Protocol - Adaptive Emission Reduction Approach (AERA)

1. General idea

The adaptive emission reduction approach (AERA) aims to quantify CO_2 forcing equivalent (CO_2-fe) emission reductions every five years following the stocktake mechanism implemented in the Paris Agreement (Terhaar, J., T. L. Frölicher, M. Aschwanden, P. Friedlingstein, F. Joos, Adaptive emission reduction approach to reach the Paris Agreement temperature targets, *Nature Climate Change*, in review). Every five years, the AERA estimates the necessary emission reductions for a chosen temperature target only based on observations of the past annual global mean surface temperatures (GMST), globally averaged annual CO_2 concentrations, past CO_2 emissions, and radiative forcing from non-CO_2 forcing agents. The radiative forcing from non-CO_2 forcing agents is used to calculate CO_2-fe emissions, i.e., the amount of CO_2 emissions over time that would lead to the observed radiative forcing time series.

The AERA consists of three main steps: (1) determining the past anthropogenic warming and hence the remaining warming allowed, (2) estimating the remaining CO_2-fe emission budget (REB), and (3) proposing a future CO_2-fe curve.

First, the anthropogenic warming is calculated from observed global mean surface temperature (GMST) time-series using the past radiative forcing (RF) of all relevant forcing agents. The RF from CO_2 is estimated based on the time series of annual global CO_2 concentration. This approach removes temperature changes from natural internal variability and natural external forcing, such as volcanic eruptions and changes in solar activity, by fitting an Impulse-Response Function to the RF and GMST time-series, only leaving the anthropogenic contribution to the observed warming.

Second, the REB of CO_2-fe emissions that can still be emitted before the target temperature will be reached is estimated using the transient climate response to cumulative emissions (TCRE) up to the current year, defined as the ratio of past warming and past cumulative CO_2-fe emissions. The REB is estimated as the remaining warming until the temperature target is reached divided by TCRE. Here, we rely on the linear relationship between cumulative CO_2-fe emissions and warming over the past and the near-future.

When quantified, the REB of CO_2-fe emissions is distributed over the future years in a third step using a cubic polynomial function. Many possible CO_2-fe emission curves for the future may exist for one specific REB with different economic and political assumptions. For simplicity, we chose the parameters of the cubic function by minimizing the curvature, i.e., the sum of the absolute annual rates of change of the slope of the CO_2-fe emissions curve (2nd derivative) until zero-emissions are reached. Thereby, we assume that relatively small changes over a longer time starting now, like in the emission pathways of the Shared Socioeconomic Pathways, are more likely to be implemented than a strong and abrupt reduction in CO_2-fe emission in the future. It may happen that the curve with the smallest curvature has positive emissions that are later compensated by negative emissions, which would effectively result in a temporary temperature overshoot. To avoid such an overshoot, we also minimized exceedance emissions, i.e., negative emissions if the REB is still positive or positive emissions if the REB is negative. A negative REB may, nevertheless, still occur if the anthropogenic warming or the TCRE turns out to be larger than estimated in the previous stocktakes.

The successive application of the AERA every five years adjusts the future CO_2-fe emission curve each time based on the most up-to-date and best observations of GMST, RF, and CO_2-fe emissions. If the anthropogenic warming will turn out to be different than anticipated by the time of the next stocktake, the adaptive nature of the AERA will adjust future emissions successively.

The AERA has been tested intensively using the Bern3D EMIC in many different configurations (e.g. varying climate sensitivity, etc.) as a substitute for the real world.

2. Difference to prescribed scenarios

So far policymakers were presented with a limited number of socio-economic scenarios with assumptions of emissions or concentrations for the whole 21st century and sometimes beyond. By using different Earth system models, climate modelers then estimated the expected temperature increase for each scenario, yielding a best guess for the temperature for given emissions or concentration trajectories for several forcing agents. However, the estimated warming still has substantial uncertainties.

