SOLUTIONS

Date: 1 February 2024

Location: SG 1

ENV-410 Science of Climate Change final exam
Duration: 180 minutes, 15:15 – 18:15
Material allowed: 1 Din A4 page of notes (back and front) and calculator
Not allowed: phones, tablets or computers
This exam is worth 50 % of your overall grade.

Your SCIPER:

1. Figure 1 shows the measurement record of CO_2 at the Jungfraujoch in Switzerland and the Mauna Loa observatory in Hawai, USA between approximately 2004 and 2016.

1A) The observatories are thousands of kilometers apart, but the measurements show roughly the same mixing ratios of CO_2. How can that be? (1.5 pnt, 3 lines)

CO2 has a lifetime of approximately 100 years (0.5) and is therefore well mixed in the atmosphere (0.5). It does not matter where we measure it as long as the location is remote (0.5).

1B) Annual concentrations follow a seasonal cycle. Explain when and why we see the maximum mixing ratio at these two stations. Would the same observations be made at a mountain site in Southern Chile, why? (2 pnts, 6 lines)

The maximum in each year is found in late winter (0.5), when northern hemispheric growth season has been hibernating the longest, meaning less CO2 is taken up by the vegetation (0.5). When plants become photosynthetically active again, the concentrations decrease (0.5). In Southern Chile, the observation would in principle be the same, but late winter is in October, rather than March (0.5).

1C) For a (hypothetical) practical climate course at EPFL, you are asked to take your own CO_2 measurements and compare them to the long-term observatories like Jungfraujoch or Mauna Loa. A team mate suggests to do the measurements on the campus in Lausanne, because it allows you to check quite easily if the instrument is still working correctly. Why is this not a good idea? (1 pnt, 3 lines)

Climate-relevant CO2 measurements need to be made at remote locations (0.5), so local influence can be ruled out (0.5).

