universität freiburg

Know your footprint - in High Energy Physics and related fields

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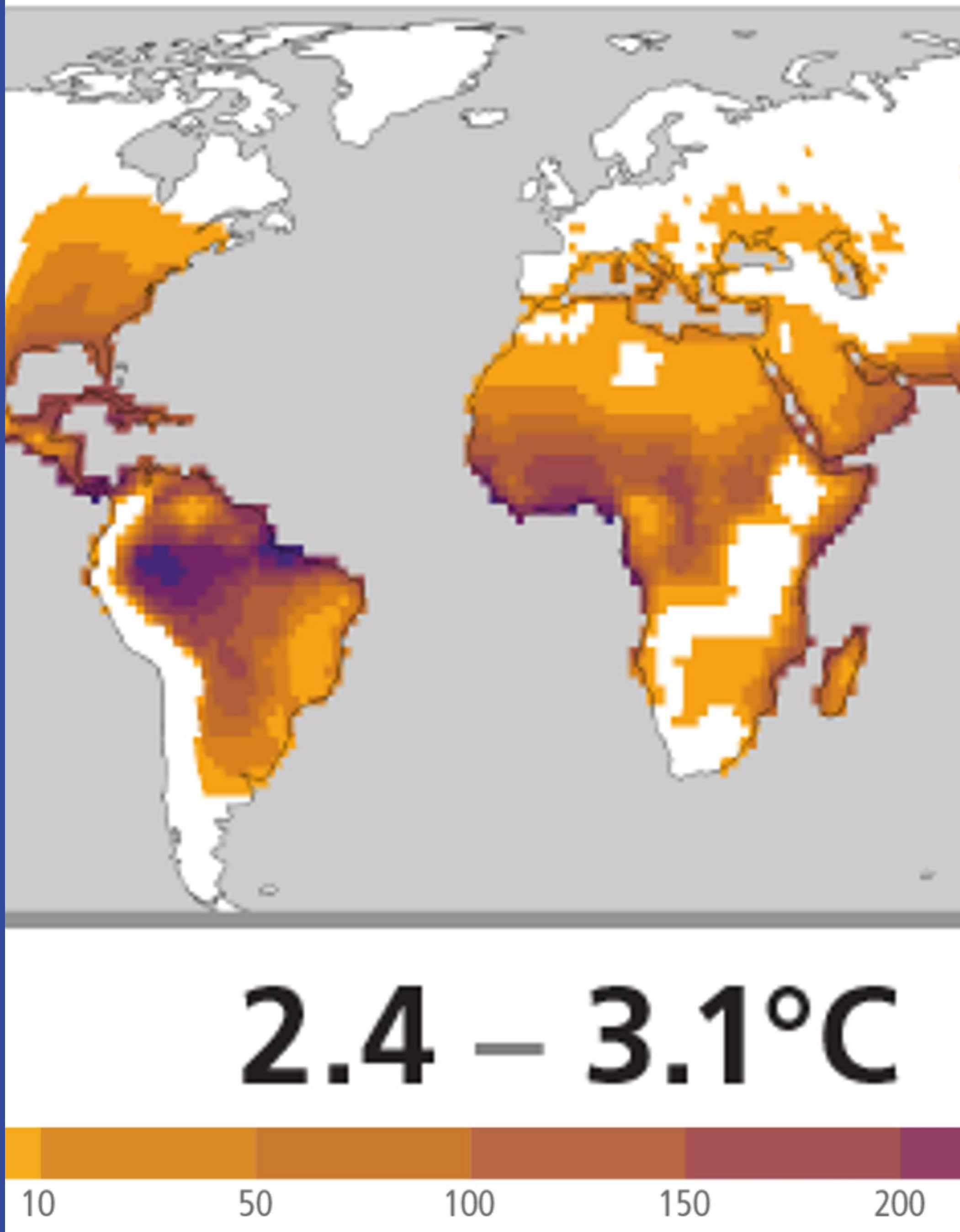
On behalf of the Know-your-footprint team

KCETA Colloqium
Karlsruhe, 2 May 2024



CO_2 in atmosphere vs. ground temperature

First publication on relationship of atmospheric CO_2 and ground temperature

- 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	7·9	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	8·0	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	8·0	7·9	7·0	7·9	7·7	9·5	9·4	8·6	9·2	9·17
40	−3·4	−3·4	−3·2	−3·3	−3·32	[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	6·7	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	6·6	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	6·4	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	6·6	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	6·7	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 >100 years ago

- Confirmed and refined since then in many studies (e.g. Nobel prize 2021)

Guess the concentration of CO_2 in the atmosphere

How high is the CO_2 content in the atmosphere currently, when the mean over the last 800k years was around 225 ppm?

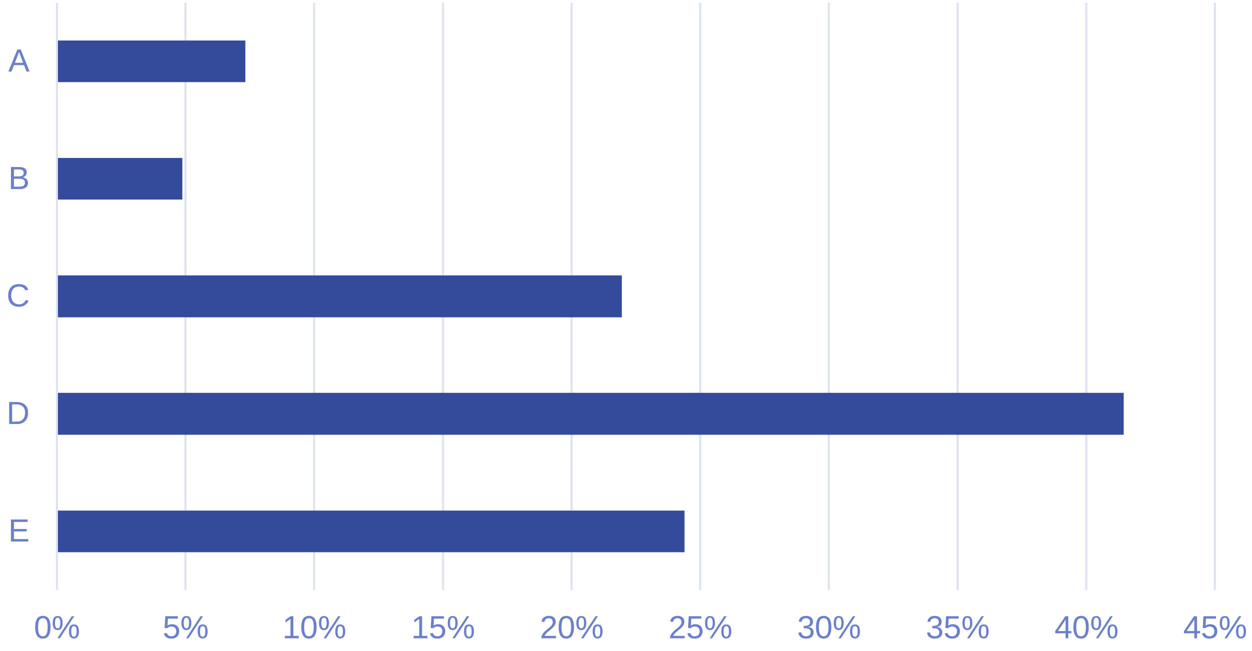
A) Between 250-300 ppm

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

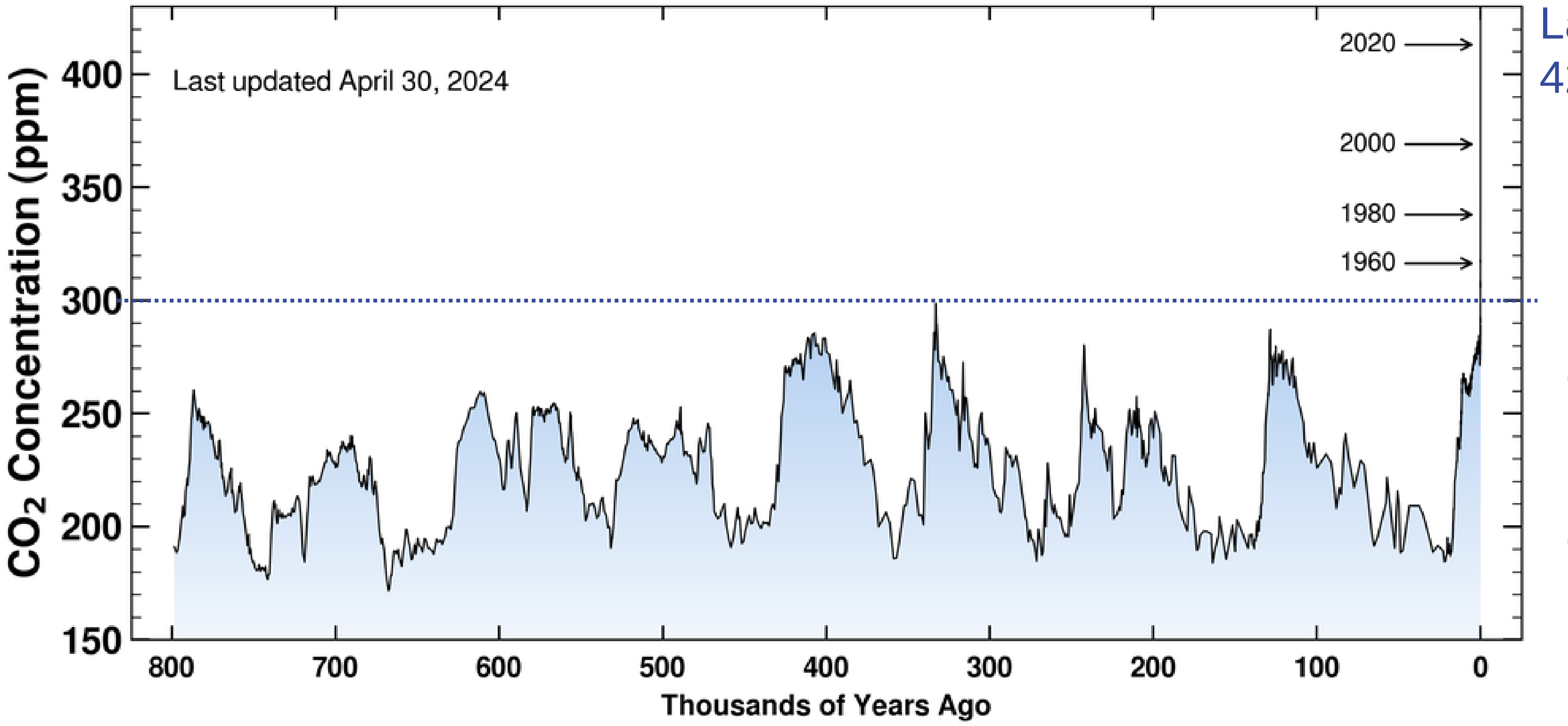
Reset Vote

ID = valerie.lang@physik.uni-freiburg.de
41 participants / Poll closed

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:
425.57ppm

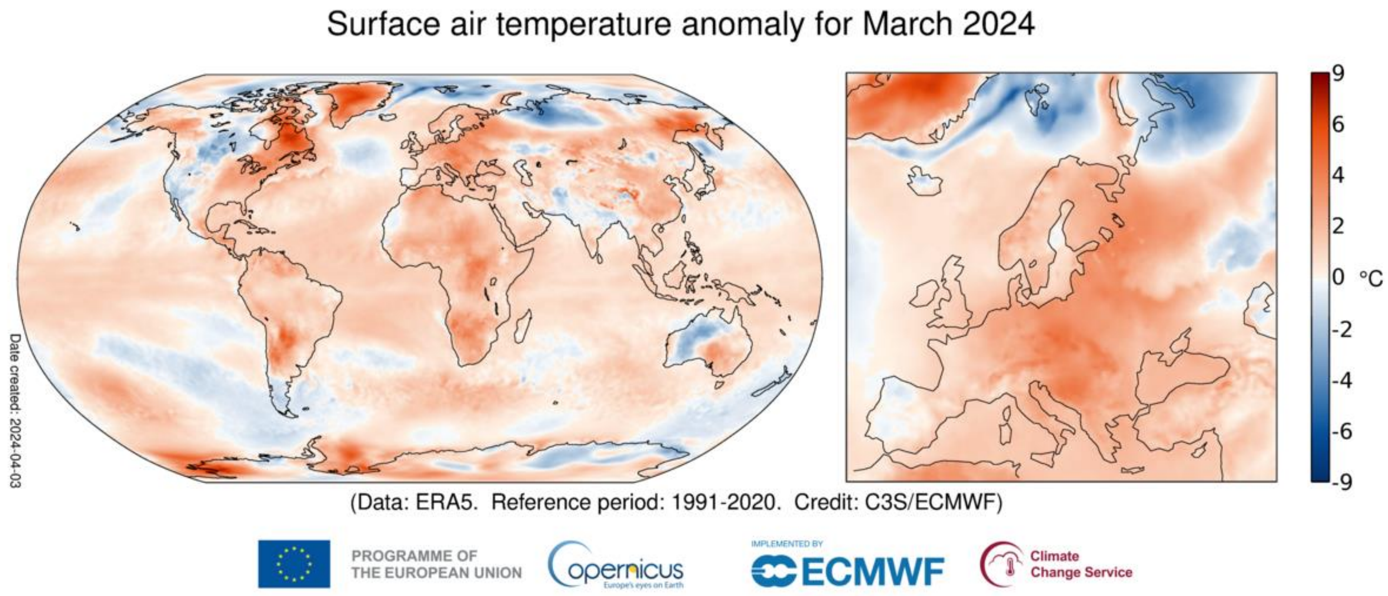
→ Reaching ~40% more than highest point in past 800k years

