
→ Far outside of variations during last 800k years

https://keelingcurve.ucsd.edu

Where are we now? – In terms of ground temperature

Copernicus Satellite Data → Sept. 2024 = 2nd warmest on record (after Sept. 2023)





- Over the last 12 months (from September 2024):
  - Average global temperature: 1.62˚C above 1850-1900 level
  - Average European temperature: 2.3˚C above 1850-1900 level

Reached (and surpassed) the global 1.5˚C increase limit, ideally targeted by Paris climate agreement 2015

https://climate.copernicus.eu/surface-air-temperature-september-2024
https://climate.copernicus.eu/climate-bulletin-about-data-and-analysis

Intergovernmental Panel on Climate Change (IPCC)

Comprehensive reports on the state of climate change, its impacts and risks, as well as mitigation strategies → Latest: Sixth Assment report (AR6)

- Working Group I – The Physical Science Basis → Released Aug 2021
- Working Group II – Impacts, Adaption and Vulnerability → Released Feb 2022
- Working Group III – Mitigation of Climate Change → Released April 2022
- Synthesis Report → Released March 2023

WMO UNEP

Nobel
2007 PEACE PRIZE
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→ From the Summary for Policy Makers of the Synthesis Report:

A.1 Human activities, principally through emissions of greenhouse gases, have unequivocally caused global warming, with global surface temperature reaching 1.1°C above 1850-1900 in 2011-2020. Global greenhouse gas emissions have continued to increase, with unequal historical and ongoing contributions arising from unsustainable energy use, land use and land-use change, lifestyles and patterns of consumption and production across regions, between and within countries, and among individuals (*high confidence*). {2.1, *Figure 2.1, Figure 2.2*}

https://www.ipcc.ch/reports/ https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Where are we heading?

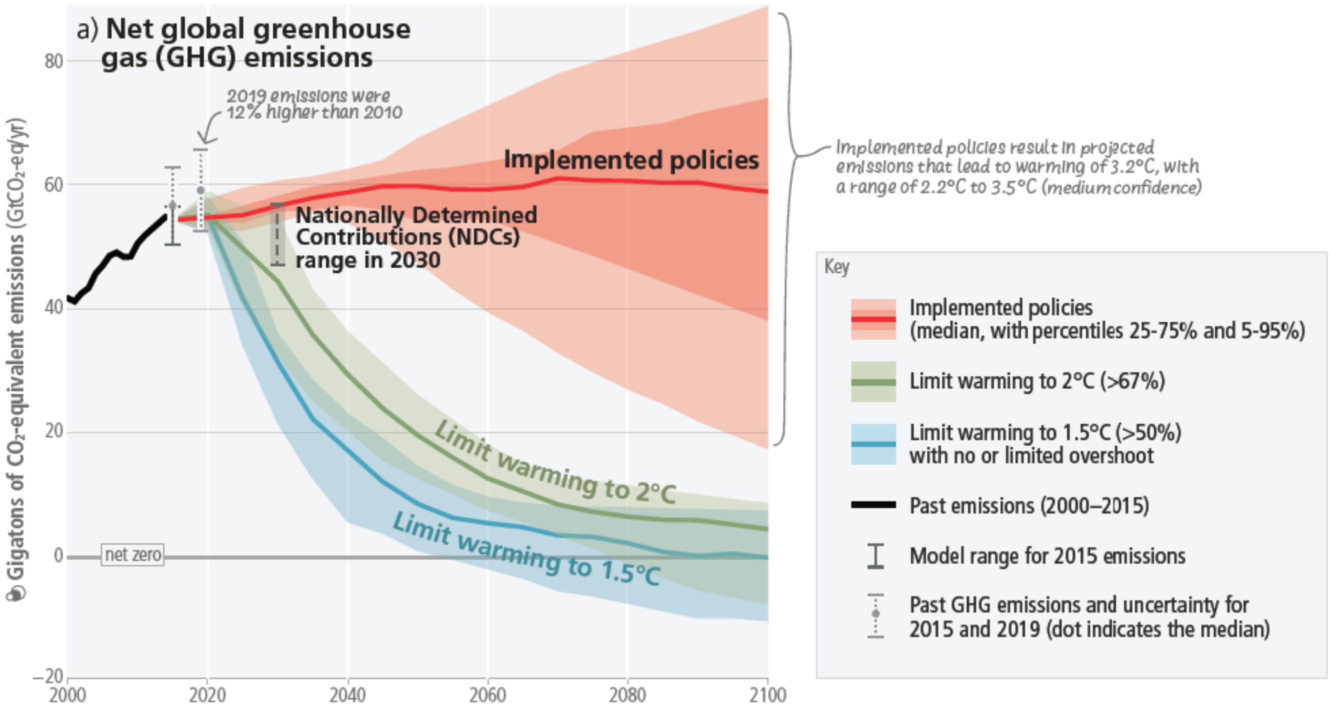
Also see IPCC WGI Interactive Atlas: https://interactive-atlas.ipcc.ch

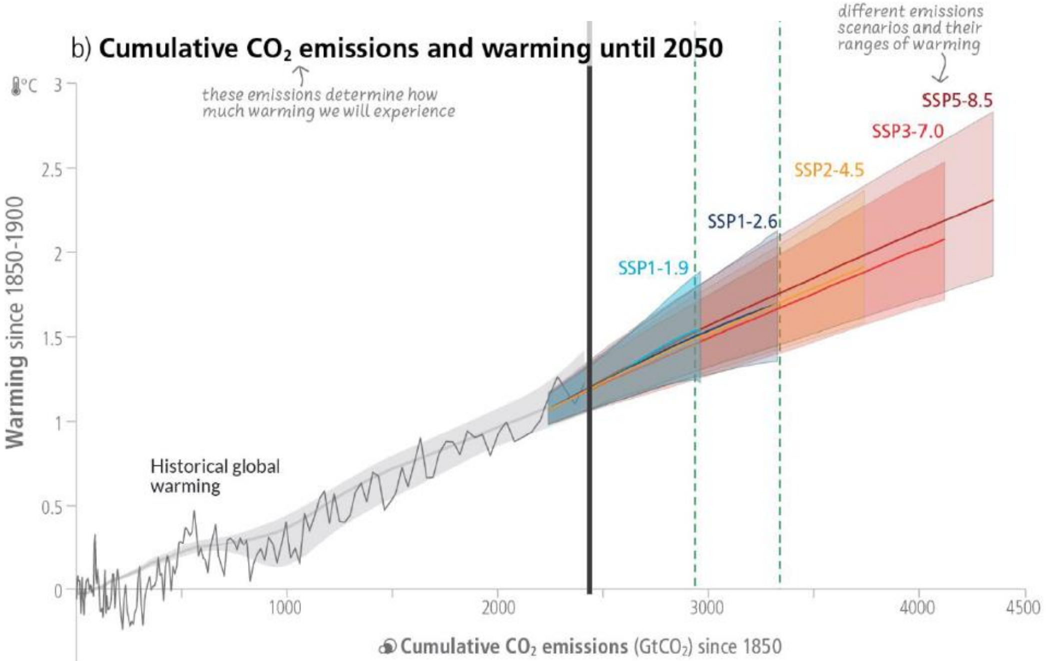
Different scenarios in IPPC report analysed

- Factoring (lack of) mitigation actions, policies, etc.

→ Pathways to 1.5˚C (2.0˚C) require rapid and deep yearly emissions reductions!

→ Why? Cumulative CO_2 emissions count





→ Currently implemented policies lead to warming of 3.2˚C

https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

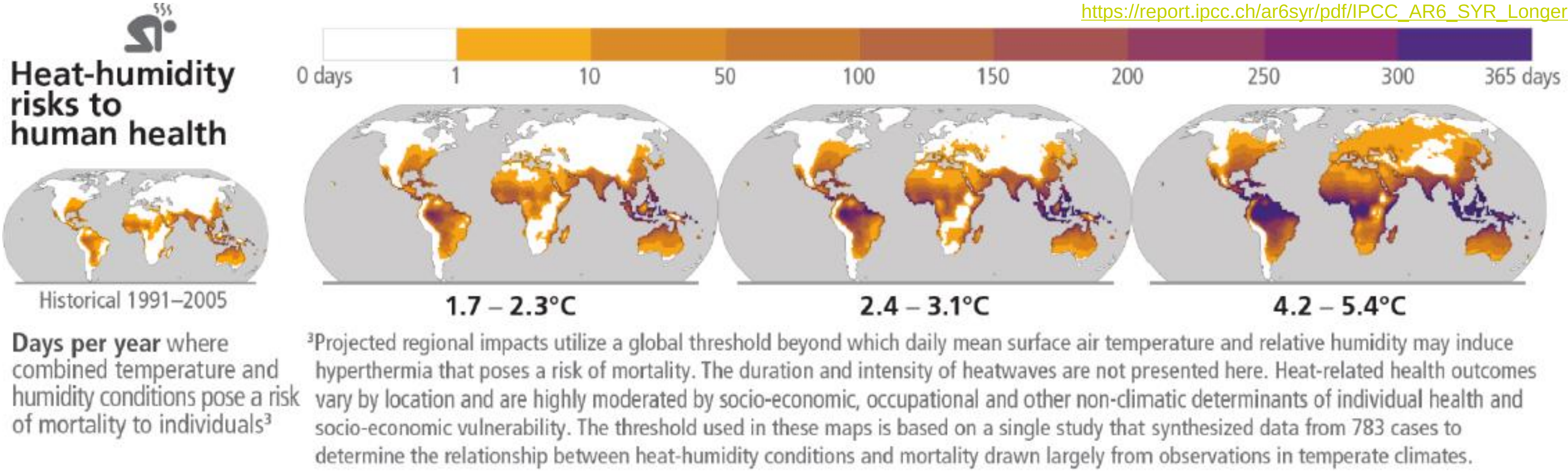
https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

Why is > 2.0˚C temperature increase a bad idea?

With warming of 3.2˚C:

- ~100% biodiversity losses in large areas near equator
- Large parts of the Earth become ~uninhabitable due to risk of hyperthermia

https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

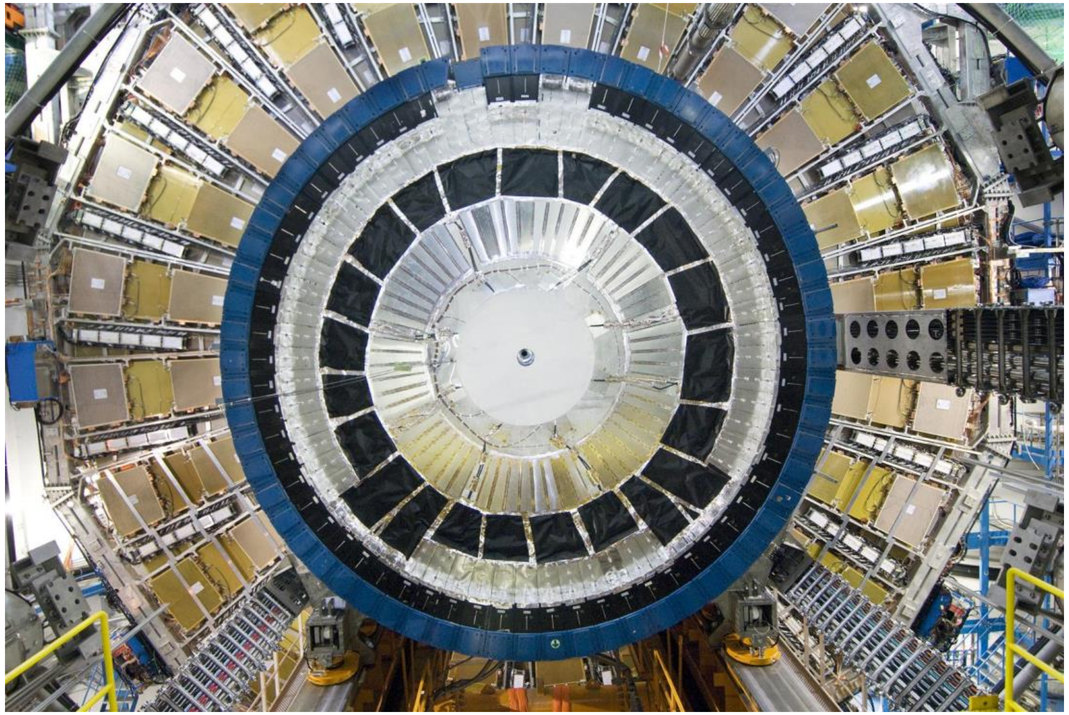


→ Hyperthermia = Failure of human heat-regulating mechanisms – deadly if not treated quickly

Why is it relevant to High Energy Physics & related fields?

High Energy Physics (HEP) and related fields contribute to CO_2 emissions

- Build large detector systems and infrastructures
  - Cause emissions from various sources
    → See environmental reports e.g. by CERN
- But: How much per researcher? → **Know your footprint!**
  - Idea: Estimate per-researcher carbon footprint
    → Put into context with private and target footprints
  - Personal identification of high-emission areas which need urgent adressing and raise awareness
  - Provide personal reference for gauging carbon emission numbers



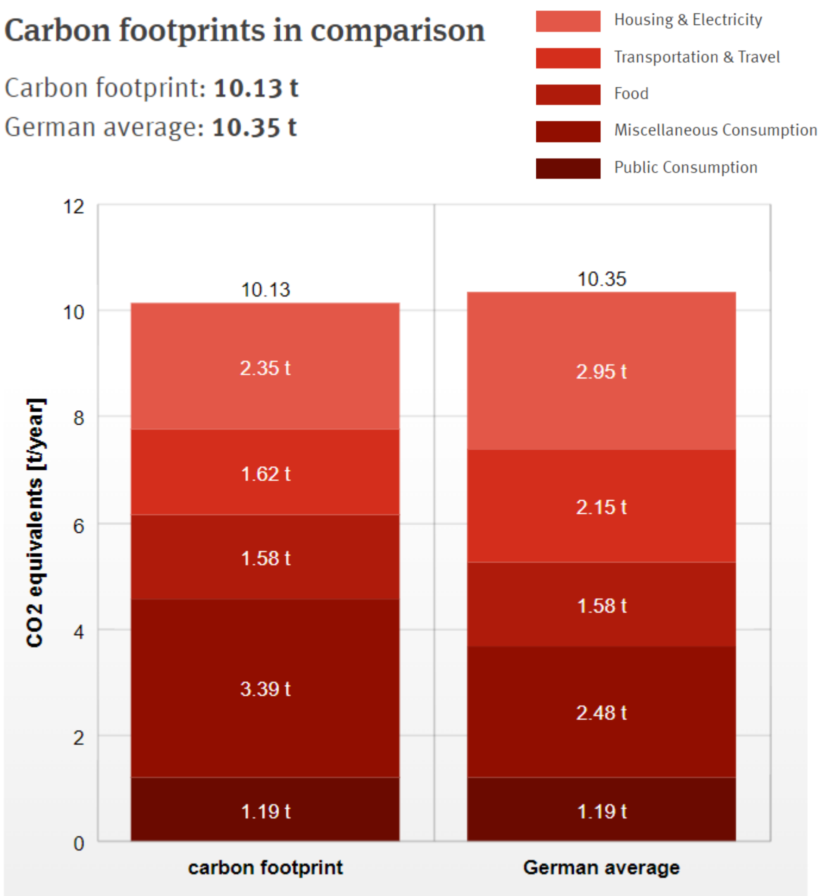
→ If we want to maintain ~liveable conditions on Earth, ALL areas of research, politics, culture, industry, etc. need to contribute to emissions reductions → This includes HEP!

Know your footprint (Kyf) calculator

Consider private and professional emissions for researchers

- Private emissions in Germany – see carbon calculator by German Federal Environment Agency (UBA)
- Professional emissions in HEP and related fields
  → Split into four categories:
  - Experiment
  - Institute
  - Computing
  - Travel

→ Investigate each category‘s impact
→ Configurable per individual researcher, i.e. your individual research situation!



