MEC666 — PC2

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The goal of this tutorial is to understand the concepts of inertia of the climate system and commitment to future global warming, the use estimates of the transient climate response to translate greenhouse-gas emissions into a global-mean temperature increase, to learn to reverse this relation to associate a carbon budget to a global-warming limiting target and to shed a critical eye on current emissions.

1 Transient Climate Response

The IPCC gives the following definition of the transient climate response:

Definition 1. *The Transient Climate Response (TCR) is the change in global and annual mean surface temperature from an experiment in which the CO_2 concentration [in the atmosphere] is increased by* $1\,\%\text{yr}^{-1}$*, and calculated using the difference between the start of the experiment and a 20-year period centered on the time of CO_2-doubling.*

Q1 *According to you, compared to the Equilibrium Climate Sensitivity (ECS) introduced in PC1, what makes the TCR an interesting measure for climate change studies?*

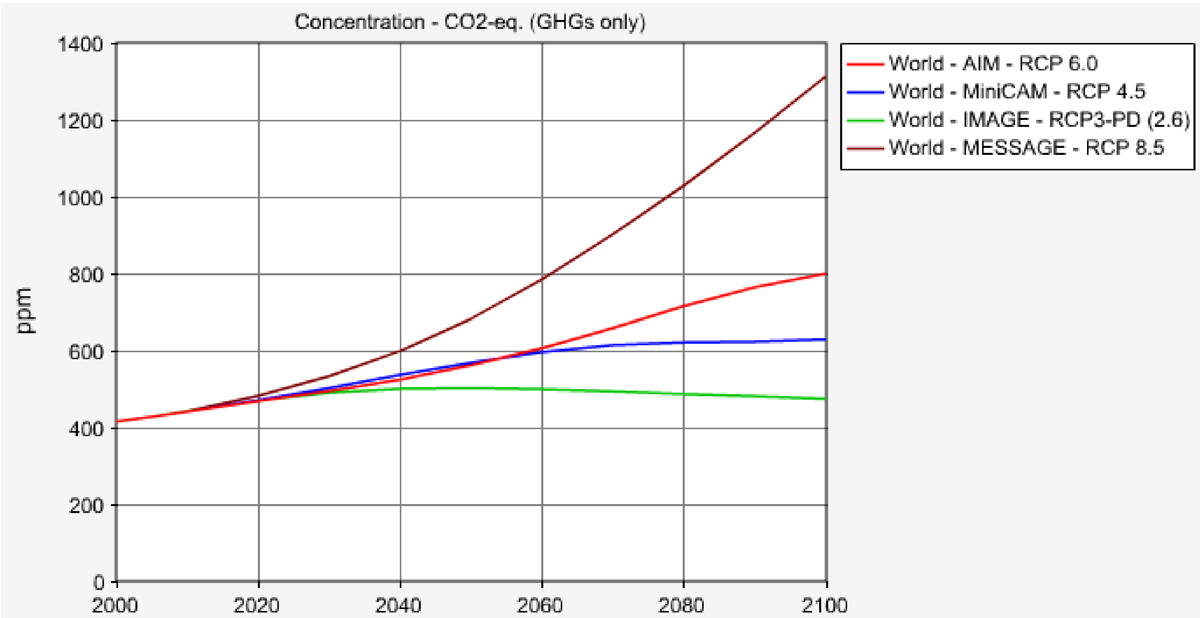
Recall that a version of the Energy Balance Model (EBM) seen in class in which CO_2 concentration can be varied is implemented in Python. It can be run in *integration* mode, for which the prognostic equations are numerically integrated to give the transient evolution of the model, and in *continuation* mode. The *integration* mode may be run from the `pc2.ipynb` notebook. The integration is set to start in 2007 from a CO_2 concentration of 370 ppm and a temperature of 288.45 K. The duration of the integration (in years) is adjusted with the slider. The `GHG Concentration Mode` is chosen with the buttons. The latter has two options:

1. `Rate`: A gradual increase of CO_2 concentration at a fixed rate given by the `Rate` parameter (in y^{-1}).
2. `Scenario`: Concentrations are prescribed by one of the RCP scenarios (see Fig. 1). The latter are chosen with the `Scenario` buttons.