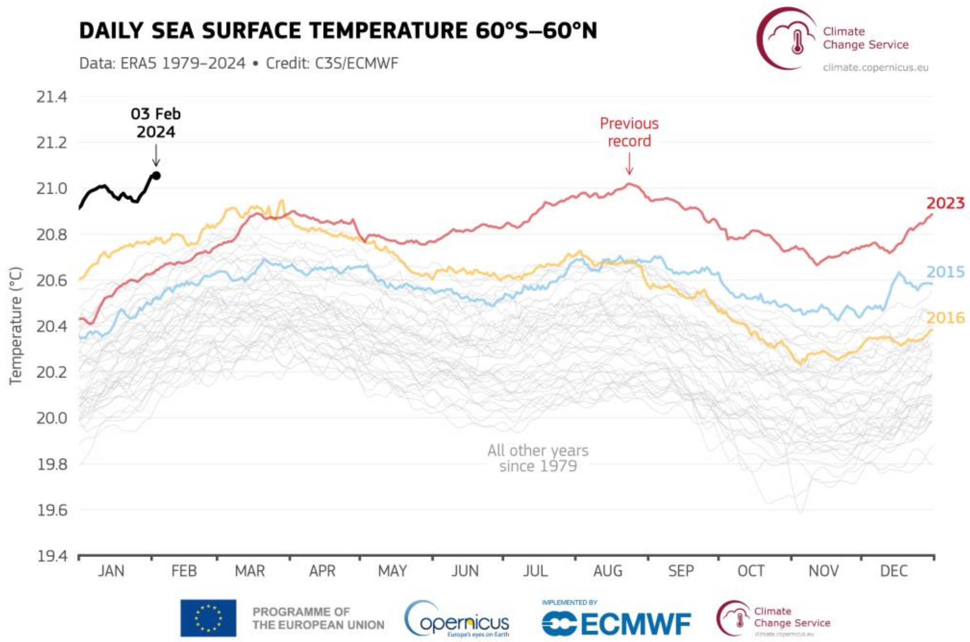
→ Far outside of variations during last 800k years

https://keelingcurve.ucsd.edu

Where are we now? – In terms of ground temperature

Data from Copernicus Satellite → March 2024 warmer than any previous March





- Over the last 12 months (from March 2024):
  - Average global temperature: 1.58˚C above 1850-1900 level
  - Average European temperature: 2.0˚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-march-2024

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

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/

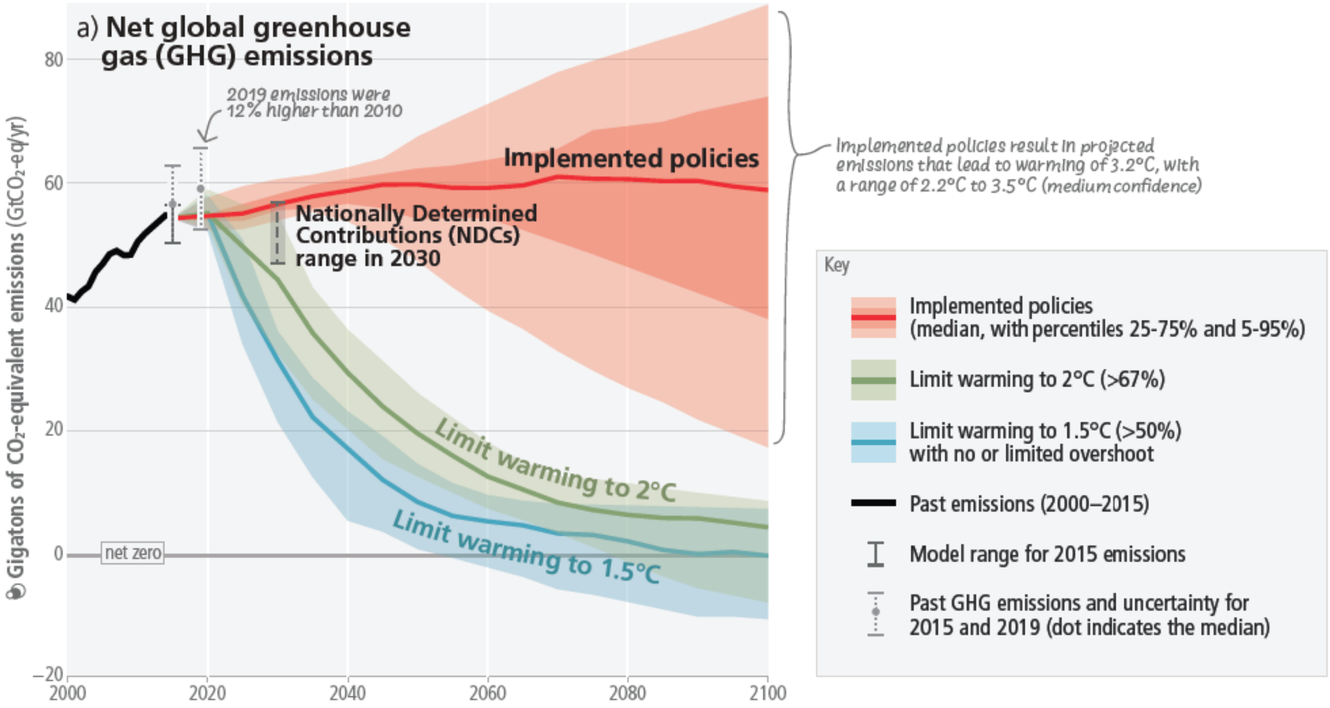
https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

Where are we heading?

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

Different scenarios in IPPC report analysed

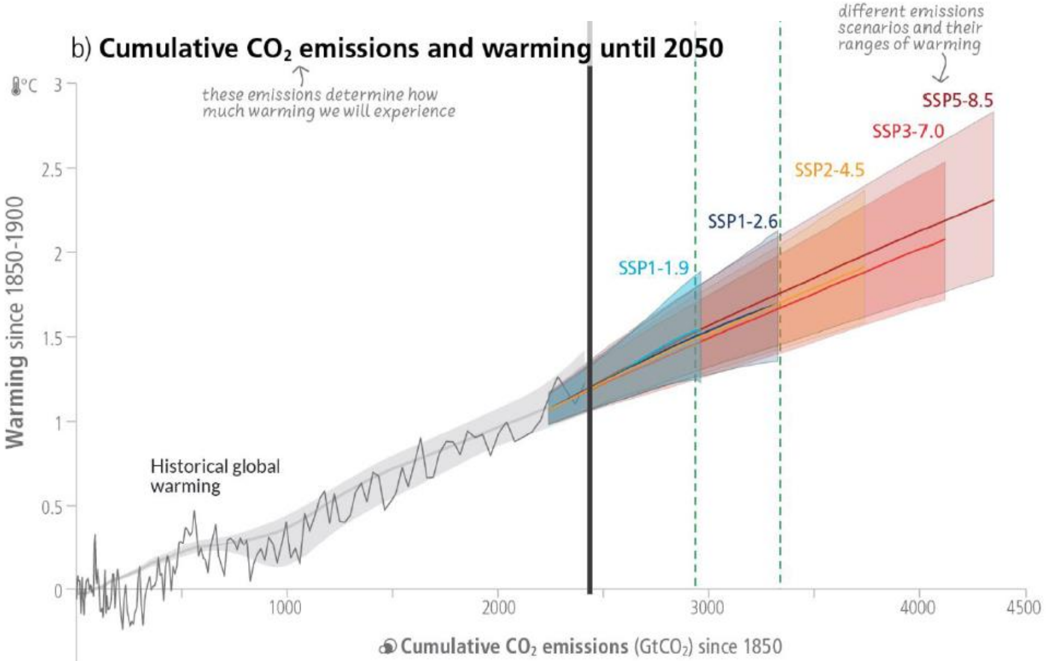
- Factoring (lack of) mitigation actions, policies, etc.



→ Currently implemented policies lead to warming of 3.2˚C

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

→ Why? Cumulative CO_2 emissions count



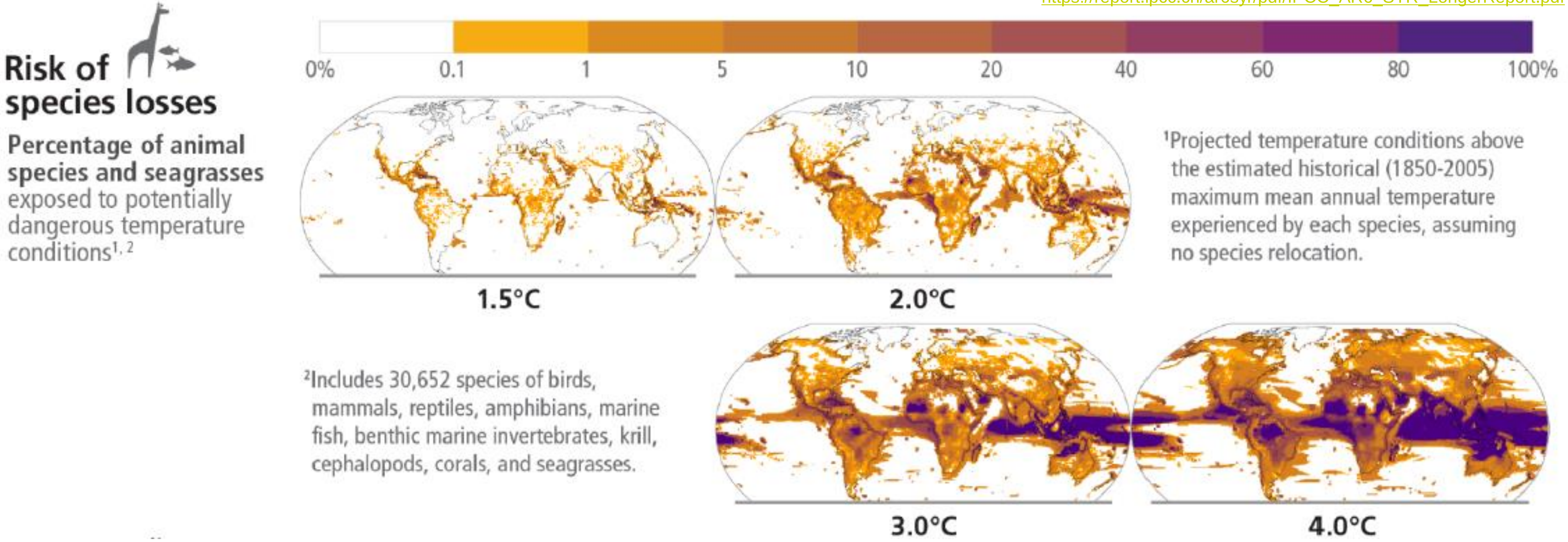
https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf

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

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

Risk of species losses

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

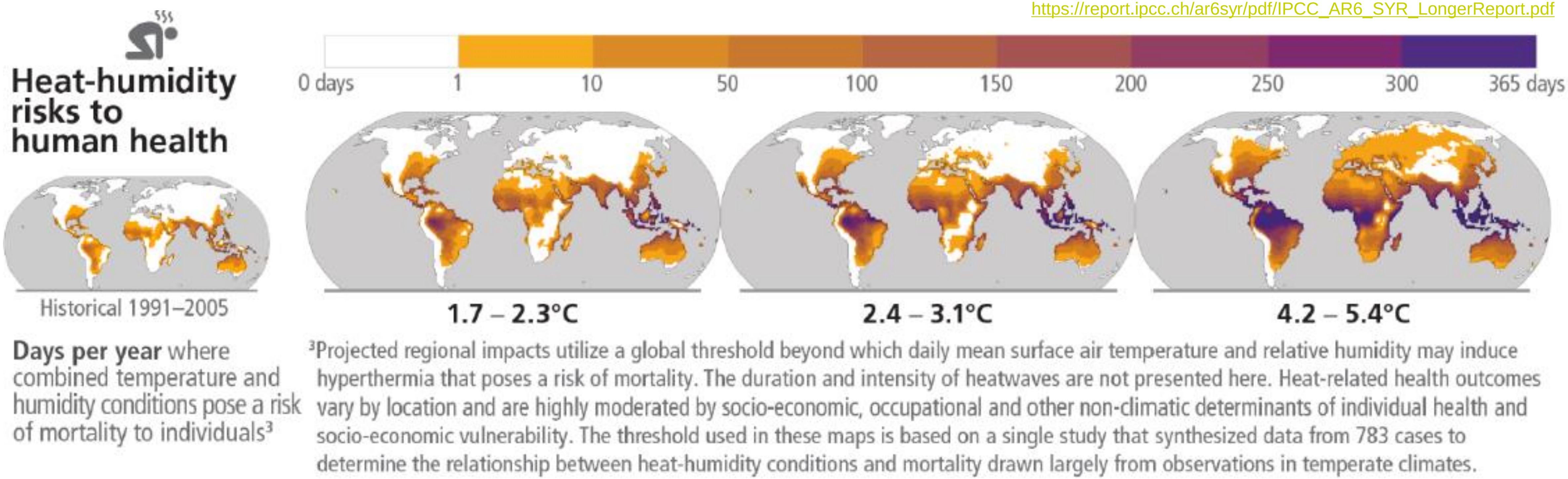


→ Huge biodiversity losses for > 2.0˚C global warming → Currently heading for 3.2˚C increase

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

Risk of human mortality from heat-humidity

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



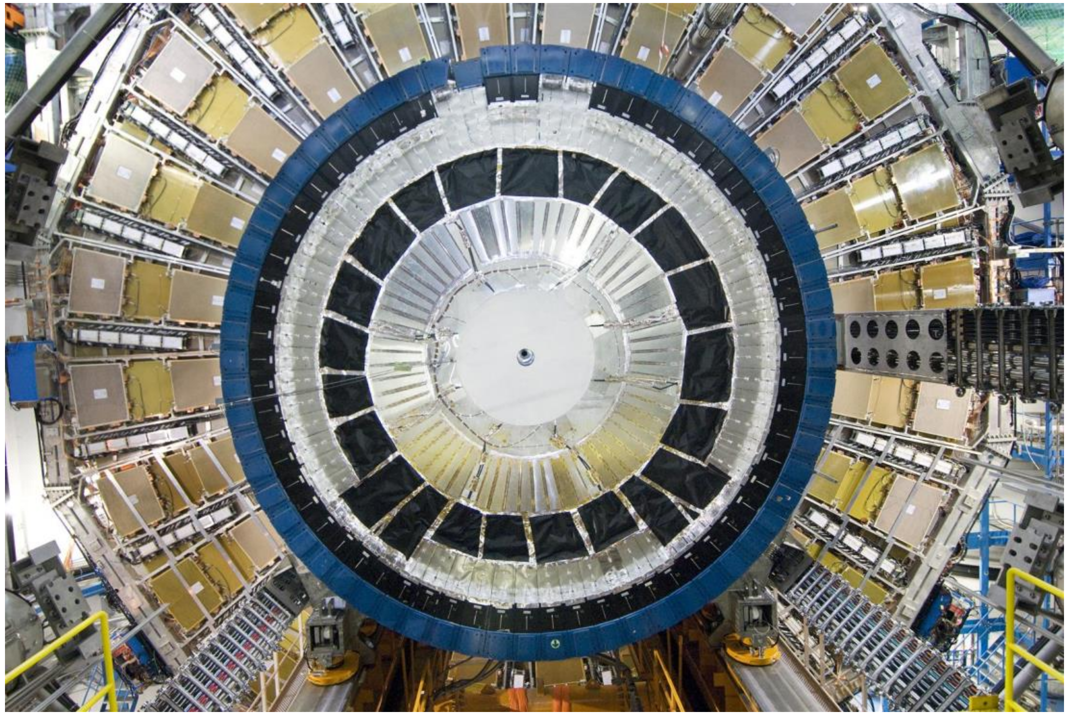
→ Current aim of 3.2˚C means: Large parts of the Earth become nearly uninhabitable due to risk of hyperthermia

→ Hyperthermia means: Failure of heat-regulating mechanisms to deal with heat from the environment

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
    → Has become apparent with first environmental reports e.g. by CERN
- But: How large 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

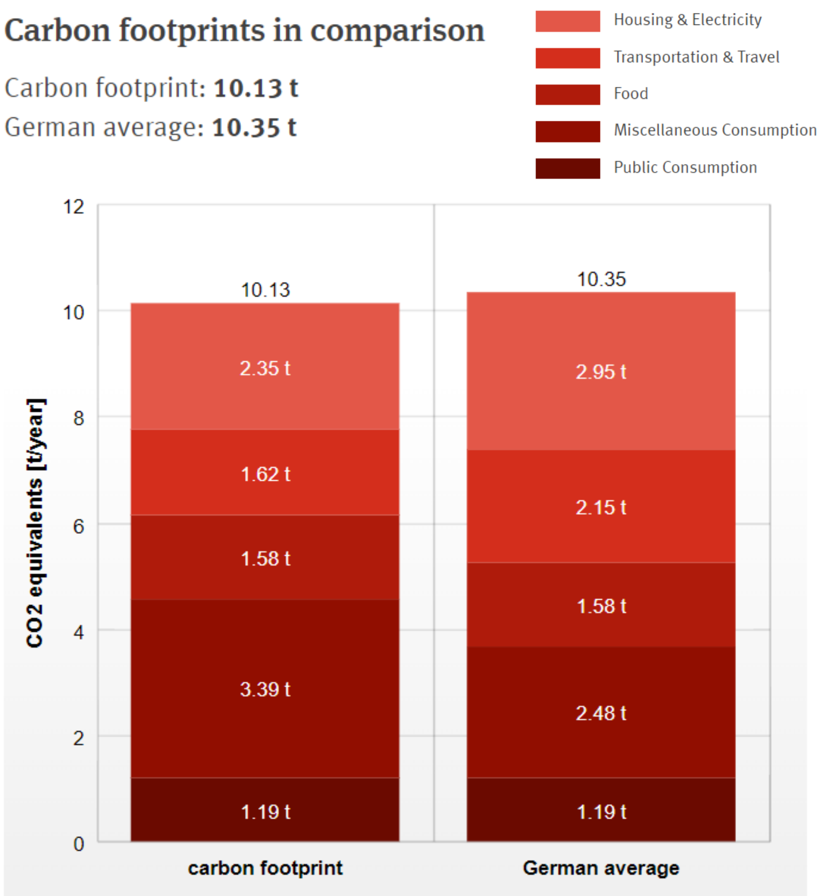
- Private emissions in Germany – refer to carbon calculator by German Federal Environment Agency (UBA): https://uba.co2-rechner.de/en_GB/ → Permission from UBA ☺
- Professional emissions in HEP and related fields
  → Split into four categories:
  - Experiment
  - Institute
  - Computing
  - Travel

  → 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)

- Small HEP experiment (with green or conventional electricity) → Based on DESY electricity consumption
- Astrophysics experiment → Based on ESO annual report → Skip today

Definition of per-researcher footprint per year

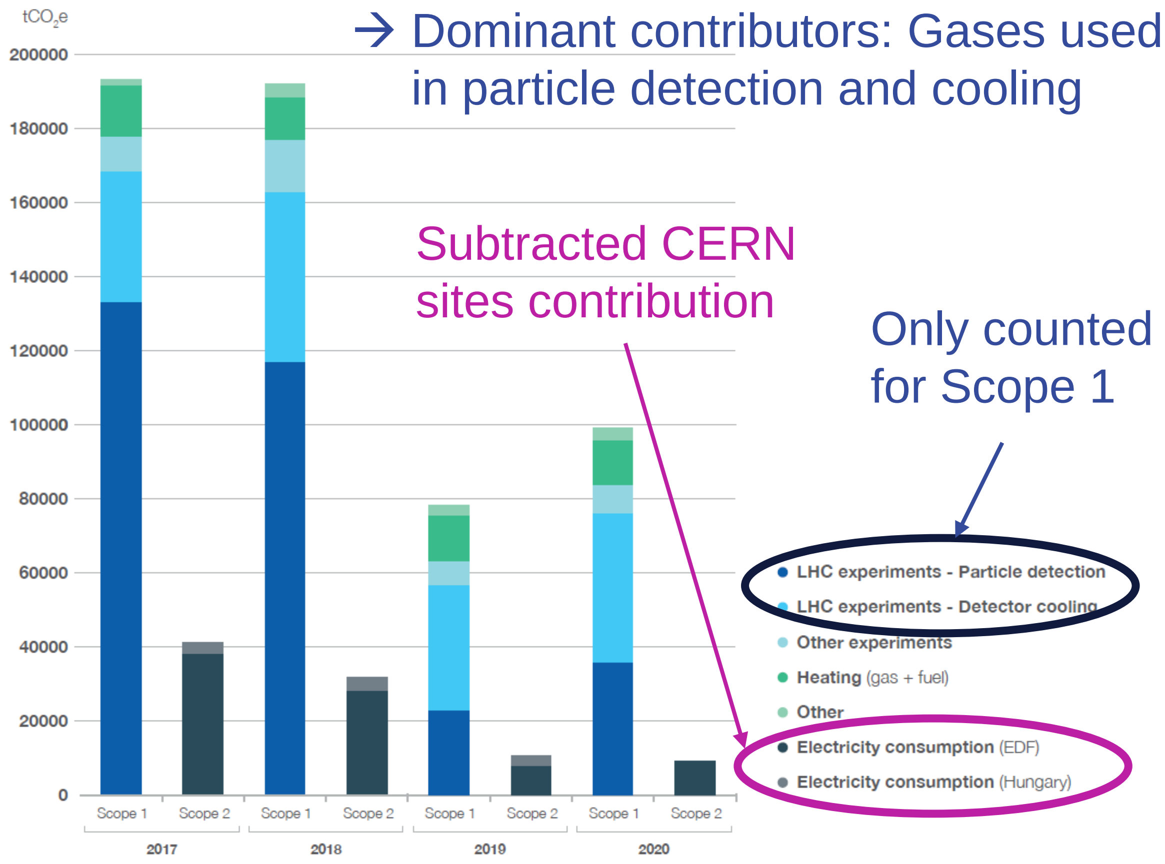
- Per-researcher footprint = (Total annual emissions from experiment) / (Number of experiment members)
  - Experiment members means: collaboration members or users (and operators) according to applicability
  - No consideration of indirect benefits for “the industry“ or “the public“ through “gained knowledge“
    → 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)

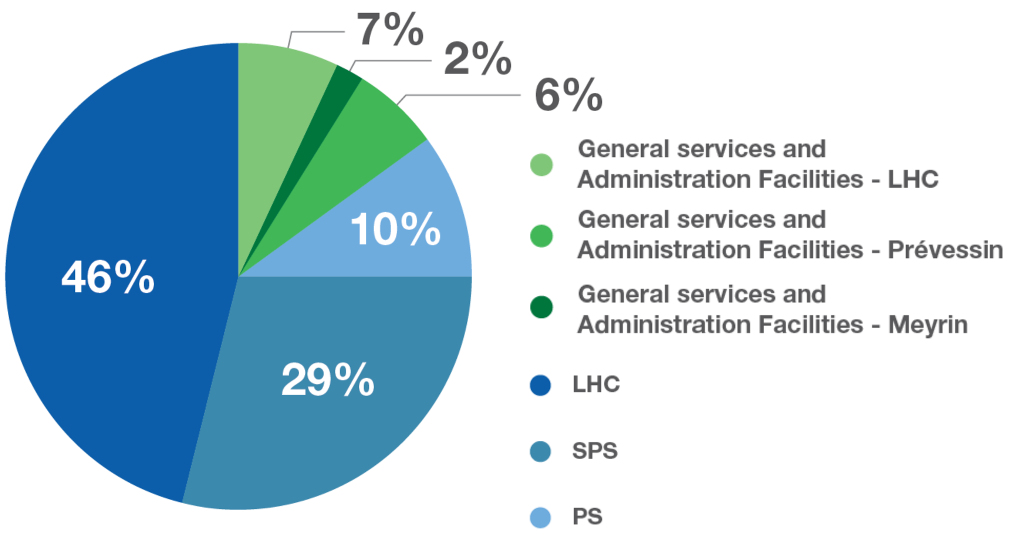
Assign emissions to large and small LHC experiments