→ Know your footprint (Kyf) calculator
https://limesurvey.web.cern.ch/863499?lang=en

→ Paper discussing the basis of the Kyf calculator
https://arxiv.org/abs/2403.03308

→ Discuss in the following

Experiment, collaboration or project footprint

Distinguish the following options

- Large LHC experiment
- Small LHC experiment

Based on CERN environmental report(s) (for the two LHC experiments above)

- Small HEP experiment → Based on DESY electricity consumption
- Astrophysics experiment → Based on ESO annual report → Skip today

Definition of per-researcher footprint per year

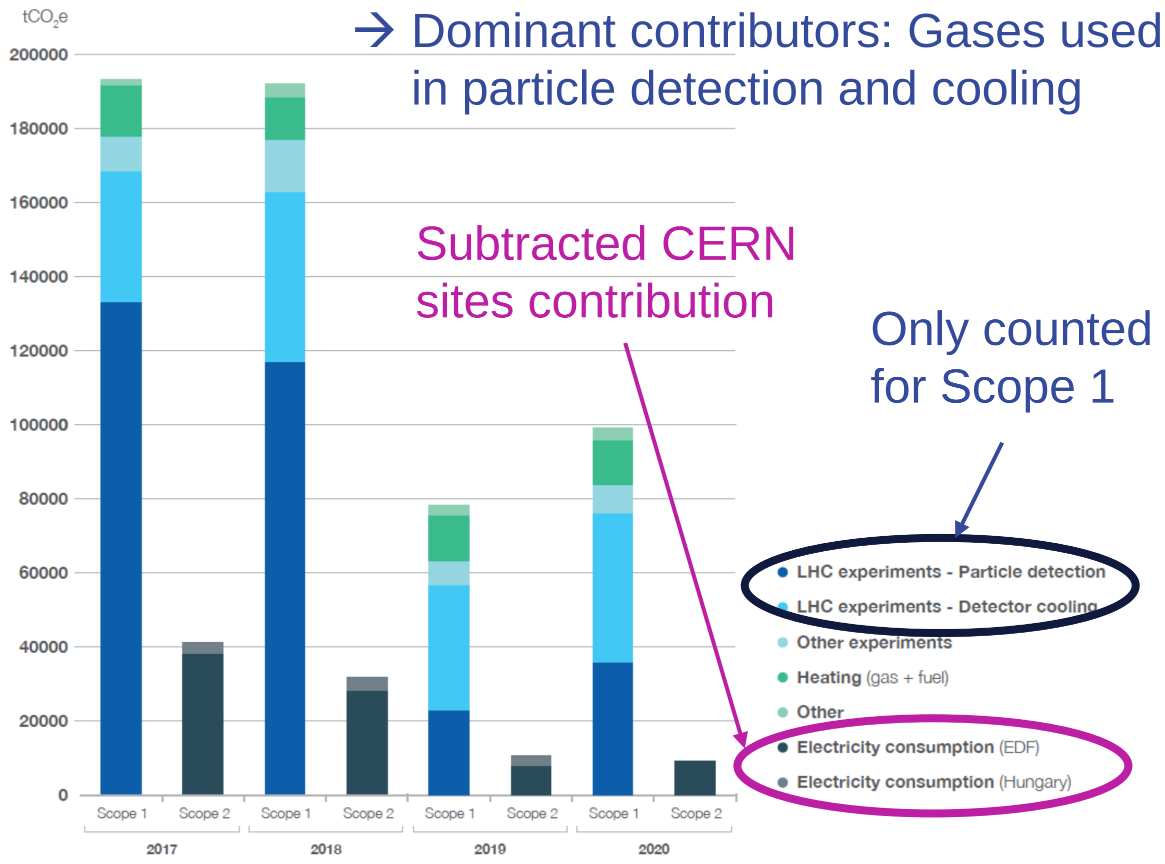
- Per-researcher footprint = (Total annual emissions from experiment) / (Number of experiment members)
  - Experiment members = collaboration members or users (and operators) according to applicability
  - No consideration of indirect benefits for “the industry“ or “the public“ through “gained knowledge“
    → Too vague and leads to responsibility diffusion
  - Responsibilty for emissions lies with researchers designing, building, and operating detectors, and analyzing their data

Footprint of large and small LHC experiments

Emissions classified into three categories by CERN environmental reports

- Scope 1
  - Direct emissions from detectors, heating, etc.
- Scope 2
  - Indirect emissions, primarily from electricity consumption
- Scope 3 → Considered only for Institute footprint
  - Indirect emissions from other sources, e.g. travel, commute, waste, catering, procurement

→ Average emissions separately over:
Running years: 2017, 2018, 2022, and
Shutdown years: 2019-2021



→ Dominant contributors: Gases used in particle detection and cooling

Subtracted CERN sites contribution

Only counted for Scope 1

Footprint of large and small LHC experiments (II)

Assign emissions to large and small LHC experiments

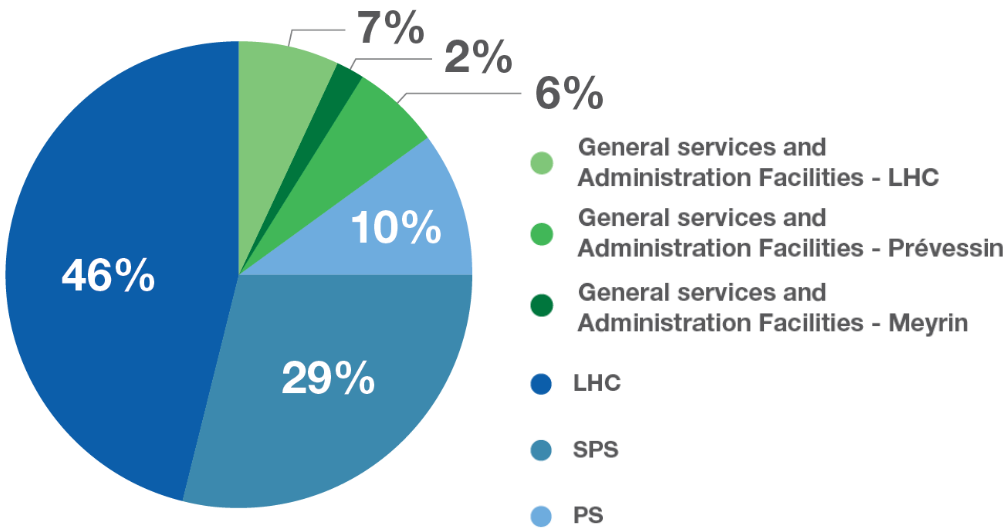
- For scope 1 emissions → LHCb Scope 1 emissions in 2022 specified in Upgrade II Technical Design report
  - Assume ALICE ≈ LHCb → Small LHC experiment: $S1_{Small}$
  - Assume ATLAS ≈ CMS → Large LHC experiment: $S1_{Large}$

$$\rightarrow S1_{Large} = \frac{S1_{All} - 2 \cdot S1_{Small}}{2}$$

- For scope 2 emissions
  - Largest consumer: LHC → Followed by pre-accelerators
    → Needed by all four experiments → Share equally
    → Subtract CERN-site contributions before

$$\rightarrow S2_{Large} = S2_{Small} = \frac{S2_{All}}{4}$$

Electrical power distribution 2018



- Typical operation pattern in last years: 4 years of running, 3 years of shutdown
  - Weight accordingly for overall annual emissions → Total emissions per experiment

Footprint of large and small LHC experiments (III)

Calculate per-researcher emissions per year

- Assume equal share among collaboration members

Emissions [tCO_2e] per experiment

	Phase	Scope 1	Scope 2	Total
Small	Run	2244	16 206	18 450
	SD	1030	8796	9826
	Overall	-	-	14 754
Large	Run	78 332	16 206	94 538
	SD	35 962	8796	44 758
	Overall	-	-	73 204

Emissions per collaboration member

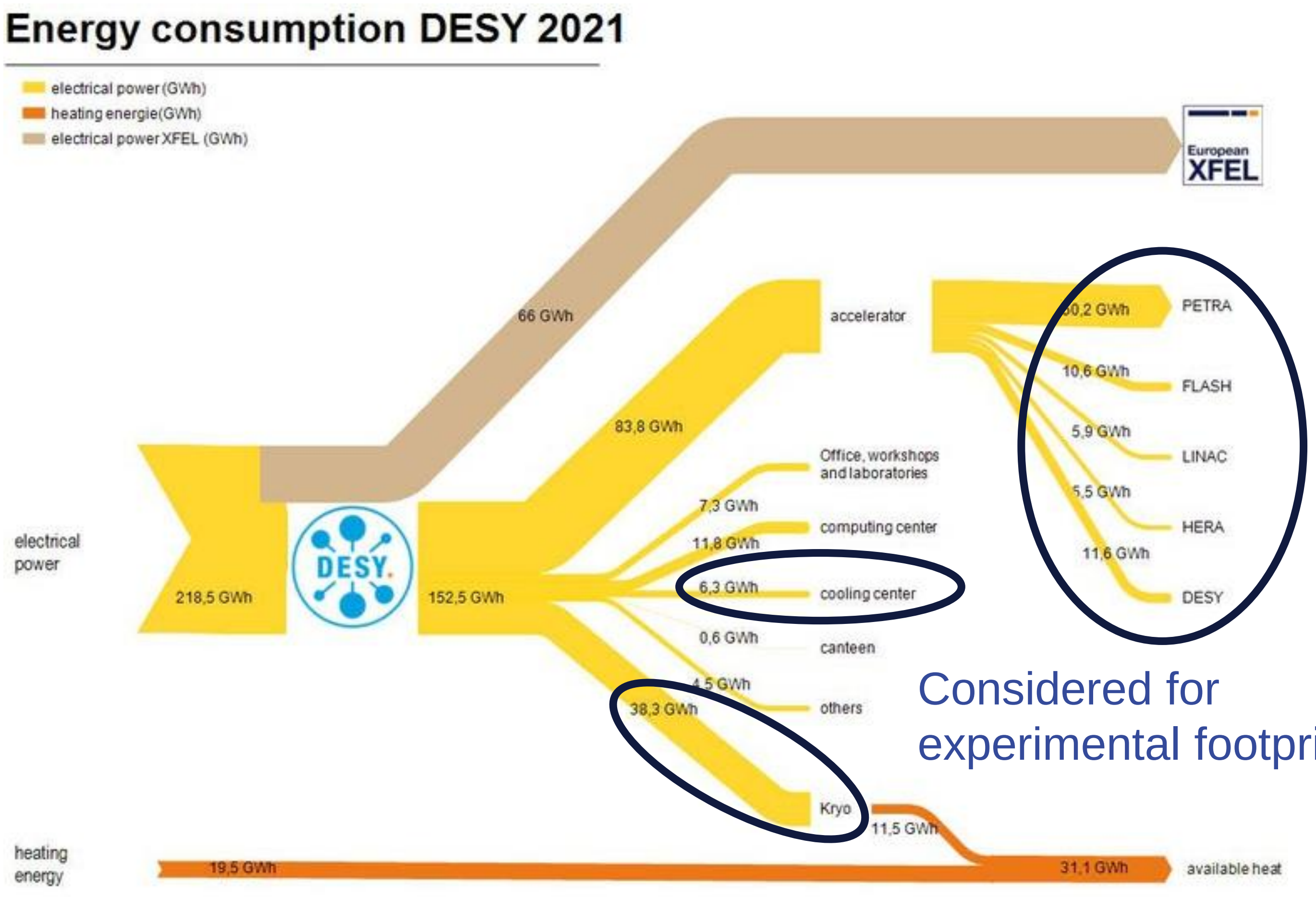
	Experiment	Members	Mean	Emissions
Small	ALICE	1968	1684	8.76 tCO_2e
	LHCb	1400		
Large	CMS	6288	6144	11.91 tCO_2e
	ATLAS	6000		

→ Slightly more (less) for large (small) LHC experiments compared to the private footprint in Germany

Footprint of a small HEP experiment

Estimate based on DESY electricity consumption

- Data from 2021: 128.3GWh annually
- Convert to tCO_2e → 2 options:
  - Green electricity
    → Assume 100% photo-voltaic (PV) based production → 35 gCO_2e/kWh
  - German electricity mix in 2023
    → Includes >40% from wind, solar and water power → 416 gCO_2e/kWh
    (for comparison: gas: 572 gCO_2e/kWh, coal: 1167 gCO_2e/kWh)



Considered for experimental footprint

→ With 3000 guest scientists + 200 operators: 1.40 tCO_2e (16.68 tCO_2e) with green (conventional) electricity

Institute or research centre footprint

Distinguish the options

- University (with green or conventional electricity)
  → Based on University of Freiburg report
  (skip Leibniz University Hannover today)
- Research centre
  → Based on CERN environmental report(s)

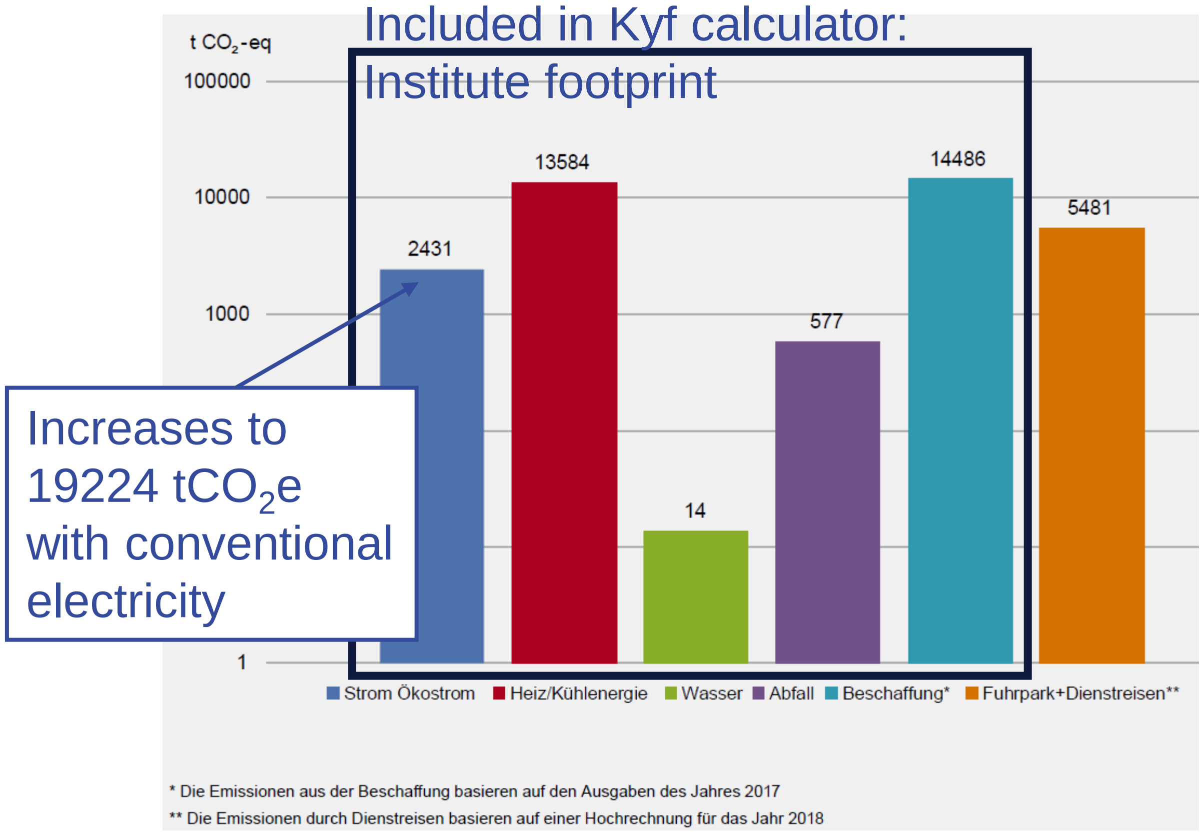
Definition of per-researcher footprint per year

- (Total institute emissions) / (Effective number of institute members)
  - One representative year outside of COVID-19 pandemic: 2019 for University of Freiburg, 2022 for CERN
- University of Freiburg as default university footprint
  - Omission of procurement information by Leibniz University Hannover
  - Decent agreement in overlapping categories between both universities