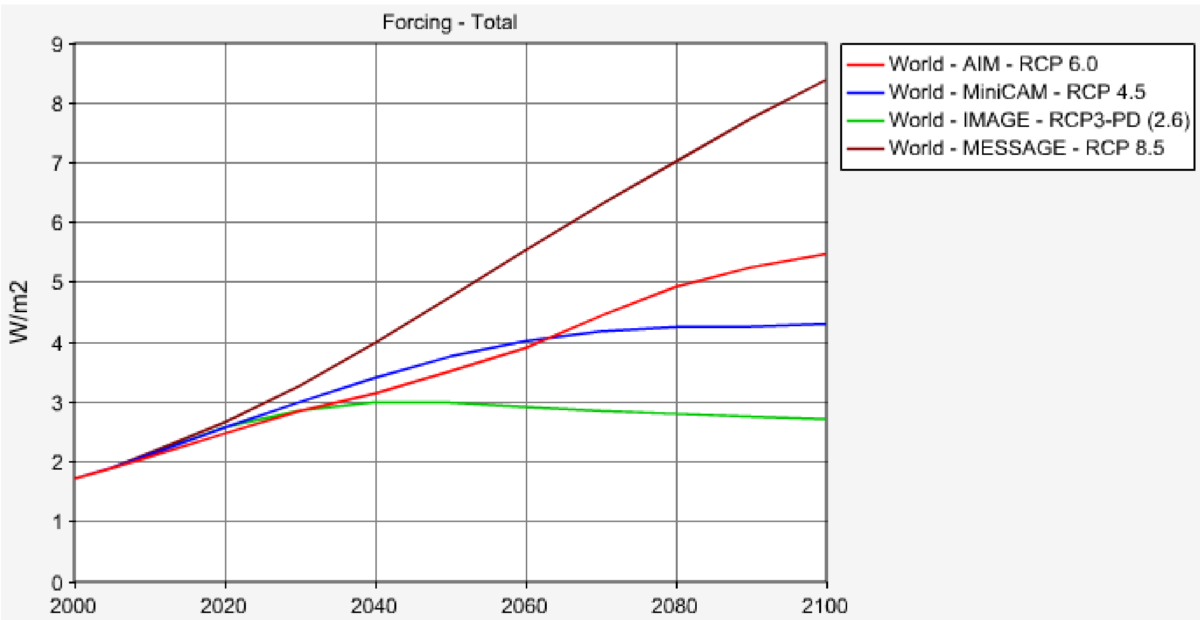
Q2 *Choose the mode of concentrations handling in order to compute the TCR numerically from the year 2007. How does the TCR compare with the ECS computed in PC1? Explain the origins of these differences from the results of the simulation in the resulting figures and from the physical mechanisms studied in class.*

2 Representative Concentration Pathways

Equivalent CO_2 concentration (aggregating all major Greenhouse Gases, GHGs) from the Representative Concentration Pathways (RCPs) via the `Scenario` parameter of the `pc2.ipynb` notebook. The RCPs equivalent concentration and total radiative forcing are given Figure 1.



(a) Equivalent CO_2 concentration for the different RCPs.



(b) Total radiative forcing for the different RCPs.

Figure 1: RCPs.

Q3 *Which of the scenarios experience a CO_2 doubling within the 21st century ($\pm 10 ppm$)? At what time? When does CO_2 doubling occur for the TCR scenario? How do these scenarios compare with the one used to compute the TCR?*

Article 2 of the Paris Agreement (UN, 2015) states that the latter aims at:

> Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

Q4 *The EBM is not resolving changes in GHG concentrations other than for CO_2. We then treat GHG concentrations from the RCPs as CO_2 concentration. Use the value of the TCR found in Question **Q2** to estimate the maximum global-mean surface temperature in the 21st century for the different RCPs. Considering that the global-mean temperature in 1750 and in 2007 were around* 287.55 K *and* 288.45 K, *respectively, and that CO_2 concentration in 2007 were about* 370 ppm, *which RCPs appear to be compatible with the objectives of the Paris Agreement?*

Q5 *Run the model in the* Scenario *mode selecting the different RCP scenarios with the buttons of the notebook to simulate the corresponding climate projections for the 21st century (after selecting a scenario click on* **`Run All Cells`** *to make sure that it is loaded). Give an update of your reply to Question **Q4** using the results of the simulations.*

Q6 *Increase the duration of the simulations to several centuries (CO_2 concentration up to 2300 are represented in Fig. 2. Beyond 2300, concentrations for each scenario are kept fixed to their 2300 value). From simulations using different RCPs what can you say about the long-term evolution of the climate? Discuss the concept of* commitment.