Instead of relying on socio-economical scenarios, the AERA provides periodically updated CO_2-fe emissions time series for policymakers that will allow reaching a chosen temperature target. The often large uncertainty in climate projections is side-stepped by the adaptive approach: proposed emission trajectories are periodically adjusted based on the most up-to-date observations, and the temperature target will be reached in the end when following the proposed CO_2-fe emissions time series.

Moreover, policy makers now get the reductions in CO_2-fe emissions and can distribute these CO_2-fe emissions reductions across the number of forcing agents (CO_2, methane, …) as it fits best at a given stocktake, leaving more freedom of choice and do not only get presented a limited number of scenarios. The split of emission reductions across different agents can be computed using the Global Warming Potential with a time horizon of 100 years (GWP_{100}), the metric of choice by the UNFCCC, e.g., in the Kyoto basket approach. In other words, the GWP_{100} metric can be used to implement the proposed CO_2-fe emission reductions and no change in the UNFCCC regulations and the Paris Agreement are needed to implement the suggested CO_2-fe emissions reductions.

3. Reasoning for Earth system model simulations

The simulations with the Earth System Models (ESMs) have two main purposes. First, they demonstrate that the AERA does not only allow reaching the chosen temperature target in a model of intermediate complexity (Bern3D), as demonstrated in Terhaar et al. (in review), but also works in more complex models. Thus, the ESM serves as a substitute for the real word implementation of the AERA in future decades; simulated temperatures and parameters are used instead of observation-based estimates. Initial testing with the fully coupled Earth system model GFDL ESM2M shows that the AERA indeed works with full ESMs. Second, the simulations should provide an estimate of emission pathways that are compatible with certain temperature targets such as 1.5°C and 2.0°C. This will allow assessing Earth System changes that are associated with the pathways to these targets. Surface ocean pH (i.e., acidity) projections, for example, have almost no uncertainty in concentration-driven ESM projections because changes in surface ocean pH follow closely the changes in the prescribed atmospheric CO_2 concentration in RCPs and SSPs. However, if all models reach the same temperature target with the AREA, atmospheric CO_2 trajectories in each model will differ and result in a wider range of surface ocean pH projections that yield a more realistic uncertainty of the ocean acidification associated with a certain temperature target.

4. Simulation strategy

Here, we describe the implementation of the AERA in ESMs. The simulation setup can be divided in three parts, (A) the 'historical period' from 1850 to 2025, (B) the 'AERA period 1' starting in 2026 with the emission reductions implemented that were estimated by the AERA in 2025 and are re-evaluated by the AERA every 5 years, and (C) the 'AERA period 2' from 2100 to 2150 using the AERA to ensure that the temperature stabilizes (Fig. 1). The applied forcing during these three parts is described in detail below.