Footprint of a university - Freiburg

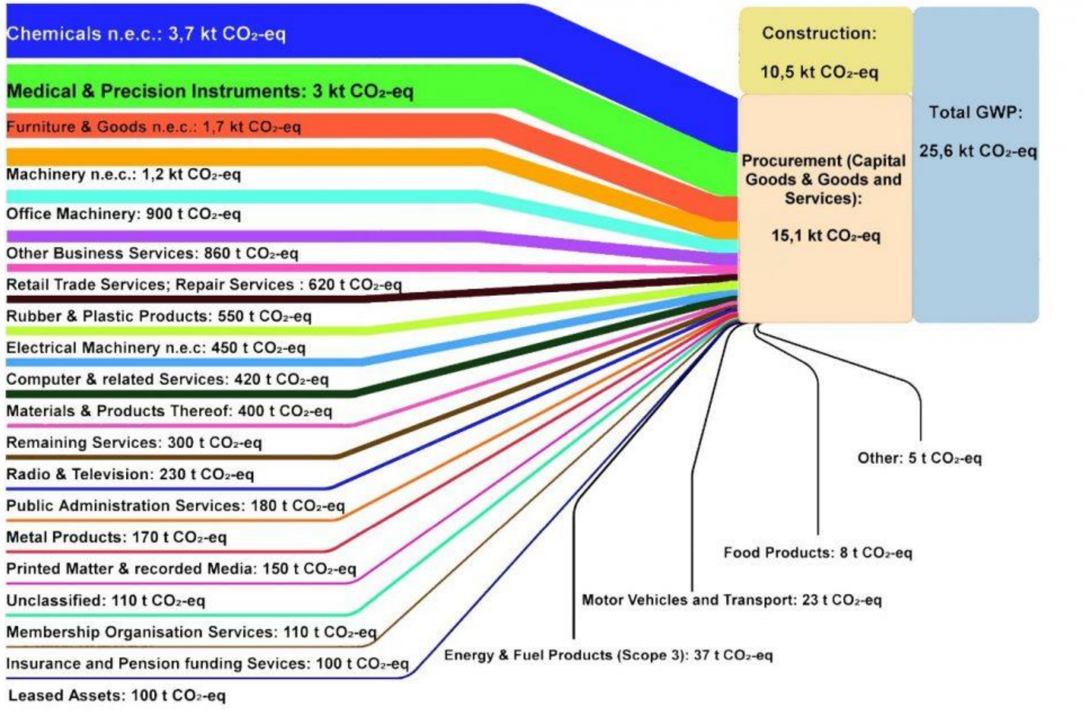
Emissions with green electricity

- Exclude emissions from travel here



Procurement → Dominating contributor

- Based on procurement data from 2017



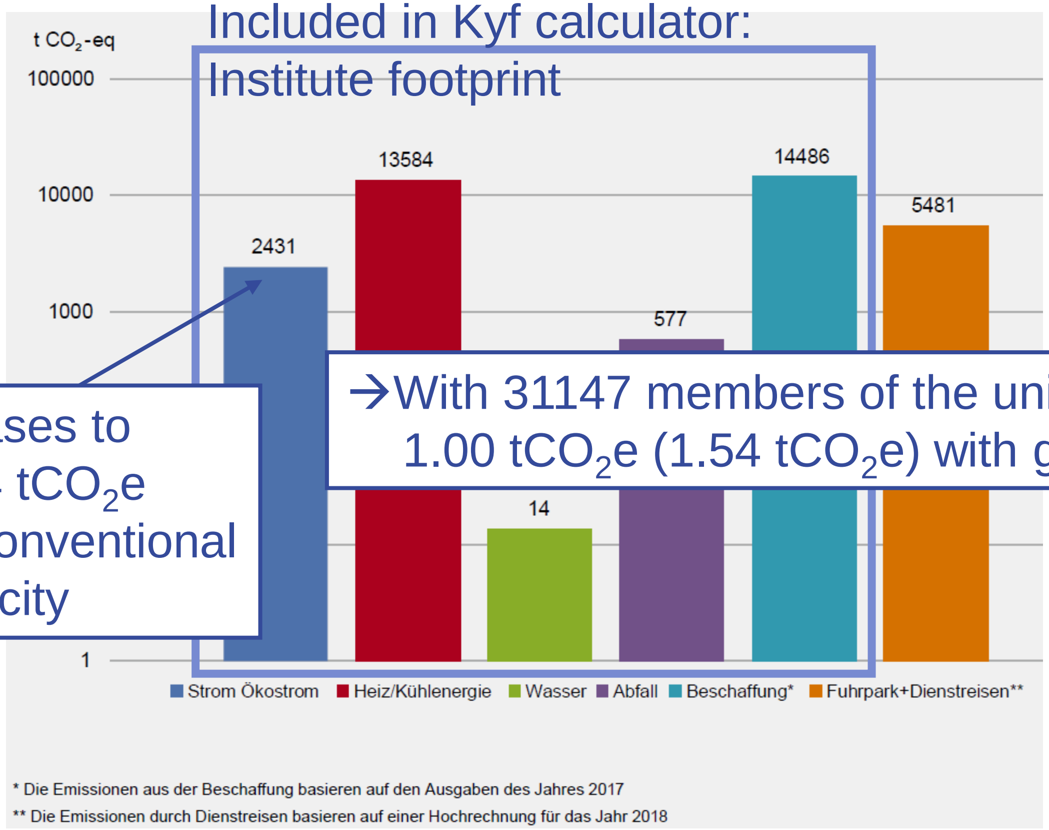
→ Many categories → Challenging to address
→ Demand management + green procurement!

Footprint of a university - Freiburg

Emissions with green electricity

- Exclude emissions from travel here

Included in Kyf calculator:
Institute footprint

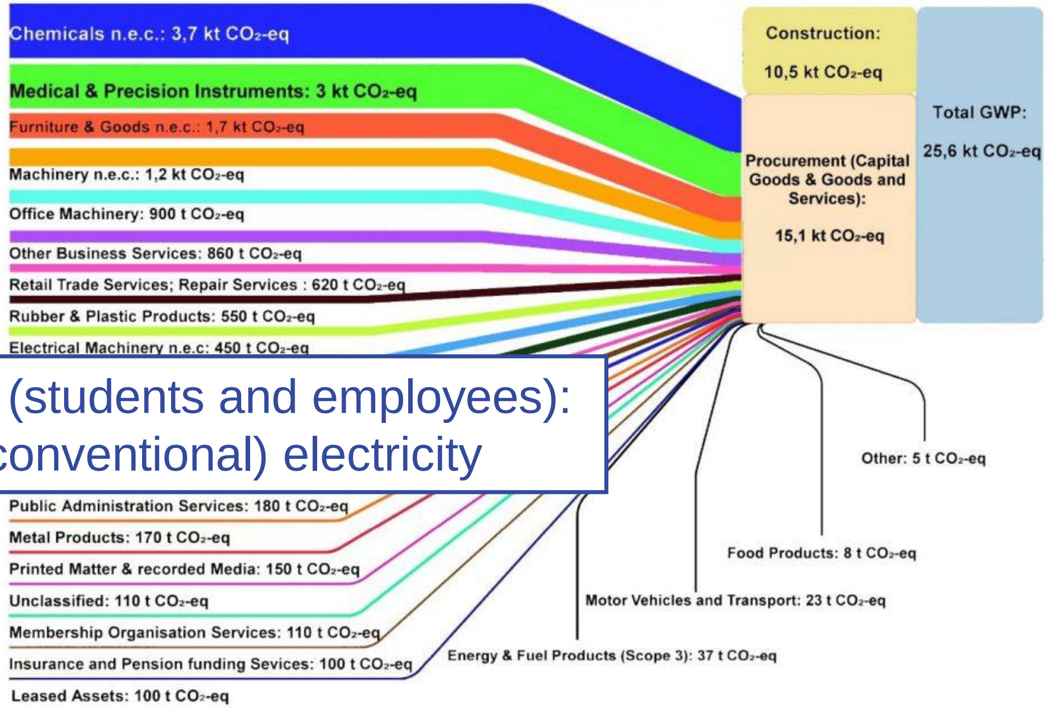


Increases to 19224 tCO_2e with conventional electricity

→With 31147 members of the university (students and employees):
1.00 tCO_2e (1.54 tCO_2e) with green (conventional) electricity

Procurement → Dominating contributor

- Based on procurement data from 2017

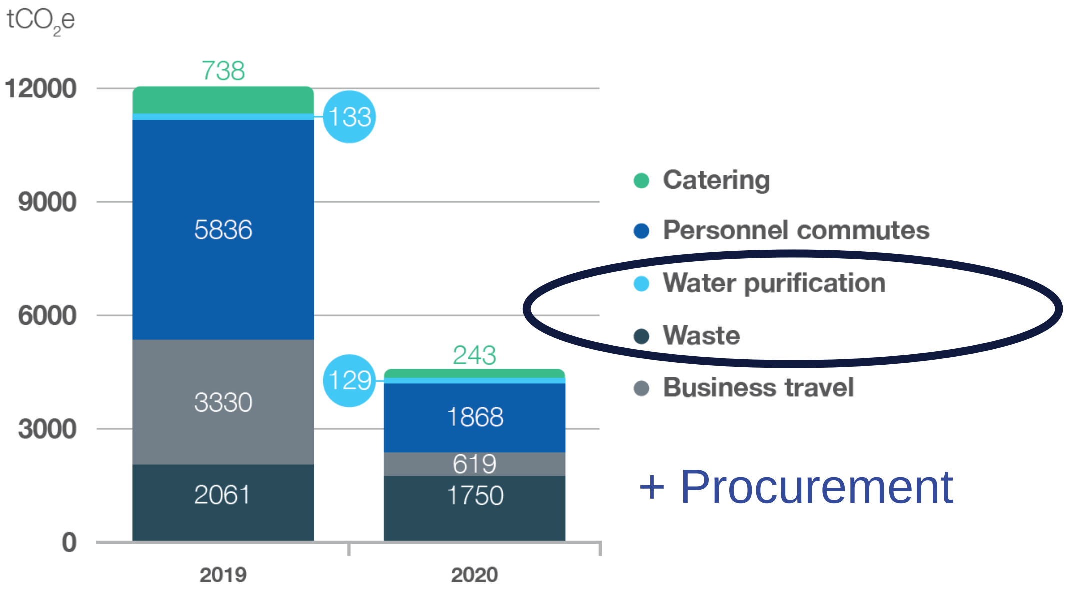


→ Many categories → Challenging to address
→ Demand management + green procurement!

Footprint of a research centre – CERN

From the CERN environmental reports

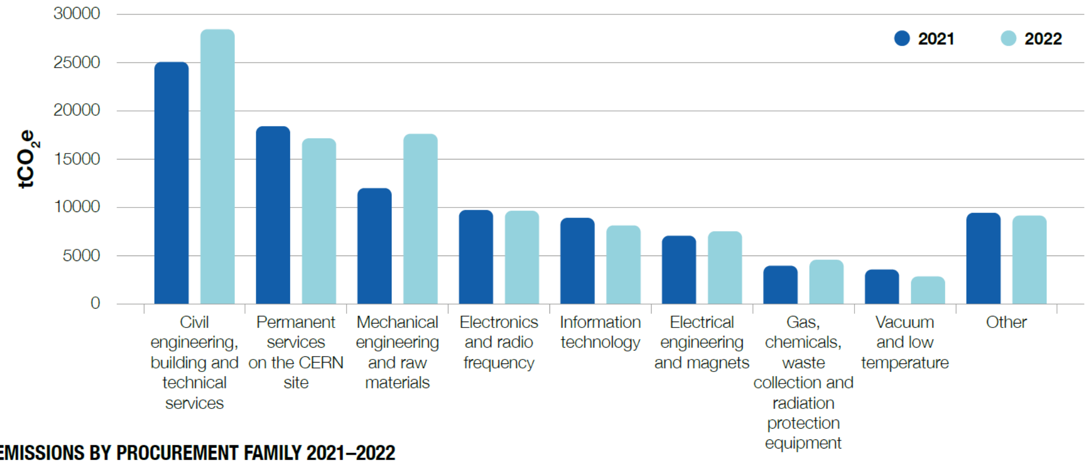
- Heating + Other category from scope 1
- 5% of electricity, i.e. scope 2
- Scope 3
  - Excluding commute, travel, and catering



+ Procurement

Procurement contribution = huge!

- Procurement emissions: 104 974 tCO_2e in 2022!
  - Corresponds to ~57% of total scope 1 emissions in same year
  - Contributions for construction of future infra-structure, etc. included → Cannot be clearly separated → Maintain fully under institute



EMISSIONS BY PROCUREMENT FAMILY 2021–2022
"Other" includes: office supplies, furniture, transport, handling and vehicles; centralised expenses and codes for internal use; particle and photon detectors; health, safety and environment; optics and photonics.

Footprint of a research centre – CERN (II)

Total institute emissions

Category	Emissions [tCO_2e]
Electricity	3158
Heating (gas+fuel) + Other	11 250
Water purification	176
Waste	1875
Procurement	104 974
Total	121 433
Total without Procurement	16 459

Effective CERN population

- At any time during the year:
  - Fraction of CERN users at CERN, using electricity, heating, water, etc.
  - Consider together with CERN personell, i.e. staff and CERN fellows

→ Effective CERN population: 7295

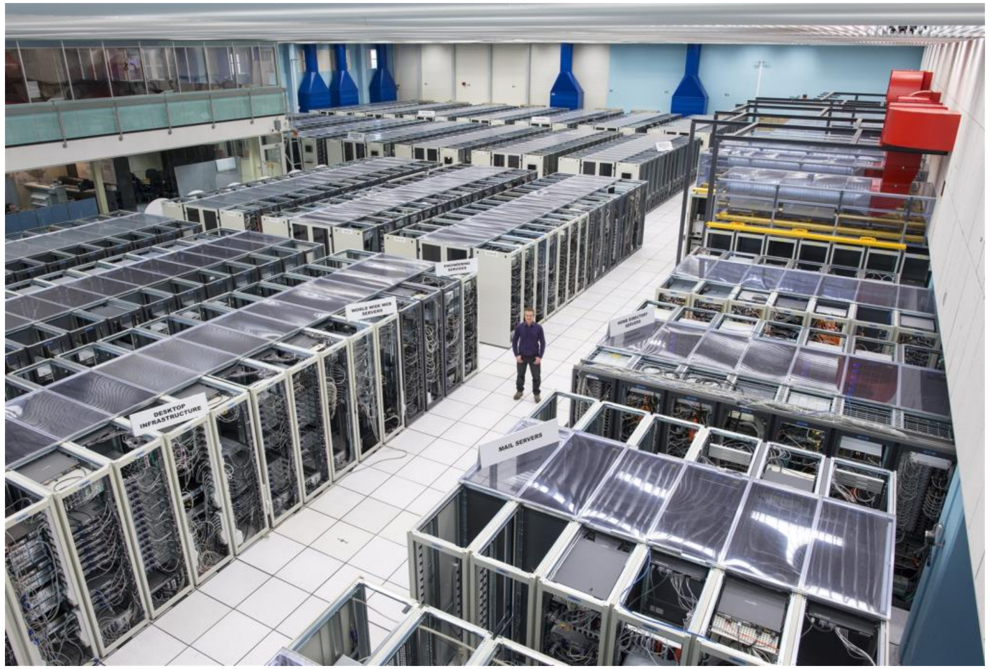
→ Per-researcher footprint:
16.65 tCO_2e (2.26 tCO_2e) including (excluding) procurement
→ With procurement, artificically increased, due to impossibility of procurement split-up
→ Needs update, once more refined data available

→ To CERN's credit:
Environmentally Responsible Procurement Policy, effective from 1 January 2024 – April 2024 CERN news
→ Hopefully, procurement footprint will reduce over the next years

Computing footprint

Focus on High Performance Computing (HPC)

- Specify individual‘s computing workloads in core hours
- Distinguish between CPU and GPU usage
  → Choice of CPU or GPU due to computational task
  - Several possibilities to tune configuration
  - Assume optimal core utilization
- Possibility to add footprint of large external (commercial) data storage resources
- Personal computers, small institute clusters, etc. not included
  → Assumed to be covered by personal or institute electricity bills and procurement → Thus included in personal or institute footprint
- Four benchmark scenarios for easy use available



Computing footprint (II)

Calculation of computing footprint

$$Total\ [tCO_2e] = f_{PUE} \cdot f_{overh} \cdot n_{WPC} \cdot f_{conv}$$

- With:
  - f_{PUE} = HPC's Power Usage Effectiveness (PUE)
    → Default: 1.5 (Global average) → New CERN computing centre target: 1.1 (Feb 2024 CERN news)
  - f_{overh} = Overhead factor for power consumption when computing cores are idle
    → Default: 1.17 (Hawk supercomputer idle time at the HPC Stuttgart)
  - n_{WPC} = Workload Power Consumption (WPC)

    $$n_{WPC} = p_{CPU-core} \cdot l_{core-h,CPU} + p_{GPU} \cdot l_{h,GPU}$$

    $p_{CPU-core/GPU}$ = Power consumption in kW for each CPU core/GPU
    → Default: 7.25W (CPU - from the DESY Maxwell cluster with AMD EPYC 75F3 CPU cores),
    250W (GPU - median of range, reported on a forum of NVIDIA GPU users)
    $l_{core-h,CPU/h,GPU}$ = CPU workload measured in core hours/ GPU usage hours → User input
  - f_{conv} = Conversion factor from kWh to gCO_2e → Both, green and conventional (default) electricity possible

Computing footprint (III)

Four benchmark scenarios

- Low usage
  - PhD student with several jobs per week → Average of 4000 CPU core-h/month
- Medium usage
  - Doctoral student or post-doctoral researcher, strongly involved in data analysis → Based on top five ranked users at the Uni-Freiburg HPC: Black-Forest Grid (BFG) → Average of 30 000 CPU core-h/month
- High usage
  - Accelerator scientist, studying accelerator performance with particle tracking codes and semi particle in-cell (PIC) codes → With code optimized for GPUs: 2500 GPU h/month (≈ 80 000 CPU core-h/month)
- Extremely high usage
  - Researcher running PIC simulations or high-resolution imaging analysis → 8000 GPU h/month (≈ 300 000 CPU core-h/month)

With conventional electricity

Scenario	**Annual footprint [tCO_2e]**
Low	0.25
Medium	1.91
High	5.48
Extremely high	17.52

Travel

Consider only business travel → Private travel included in private footprint

- Travel important in international research environment:
  - For personal connections at in-person meetings
  - For building research networks, collaborations
  - Etc.