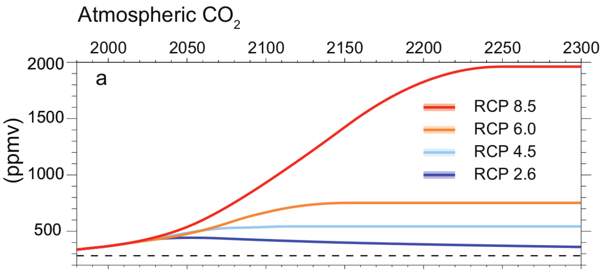


Figure 2: CO_2 concentration in the RCPs up to 2300. Source: Chap. 12.5.2 in IPCC (2014).

3 Remaining CO_2 budget

Q7 *Assuming that oceans continue to absorb about 22% of CO_2 emissions and vegetation about 25% (see Fig. 3), use the TCR to give an estimate (in* $GtCO_2$*) of the maximum amount of CO_2 that we can afford to emit in order to limit global warming to* 1.5 °C *compared to pre-industrial ;* 1 ppm *is equivalent to* 7.81 $GtCO_2$.

According to the *Global Warming of* 1.5 °C report of the IPCC (2018):

> Cumulative CO_2 emissions are kept within a budget by reducing global annual CO_2 emis-

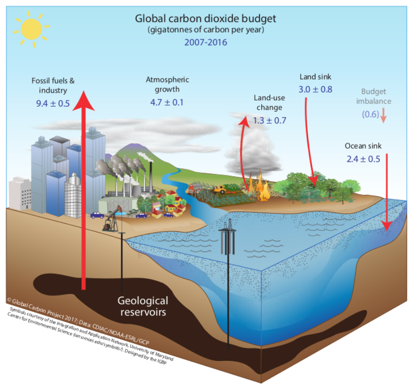


Figure 2. Schematic representation of the overall perturbation of the global carbon cycle caused by anthropogenic activities, averaged globally for the decade 2007–2016. The values represent emission from fossil fuels and industry (E_{FF}), emissions from deforestation and other land-use change (E_{LUC}), the growth rate in atmospheric CO_2 concentration (G_{ATM}), and the uptake of carbon by the sinks in the ocean (S_{OCEAN}) and land (S_{LAND}) reservoirs. The budget imbalance (B_{IM}) is also shown. All fluxes are in units of GtC yr^{-1}, with uncertainties reported as $\pm 1\sigma$ (68 % confidence that the real value lies within the given interval) as described in the text. This figure is an update of one prepared by the International Geosphere-Biosphere Programme for the GCP, using diagrams created with symbols from the Integration and Application Network, University of Maryland Center for Environmental Science (http://ian.umces.edu/symbols/), first presented in Le Quéré (2009).

Figure 3: Source: Le Quéré *et al.* (2018).

sions to net zero. This assessment suggests a remaining [emission] budget of about 420 $GtCO_2$ for a two-thirds chance of limiting warming to 1.5 °C, and of about 580 $GtCO_2$ for an even chance (medium confidence).

Q8 *Using the IPCC's carbon-budget estimate, how much can we afford to emit on average each year and for how long in order to have a chance to respect the objectives of the Paris Agreement?*

Q9 *GHG emissions per gas for the Annex I parties*[1] *and the European Union are given in Table 1 for the year 2016. Assuming that emissions remain fixed to the same value as 2016 throughout the 21st century, will the aims of the Paris Agreement be met?*

Gas	Annex I	EU (Convention)
CO_2	13.47416662	3.48905637
CH_4	2.37584356	0.44792733
N_2O	0.86557387	0.23271400

Table 1: GHG emissions per gas in 2016 ($GtCO_2$eq). Source `http://di.unfccc.int/comparison_by_gas`