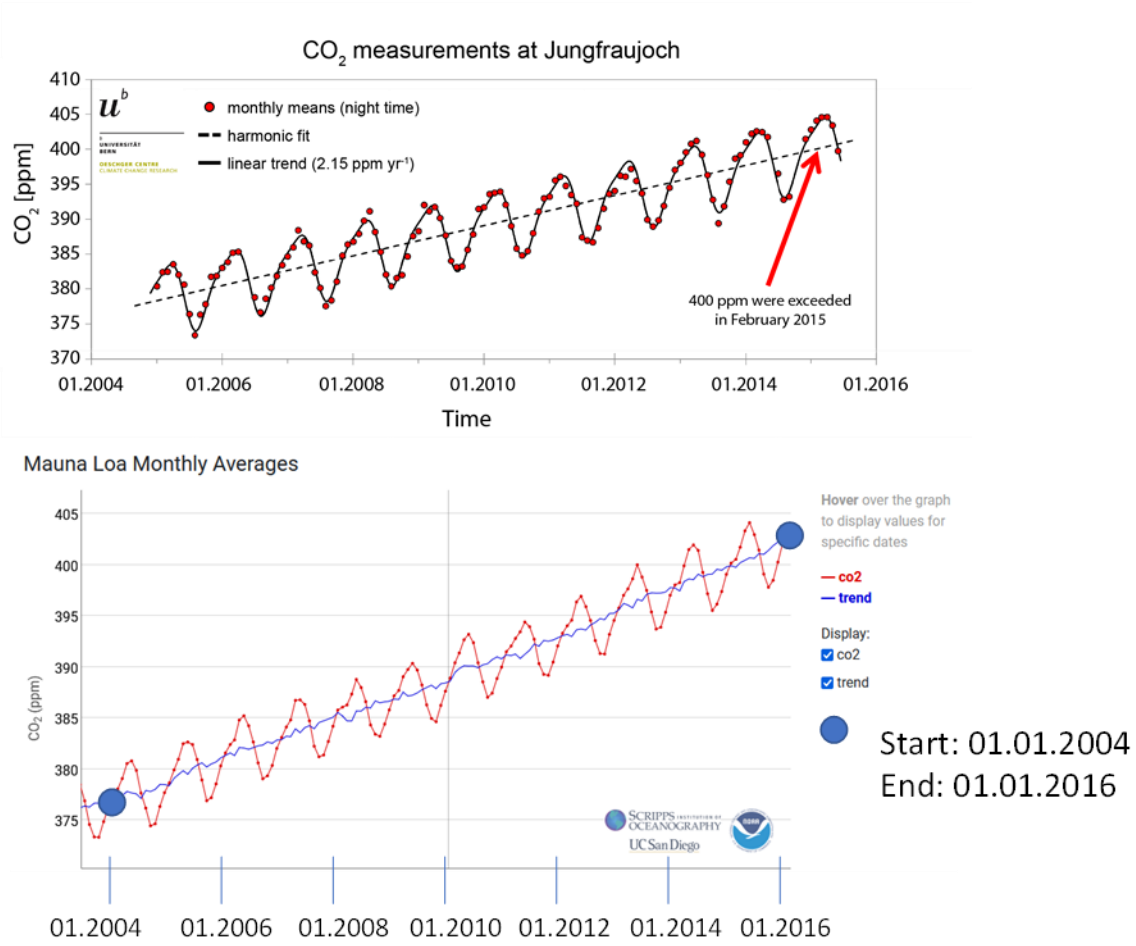

Figure 1: CO_2 observation from the Jungfraujoch, Switzerland (top panel) and Mauna Loa on Hawai, USA (bottom panel). Sources: https://www.hfsjg.ch/de/stiftung/showcase/2016-juni/, https://gml.noaa.gov/ccgg/trends/graph.html

2. Which of the following statements is true?

- ☐ Longwave and shortwave radiative effects act on comparable time scales.
- ☐ The snow and ice albedo effect acts on time scales longer than absorbing aerosol.
- ☐ CO_2 acts on shorter timescales than CH_4.
- ☐ O_3 acts on shorter time scales than CH_4.

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3. Which processes force climate?

- ☐ Emission of air pollutants.
- ☐ Stratospheric aerosol injection.

- ☐ Sea level rise.
- ☐ Heat waves.

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4. Why is carbon monoxide not a greenhouse gas? (3 lines, 2 pnts)

A greenhouse gas needs to be able to have a dipole (1). Such a lack of charge equilibrium can only be achieved with molecules that have more than 2 atoms (1).

5. Why are the two atmospheric windows critical for life on Earth?

- ☐ Both allow shortwave radiation to reach Earth's surface, which is necessary for photosynthesis and to maintain a reasonable surface temperature.
- ☐ They are not critical for life on Earth.
- ☐ One allows longwave radiation to escape to space. Without this window our planet would be a hot-house.
- ☐ One keeps detrimental UV radiation from reaching the Earth's surface.

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6. If there were no convection on Earth and the vertical temperature profile were only determined by radiation,

- ☐ The surface would be much hotter.
- ☐ The surface would be much colder.
- ☐ The upper troposphere would be much hotter.
- ☐ The upper troposphere would be much colder.
- ☐ There would be no change in stratospheric temperatures.
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7. Fill in below table with the correct time scales: days, weeks, months, years (2 pnts)

Type of radiative forcing and temperature adjustment	**Time scale of temperature adjustment**
Fixed surface temperature (land and ocean) forcing with adjustment of tropospheric and stratospheric temperatures	
Fixed sea surface temperature forcing (effective radiative forcing), with adjustment of land surface temperature, tropospheric and stratospheric temperature	
Fixed surface temperature forcing (radiative forcing – RF) with adjustment of stratospheric temperature	
Forcing with temperature adjustments of the land and ocean surface, deep ocean, troposphere and stratosphere	