  → Most notably missed during COVID-19 pandemic
- BUT: Travel creates CO_2 emissions
  - Which travel is essential and which is not?
  - Re-evaluate how travel is performed:
    → Longer travel times with non-air based travel
      = longer-duration stays preferrable
    → Constraints from teaching, family, etc. = non-trivial


Foto von detait auf Unsplash

- Possibility for detailed calculations of business trip emissions in Kyf calculation OR benchmark trips

Travel (II)

Based on information from the German UBA

- German numbers for hotel and venue assumed to be valid internationally

Source of Emission	Emission Factor	
Long-distance Buses	0.031	$kgCO_2e/km$
Long-distance Trains	0.031	$kgCO_2e/km$
Personal Car	0.17	$kgCO_2e/km$
Flights within Europe	130	$kgCO_2e/h$
Transcontinental Flights	170	$kgCO_2e/h$
Hotel room	12	$kgCO_2e/night$
Event venue	0.19	$kgCO_2e/day$

Benchmark	Situation	Emissions [tCO_2e]
Travel within Germany	5-day trip by trains from Freiburg to Hamburg	0.1
	Same but by plane (1.5h flight/direction)	0.5
Travel within Europe	5-day trip by plane from Freiburg to Thessaloniki (2.5h flight/direction)	0.7
Travel across continents	2-week trip by plane from Freiburg to Seoul (12h flight/direction)	4.3

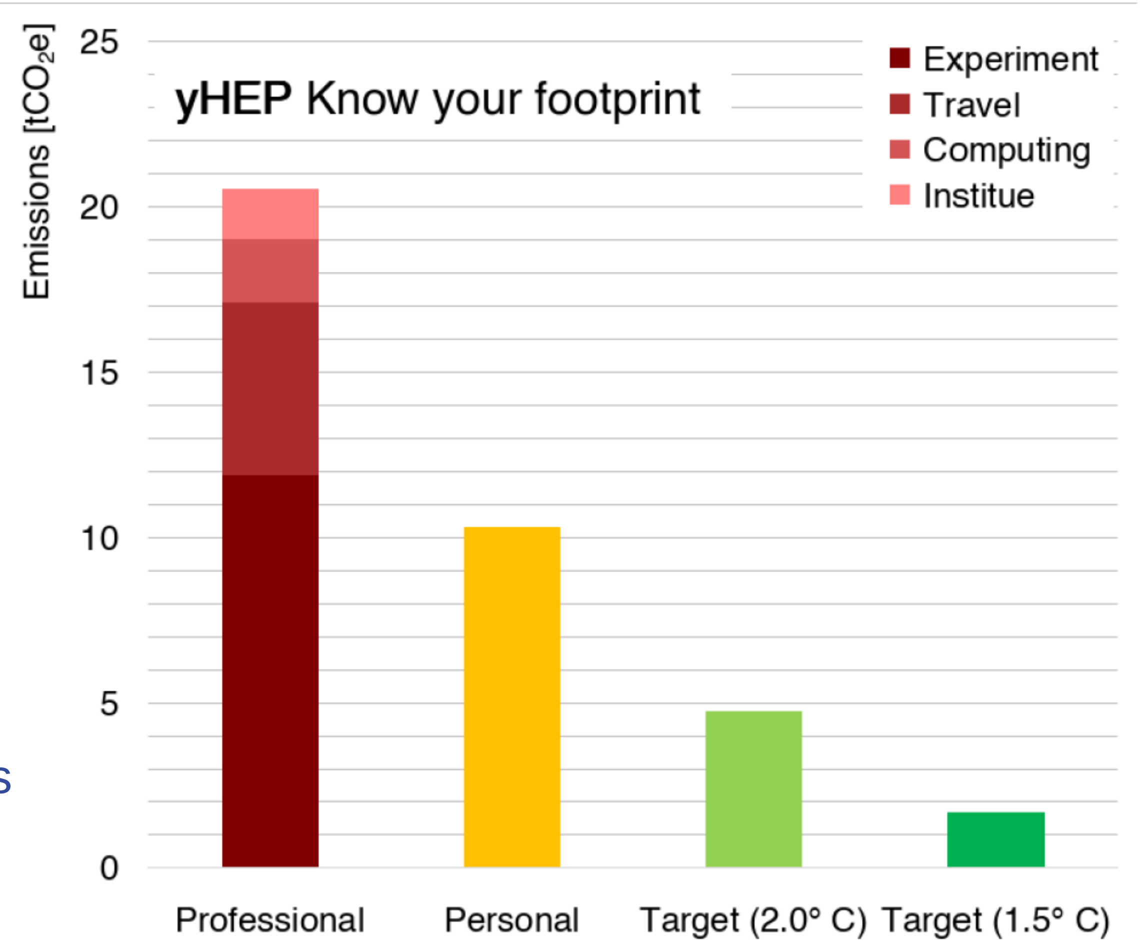
→ In particular, cross-continental flights contribute significantly
→ CO_2 compensation for flights possible to indicate in Kyf calculator

Benchmark researcher

Putting everything together

- Benchmark for early-career researcher in Germany: Doctoral student
  - Working on one of the large LHC experiments
  - Employed by university with conventional electricity
  - Medium computing level with conventional electricity
  - Annual travel: Two 1-week trips by train in Germany, one 1-week flight travel in Europe, 1 2-week cross-continental travel (e.g. for summer school)

→ Professional footprint exceeds private footprint by factor of ~2
→ Both by far exceed targets for mitigating climate crisis to only 2.0˚C or 1.5˚C warming
→ HEP research urgently needs to address this
→ Become part of the solution of the climate crisis!



Summary

Climate crisis in progress and intensifying every year

- Mechanism of CO_2 concentration and ground temperature increase known since more than 100 years
  - Currently heading towards 3.2˚C temperature increase → Will cause in some areas ~100% biodiversity loss, and makes large regions on the planet deadly for human life
  - Targeted action for mitigation urgently needed!
- High Energy Physics (HEP) and related areas contribute to global emissions → Reductions urgent
  - Know your footprint (Kyf) calculator for individual researcher emissions
  - Evaluation for early-career benchmark researcher: Professional and private footprint together factor of ~6 (~18) larger than needed for 2.0˚C (1.5˚C) temperature increase mitigation

→ Every gram of CO_2 not emitted counts!

→ Know your footprint to know where to start! → If large contributions from:
- Experiment and institute: Send e-mail to your experiment and institute responsibles asking for details
- Computing: Send e-mail to your computing center about using renewables, think about efficient coding
- Travel: Think about which travel is needed and which means is possible

Take-away from today

What is your most important take-away from this seminar today? (1-2 words max.)

Start Vote

ID = valerie.lang@physik.uni-freiburg.de
Vote has not been started yet

Know your footprint! – Questions?

Thanks for your attention

→ If possible, please submit your data (anonymously) so that we can get an overview of the averages

Sustainability at PSI

PSI environmental mission statement and PSI Energy mission statement

- Environmental performance based on the following indicators
  - Efficient energy use in infrastructure and research (see PSI Energy Mission Statement)
  - Reduction of the emissions caused directly and indirectly
  - Optimised use of resources (water, paper, chemicals etc.)
  - Advanced waste management with a high proportion of recycling
- Also annual reports, but not public? → **For the last twenty years, PSI has been recording its energy statistics systematically and reporting them transparently both internally and externally.**
  - PSI submits a comprehensive and transparent annual report to the ETH Board on key figures, measures and the achievement of objectives

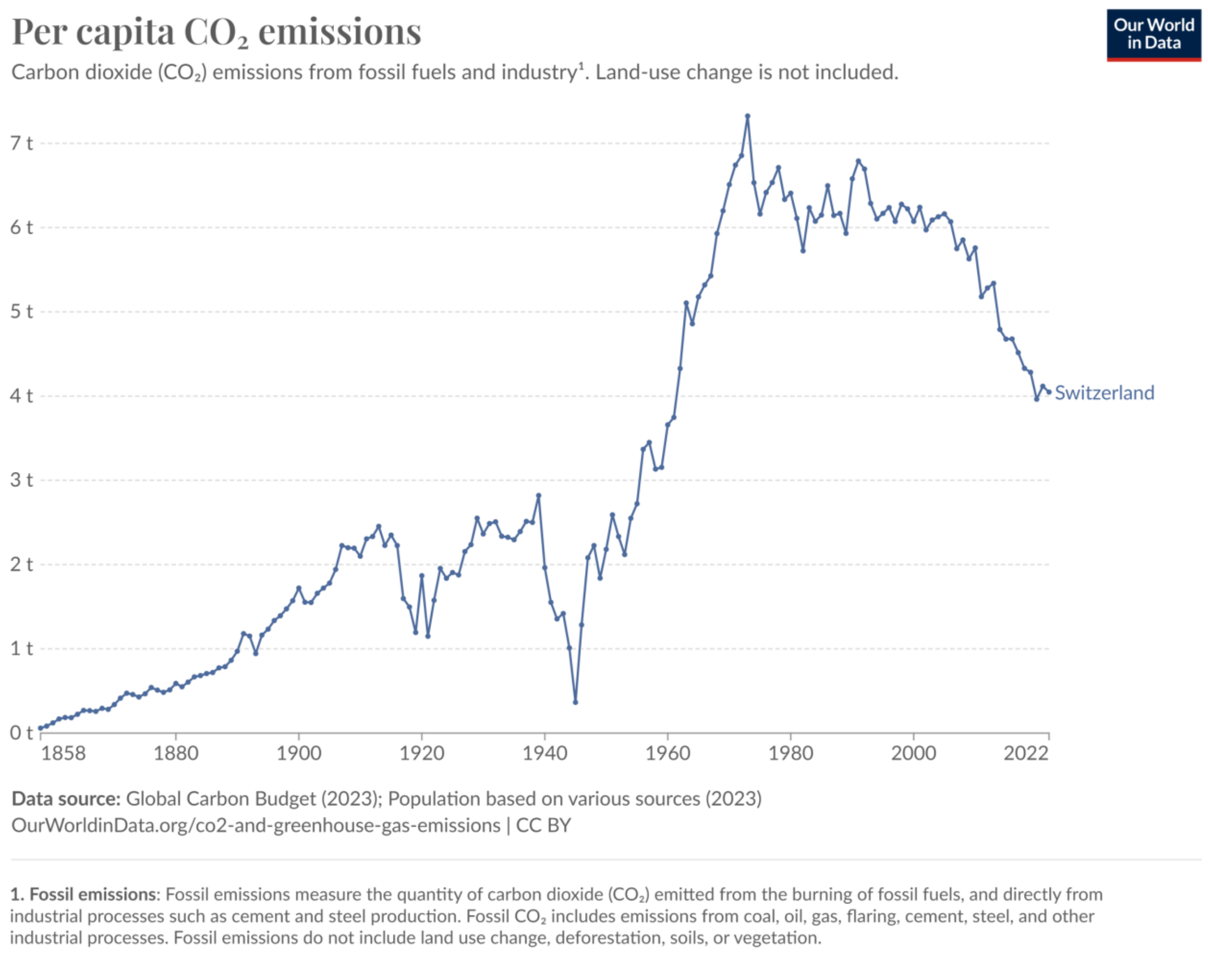
→ Two very important steps for emission reductions:

- Since 2020, PSI has been obtaining all its electricity with hydropower certificates and implements the targets for increased electricity generation with photovoltaics.
- PSI specifically advocates the operation of the new comprehensive heat recovery system and its expansion.

- Core objectives
  - Increasing energy efficiency
  - Expansion of green power generation
  - Reduction of direct and indirect emissions
    - e.g. reduction of 50% of greenhouse gas emissions from 2006 to 2030
  - Efficient use of resources (water, paper, chemicals, etc.)
  - Progressive waste management with a high proportion of material recycling

→ How? What are absolute emission numbers?
→ More quantitative information important

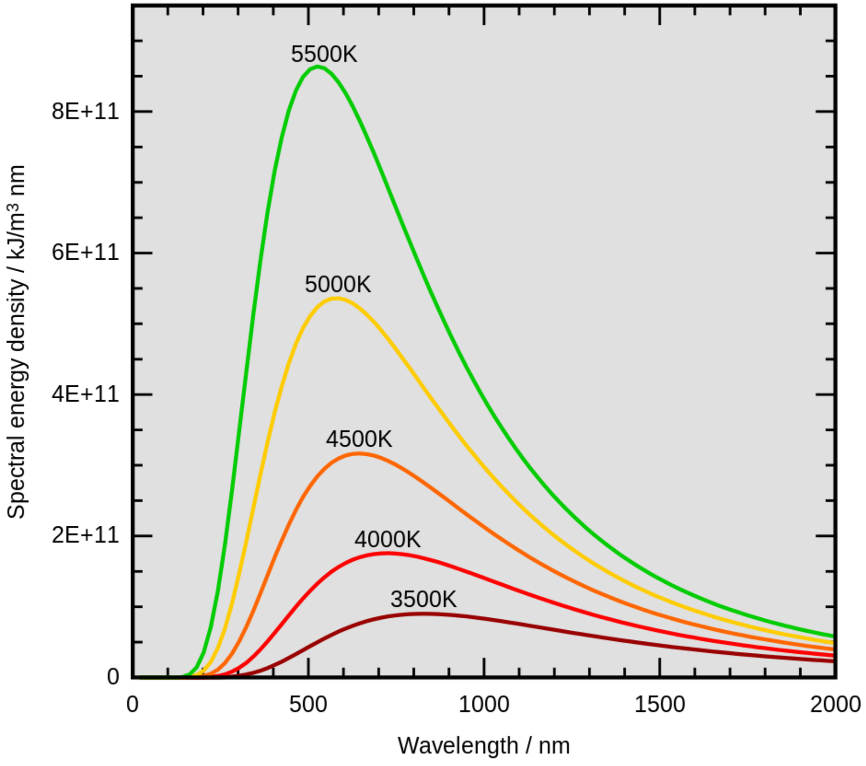
Carbon footprint Switzerland



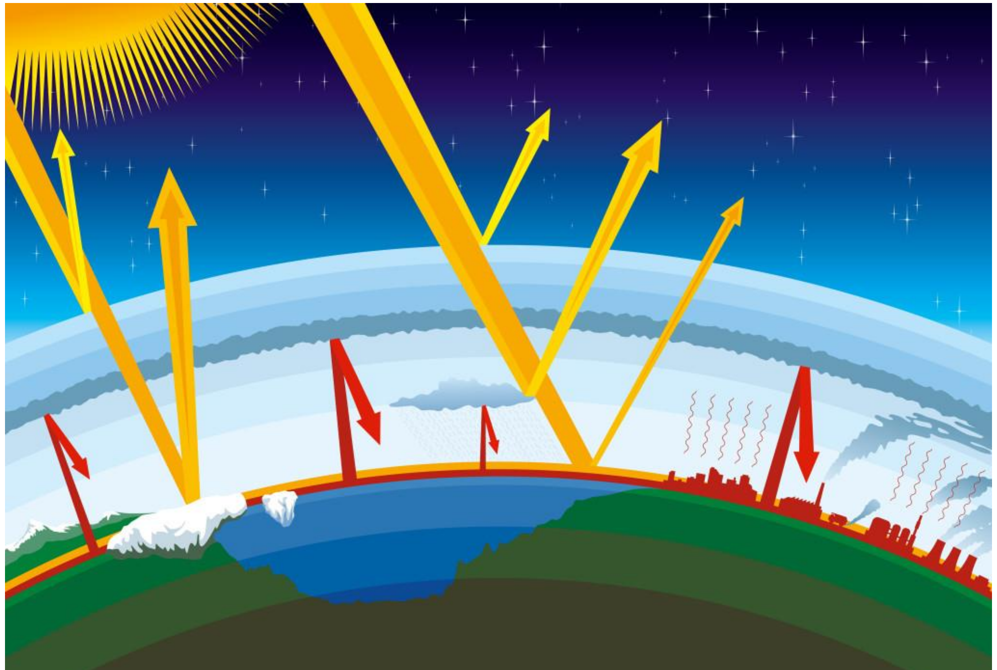
The basics: Green house effect

Black body radiation of the sun and Earth

- Sun at 6000°C, Earth at 15°C → Sun radiates in the visible, Earth radiates in the infra-red



Credit: By 4C - Own work based on JPG version Curva Planck TT.jpg, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=1017820

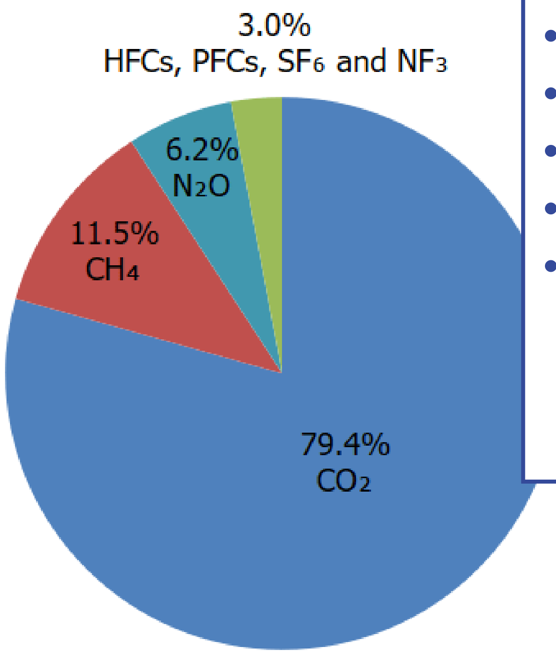


Credit: US EPA [Public domain], via Wikimedia Commons

→ If atmosphere did not re-absorb Earth‘s emissions, surface temperature on Earth around -18˚C!