- 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

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



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

Footprint of large and small LHC experiments (III)

Total emissions per experiment [tCO_2e]

	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

Members and emissions/member

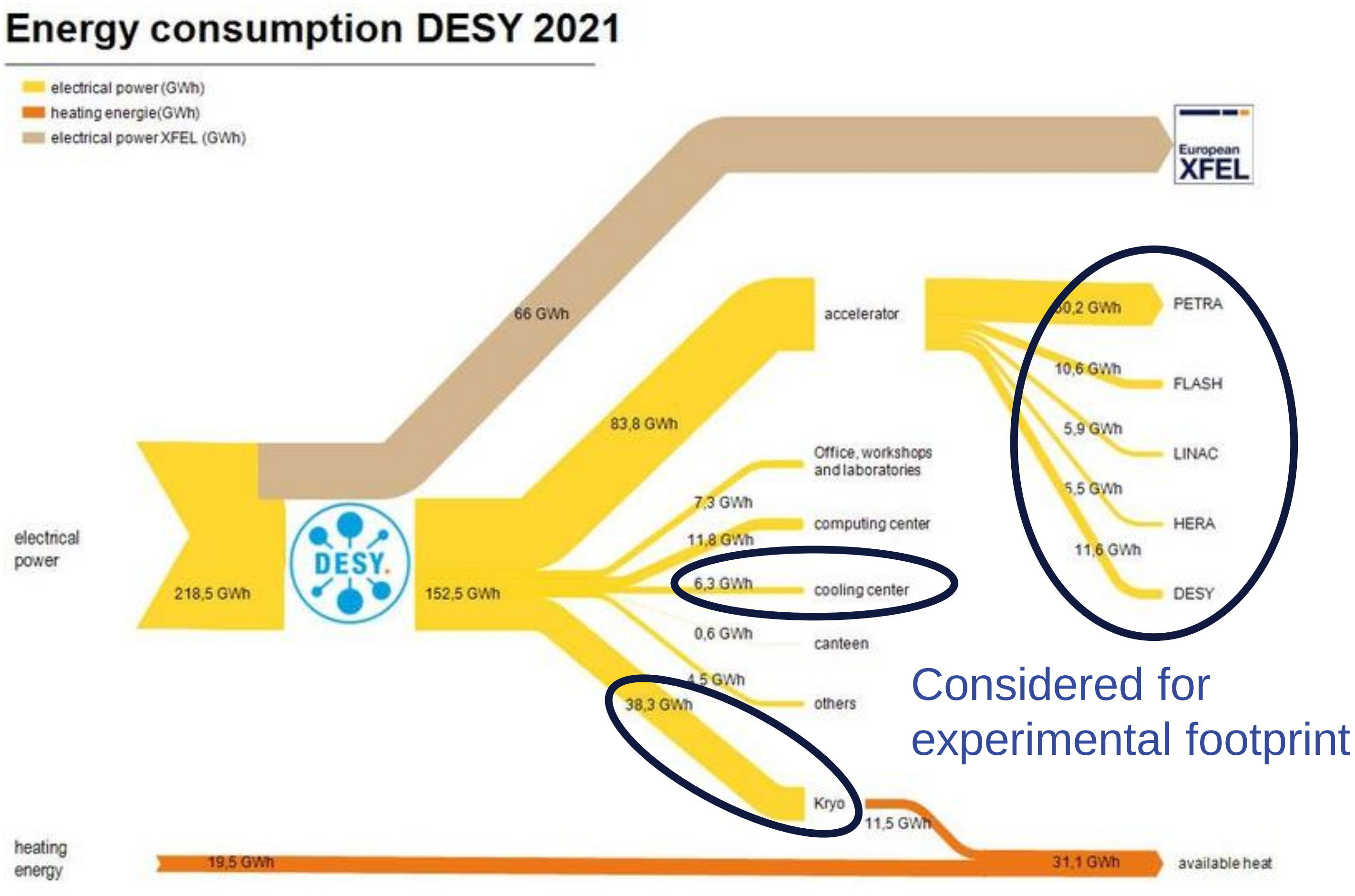
	Experiment	Members	Mean	Emissions
Small	ALICE	1968	1684	8.76 tCO_2e
	LHCb	1400		
Large	CMS	6288	6144	11.91 tCO_2e
	ATLAS	6000		

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

Footprint of a small HEP experiment

Footprint estimated based on DESY electricity consumption

- Available data from 2021
  - Obtained: 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 already >40% from wind, solar and water power → 416 gCO_2e/kWh (for comparison: gas: 572 gCO_2e/kWh, coal: 1167 gCO_2e/kWh)



→ 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

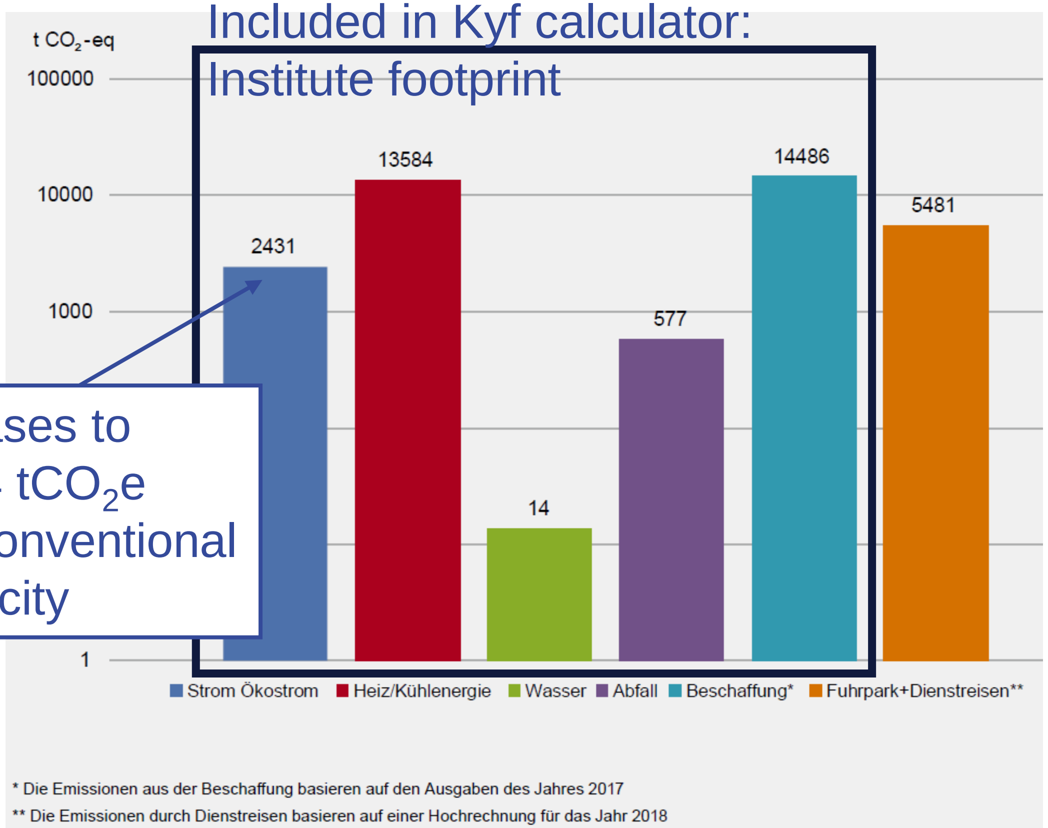
- (Total institute emissions) / (Effective number of institute members)
  - One year outside of COVID-19 pandemic considered as representative:
    → 2019 for University of Freiburg, 2022 for CERN
- Reason for choice of University of Freiburg vs. Leibniz University Hannover as default university footprint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

Footprint of a university - Freiburg

Emissions with green electricity

- Exclude emissions from travel here

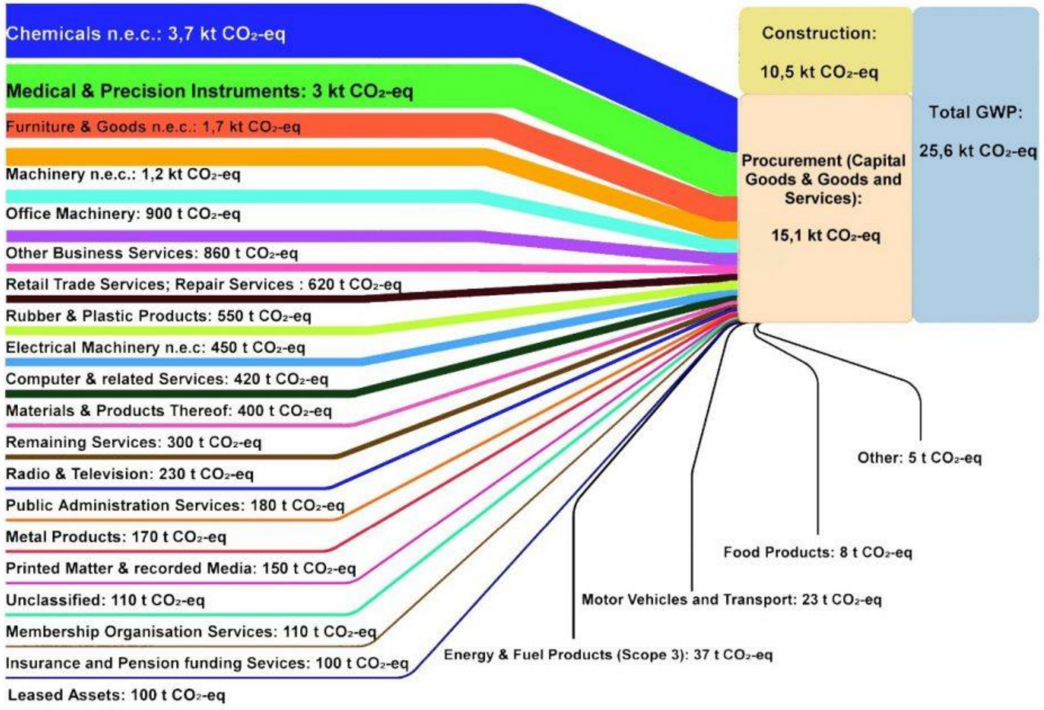
Included in Kyf calculator:
Institute footprint



Increases to 19224 tCO_2e with conventional electricity

Procurement → Dominating contributor

- Based on procurement data from 2017

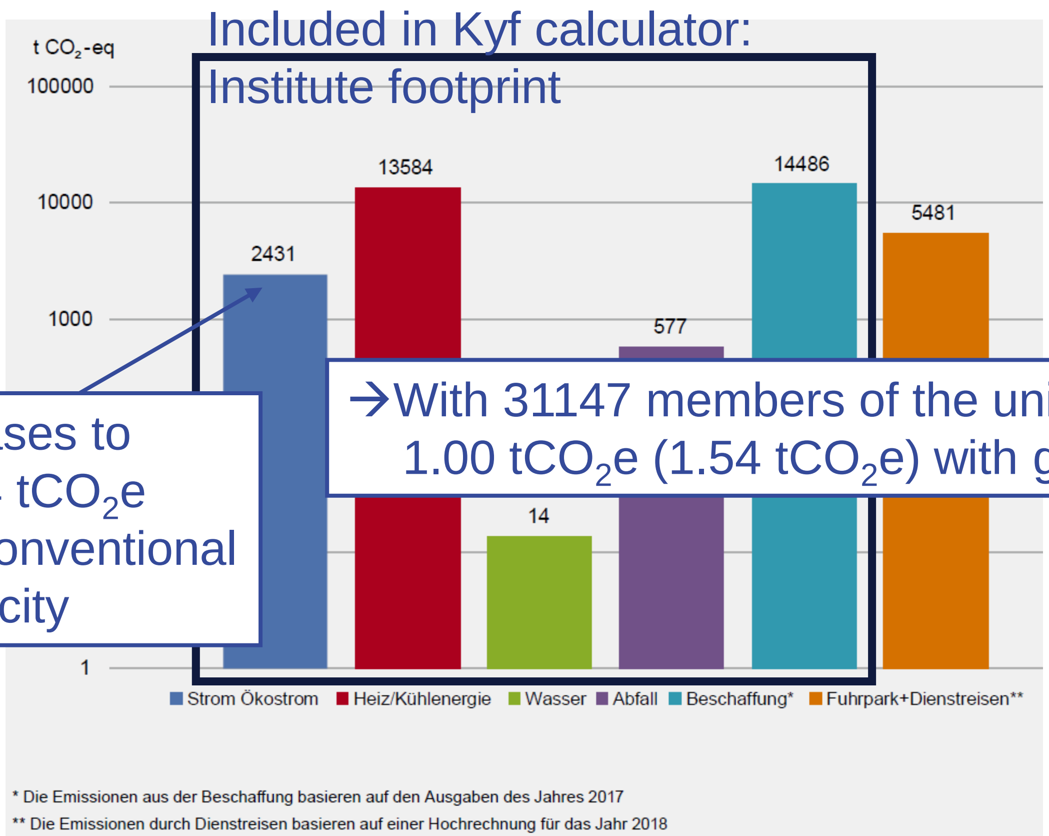


→ Many categories → Challenging to address
→ Demand management + green procurement!