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Fixed surface temperature (land and ocean) forcing with adjustment of tropospheric and stratospheric temperatures	weeks
Fixed sea surface temperature forcing (effective radiative forcing), with adjustment of land surface temperature, tropospheric and stratospheric temperature	months
Fixed surface temperature forcing (radiative forcing – RF) with adjustment of stratospheric temperature	days
Forcing with temperature adjustments of the land and ocean surface, deep ocean, troposphere and stratosphere	years

8. Why is it a real challenge for climate science to determine the radiative forcing of greenhouse gases accurately?

- ☐ The radiative forcing of greenhouse gases in the atmosphere is two orders of magnitude smaller than the natural radiative fluxes.
- ☐ The natural radiative fluxes are highly variable and much larger than the radiative forcing induced by greenhouse gases.
- ☐ Measurements would have to be made at the top of the atmosphere, which only works well with satellites, but satellites have a spatial resolution that is too coarse.

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9. The Planck feedback factor is
- ☐ Positive
- ☐ Negative

- ☐ Positive
- ☐ Negative

10. The water vapor feedback factor is
- ☐ Positive
- ☐ Negative

- ☐ Positive
- ☐ Negative

11A) You're having a nice evening out with your "Science of Climate Change" course peers at Satellite on the campus. You are discussing the course material before the exam and suddenly somebody interrupts your conversation and says: "Sorry, to have eavesdropped on your conversation about climate change, but I think you are mistaken. Today's CO_2 concentrations are not the highest in the last 800'000 years. Temperatures in the Pleistocene were higher than today's." You quickly think and then point out "This is right, temperatures have been higher, but that does not mean that the CO_2 mixing ratios have been higher. Actually, from ice cores we know that the current CO_2 mixing ratios are the highest in the last 800'000 years." Now you still need to explain to the person that greenhouse gas concentrations are not the only factor that determine global surface temperature. (3 pnts, 8 lines).

For greenhouse gases to warm the planet, they need to absorb and re-emit the terrestrial radiation (1). The warmer the surface is, the more it will radiate (blackbody radiation) (1). So if the insolation is larger, the planet will be warmer, roughly speaking (assuming the same albedo), and therefore will radiate more. The insolation depends on the Earth's orbit (1). So in summary, the combination of the insolation and amount of greenhouse gases determines the temperature on Earth.

11B) Your answer sounds plausible to the person who interrupted your conversation, but they are still not convinced that today's climate change is special compared to past climate change. They pull out a figure from their pocket (Figure 2 below based on Mann et al. (2009) that shows the medieval climate anomaly (MCA) and the little ice age (LIA). They argue: "Yes, ok, I see what you say, but just look at the medieval warm period on the map here. Greenland has been warm in the past and now it's getting warmer again. I don't see why now this should be special and only due to human greenhouse gas emissions." You look at the map and take out a figure from your pocket. What will you show the fellow and what argument will you make that today's warming is different and human-made? (2 pnts, 6 lines)

“Sure, Greenland was warmer previously than today, but what is happening today on our planet is global (1). The medieval warm period was a regional phenomenon, as you can see on your map. Today temperatures increase generally everywhere, just look at this map from the IPCC that shows the warming on the map. The IPCC report shows clearly that the temperature increase results from anthropogenic emissions of greenhouse gases, and that natural factors do not play a significant role. (1)”