The basics: Green house effect

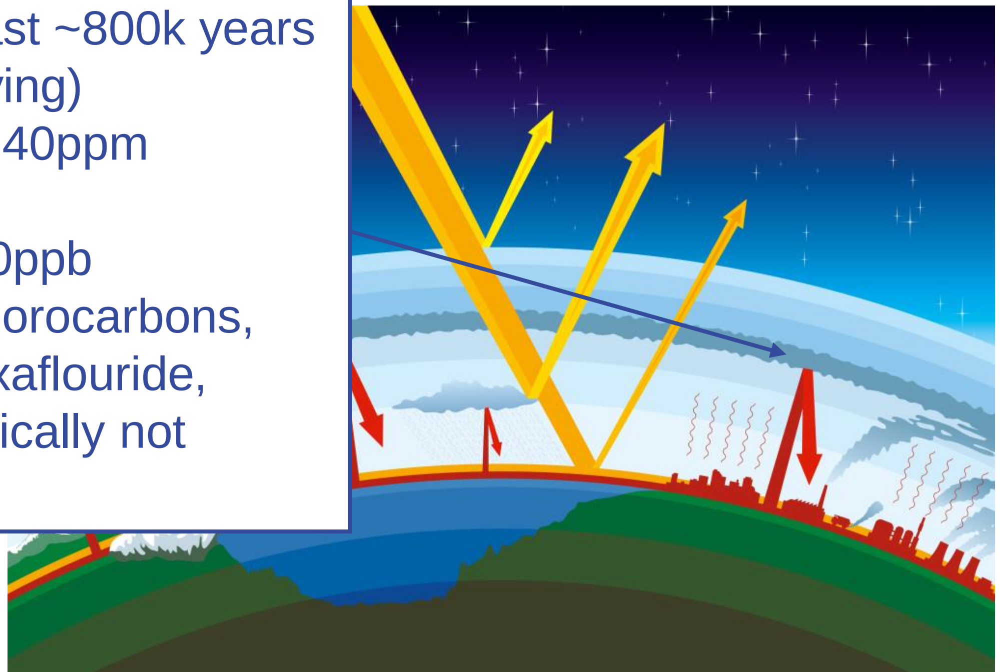
Re-absorption done by greenhouse gases



Main greenhouse gases

→ Historic concentrations in last ~800k years

- Water vapour (strongly varying)
- Carbon dioxide (CO_2) → ~240ppm
- Methane (CH_4) → ~500ppb
- Nitrous oxide (N_2O) → ~250ppb
- Fluorinated gases: Hydrofluorocarbons, perfluorocarbons, sulfur hexaflouride, nitrogen trifluoride → Historically not existing



Credit: US EPA [Public domain], via Wikimedia Commons

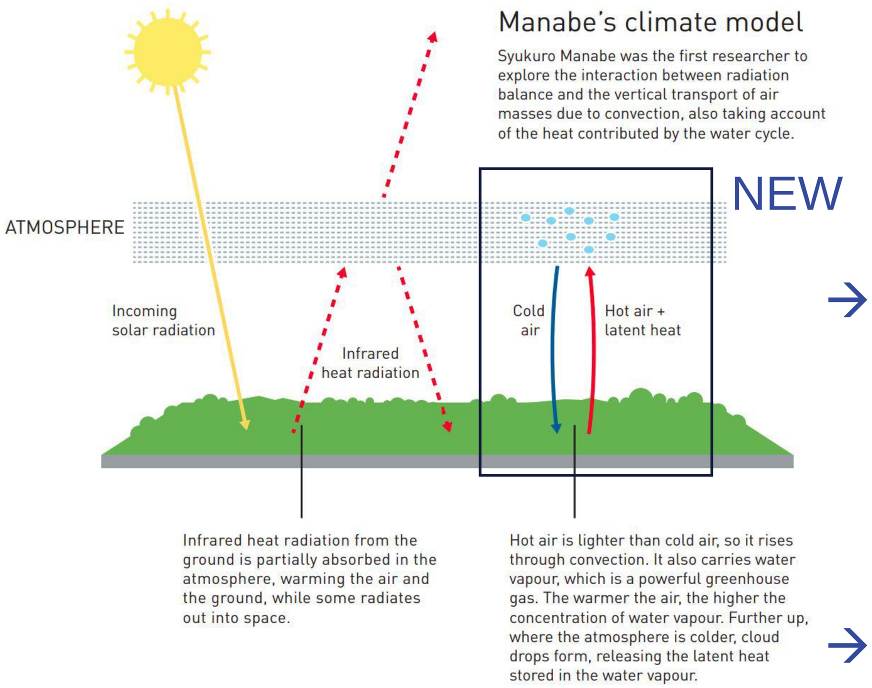
https://www.epa.gov/ghgemissions/overview-greenhouse-gases

Historic contributions (pre-industrial age) read off from figures from: https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

Improving the predictions of Earth‘s surface temperature

Nobel prize 2021 - *”for groundbreaking contributions to our understanding of complex physical systems”*

- 1967: Syukuro Manabe: Adding convection and latent heat

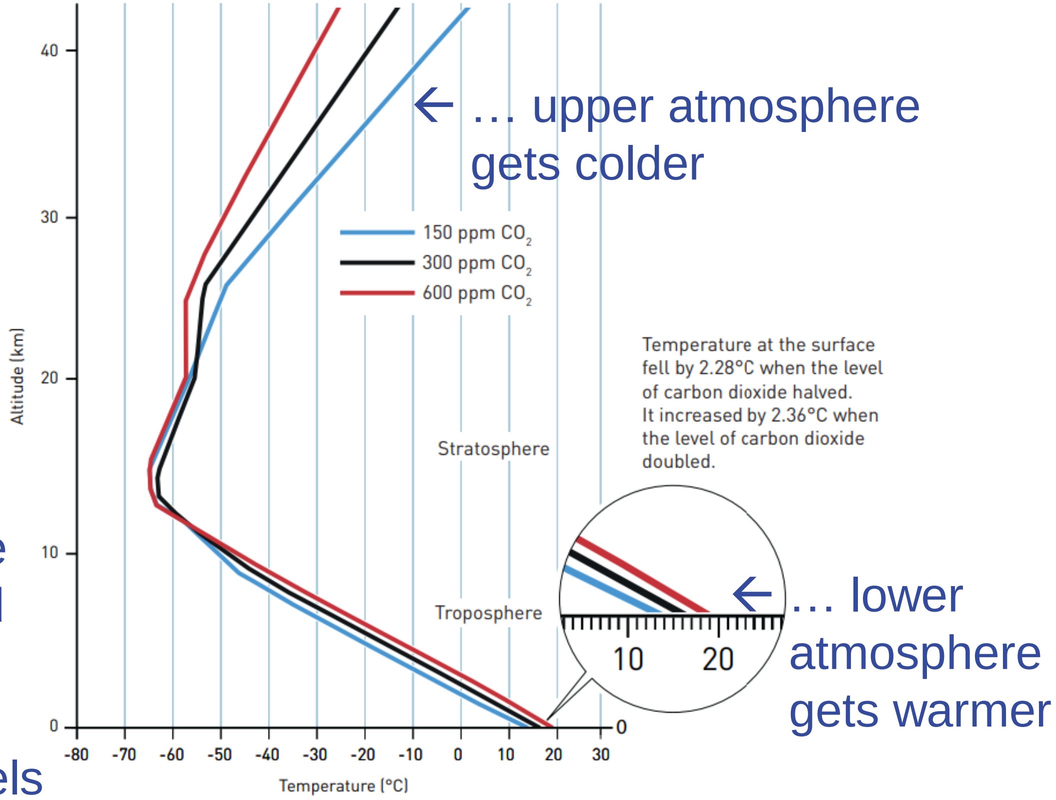


https://www.nobelprize.org/prizes/physics/2021/popular-information/

→ If the cause for warming was increased solar radiation, the entire atmosphere should have warmed up

→ Hence, cause is increased CO_2 levels

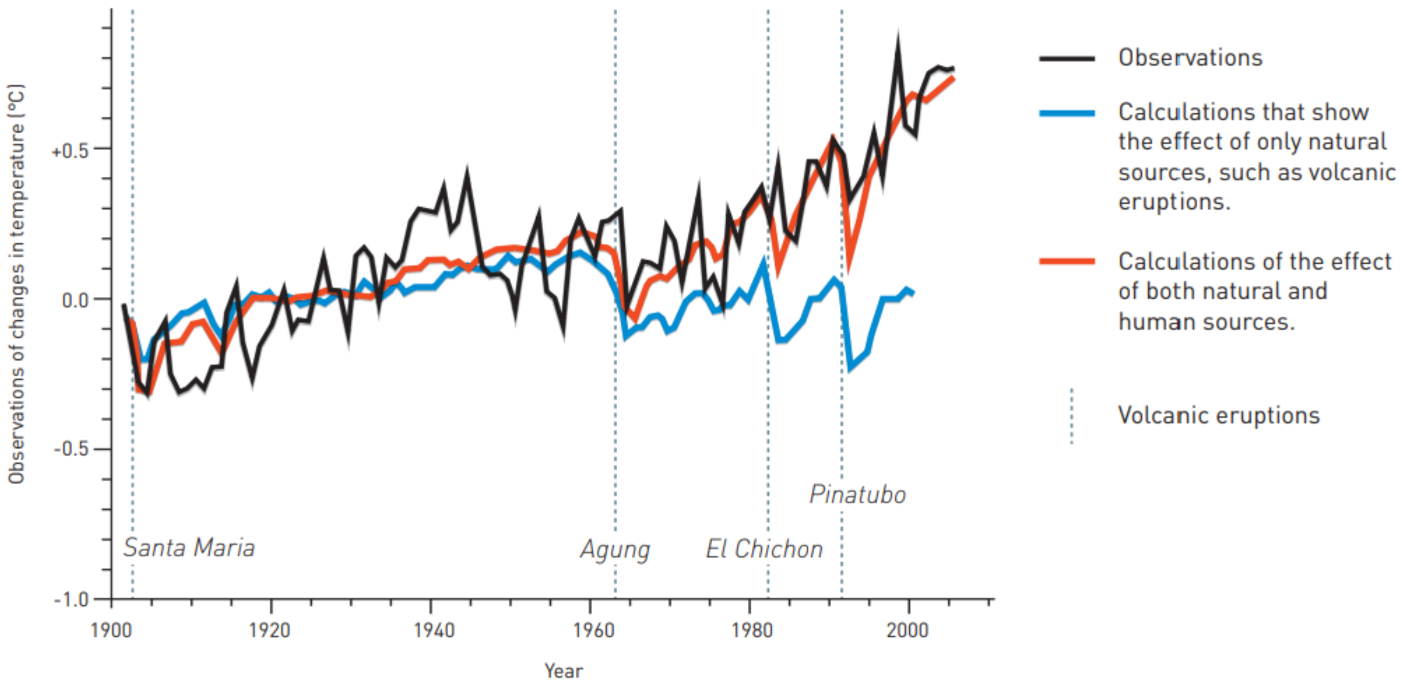
With higher CO_2 levels …



Improving the predictions of Earth‘s surface temperature

Nobel prize 2021 - *”for groundbreaking contributions to our understanding of complex physical systems”*

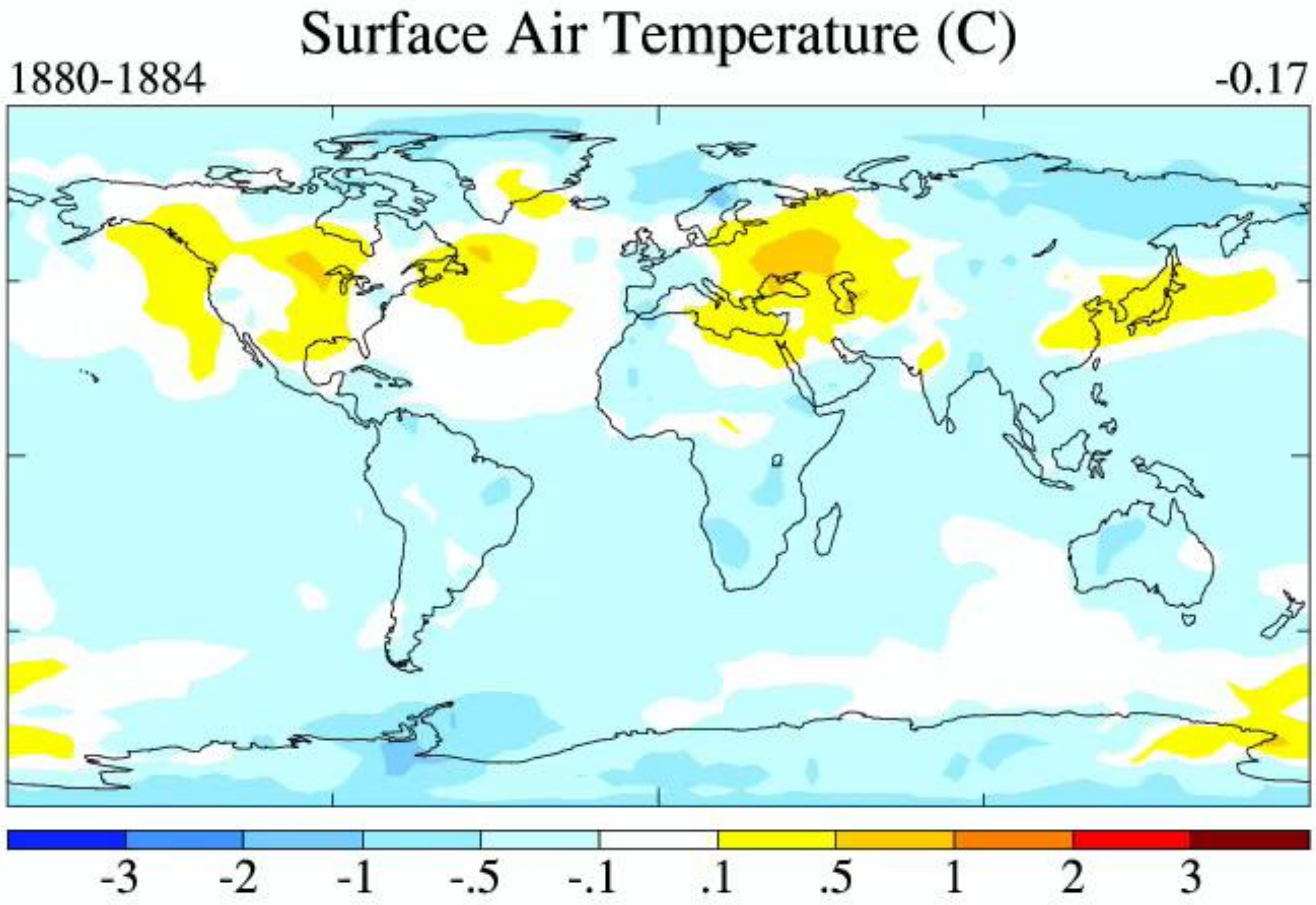
- Around 1980: Klaus Hasselmann: Building a stochastic climate model
  - How to make reliable climate predictions, while weather forecasts are notoriously imprecise in the long-term?
  - Treatment of weather as rapidly changing noise
  - Human impact separated out by properties of noise and signals → Unique fingerprints
    → Solar radiation
    → Volcanic particles
    → Levels of greenhouse gases
    → Human impact