Some references

- IPCC (2014). *Climate Change 2014: Assessment Report 5 — WGI: The Physical Science Basis*, `https://archive.ipcc.ch/report/ar5/wg1/`
- Chap. 1.2.4 IPCC, 2018, *Global Warming of 1.5 °C — Technical Summary*, `https://www.ipcc.ch/sr15/`
- Le Quéré, C., Andrew, R.M., Friedlingstein, P., Sitch, S., Pongratz, J., Manning, A.C., Korsbakken, J.I., Peters, G.P., Canadell, J.G., Jackson, R.B., Boden, T.A., Tans, P.P., Andrews, O.D., Arora, V.K., Bakker, D.C.E., Van Der Laan-Luijkx, I.T., Van Der Werf, G.R., Van Heuven, S., Viovy, N., Vuichard, N., Walker, A.P., Watson, A.J., Wiltshire, A.J., Zaehle, S., Zhu, D., 2018. Global Carbon Budget 2017. *Earth Syst Sci Data* 10, 405-448. `https://doi.org/10/gc5r9r`
- UN (2015) *PARIS AGREEMENT*, pp. 25, `https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement`

[1] Annex I Parties include the industrialized countries that were members of the OECD (Organisation for Economic Co-operation and Development) in 1992, plus countries with economies in transition (the EIT Parties), including the Russian Federation, the Baltic States, and several Central and Eastern European States.

Take-home message

- The ECS determines the eventual warming in response to stabilization of atmospheric composition on multi-century time scales, while the TCR determines the warming expected at a given time following any steady increase in forcing over a 50- to 100-year time scale.
- When GHG concentration increases the radiative forcing becomes positive, pushing the Earth system out of radiative equilibrium.
- Due to the inertia of the Earth system — associated with e.g. the ocean or ice sheets —, its return to equilibrium may take centuries or more.
- Today, we are commited to a climate change — e.g. sea-level rise — in the next centuries independently of our capacity to curb GHG emissions. Yet, increased emissions will continue to intensify climate change.
- In 2018, the remaining budget for a two-thrids chance of limiting global warming to 1.5 °C was about 420 $GtCO_2$, implying that CO_2 emissions should reach carbon neutrality in about 20 years from 2018 (IPCC, 2018).
- Today's world GHG emissions are incompatible with the Paris Agreement.

Correction

Q1 The ECS gives a measure of the change in temperature in response to a change in CO_2 concentration *at equilibrium*. However, the return to equilibrium of the climate system after a change in forcing is not instantaneous. Due to the slow response of components of the climate system such as the ocean or ice sheets, this return to equilibrium may take centuries or more. Thus, today and in the near future, the climate system is not expected to be at equilibrium.

The TCR is defined to take into account this transient response of the climate system to forcing and thus to better represent the climate change expected during the 21st century. On the other hand, contrary to the ECS which only depends on the initial and the last value of CO_2 concentration, the transient climate response depends on the actual concentration pathway to the doubling of CO_2. This is why the TCR is precisely defined for 1 %yr^{-1} increase in CO_2 concentration up to a doubling. Moreover, as for the ECS, a necessary condition for the TCR to be used to compute the response of the climate system for an other value of CO_2 change is for the global-mean surface temperature change to be proportional to the CO_2 change (linear relationship).

In other words, the ECS determines the eventual warming in response to stabilization of atmospheric composition on multi-century time scales, while the TCR determines the warming expected at a given time following any steady increase in forcing over a 50- to 100-year time scale.

Q2 According to Definition 1 of the TCR, the model should be integrated for CO_2 concentration rising by 1% each year (geometric increase). The `Rate` mode should thus be chosen and the value of the `Rate` parameter should be set to $0.01\,y^{-1}$. The TCR is then given by the difference ΔT^{ref} in temperature for an increase in CO_2 of $\Delta {CO_2}^{\text{ref}} = 2 \times 370 - 370 = 370\,\text{ppm}$.

Having set these parameters and run the model, we find a TCR of 1.34 K. This value is much smaller than that of 4.0 K found for the ECS. We can see from the third panel of the resulting figures that, the outgoing radiation fails to balance the incoming radiation. The outgoing radiation decreases with time because of the increase in CO_2 concentration (first panel). Thus, the model is out of radiative equilibrium. The only way for the outgoing radiation to rise up to the incoming radiation again is for temperature to increase. Yet, while temperature is increasing with time, temperature is smaller than the equilibrium temperature (first panel). This shows that temperature is not rising fast enough for a new radiative equilibrium to be reached. This delay in the rise in temperature may be explained from the slow response of some components of the Earth system, as modeled in the EBM. This is indeed the case of ocean temperature and ice-sheet extent which may take centuries to millennia to adjust.