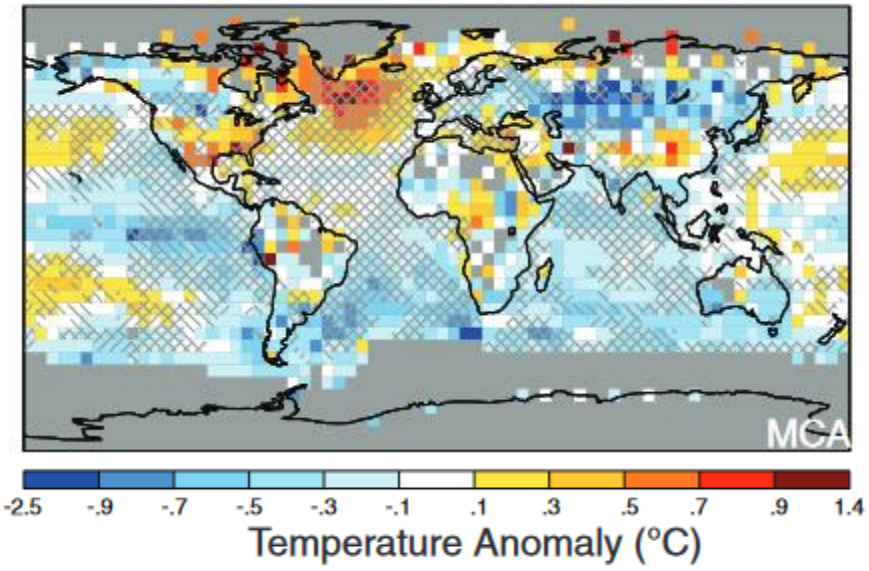

Figure 2. Reconstructed surface temperature pattern for the medieval climate anomaly *MCA (950 to 1250 C.E.). Shown are the mean surface temperature anomaly. Anomalies are defined relative to the 1961–1990 reference period mean. Statistical skill is indicated by hatching [regions that pass validation tests at the P = 0.05 level with respect to the reference (CE) are denoted by / (\) hatching]. Gray mask indicates regions for which inadequate long-term modern observational surface temperature data are available for the purposes of calibration and validation. Source: Mann et al. (2009),* http://www.meteo.psu.edu/holocene/public_html/shared/articles/MannetalScience09.pdf*, caption has been modified for the exam.*

12. Which of the following are modes of internal climate variability?

- ☐ El Niño Southern Oscillation
- ☐ The monsoon
- ☐ Atlantic Meridional Oceanic Circulation
- ☐ North Atlantic Oscillation
- ☐ Northern Annular Mode

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13. Based on Figure 3. answer the following:

13A) Explain what a temperature anomaly is. (3 lines, 1 pnt)

(i) an anomaly is calculated based on a ***reference*** value (0.5), e.g. the average of annual values between 1850 and 2023 that is ***subtracted*** from individual annual values (0.5).

13B) Previous to 2022, what was likely the most recent strong El Niño year? (1 pnt, 1 line)

2015.

13C) Why is the global trend in air temperature increase (top panel) larger than in the ocean (bottom panel)?

- ☐ Local air measurements can be influenced by local climate and therefore such a figure can contain bias.
- ☐ The difference in the trends is about a factor 3. This is within the measurement uncertainty and therefore there is no difference in the trends.
- ☐ The water from the ocean bottom cools the top ocean water quickly enough, so we see less temperature increase.
- ☐ The air has a smaller heat capacity.

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13D) Explain how we can observe climate variability in below graph. Give one concrete example. (5 lines, 2 pnts)

Even though there is a general trend of increasing temperature, there is year to year variability in the monthly air and ocean temperature, meaning the temperature anomaly does not increase monotonically (1). An example is the warmer years around 1980 that are preceded and followed by colder years (1).