https://www.nobelprize.org/prizes/physics/2021/popular-information/

Climate simulation

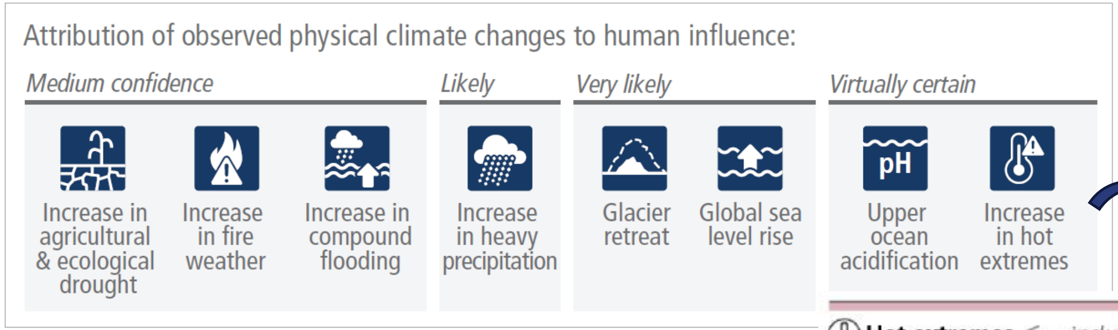
In 2007

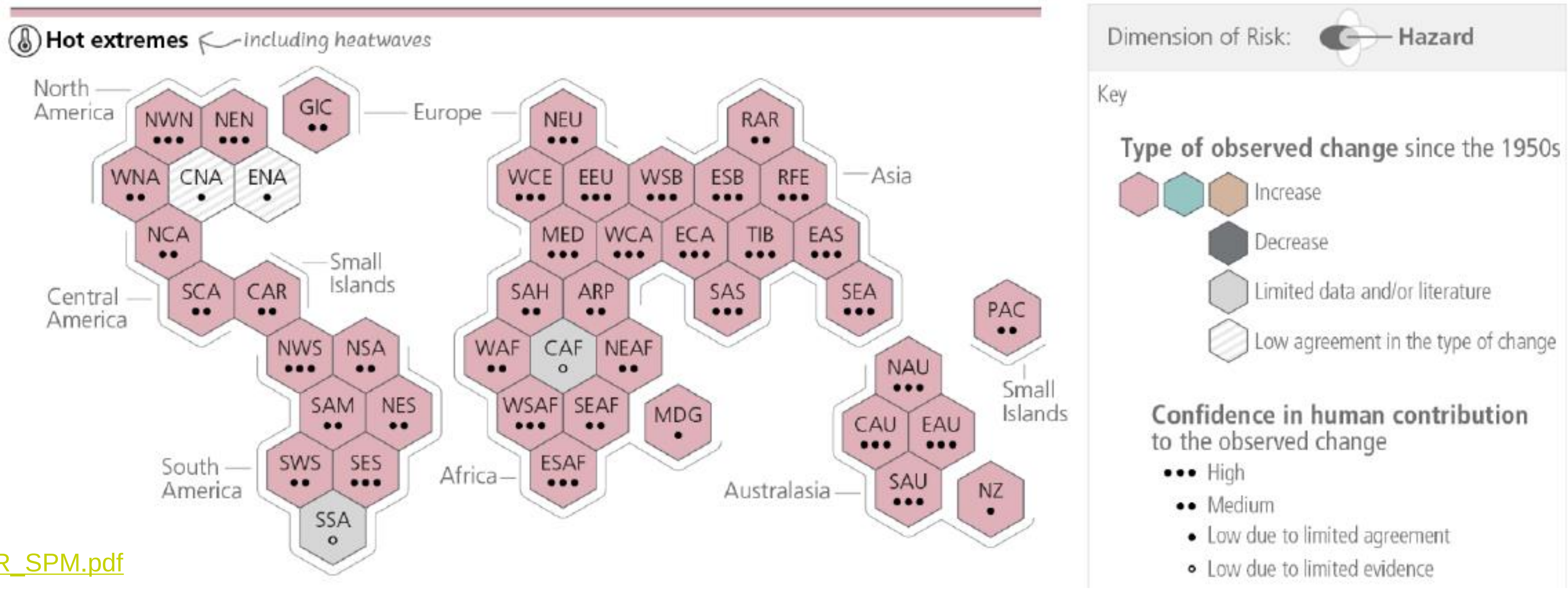


https://data.giss.nasa.gov/modelE/sc07/

Impacts attributed to human influence

Driven by changes in multiple physical climate conditions



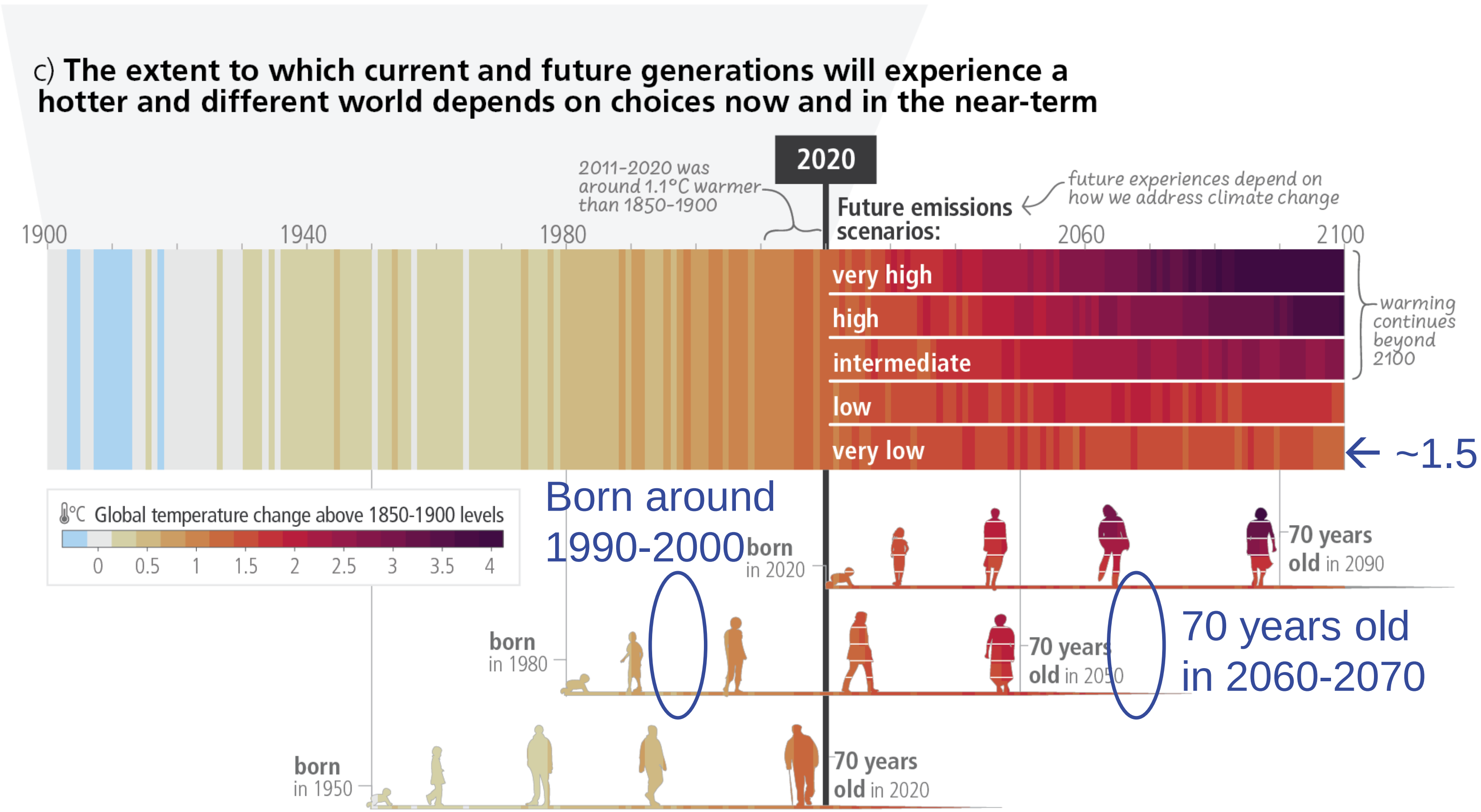


→ Increase in hot extremes well established almost everywhere in the world to result from human influence

https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf
https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

Generations affected by climate change

Considering the different scenarios



← ~1.5˚C increase only

Born around 1990-2000

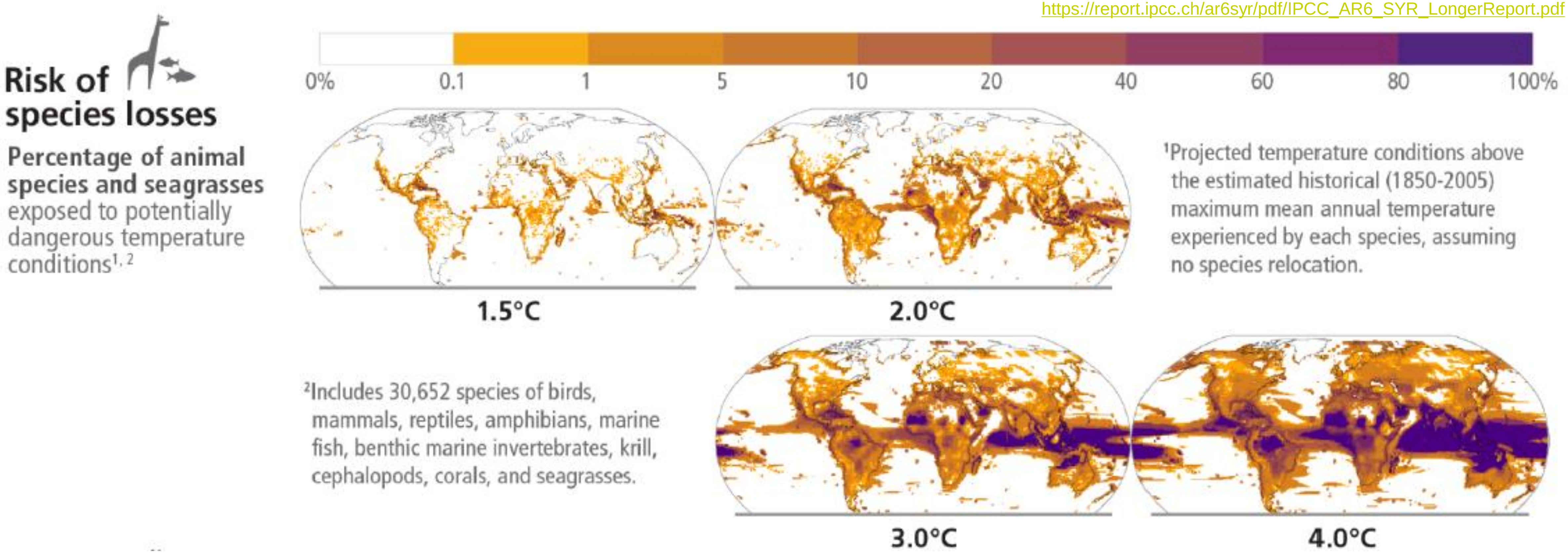
70 years old in 2060-2070

→ Majority of today's audience will live to see the consequences of our actions

https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Risk of species losses

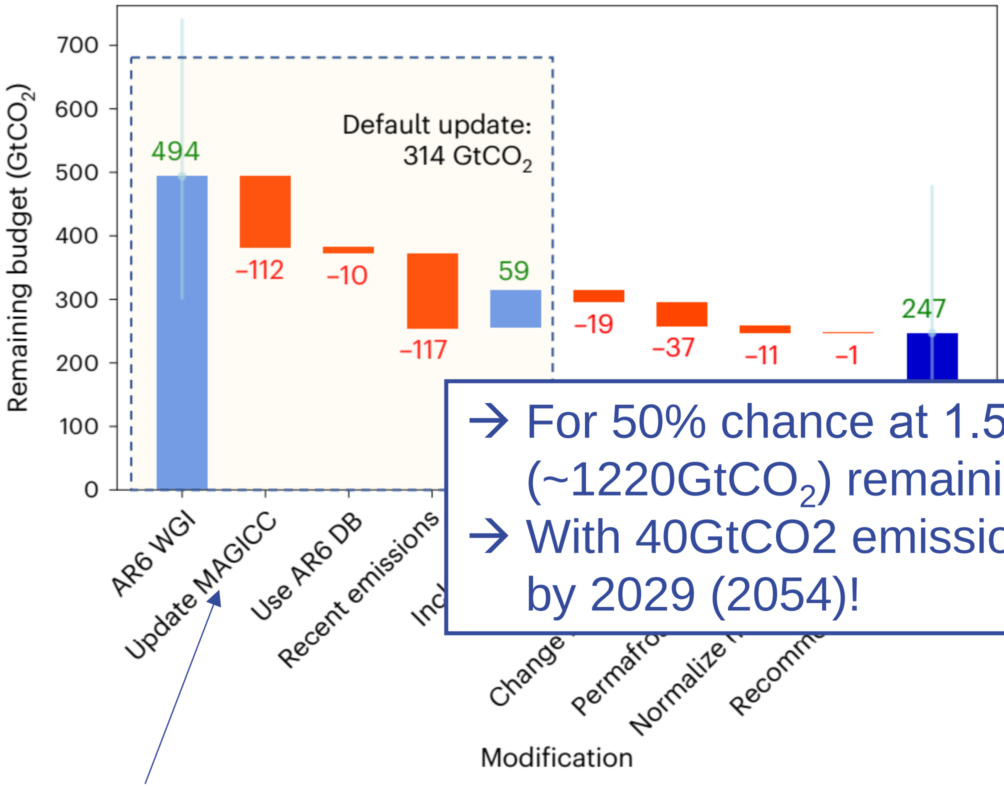
https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf



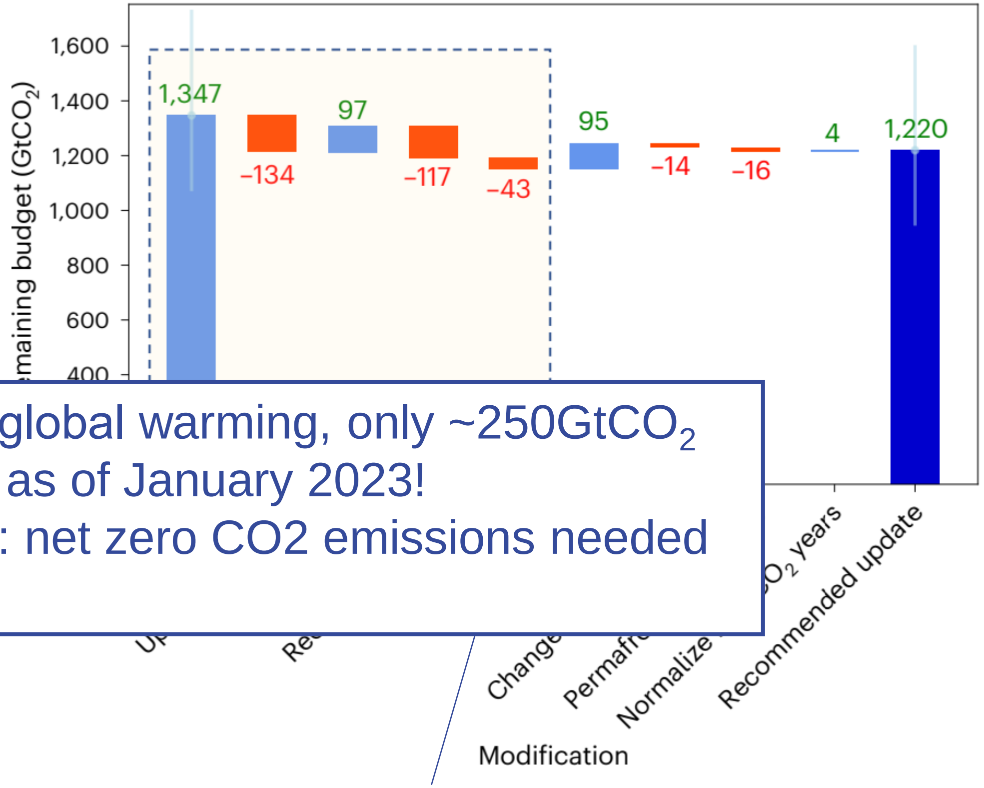
Study of remaining carbon budget newer than IPPC report

Lamboll et. Al., Nature Climate Change 2023

For 1.5˚C increase max



For 2.0˚C increase max



→ For 50% chance at 1.5˚C (2.0˚C) global warming, only ~250$GtCO_2$ (~1220$GtCO_2$) remaining budget, as of January 2023!