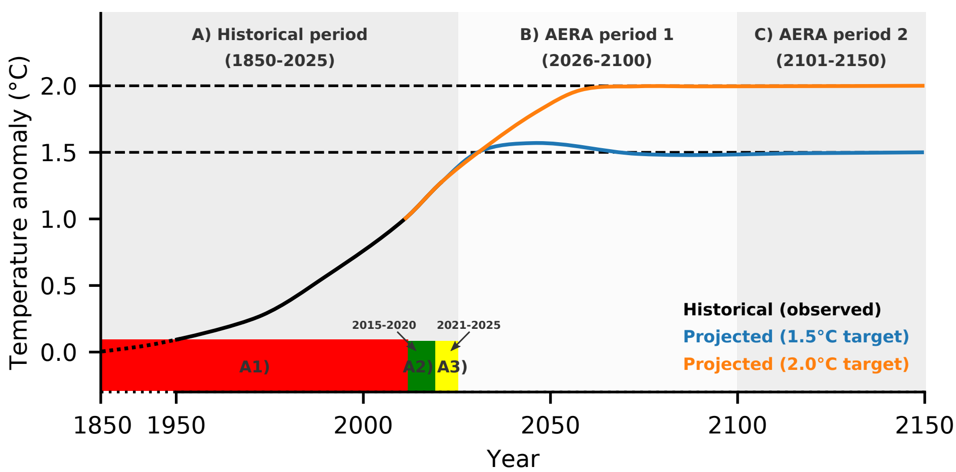

Fig. 1: Schematic of the three different AERA periods. The scheme shows idealized temperature time series for the 1.5°C (blue) and 2.0°C (orange) temperature targets and the three simulation periods.

A) Historical period (1850-2025)

A1) 1850-2014:
- Historical fossil fuel CO_2 emissions (CMIP6 protocol for emission driven scenarios)
- Non-CO_2 forcing agent concentrations (CMIP6 protocol)
- Land use and land cover (CMIP6 protocol)

A2) 2015-2020:
- Historical fossil fuel CO_2 emissions (Global Carbon budget)
- Non-CO_2 forcing agent concentrations (SSP1-2.6)
- Land use and land cover change (SSP1-2.6)

A3) 2021-2025:
- Fossil fuel CO_2 emissions (NDC – Nationally determined contributions)
- Non-CO_2 forcing agent concentrations (SSP1-2.6)
- Land use and land cover (SSP1-2.6)

B) AERA period 1 (2026-2100)

- 2026-2030:
  - CO_2 emissions determined from the adaptive emissions reduction algorithm (AERA) in 2025
  - Non-CO_2 forcing agent concentrations (SSP1-2.6)
  - Land use and land cover (SSP1-2.6)
- 2031-2035:
  - CO_2 emissions determined from the adaptive emissions reduction algorithm (AERA) in 2030
  - Non-CO_2 forcing agent concentrations (SSP1-2.6)
  - Land use and land cover (SSP1-2.6)

- Repeating until 2100

C) AERA period 2 (2101-2150)

- 2101-2105:
  - CO_2 emissions determined from the adaptive emissions reduction algorithm (AERA) in 2100
  - Non-CO_2 forcing agent concentrations (if possible: constant values from year 2100 under SSP1-2.6; if not possible: follow SSP1-2.6 extension)
  - Land use and land cover (if possible: constant values from year 2100 under SSP1-2.6; if not possible: follow SSP1-2.6 extension)

- Repeating until 2150 or longer (to be sure that the temperature is really stabilized)

Non-CO_2 forcing agents also include aerosols. Please note that the spatially resolved CO_2 emission input file for the ESM after 2014 needs be prepared by yourself as the AERA 'only' provides a global, annual CO_2 emission number. To do so, please divide the spatially resolved, monthly CO_2 emission file from 2014 (the last one of the historical period) in each cell *(x,y)* and in each month (*m*) by the total annual CO_2 emissions in year 2014 and multiply it by the prescribed CO_2 emissions for the year you need it for (e.g. for year 2015). Here is an example for the year 2015:

$$E_{CO_2}^{2015}(x,y,m) = \frac{E_{CO_2}^{2015}(global)}{\sum_m \int E_{CO_2}^{2014}(x,y,m)dxdy} * E_{CO_2}^{2014}(x,y,m)$$

By doing so, we assume that the spatial and monthly distribution does not change. This assumption has negligible impacts on climate and the carbon cycle, due to the relatively fast transport of CO_2 in the atmosphere.

Please use the land use cover from 2100 for all years afterwards assuming no change in land use and use the same concentrations for non-CO_2 radiative agents as in 2100 if possible. If that is not possible, please use the extension of SSP1-2.6. Please contact us if none of the proposed solutions works for you.