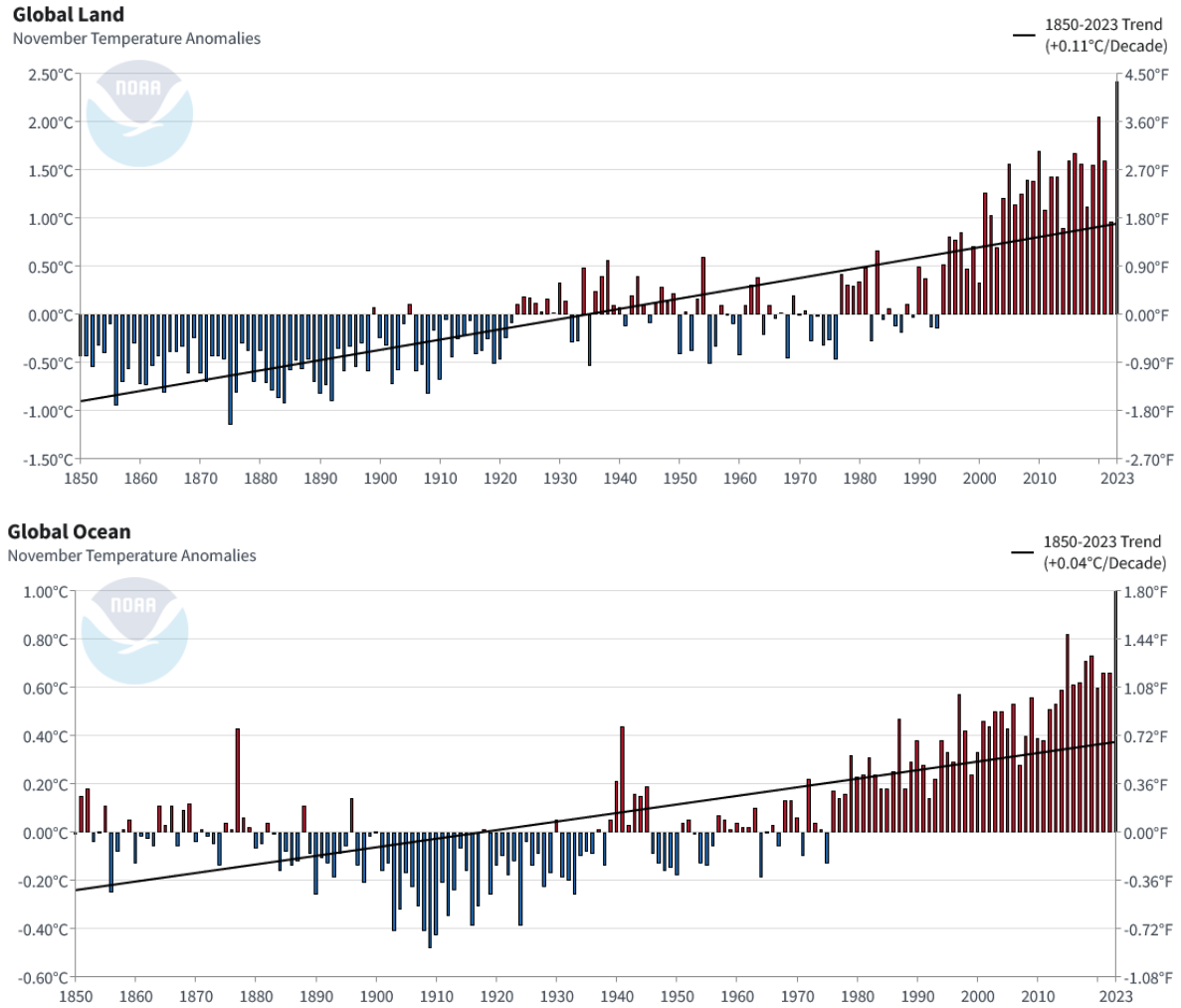

Figure 3. Global land (top) and ocean (bottom) temperature anomalies for November between 1850 and 2023 (including). Source: https://www.ncei.noaa.gov/access/monitoring/climate-at-a-glance/global/time-series/globe/

14. You are doing your PhD in climate science and have developed a new regional version of a climate model with the aim of simulating the climate of Africa much better than any other regional model currently available. You could run the model in 20 different configurations that all have different equilibrium climate sensitivities (ECS), but you don't know the ECS yet. Before running any serious scenarios for the future, you need to make sure you run your model in a trustworthy configuration. Having access to surface temperature measurements at 1000 different stations across the continent with data for the last 10 years, and tree ring records from the rainforest area, how would you determine a model configuration with a trustworthy ECS?

- ☐ Using the Gregory method to determine the ECS for each model version.
- ☐ Using the emergent constraints method with the many surface observations.
- ☐ Using the historic climate records to compare all model versions against them.