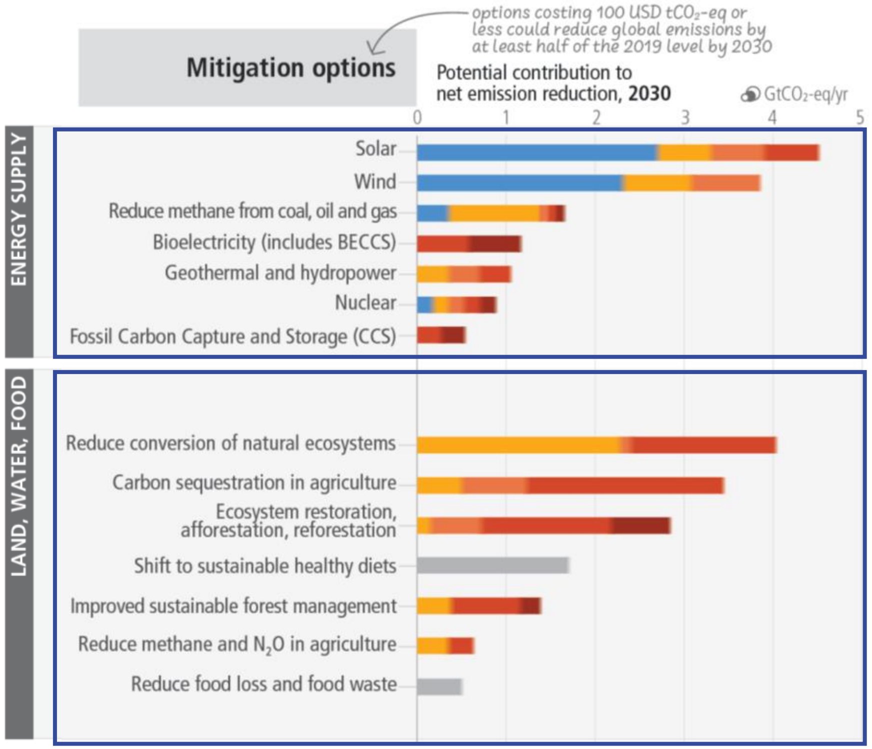
→ With 40GtCO2 emissions in 2022: net zero CO2 emissions needed by 2029 (2054)!

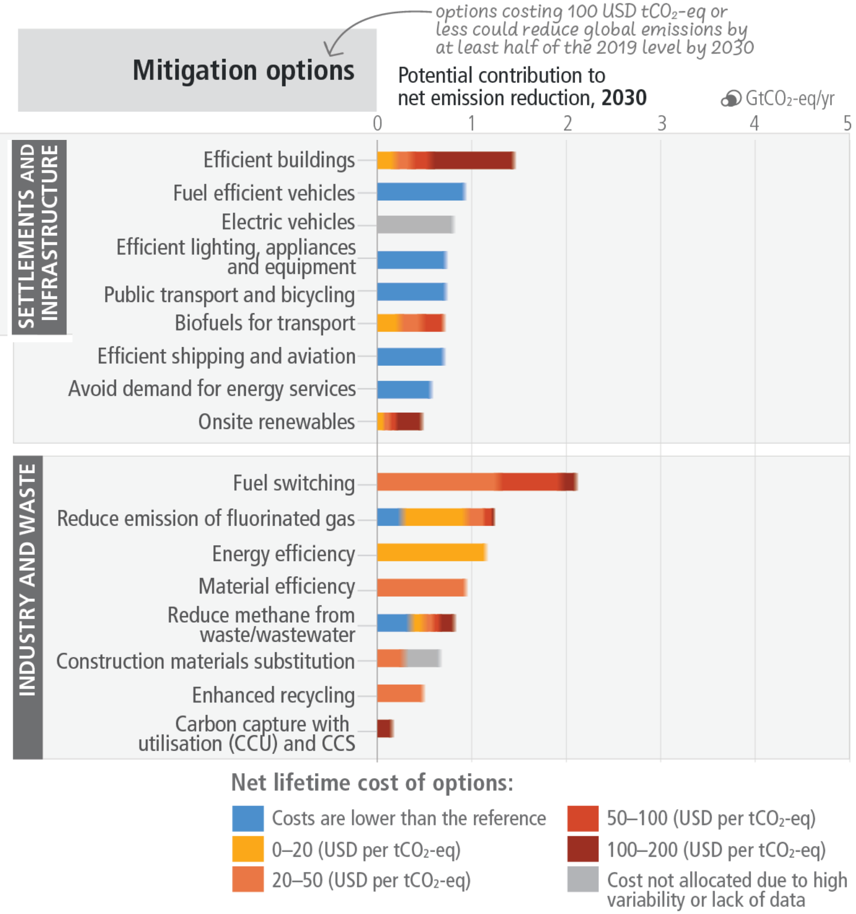
Reduced complexity climate model for non-CO_2 emissions

Additional simple climate model calibrated for use in the latest IPCC report

IPCC report: Mitigation potentials

Cost estimates of different mitigation options



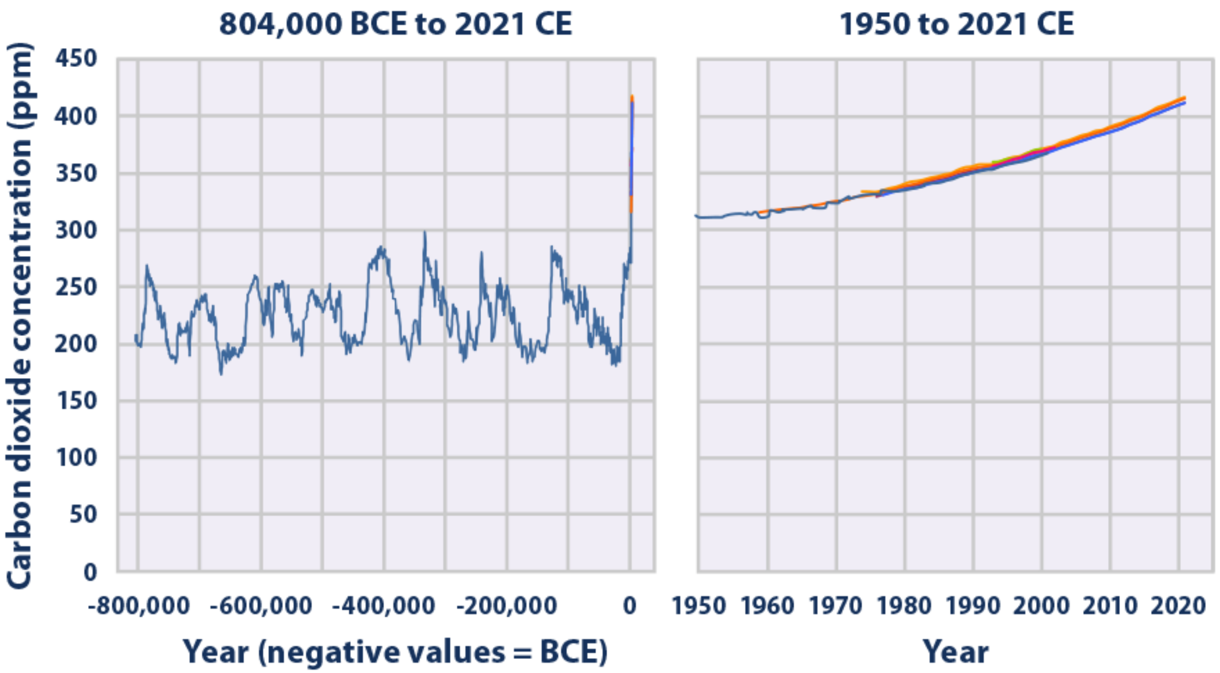


→ Energy and food production with large impacts
→ Take a closer look at these two next

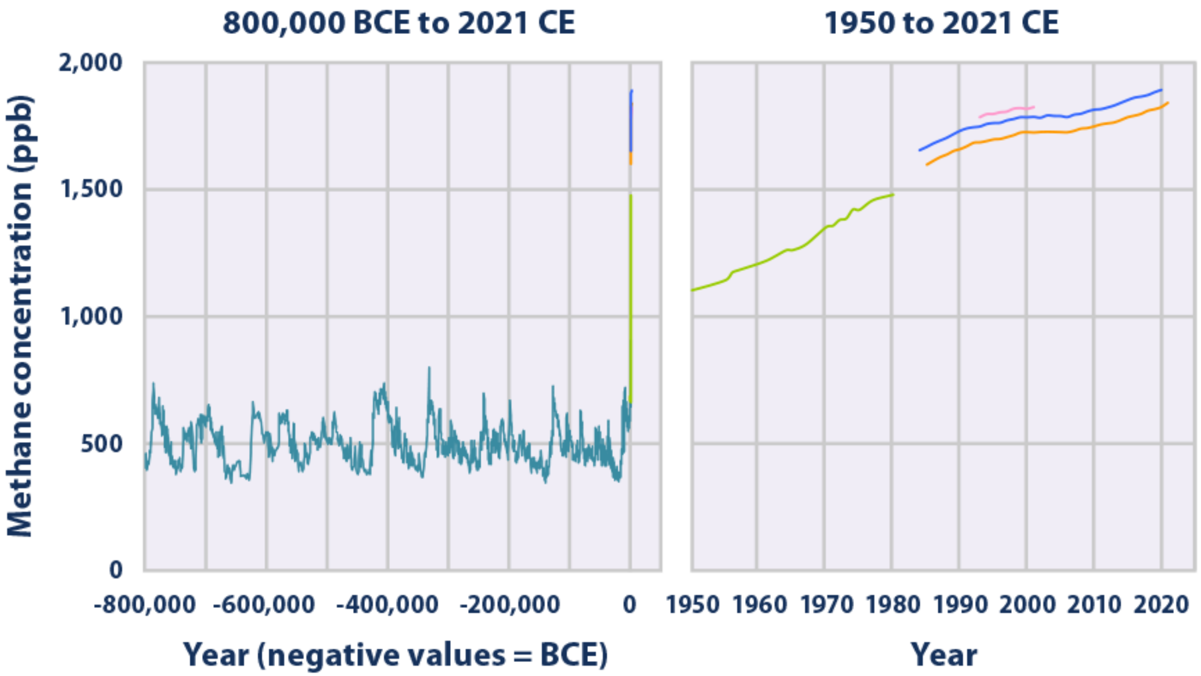
https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

Greenhouse gases

CO2



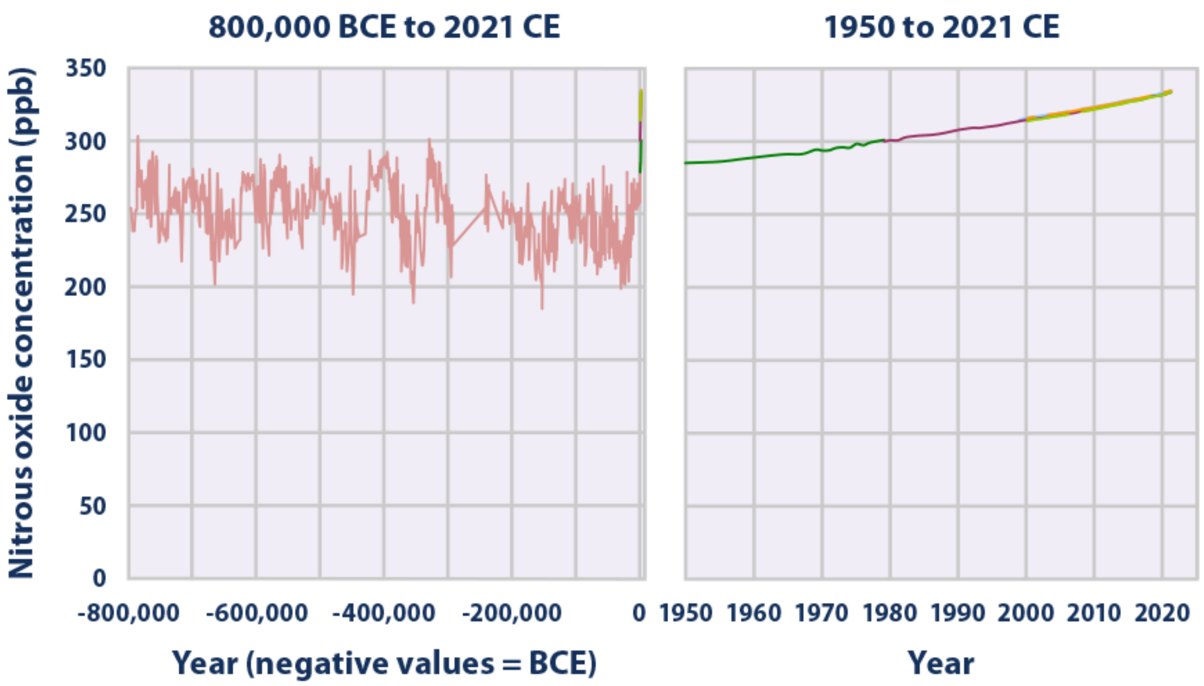
Methane



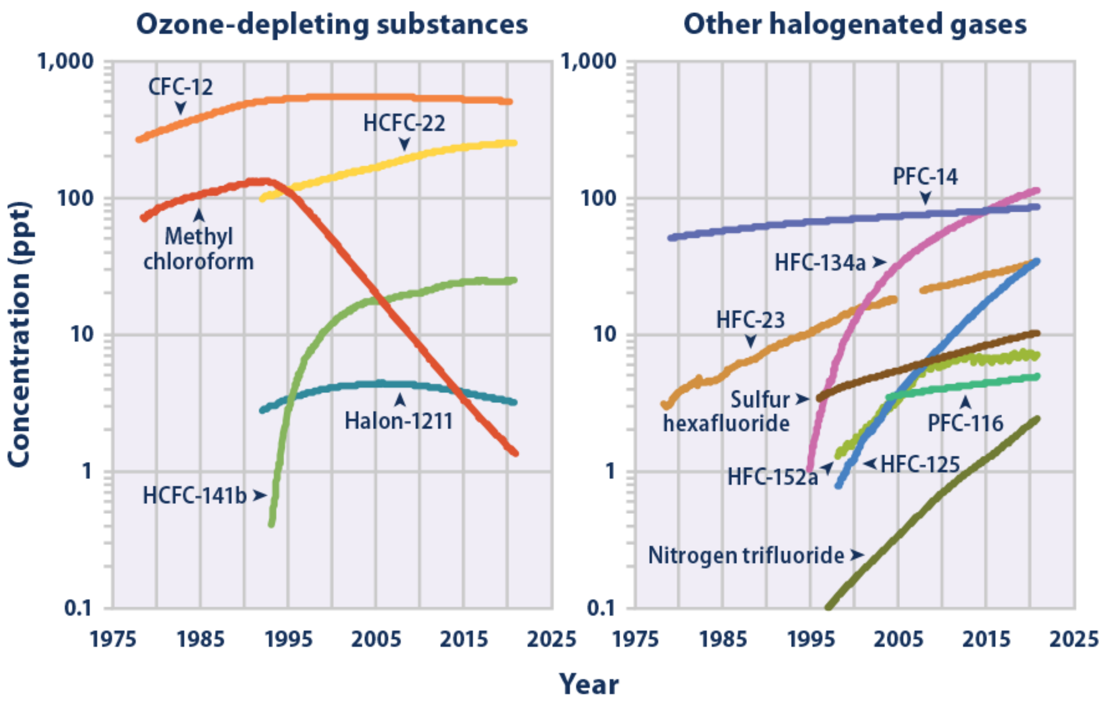
https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

Greenhouse gases

Nitrous Oxide



Halogenated Gases



https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

Gas emissions as main driver of CO_2 footprint

Global warming potential (GWP) of gas

- How much energy will be absorbed by 1t of the gas in 100 (500) years compared to 1t of CO_2?