Footprint of a university - Freiburg

Emissions with green electricity

- Exclude emissions from travel here

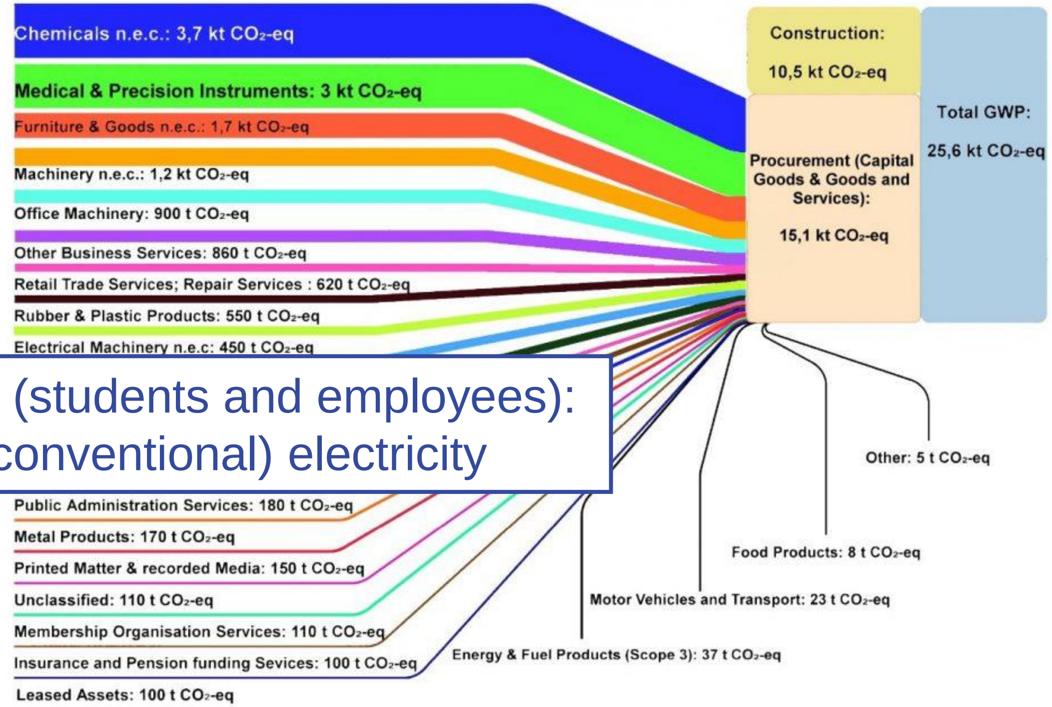


Increases to 19224 tCO_2e with conventional electricity

→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

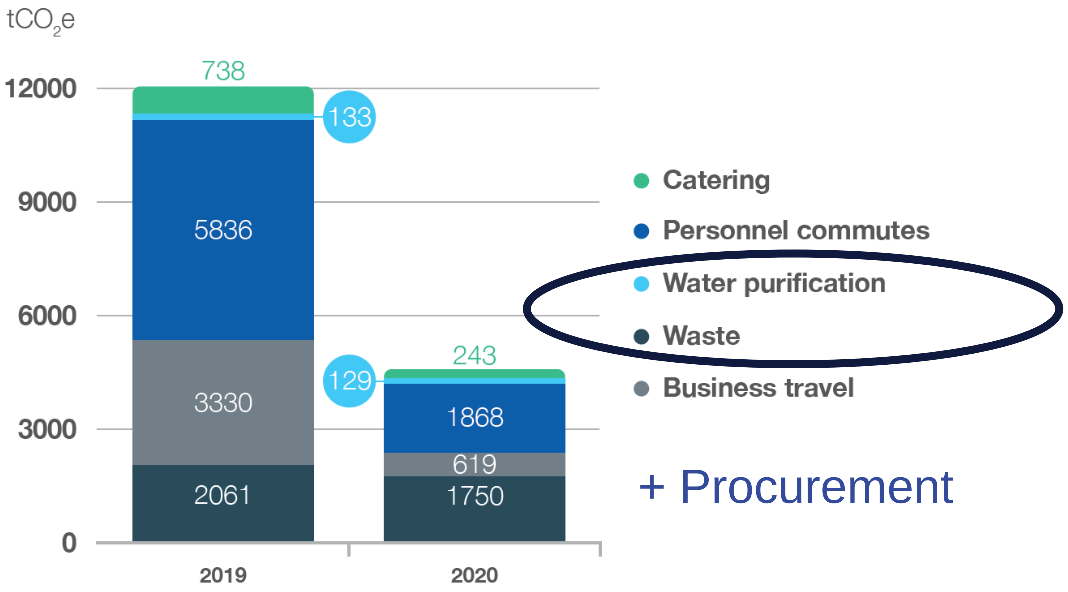


→ Many categories → Challenging to address
→ Demand management + green procurement!

Footprint of a research centre – CERN

From the CERN environmental reports

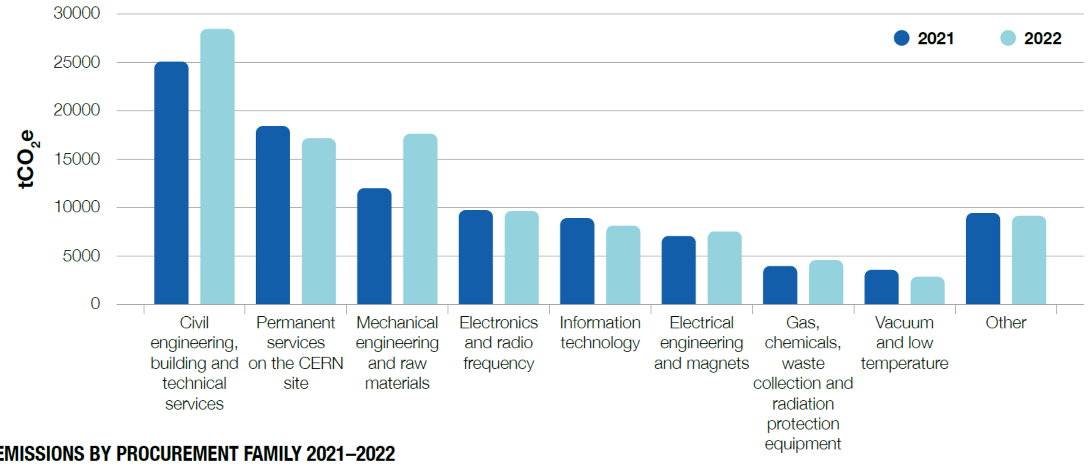
- Heating + Other category from scope 1
- 5% of electricity, i.e. scope 2
- Scope 3
  - Excluding commute, travel, and catering



+ Procurement

Procurement contribution = huge!

- Procurement emissions: 104 974 tCO2e in 2022!
  - Compare total scope 1 in same year: 184 173 tCO_2e
  - 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

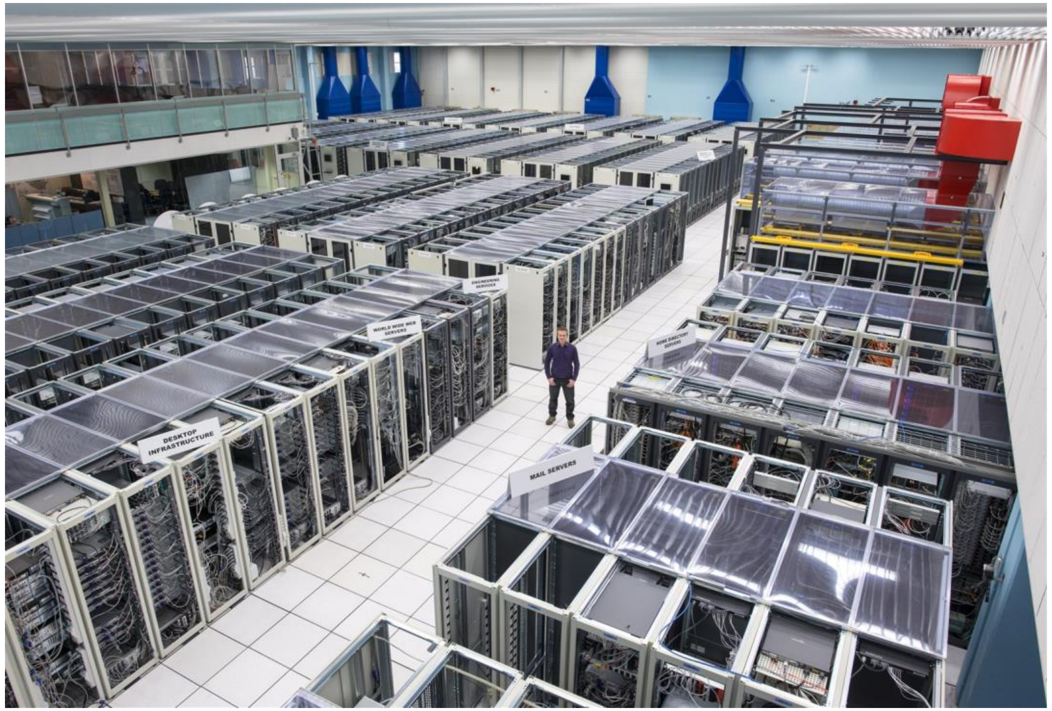
→ Effective CERN population: 7295

→ Per-researcher footprint:
16.65 tCO_2e (2.26 tCO_2e) including (excluding) procurement
→ With procurement, artificially increased, due 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 researcher‘s individual computing workloads in core hours
- Distinguish between CPU and GPU usage → Choice between CPU and GPU needs to be based on computational task
  - Several possibilities to tune configuration of actually used HPC centre
  - Assume optimal core utilization
- Potential to add footprint of large external (commercial) data storage resources
- Personal computers, small institute clusters, etc. assumed to be covered by personal or institute electricity bills and procurement, and thus included in personal or institute footprint
- Provide benchmark scenarios for easy use

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 available in Kyf calculator

- 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

- With international research environment, travel important for personal connections at in-person meetings, etc.
  - Building research networks, collaborations, etc.
    → Most notably missed during COVID-19 pandemic
- BUT: Travel creates CO_2 emissions → Conscious which travel is essential and which is not
  - Necessity to re-evaluate how travel is performed
    → Longer travel times through non-air based travel might make longer-duration stays preferrable
    → Though constraints from teaching, family, etc. makes it non-trivial

Foto von detait auf Unsplash

- Provide possibility for detailed calculations of business trip emissions in Kyf calculation
  - In addition: Provide 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