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15. According to the Copernicus Climate Change Service (C3S), the year 2023 has been 1.48°C above preindustrial temperatures and each single day was > 1°C above preindustrial records. The likelihood of the year 2024 being the first year in history to exceed a warming of ≥ 1.5°C is very high. If by 31.12.2024 C3S tells us that warming was indeed ≥ 1.5°C, will we have breached the Paris Agreement? Explain your answer. (2 pnts, 3 lines)

No (1), a single year above 1.5°C is not sufficient. While there is no exact number of years that must be above 1.5°C, there need to be at least several (1).

16. The EU emitted 2.73 billion metric tons of CO_2 in 2022 and 15 million metric tons of CH_4 in 2020. The global warming potential of CH_4 is 28 over 100 years, and 84 over 20 years. The atomic weights are of H, C and O are 1 amu, 12 amu and 16 amu, respectively.

16A) What is the share of the CH_4 emissions in the total yearly carbon emissions of the EU if we only consider CO_2 and CH_4 and assume a short time horizon. For this calculation it does not matter that CO_2 emissions are reported for 2022 and CH_4 for 2020.

- ☐ < 1 %
- ☐ 5.6 %
- ☐ 56 %
- ☐ > 60 %

- ☐ < 1 %
- ☐ 5.6 %
- ☐ 56 %; converted CH4 emissions to CO2eq by factor 84 then converted CO2 and CO2eq to carbon only, summed up both and derived fraction
- ☐ > 60 %

16B) What is the fraction of greenhouse gas emissions that the EU could avoid over a short time horizon if they were to cut CH_4 emissions by 30 % immediately. How does the result change when calculating over a long time horizon? Calculate the fraction based on the total yearly greenhouse gas emissions of CO_2 and CH_4. Show your calculation. (4 pnts)

Over the short period (GWP20) about 9.5 % can be avoided.
Over the long period (GWP100) about 3.2 % can be avoided.

Calculation:
Convert CH4 to CO2eq over 20 years: 15'000'000*84=1.26*10^9 (1)
30 % of 1.26*10^9 = 378'000'000 CO2eq (0)
Fraction: 378'000'000/(1.26*10^9 +2.73*10^9) = 0.095 (1)

Conversion for 100 years and 30 %: 15’000’000*28*0.3=126’000’000 (1)
Fraction: 126’000’000/(1.26*10^9 +2.73*10^9) = 0.032 (1)

16C) It is the year 1990 and you live in a petro-state. You are the climate advisor to your country’s environmental minister. Your country is progressive and has decided to reduce its greenhouse gas emissions by 50 % until 2030 based on the 1990 levels. Using the GWP20 for CH_4, your country could achieve this cut easily by mainly focusing on methane, which is easy in your country because there is nearly no agriculture, but a lot of natural gas extraction where large amounts of CH_4 escape. Using the GWP100 for CH_4, substantial cuts in CO_2 would also be required, which is much harder because the whole energy and transport system is based on fossil fuel combustion. The environmental ministry strongly favors using the GWP20 to achieve the goal. You disagree and give the minister 3 key arguments. Hint, you are thinking more long-term than 20 years. (3 pnts, 8 lines).

Possible three key points. Others are also valid.

1. The time horizon is 40 years, which means that using GWP20 would overestimate the potential of CH4 reduction. (1)
2. For the general goal of climate change mitigation, CO2 emissions reductions are necessary. So focusing too much on methane would not address the warming in the more distant future. (1)
3. In 1990 we were still far from 1.5 or 2.0°C warming and mitigating peak warming could not have been a priority. (1)

17. Emissions Gap

17A) Based on Figure 4, what is the approximate (± 3 $GtCO_{2e}$) unconditional emissions gap for the 1.5°C target for the year 2035 considering the 90th percentile for all values? You will need to eyeball the axis, hence the allowed uncertainty in emissions. (1 pnt, 1 line, indicate in the graph which values you are using)

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33 GtCO2e (60-27=33)

17B) Which of the following statements is true?

- ☐ Unconditional NDCs imply more rigorous emissions reductions.
- ☐ Conditional NDCs imply that countries only reduce their emissions if their population agrees in a referendum to do so.
- ☐ Most of the NDCs are tied to international climate finance.