Gases used at CERN

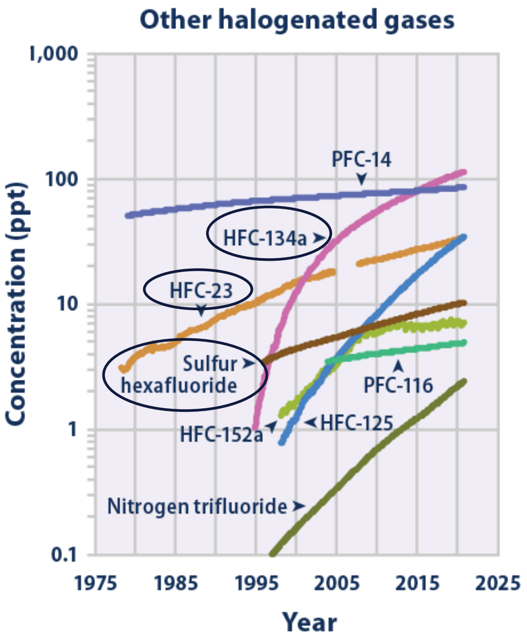
- Have significant GWPs > 1000 or even 10000

GROUP	GASES	tCO_2e 2019	tCO_2e 2020	GWPs (100 years) (*)	GWPs (500 years) (*)
PFC	CF_4, C_2F_6, C_3F_8, C_4F_{10}, C_6F_{14}	43277	45678	7390, 12200, 8830, 8860, 9300	11200, 18200, 12500, 12500, 13300
HFC	CHF_3 (HFC-23), $C_2H_2F_4$ (HFC-134a), HFC-404a, HFC-407c, HFC-410a, HFC R-422D, HFC-507	17540	34899	14800, 1430	12000, 435
Other F-gases	SF_6, NOVEC, R1234ze	3840	5377	22800	32600
CO_2	CO_2	13512	13046	1	
TOTAL SCOPE 1		78169	98997		

Note: C_4H_{10} = Butane: GWP(100years) = 4.0 (*)

→ Already very small leaks have a major impact

(*) https://www.ipcc.ch/site/assets/uploads/2018/02/ar4-wg1-chapter2-1.pdf

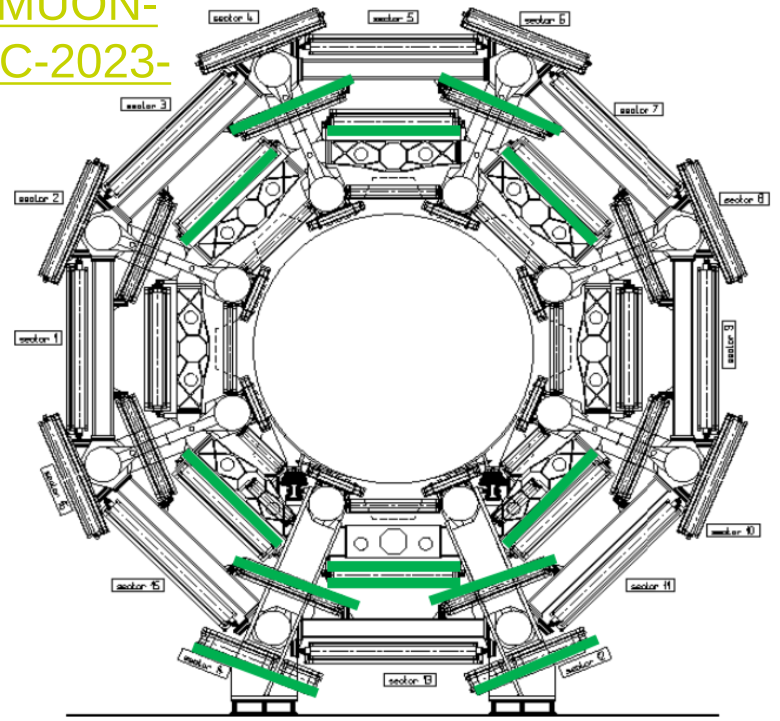


→ Circled gases are also used at CERN

https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

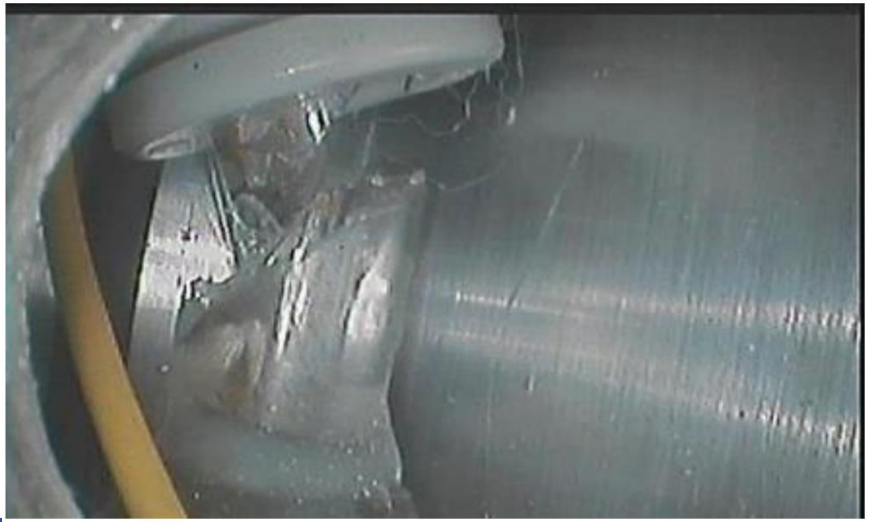
Hands-on: Fixing leaks in ATLAS

ATL-MUON-PROC-2023-001



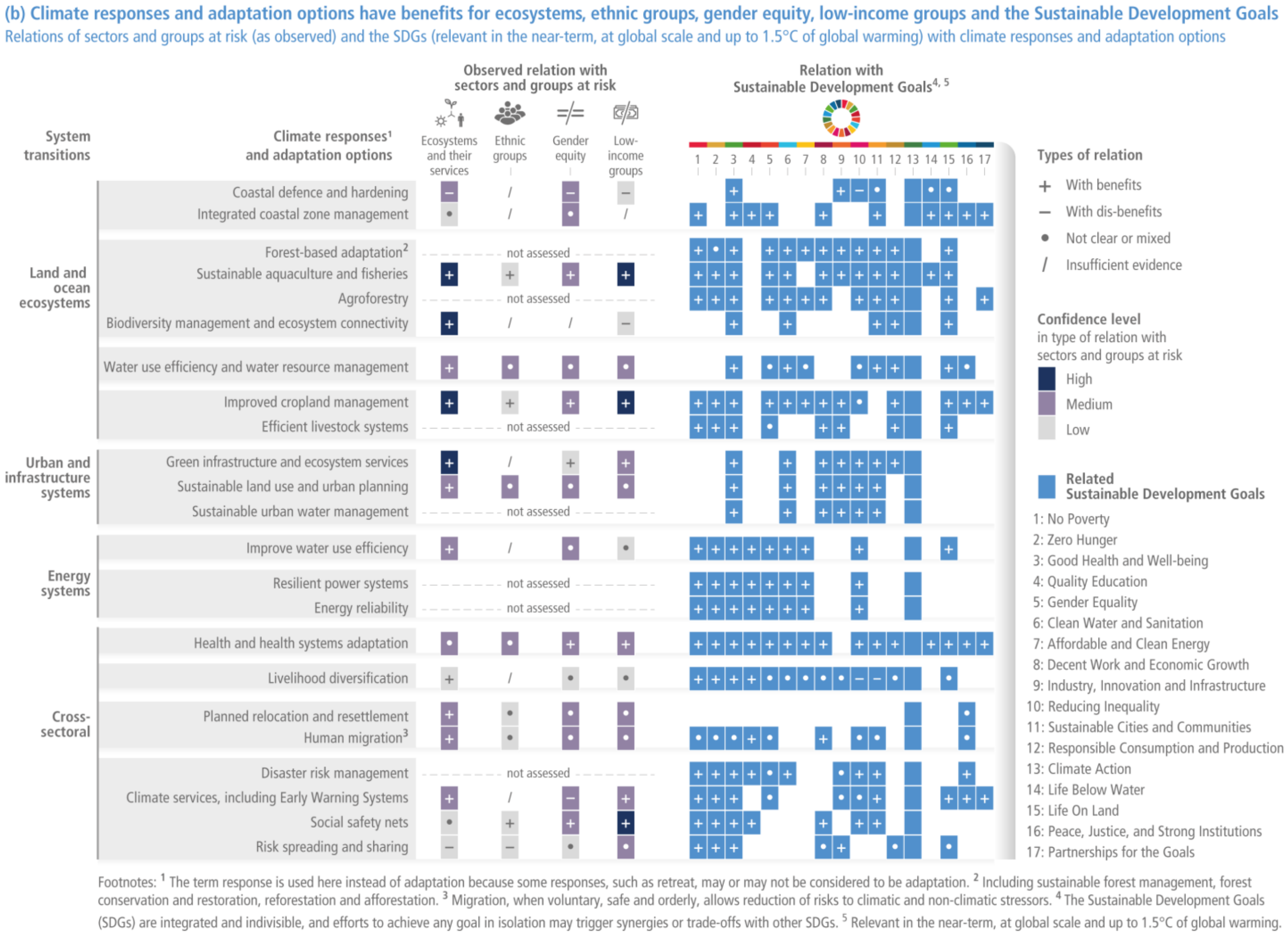
Gas leaks in the ATLAS muon system

- Plastic connectors of the gas flow lines to the Resistive Plate Chambers (RPCs) → Tend to develop leaks
- 8000 potentially leaky connection points in ATLAS RPCs → Often difficult to reach → Break faster than can be repaired
- Gas mixture in RPCs: $C_2H_2F_4$+iso-C_4H_{10}+SF_6 → GWP ~ 1400 → Studies with replacing gas mixture not trivial!
  - 1l of RPC mixture ~ 5-6kg CO_2-eq. (*) → Loss of ~1000l/h → If constant throughout the year: ~44k-53k tCO_2-eq./year emissions → ~20-23% of 2018 emissions by CERN (own estimate)
- Campaign in ATLAS with new repair technique and teams of volunteers to fix leaks during end-of-year shutdowns
  - First test campaign early 2023: Reduction of RPC losses by 23%!
  - Needs follow-up in further shutdowns



(*) Based on main component: $C_2F_2F_4$ → Conversion of l to kg → Convert to CO2-eq. by multiplying with GWP for HFC-134(a)

Relation to SDGs

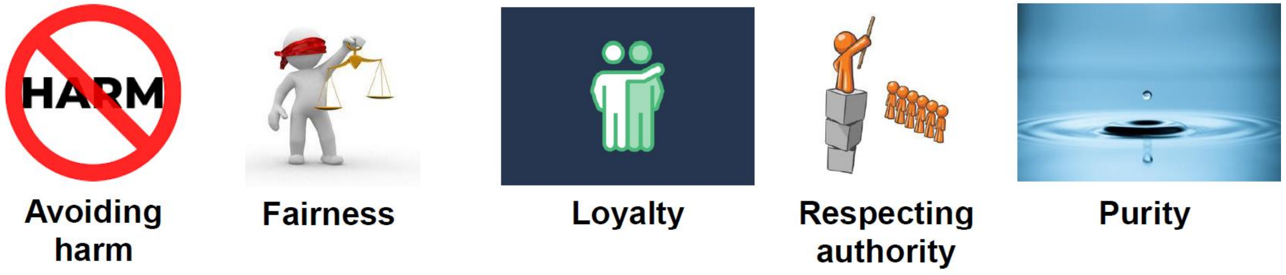


What barriers exist for getting involved?

Pyschological barriers to climate action

Source: [Presentation by Prof. Brosch,]() at [CERN and the environment]() workshop, Oct 2022

Example: Moral barrier
→ Broad categories of morality



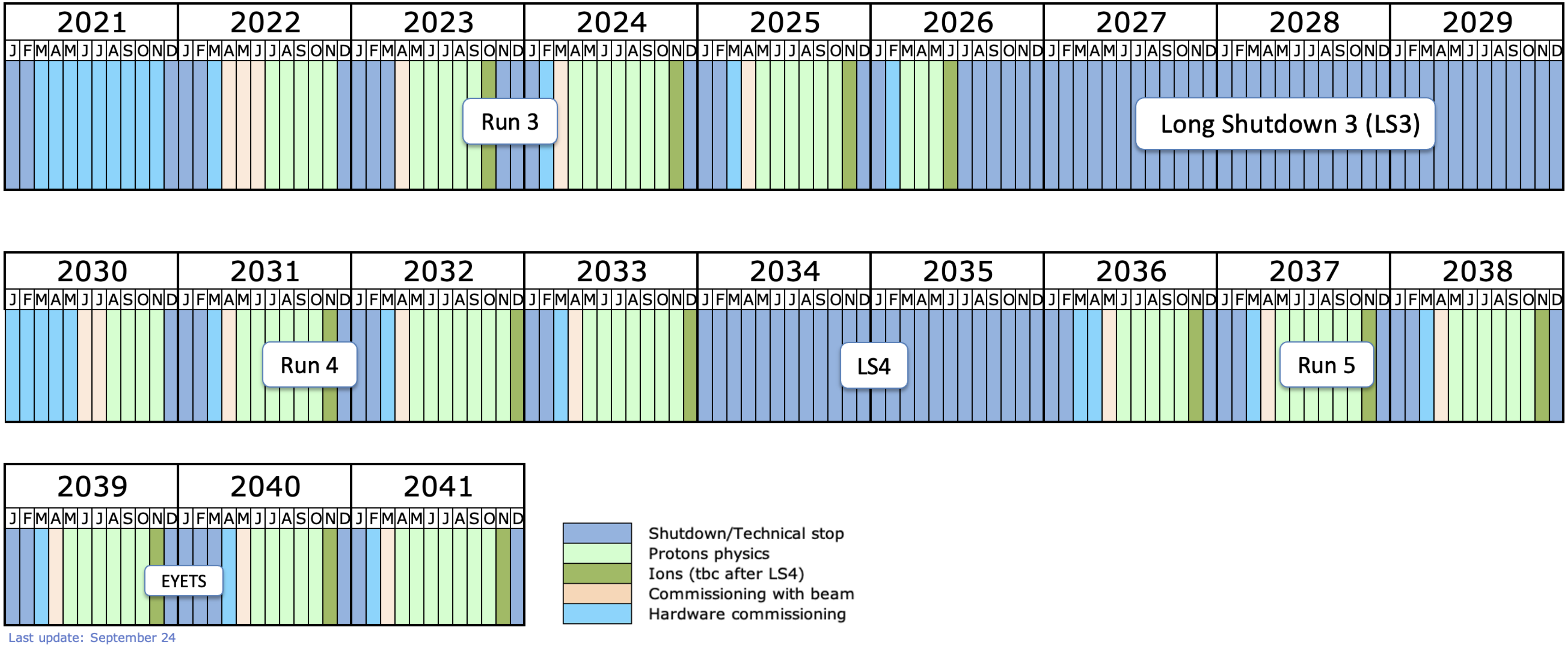
→ Most often addressed by climate crisis communication
→ Leaves out a huge part of the population

Left-leaning ⟷ Right-leaning
Political spectrum

→ Need to adjust messaging to include entire population!

HL-LHC operation schedule

Start of HL-LHC with Run 4



Details on travel

Long-distance buses vs. Long-distance trains

Source of Emission	Emission Factor	
Long-distance Buses	0.031	$kgCO_2e/km$
Long-distance Trains	0.031	$kgCO_2e/km$
Personal Car	0.17	$kgCO_2e/km$
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Transcontinental Flights	170	$kgCO_2e/h$
Hotel room	12	$kgCO_2e/night$
Event venue	0.19	$kgCO_2e/day$

→ Why the same emission factor?

- By chance! → For UBA numbers from 2022 (https://www.umweltbundesamt.de/themen/verkehr/emissionsdaten)
  - Tank-to-wheel (TTW) for buses much higher than for trains, i.e. running a bus has higher emissions than a train
  - Compensated by well-to-tank (WTT) for trains and infrastructure, i.e. the extraction of the fuel (using German conventional electricity mix) + the building of the infrastructure (rails, etc.) more costly for trains than for buses