5. Relative and absolute temperature target

Following this strategy, each model will have a different anthropogenic warming in 2025 and hence a different remaining allowable warming until the respective temperature target, e.g., 1.5°C is reached. Therefore, the remaining warming can be calculated in the AERA with two options:

- Option 1 ('relative' temperature target): Here, the remaining warming is calculated in 2020 based on observations. Step one of the AERA gives an anthropogenic warming of 1.22°C in 2020 when applied to observations. Therefore, the remaining allowable warming is 0.28°C for the 1.5°C target and 0.78 for the 2°C target. The AERA thus calculates the temperature target in each model based on the models anthropogenic warming in 2020 plus the remaining allowable warming in 2020 estimated from observations (Fig. 2). In other words, each model estimates the emission curve over the 21st century for the same remaining allowable warming.

- Option 2 ('absolute' temperature target): Here, the remaining warming is calculated in 2020 based on the ESM simulation output and does not account for observation. The anthropogenic warming in 2020 is calculated from the modeled change in GMST relative to 1850-1900 using the prescribed past radiative forcing of all relevant forcing agents. In our example in Figure 2, we assume that the model simulates an anthropogenic warming of 0.92°C in year 2020, i.e., an underestimation of 0.3°C compared to the observation-based estimate. Therefore, the remaining allowable warming is 0.68°C for the 1.5°C target and 1.18°C for the 2°C target. The approach for this option 2 is identical to option 1 except that the modeled temperature is used instead of the observed temperature.

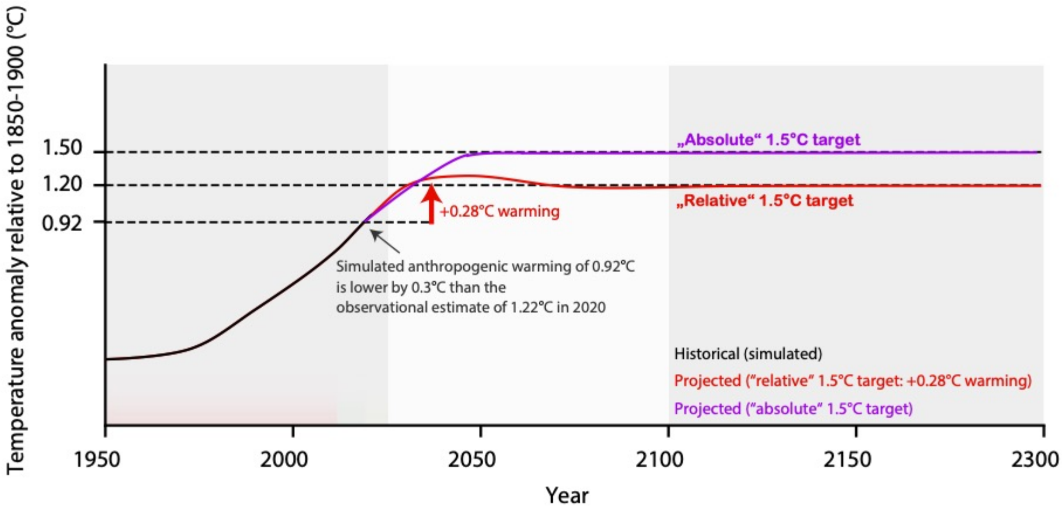

Fig. 2: Schematic of the 'absolute' and 'relative' temperature targets. The schematic shows idealized temperature time series for the relative (red) and absolute (magenta) 1.5°C temperature target. In this idealized case, the model has 'only' warmed by 0.92°C until 2020 compared to the simulated average temperature from 1850 to 1900. For the relative target, the remained warming estimated from observations (0.28°C) is added to the realized warming in 2020, so that the relative temperature target is at 1.2°C. The absolute temperature target does not account for observations and defines the temperature target only with respect to the simulated average temperature from 1850 to 1900.

6. Executing the AERA algorithm

The AERA is implemented as an installable python module called *aera*. The module can be installed by cloning the official GitHub repository (https://github.com/Jete90/AERA) and then running "pip install ." inside the cloned directory (see README.md in the repository for more information).