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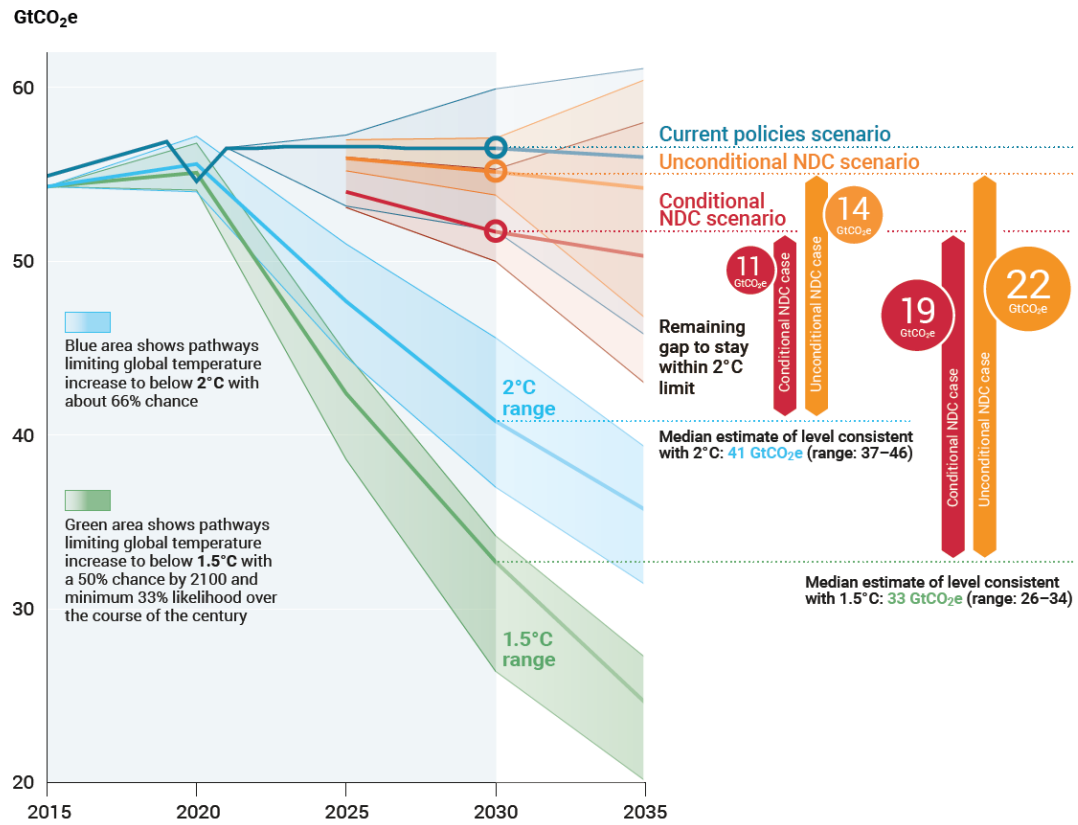

Figure 4. Global GHG emissions under different scenarios and the emissions gap in 2030 and 2035 (median estimate and tenth to ninetieth percentile range). Source: Fig. ES4, Emissions Gap report 2023

18. In their work from 2020, Cox et al. present an evaluation of daytime versus nighttime maximum temperature change across the globe (see Figure 5).

18A) Based on panel (a), did day or nighttime temperatures increase more rapidly in (i) the US and (ii) Italy? (1 line, 2 pnts)

USA: daytime increased more rapidly (1); Italy: nighttime increased more rapidly (1).

18B) Based on panel (d), explain the radiation effect observed in Italy. (6 lines, 2 pnts)

Panel (d) shows a *positive relationship* (0.5) between nighttime temperature and increased cloud cover. More *cloud cover during the night means* (0.5) that Earth's infrared radiation is absorbed (0.5) and re-emitted by the clouds, leading to a warming effect compared to absence of clouds, where the IR radiation is lost to space (0.5).