Q3 Both RCP 6.0 and RCP 8.5 are associated with a CO_2-doubling around 2100 and 2060–65, respectively. With a rate of increase r of 1 % a year, the scenario used to compute the TCR leads to a CO_2-doubling after $\log 2 / \log(1 + r) = 70$ years. This scenario is thus relatively close to RCP 8.5.

Q4 Assuming a linear dependence of global-mean surface temperature with CO_2 concentration, the TCR may be used to quickly give estimates of the warming induced by a transient increase in CO_2 concentration. Using the TCR,

$$T(2100) = T(2007) + \frac{\text{TCR}}{\Delta {CO_2}^{\text{ref}}} \times (CO_2(2100) - CO_2(2007)).$$

For the RCP 8.5 scenario, we get $T(2100) = 288.5 + 1.34/370 \times (1300 - 400) = 291.8\,\text{K}$, so that temperature increase between 1750 and 2100 is of 4.1 °C. For the RCP 6.0, RCP 4.5 and RCP3-PD (2.6) scenarios, we get a temperature increase of 2.3 °C, 1.7 °C and 1.3 °C, respectively. Our calculations thus suggest that only the RCP3-PD (2.6) scenario is compatible with the below-1.5 °C objective, while the RCP 4.5 scenario is also compatible with the below-2 °C objective. However, the reliability of these results depends on:

- the accuracy of the TCR estimate,
- the closeness of the RCP scenarios to the one of the TCR,
- the linearity of the response of global-mean surface temperature to CO_2 changes (see Fig. 4).

These results may thus only be used to get a rough idea of the expected global-mean surface temperature increase with CO_2 concentration.

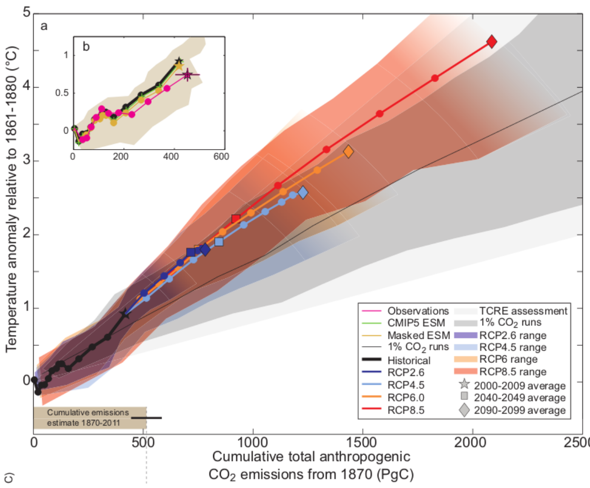


Figure 4: Source: Chap. 2 in IPCC (2018).

Note that, although weaker than geographic and seasonal variations in temperature to which humans and ecosystems have adapted to, a global warming of 4–5 °C corresponds to a heterogeneous increase in temperatures in space (amplification over land and towards the poles) and with seasons (stronger warming in winter), and is associated with large impacts in terms of extremes (droughts, floods, heat waves, hurricanes) and sea-level rise. The magnitude of this warming is comparable to that experienced when transiting from the last ice-age to our inter-glacial period (the Holocene), about 12000 years ago, and one needs to go back several million years in the past to find such warm temperatures.

Q5 The model yields values for the global-mean surface temperature in 2100 of 291.0 K, 290.0 K, 289.8 K and 289.1 K for the RCP 8.5, RCP 6.0, RCP 4.5 and RCP3-PD (2.6) scenarios, respectively. This corresponds to warming with respect to 1750 of 3.4 °C, 2.4 °C, 2.3 °C and 1.6 °C. The EBM thus gives a weaker warming for the two warmest scenarios and a stronger warming for the two other scenarios. The RCP 4.5 scenario is no longer compatible with the objectives of the Paris Agreement and the RCP3-PD (2.6) scenario is only in agreement with the below 2 °C objective. The EBM model is, however, a very coarse approximation of the Earth system. Moreover, even in the case of more realistic GCMs, several sources of uncertainties persist (clouds, aerosols, climate variability, etc.), thus motivating the use of a large panel of different models to estimate the uncertainty in the projected global warming.

Q6 Let us select, as an example, the RCP 6 scenario, for which CO_2 concentration stabilize around 2150, set the duration to 300 years and re-run all cells. The first panel of the resulting plot shows that temperature reaches an equilibrium after more than 300 years. Before that, it continues to increase even though CO_2 concentration is kept constant already since 2150. This is due to the inertia of some components of the climate system (see Fig. 5) and shows that even if efforts are made to cut net CO_2 emissions at a given date, global warming may continue to occur for centuries or more, unless more CO_2 is removed sufficiently quickly from the atmosphere (by which means?). This is what is called our *commitment* to global warming.