Mainly two functions of the *aera* module are used by the end user:

- aera.get_base_df(): This function provides a template pandas.DataFrame (used as the data container for all time series) which is provided as an input parameter to aera. get_adaptive_emissions().
- aera.get_adaptive_emissions(): This function calculates and returns near future fossil fuel emissions. As input, it requires several time series and constants as described below.

To simulate „AERA period 1" and „AERA period 2" (see section 4), new near future fossil fuel emissions must be calculated every five years (2025, 2030, …) with the AERA. These emissions from the AERA are then be provided to the model. To achieve this, each modeling group has to write a script that calls aera.get_adaptive_emissions and then generates a CO_2 emission file for the ESM based on the annual emission output by the aera.get_adaptive_emissions.

To get started, first read through the documentation in the official GitHub repository (README.md) and then have a look at the example and template scripts.

- **Required time series input for the AERA at each stocktake/iteration**

  The required input time series for the AERA is divided into two categories, (A) input from the respective ESM and (B) prescribed input as provided through this protocol. The time series are given to the function in form of a pandas dataframe that is created within the script that calls the function. An example is attached to the code.

  A) Input from the ESM

  - **Annual timeseries of global mean surface temperature (GMST) from 1850 to the year of the stocktake [Kelvin].** This timeseries is used to derive the anthropogenic warming in combination with the radiative from CO_2 and non-CO_2 forcing agents. You can use here also the global surface air temperature (globally averaged 2-m temperature). The trends are usually almost identical.

  - **Annual timeseries of global mean atmospheric CO_2 concentration [ppm]**. This time series is used to estimate the radiative forcing from CO_2 and hence the anthropogenic warming.

  B) Prescribed input

  - **Annual timeseries of global CO_2 emissions from 1850 to the year of the stocktake [Pg C yr^{-1}].** This timeseries is prescribed as defined in section 4 and hence extends itself adaptively over time after 2025. As the AERA yields the CO_2-fe emissions for the next five years, the CO_2 emissions are calculated as the difference of the AERA estimated CO_2-fe emissions and the prescribed CO_2-fe emissions derived from land use change and non-CO_2 radiative agents. It is used to estimate the TCRE and the REB.

  - **Annual timeseries of the aggregated radiative forcing of all non-CO_2 radiative agents from 1850 to the year of the stocktake [W m^{-2}].** It is prescribed as in section 4 following the historical time series until 2014 and SSP1-2.6 afterwards. This timeseries is used to estimate the anthropogenic warming and to derive CO_2-fe emissions from non-CO_2 forcing agents. The timeseries from the RCP/SSP databases is provided. If your model can estimate the radiative forcing from all non-CO_2 radiative agents from 1850 to 2100, you should use that time series and constant radiative forcing after 2100. The latter is the preferred approach.

- **Annual timeseries of CO_2-fe emissions from non-CO_2 radiative agents from 1850 to the year of the stocktake [Pg C yr^{-1}].** This time series is derived from the annual timeseries of the aggregated radiative forcing of all non-CO_2 radiative agents. This timeseries is used to estimate the TCRE and REB. The emissions corresponding to the timeseries from the RCP/SSP databases are provided. If you use a model specific time series for the radiative forcing of non-CO_2 forcing agents, please contact us and we will calculate the corresponding CO_2-fe emissions for you.

- **Annual timeseries of CO_2 emissions from land use change and land cover [Pg C yr^{-1}].** This time series is used to calculate the TCRE and REB. It should be calculated as the difference in carbon land-air flux between two concentration-driven simulations following historical+SSP1-2.6 CO_2 concentrations, one with land use change activated and without. The air-land and air-sea carbon flux have thus no influence on the atmospheric CO_2 concentrations. As the atmospheric CO_2 concentration is the same in both runs, the difference in land-air fluxes stems mainly from direct land use change emissions (we neglect in this way some feedbacks between land use emissions CO2 and climate influencing LU emissions). This is the preferred approach. If this is not possible, the CO_2 emissions from land use change calculated by the Bern3D model can be used and are provided.