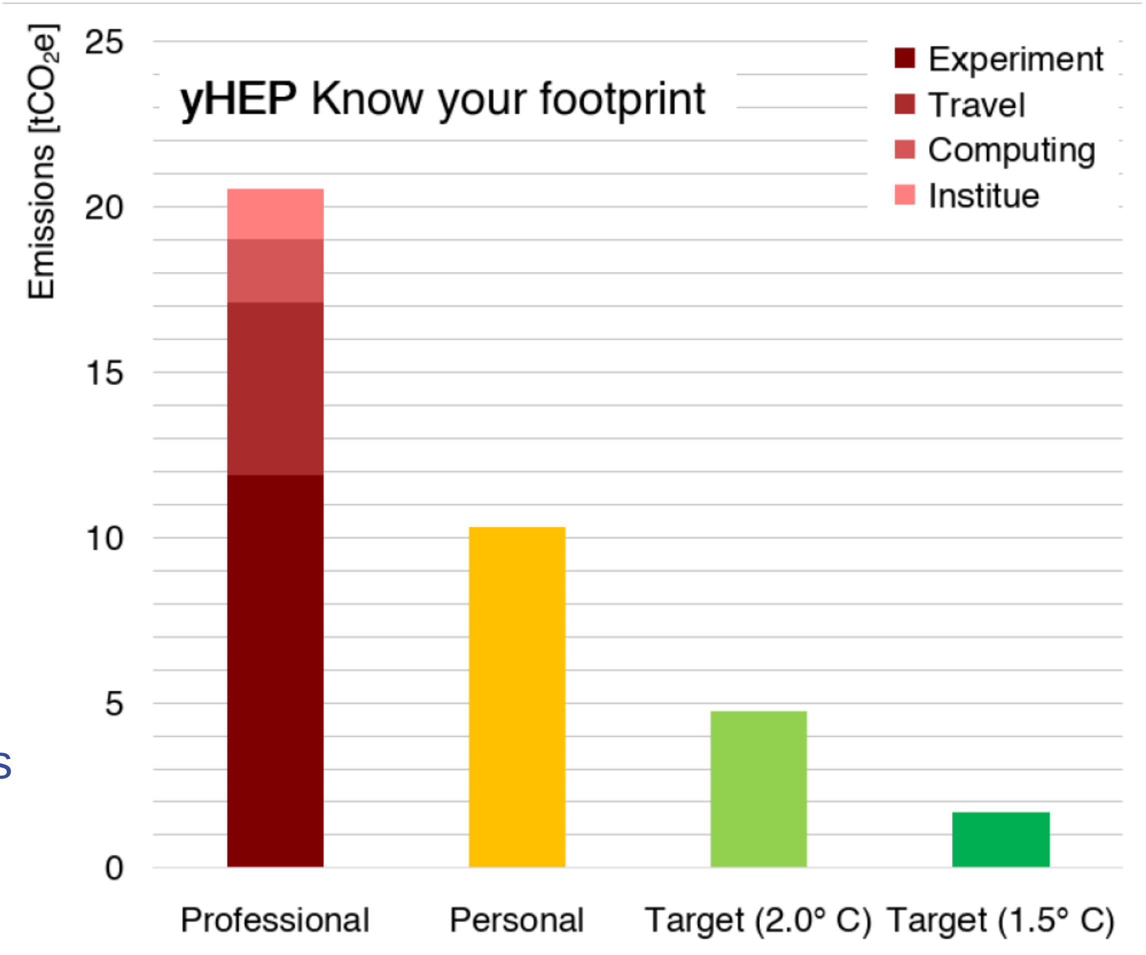
→ In particular, cross-continental flights contribute significantly
→ CO_2 compensation for flights possible to indicate in Kyf calculator

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
  - Cumulative emissions from human activities drive temperature increase → 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
  - Nevertheless: Targeted action for mitigation missing still until today!
- High Energy Phyiscs (HEP) and related areas contribute to global emissions → Reductions urgent
  - Per-researcher emissions estimated → Know your footprint (Kyf) calculator for individual configuration
  - Four categories included: Experiment, Institute, Computing, Travel
  - 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

→ Know your footprint to know where to start!
→ Every gram of CO_2 not emitted counts!

Take-away from today

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

Reset Vote

ID = valerie.lang@physik.uni-freiburg.de
31 Posts / Poll closed

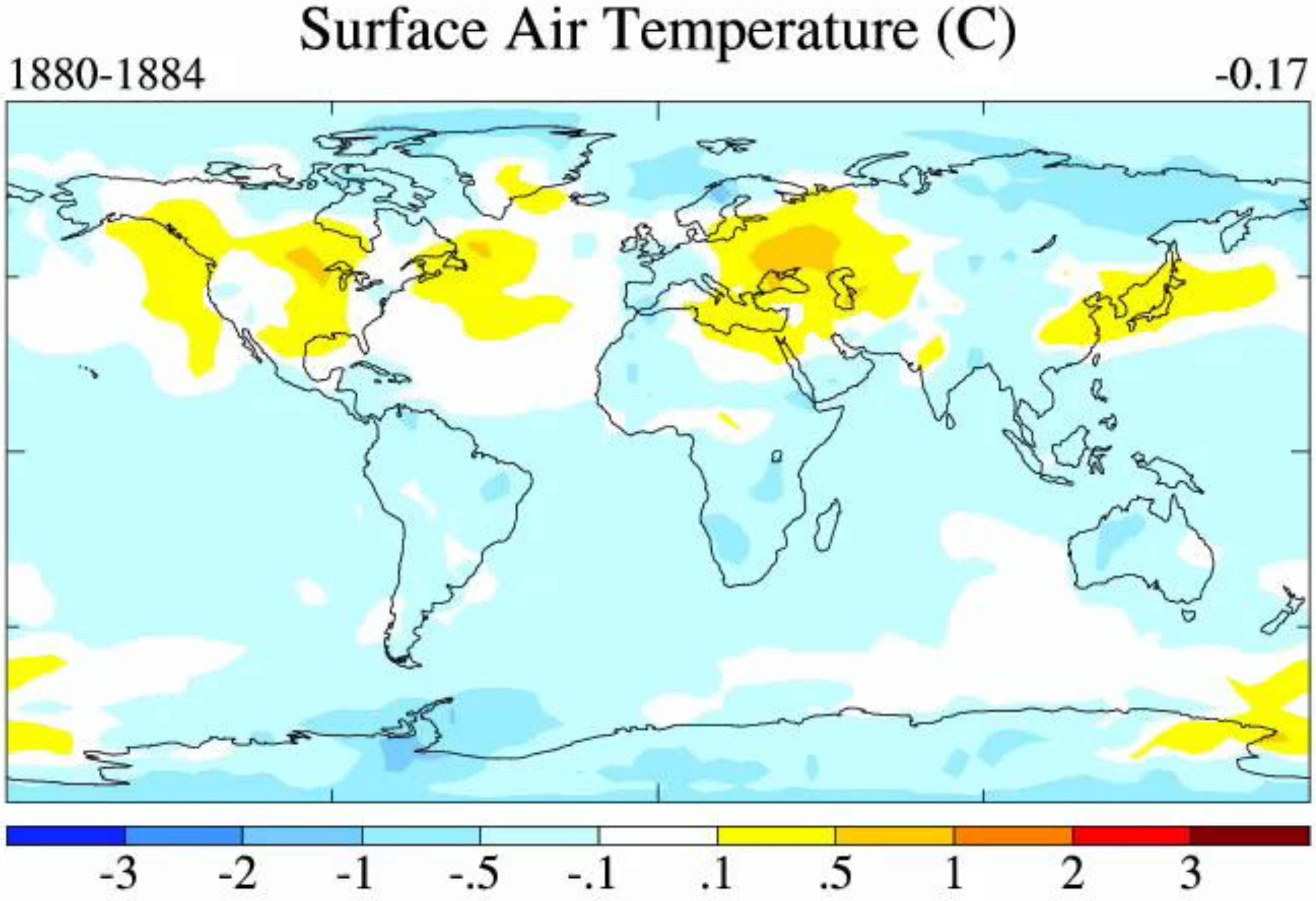
Know your footprint! – Questions?