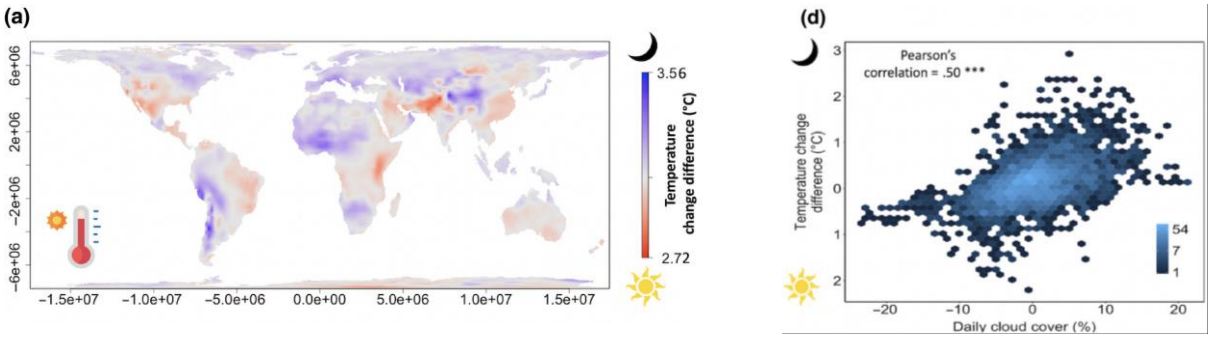

Figure 5. Spatial variation in diel warming asymmetry and change in daily cloud cover. From Cox et al. (2020) https://onlinelibrary.wiley.com/doi/10.1111/gcb.15336.

(a) Spatial variation in the warming asymmetry between daytime maximum temperature and night-time minimum temperature. In each pixel the 35 year change in the daytime temperature was subtracted from the 35 year change in the night-time temperature.

*(d) The relationship between the difference in change in temperature between the daytime and night-time and the change in daily cloud cover. The legend shows the log of the number of pixels, and *** denotes a statistical significance of $p < .001$. Negative values for temperature change difference were converted to absolute values and the direction of greater change is represented by a sun (daytime) or a moon (night-time). The map projections are Behrmann's equal area.*

19. You have been wanting to talk to your local Climate Policy Officer for a while that action is needed in this “decisive decade” to reach the 1.5°C goal by 2100, but they unfortunately did not have time to meet. Now you meet them by chance in the tram as you go to work. You know that the Climate Policy Officer will get off the tram at the next stop, which is in 1 minute. This is the prefect opportunity to tell them why we are in the “decisive decade” and that postponing action to 2032 as they suggested is not a good way forward. Make sure to highlight at least two important consequences of delayed action.
Note: One can reasonably speak 130 words per minute. (4 pnts)

Possible answer. Other points are also valid.
We call this decade “decisive decade” because to reach the 1.5°C goal, we must half our GHG emissions by 50 % (1). Since we are already 3 years into the decade and GHG emissions are still rising, action becomes even more urgent. If we do not halve emissions by 2030, i.e. leaving mitigation too late, we might warm the planet by more than 1.5°C (2). The more we warm the planet, the stronger will be the impact. Important impacts are extreme events (1) such as storms, floods and heat waves, but also sea level rise that puts for example small island states at risk (1).

20. You are a climate delegate for Small Island States and refuse to sign a COP agreement that allows the global community to overshoot emissions as much as to reach a maximum of 2.1°C within this century, under the condition that emissions will be reduced and made net-negative to reach 1.5°C by 2120. You are asked to justify your refusal. (7 lines, 3 pnts)

Possible answer. Other points are also valid, but sea level rise must be mentioned.

Overshooting emissions and reaching higher temperatures than 1.5°C within this century means that sea level will rise significantly (1), not only within this century but also later, because the cryosphere reacts slowly (1). So even if temperatures are brought back to the original 1.5°C goal, our Small Island State would be affected too much (1).