- **Annual timeseries of atmospheric N_2O [ppb].** This time series is used to calculate the radiative forcing of anthropogenic CO_2 that is due to the overlap of CO_2 and N_2O (AR6 WG1 IPCC, Table 7.SM.1).

- **Required parameters**

  - The target temperature described as a temperature anomaly (temp_target_rel). This must be set by the user.

  - The year of the stocktake (year_x). This needs to be set to the year of the stocktake at each time the AERA is applied. It hence changes from 2025 to 2030 to 2035 to … 2150.

  - The year in which the historical simulation has started. This is usually 1850 but can be later, for example for the GFDL models in CMIP5.

  - The pre-industrial CO_2 concentration in the model [ppm]. In Bern3D this is 287.05 ppm.

  - The AERA creates 3 outputfiles with meta data that allows to recalculate the different steps of the AERA at each iteration. One file is a netcdf file and the other two are text files. All files are updated at each iteration and hence grow with time. The location of the files and the name of the netcdf file needs to be precisely specified (/path/*nc). The text file names do not need a name as they are generated automatically based on the netcdf file as follows: /path/*nc.scalar.csv and /path/*nc.timeseries.csv.

- Choose between a relative temperature target based on the estimated remaining warming from observations (option 1) or an absolute temperature target based on the warming in the model (option 2).

7. Output of the AERA at each iteration

The AERA calculates the future CO_2-fe emissions time series for the years following the year of the stocktake. Within the algorithm, the CO_2-fe emissions from non-radiative forcing agents and from land use change are already subtracted. Therefore, the effective output is 'only' the CO_2-emissions per year. For the stocktake in 2025, for example, the CO_2-emissions from 2026 onwards are given as output.

To avoid model errors with boundary conditions (such as calculation CO_2 emissions in the model in December 2030 by making an interpolation of annually averaged prescribed emissions in 2030 and 2031), the CO_2-emissions file contains CO_2 emissions for an additional 5 years after zero emissions is reached. 5 additional years were chosen arbitrarily here; please edit this file so that it can be read in by the respective ESM.

8. Simulations that should be delivered by all participants

To participate in the AERA inter-model comparison project, the participants are asked to perform the following mandatory simulations (Tier 1):

- Two simulations with a temperature target of 1.5°C ('absolute' and 'relative' temperature target) till 2100 but strongly encouraged to run to at least 2150

- Two simulations with a temperature target of 2.0°C ('absolute' and 'relative' temperature target) till 2100 but strongly encouraged to run to at least 2150

In addition, the following simulations are optional (Tier 2):

- Two simulations with a temperature target of 1.75°C ('absolute' and 'relative' temperature target)

- Two simulations with a temperature target of 2.5°C ('absolute' and 'relative' temperature target)

  - Four more simulations with a temperature target of 2.0°C (‘absolute’ and ‘relative’ temperature target) (slightly perturbed initial conditions)

9. Necessary output from model simulations

From each simulation, the following output must be saved:

- AERA output and meta data files as described in section 6.
- Standard CMIP output as netcdf files; CMORIZED;
- Text files of global annual mean quantities (if not specified otherwise):
  - Atmosphere Amon:
    - tas: Near-Surface air temperature [K]
    - pr: Precipitation [mm yr^{-1}]
    - rsdt: TOA incident shortwave radiation [Wm^{-2}]
    - rsut: TOA outgoing shortwave radiation [Wm^{-2}]
    - rlut: TOA outgoing longwave radiation [Wm^{-2}]
    - rtmt: Net downward radiative flux at top of model, Wm^{-2}
    - co2: Mole fraction of CO_2 in air [ppm]
    - fco2antt: Carbon mass flux into atmosphere due to all anthropogenic emissions of CO_2 [kg C m^{-2} s^{-1}]
    - fco2fos: Carbon mass flux into atmosphere due to fossil fuel emissions of CO_2 [kg C m^{-2} s^{-1}]
  - Ocean Omon:
    - tos: Sea surface temperature [K]
    - hfds: Downward heat flux at sea water surface, [Wm^{-2}]
    - fgco2: Surface downward flux of total CO_2 [Pg C yr^{-1}]
    - intpp: Vertically integrated total primary (organic carbon) production by phytoplankton [Pg C yr^{-1}]
    - o2: Dissolved oxygen concentration (global integrated) [Pmol]
    - o2 (200m-600m): Dissolved oxygen concentration within the thermocline (averaged 200m-600m) [mmol m^{-3}]
    - ph (surface): Negative log of hydrogen ion concentration [-]
    - no3 (0-100m): Euphotic zone no3 concentration (averaged 0-100m) [mol m^{-3}]
    - epc100: Downward flux of particulate organic carbon at 100m [PgC yr^{-1}]
    - monthly area of Arctic sea ice (siconc > 0.15) [km^2]
    - monthly area of Antarctic sea ice (siconc > 0.15) [km^2]

- Land Omon:

    - gpp: Carbon mass flux out of atmosphere due to gross primary production on land [PgC yr^{-1}]
    - npp: Carbon mass flux out of atmosphere due to net primary production on land [PgC yr^{-1}]
    - rh: Carbon mass flux into atmosphere due to heterotrophic respiration on land [PgC yr^{-1}]
    - nbp: Carbon mass flux out of atmosphere due to net biospheric production on land [PgC yr^{-1}]
    - cland: Total carbon in all terrestrial carbon pools [PgC]
    - fFireAll: Carbon mass flux into atmosphere due to CO_2 emissions from fire including all sources [PgC yr^{-1}]
    - cSoil: Carbon mass in model soil pool [PgC]
    - cVeg: Carbon mass in vegetation [PgC]
    - cLitter: Carbon mass in litter Pool [PgC]

10. Provided files:

To execute the AERA algorithm, several files are provided:

- **Time series of annual mean CO_2 fossil fuel emissions [Pg C yr^{-1}]**: Emissions until 2020 are from the Global Carbon Project and emissions from 2021 to 2025 are estimated based on NDCs. The file contains constant emissions from 2026 onwards, but only to avoid computational problems. These numbers are not used. Please rename this file for each run as the emissions will be updated at each stocktake by the AERA and the file will be overwritten. Please also check if the emissions until 2014 are consistent with the prescribed emissions by the CMIP protocol. If not, please use the prescribed emissions until 2014 and replace them in this file accordingly (Filename: co2_ff_GCP_plus_NDC_v1.dat).

- **Radiative forcing from non-CO_2 forcing agents [W m^{-2}]**: Historical values are extracted from the RCP database and values from 2010 onwards are taken from the SSP database. The file contains four columns: Year, total RF, RF from CO_2, and the difference (non-CO_2) (Filename: nonco2_rf_ssp126_v1.dat). If this can be generated by your model as described above (point 6b), please use that instead.

- **CO_2-fe emissions from non-CO_2 forcing agents [Pg C yr^{-1}]**: CO_2-fe emissions derived from the radiative forcing time series for non-CO_2 forcing agents (Filename: nonco2_emis_ssp126_v1.dat). If the radiative forcing from non-CO_2 forcing agents can be generated by your model as described above (point 6b), we will calculate the CO_2-fe emissions from non-CO_2 forcing agents for you. Please contact us in this case.

- **CO_2 emissions from land use change [Pg C yr^{-1}]**: CO_2 emissions derived from land use change by the Bern3D model. If this can be generated by your model as described above (section 6b), please use that instead (Filename: lu_emis_ssp126_bern3d_v1.dat).