Thanks for your attention

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

Climate simulation

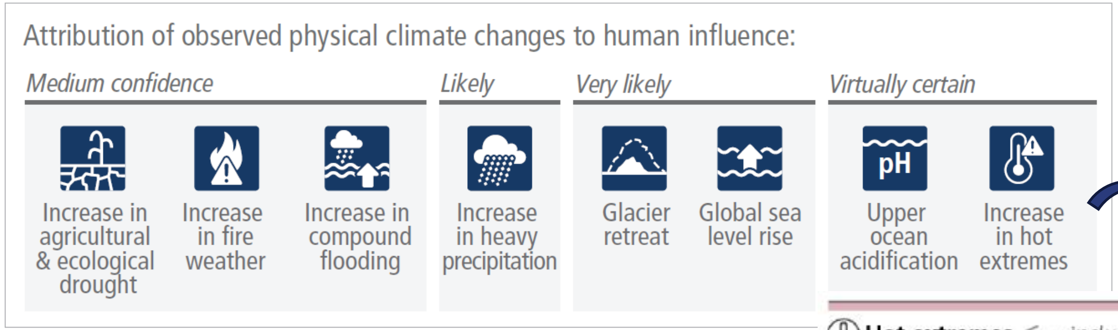
In 2007

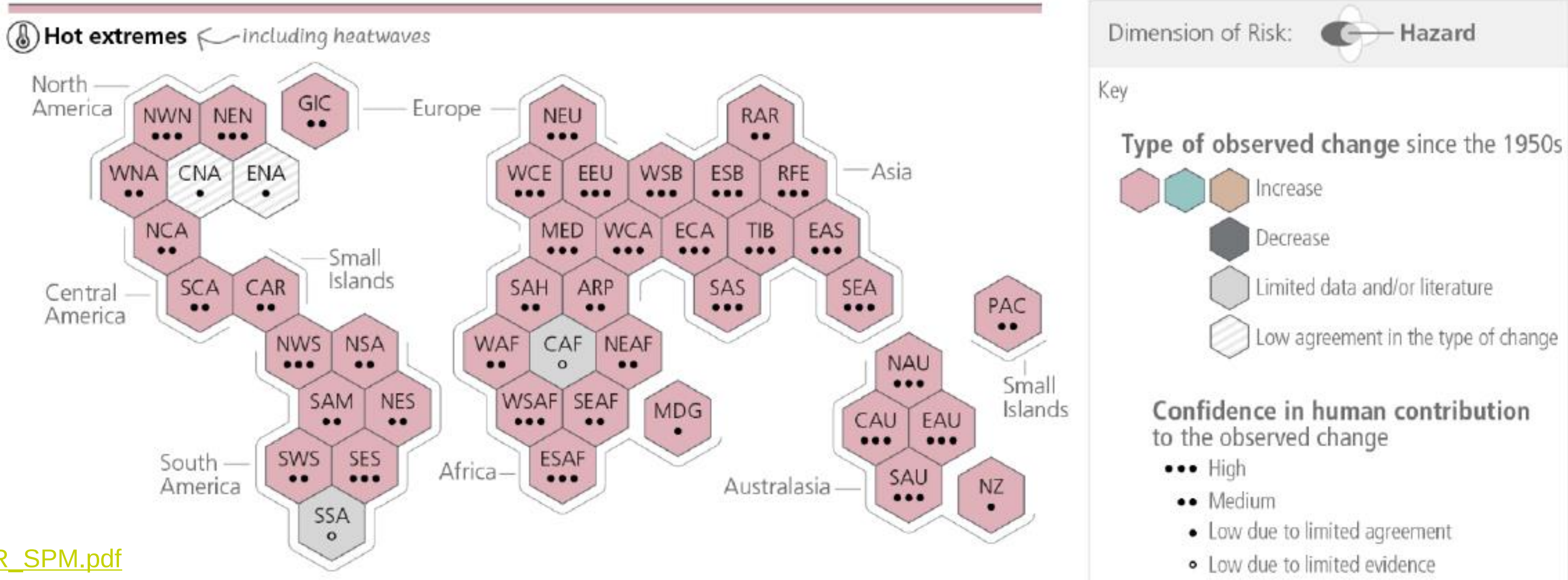


https://data.giss.nasa.gov/modelE/sc07/

Impacts attributed to human influence

Driven by changes in multiple physical climate conditions



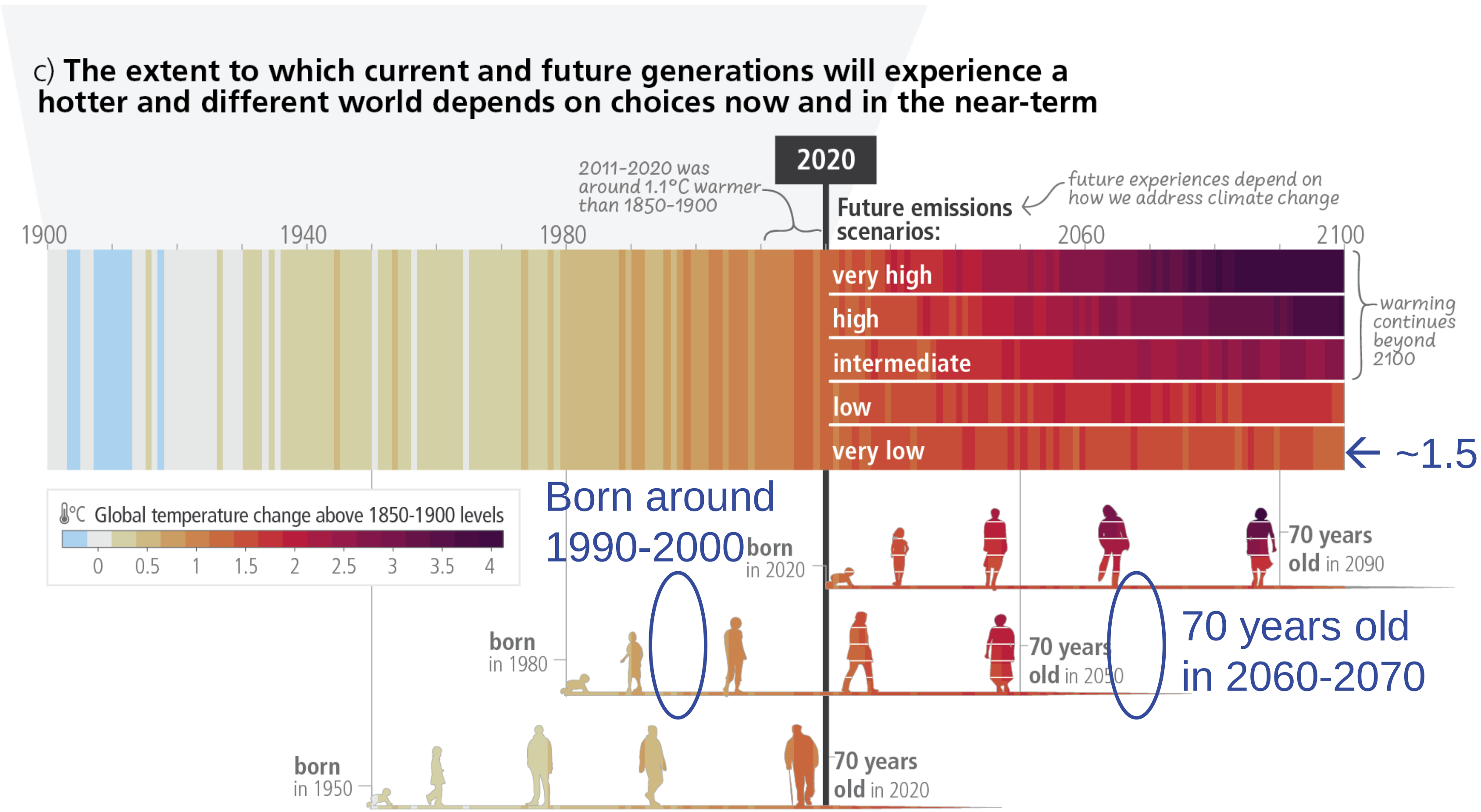


→ Increase in hot extremes well established almost everywhere in the world to result from human influence

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

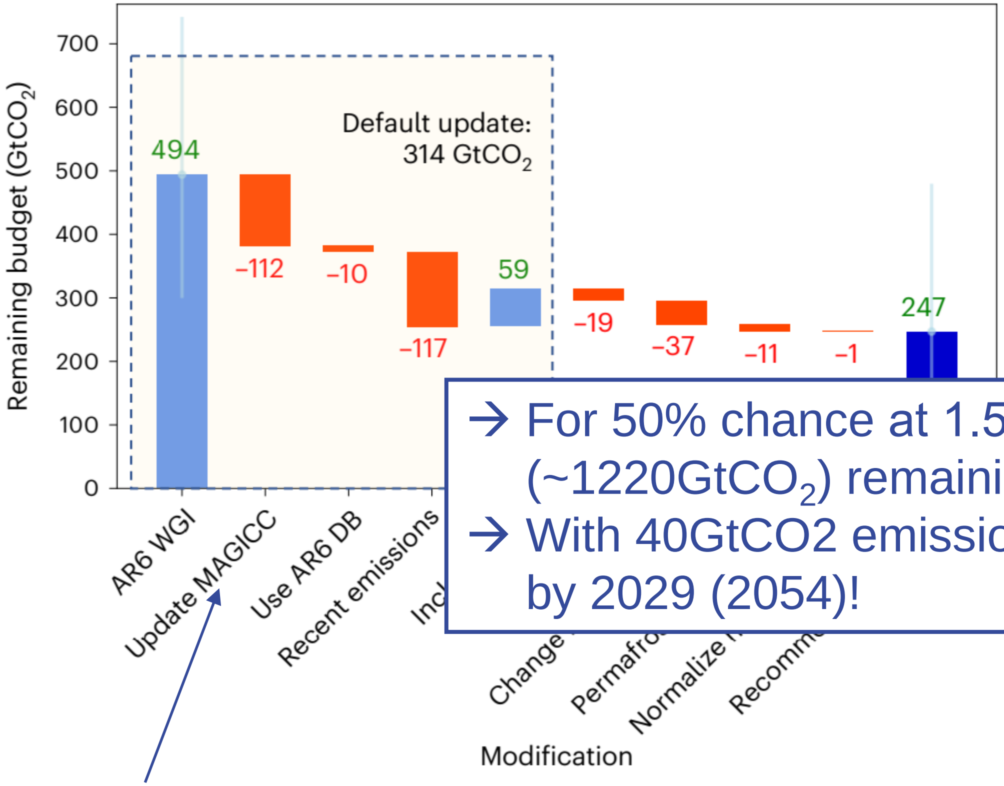
→ Majority of today's audience will live to see the consequences of our actions

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

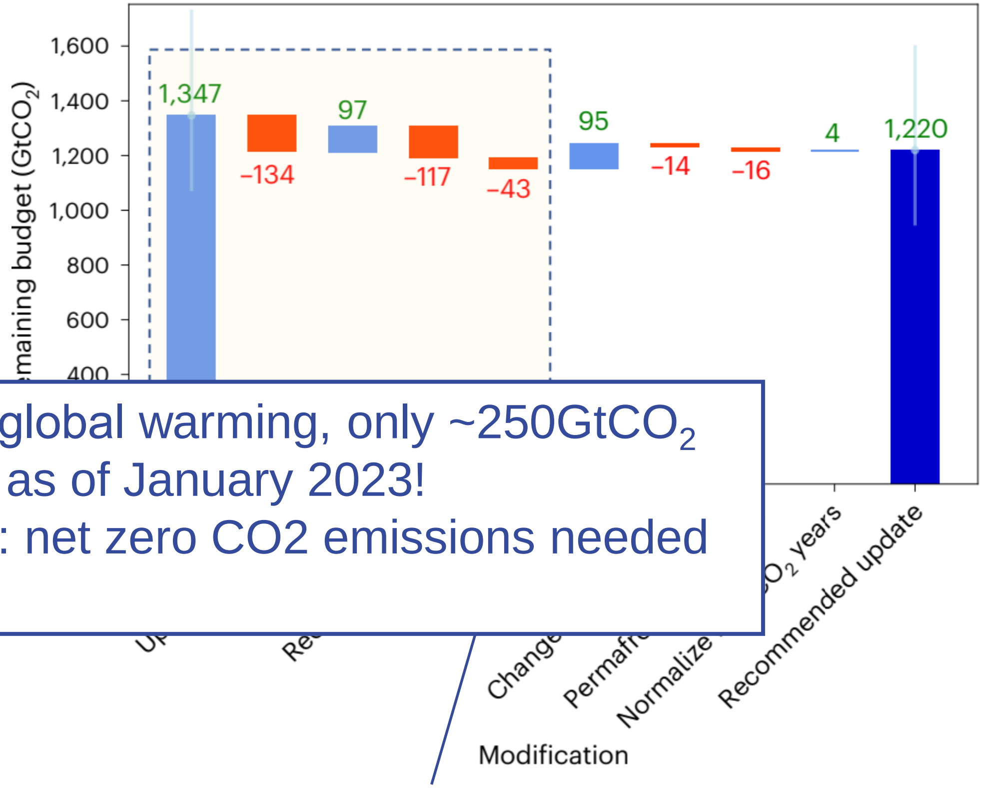
Study of remaining carbon budget newer than IPPC report

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!

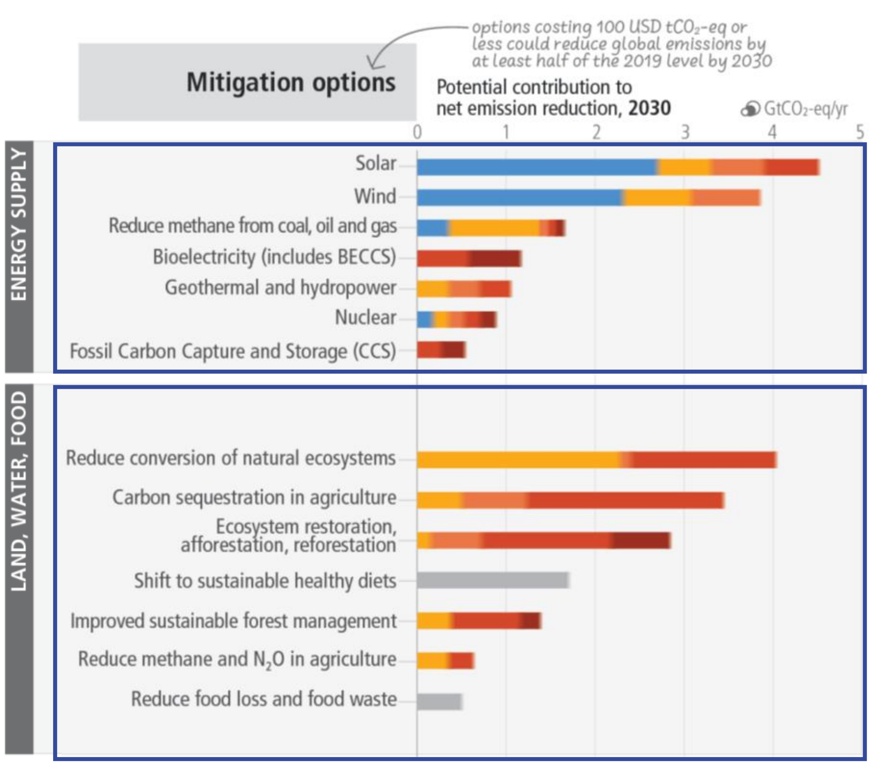
→ With 40GtCO2 emissions in 2022: net zero CO2 emissions needed by 2029 (2054)!

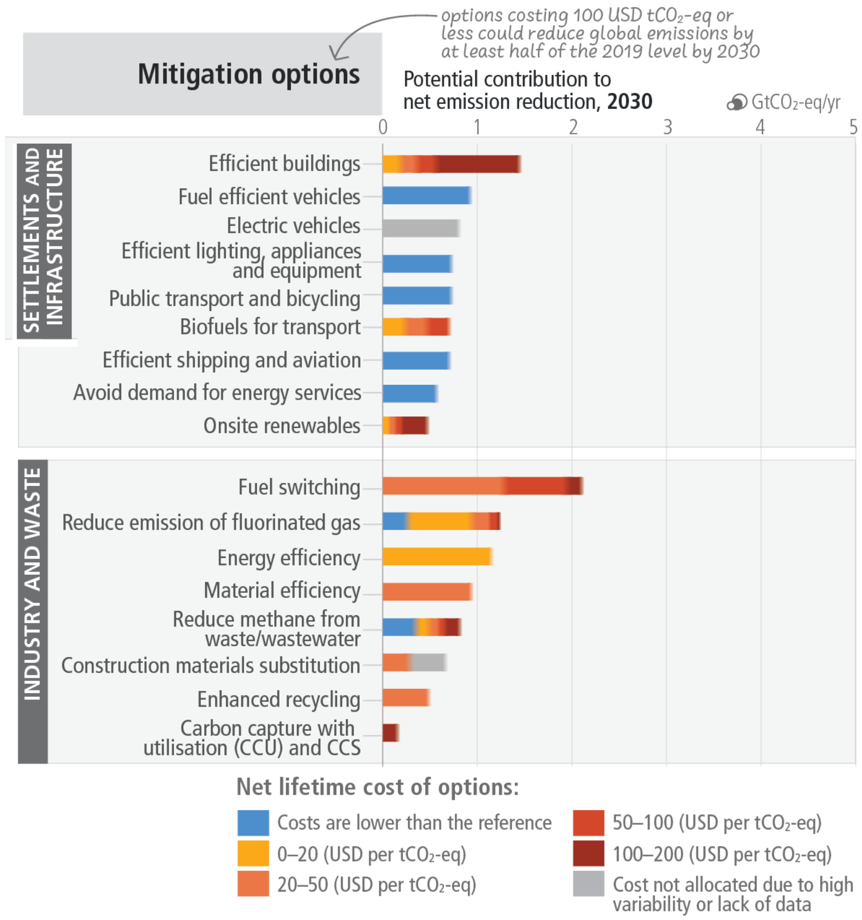
Reduced complexity climate model for non-CO_2 emissions