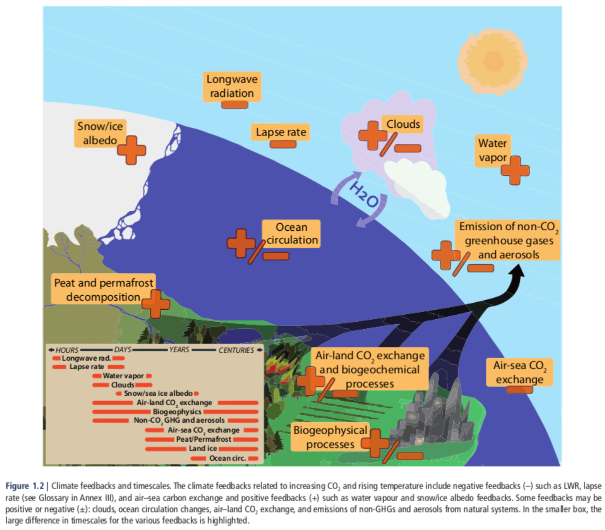


Figure 5: Source: Chap. 1 in IPCC (2014).

Definition 2. *Climate change commitment is defined as the future change to which the climate system is committed by virtue of past or current forcing.*

However, this commitment does not only concern the warming. Let us set the duration of the integration to 1000 years and re-run all cells. We can see from the plots that even though temperature is close to reaching an equilibrium after a few centuries, the ice extent, the ocean temperature and the sea level take more than a millennium to equilibrate. This is corroborated by the GCMs which project increasing sea levels of several meters during the next millennium (to be compared to the approximately 20 cm sea level rise which has occurred during the 20th century).

For quantitative results about the climate change we're committed to, see Chap. 1.2.4 in IPCC, 2018 and Chap. 12.5 in IPCC, 2014.

Q7 Assuming a linear dependence of global-mean surface temperature with CO_2 concentration, we invert the TCR to convert a temperature difference into a CO_2 concentration difference. A warming of about 1 °C has already occured. To limit future warming to about $\Delta T = 0.5\,°C$, the TCR yields a permissible increase in CO_2 concentration of

$$\begin{aligned}\Delta CO_2 &= \frac{\Delta {CO_2}^{ref}}{TCR} \times \Delta T \\ &= \frac{370}{1.34} \times 0.5 \\ &= 138\,\text{ppm}.\end{aligned}$$

To convert this concentration in CO_2 emissions, we need to take into account that about $22\% + 25\% = 47\%$ of these emissions are absorbed by oceans and land (to the extent that these sinks are preserved) and convert ppm in $GtCO_2$, to wit

$$\begin{aligned}\Delta CO_2 \text{ emissions} &= 137\,\text{ppm}/0.47 \times 7.81 \\ &= 2.3 \times 10^3\,GtCO_2.\end{aligned}$$

This simple calculation does not, however, account for the warming induced by other GHGs, for uncertainties in the TCR and in the fraction of CO_2 emissions that end up in the atmosphere, and for the extra warming we are commited even after carbon neutrality has been reached.

Q8 Let us assume that we have a remaining CO_2-emission budget of 420 $GtCO_2$. If we want to have constant net emissions from 2019 to 2100, year at which net emissions are abruptly stopped, the world may emit $420/(2100-2019) = 5.2\,GtCO_2$ per year. If instead we want constant net emissions up to 2050, the world may emit $420/(2050-2019) = 14\,GtCO_2$ per year. Considering the cumulative nature of the effect of CO_2 emissions of the climate, the more we continue to emit today, the less we should emit tomorrow.

Q9 Even if we consider CO_2 emissions only, we can see from the emission data in Table 1 and the result of Question **Q8** that Annex I parties alone emitted in 2016 as much as what would allow us to remain below a 1.5 °C warming with a two-third chance, if net emissions were kept fix until 2050 and then dropped to zero net emissions. This is without considering emissions from other parties and their growth. Although more elaborate emission scenarios are needed to take into account the possible pathways to a carbon-neutral world, this shows the magnitude of the effort that needs to be done to achieve this objective.