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

IPCC report: Mitigation potentials

Cost estimates of different mitigation options





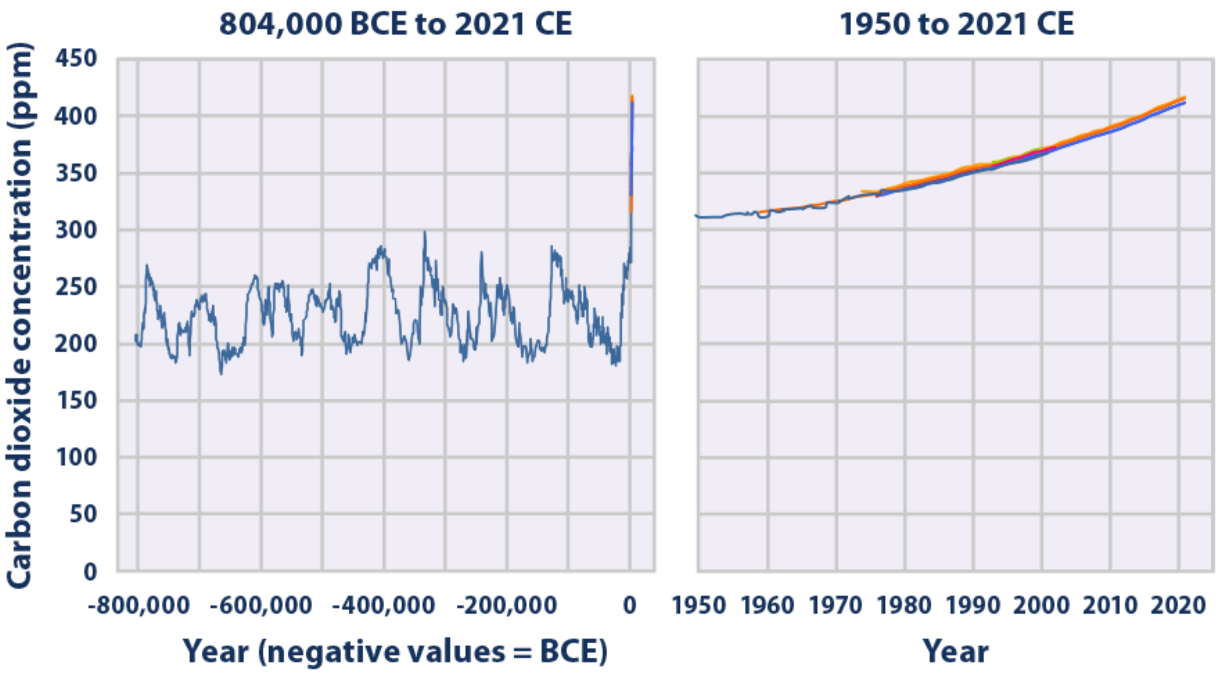
→ Energy and food production with large impacts

→ Take a closer look at these two next

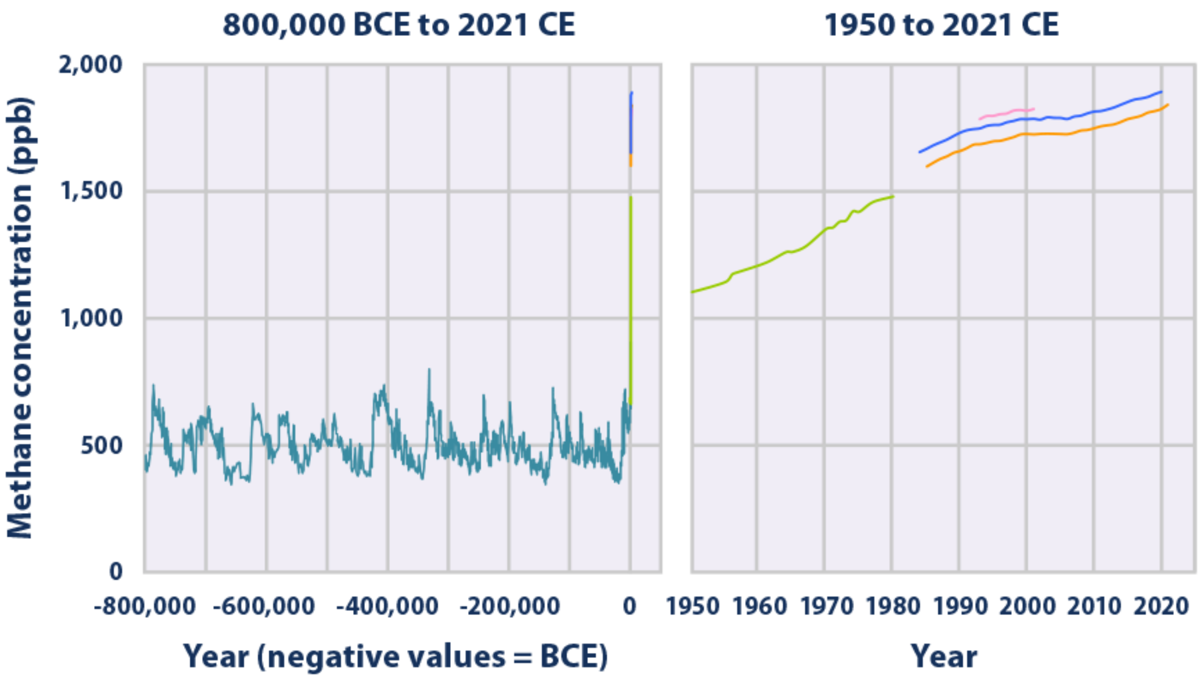
https://report.ipcc.ch/ar6syr/pdf/IPCC_AR6_SYR_LongerReport.pdf

Greenhouse gases

CO2



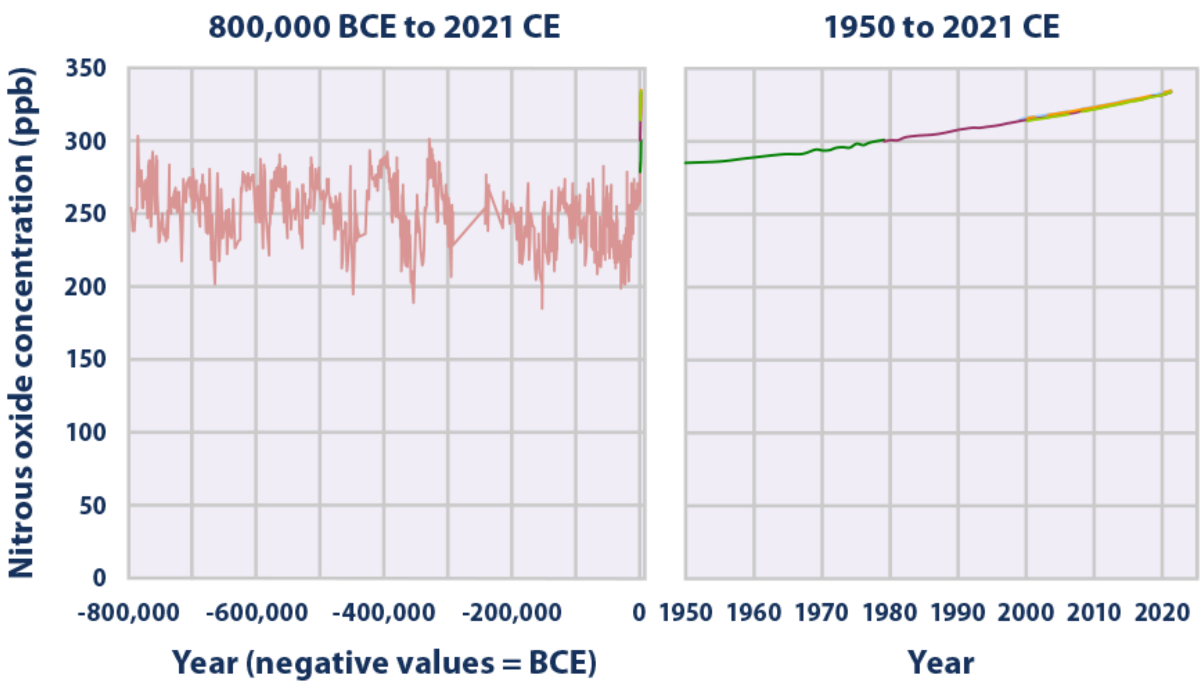
Methane



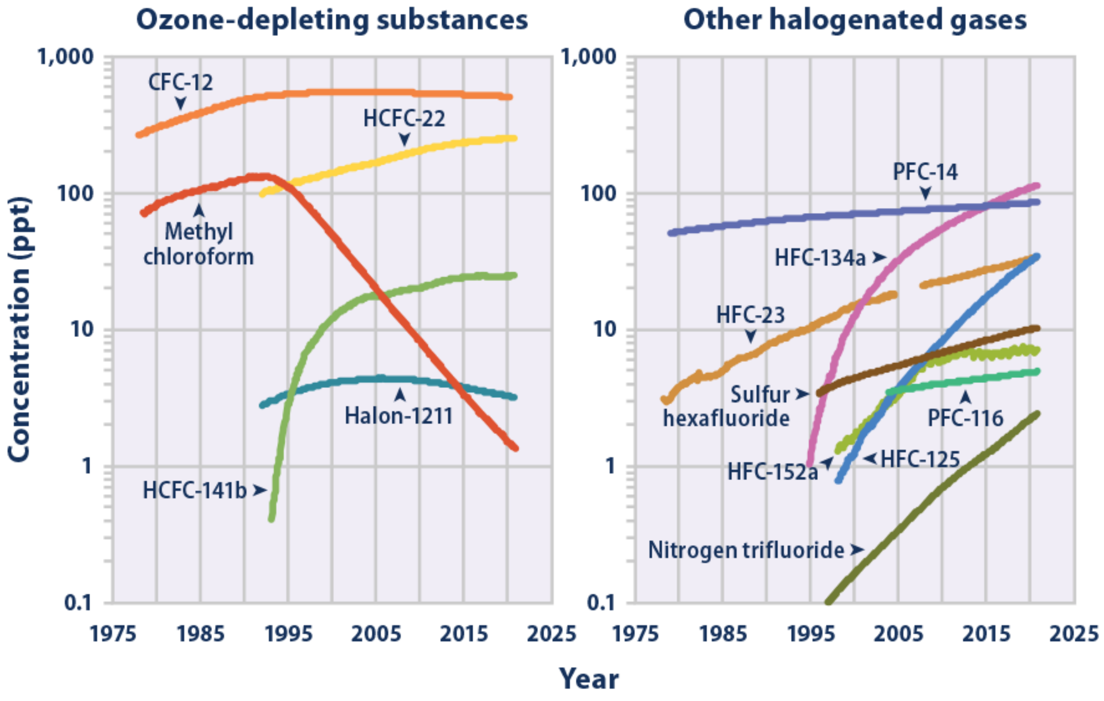
https://www.epa.gov/climate-indicators/climate-change-indicators-atmospheric-concentrations-greenhouse-gases

Greenhouse gases

Nitrous Oxide



Halogenated Gases



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

Relation to SDGs

(b) Climate responses and adaptation options have benefits for ecosystems, ethnic groups, gender equity, low-income groups and the Sustainable Development Goals

Relations of sectors and groups at risk (as observed) and the SDGs (relevant in the near-term, at global scale and up to 1.5°C of global warming) with climate responses and adaptation options

Footnotes: [1] The term response is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation. [2] Including sustainable forest management, forest conservation and restoration, reforestation and afforestation. [3] Migration, when voluntary, safe and orderly, allows reduction of risks to climatic and non-climatic stressors. [4] The Sustainable Development Goals (SDGs) are integrated and indivisible, and efforts to achieve any goal in isolation may trigger synergies or trade-offs with other SDGs. [5] Relevant in the near-term, at global scale and up to 1.5°C of global warming.