Learning about the Global Warming Potential through Programming - Understanding by Quantifying and Playing

by Mike Müller

Climate Change - Global Warming

- Human impact on our climate
- Increases the (necessary) greenhouse effect
- Greenhouse gases (GHG)
    - Water vapor and clouds (36 - 72%)
    - Carbon dioxide (CO_2) from burning fossil fuels and land use (9 - 26%)
    - Methane from oil and natural gas production, bogs and swamps, agriculture (4 - 9%)
    - Nitrous oxide (N_2O) from Nitrogen fertilizing
    - Many more (35 substances, Ozone, CFC, HCFC), example: air condition fluids

Focus on Carbon dioxide (CO_2) and Methane (CH_4)

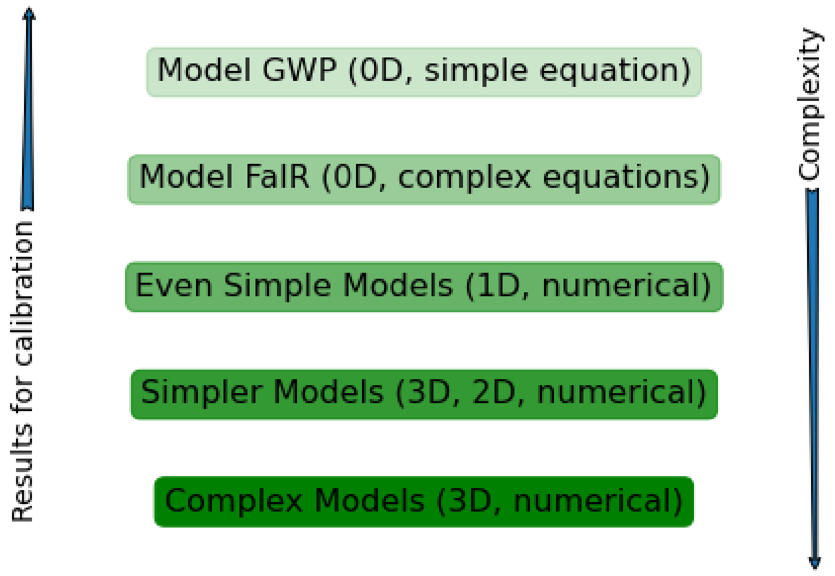
- CO_2 - long-lived climate pollutant (LLCP)
    - atmospheric lifetime of 100s to 1,000s of years
- CH_4 - short lived climate pollutant (SLCP)
    - atmospheric lifetime of 12 ± 3 years

RCP - Representative Concentration Pathways

- Historical data plus projections from 1765 to 2300
- Combination of several estimates for historical emissions
- Plus 4 different Integrated Assessment Models

Radiative forcing [W/m_2]	**Explanation**
2.6	strong mitigation scenario, net_zero CO_2 by 2100 temperature increase < 2K
4.5	temperature increase 2 - 3 K by 2100
6.0	emissions peak around 2080, then decline
8.5	"business as usual" - worst case scenario, temperature increase 4.5 K by 2100

Types of Climate Models



Simulate Temperature with FaIR

- Finite Amplitude Impulse-Response simple climate-carbon-cycle model
- Calculate past and projected temperature increase caused by Methane **only**

In [72]:

```
import numpy as np

from fair.forward import fair_scm
from fair.RCPs import rcp26, rcp45, rcp6, rcp85


def calc_temp_increase():
    forcings = {
        'RCP 2.6': rcp26.Forcing.forcing,
        'RCP 4.5': rcp45.Forcing.forcing,
        'RCP 6': rcp6.Forcing.forcing,
        'RCP 8.5': rcp85.Forcing.forcing
    }

    temps = {}
    for name, forcing in forcings.items():
        noco2 = np.zeros_like(forcing[:, 9])
        *_, temp = fair_scm(useMultigas=False, emissions=noco2, other_rf=forcing[:,9] * 1.65)
        temps[name] = temp
    temperature_increases = pd.DataFrame(temps)
    temperature_increases .index = forcing[:, 0]
    return temperature_increases
```

Greenhouse Warming Potential (GWP)

- Normalization to a time period of 20, 100, or 500 years

Gas	GWP_{20}	GWP_{100}	GWP_{500}
CO_2	1	1	1
CH_4	84	28	7.6

- Carbon dioxide equivalent CO_2-e (sometimes CO_2-C_{eq})
- Most used is GWP_{100}
- Therefore, we focus on this

Problems with GWP

- Deeply embedded in climate policy
- But leads to wrong conclusions:
    - Falling SLCP emissions lead to **falling** global temperatures
    - GWP-based calculations show **raising** global temperatures
- Complex, physical-based climate models confirm this
- Much simpler tools like GWP are very useful because complex models are very resource-intensive

GWP* and CO_2-e

- Emissions based on GWP:

$$E_{CO_2\text{-}e} = E_{SLCP} * GWP_H$$

- Emissions based on GWP*:

$$E_{CO_2\text{-}e*} = \frac{\Delta E_{SLCP}}{\Delta t} * GWP_H * \mathrm{H}$$

Reading data with pandas

In [73]:

```
import pandas as pd

def read_data(file_name, sep = ',', skiprows=36, index_col=0, species='CH4',
              unit_converter=0.001):
    """"""
    data = pd.read_csv(file_name, sep=sep, skiprows=skiprows, index_col=index_col)
    return data[species] * unit_converter
```

Calculate GWP*

In [74]:

```python
GWP100_CH4 = 28

def calc_gwpstar_emissions(emissons, gwp_h=GWP100_CH4, h=100, delt=20):
    """
    Calculation of GWP* from GWP

    Based on Allen et. al 2018


    :param: emissons pandas Series with emission values, index is year
    :param: gwp_h GWP for `h` years
    :param: h time in years
    :param: delt delta tine in years
    :return: GWP*
    """
    emissons_0 = emissons.iloc[:-delt]
    emissons_1 = emissons.iloc[delt:]
    emissons_1.index = emissons_0.index  # assume pandas Series
    return ((emissons_1 - emissons_0) / delt) * gwp_h * h
```

Compute GWP and GWP* in a DataFrane

In [75]:

```
def make_gwp_df(file_name, start_year=1765, end_year=2500, base_year=1765):
    emissons = read_data(file_name)
    start_index = start_year - base_year
    end_index = end_year - base_year + 1
    e_co2_eq = (emissons * GWP100_CH4)[start_index:end_index]
    e_co2_eq_star = calc_gwpstar_emissions(emissons)[start_index:end_index]
    e_co2_eq.name = '$CH_4$ GWP'
    e_co2_eq_star.name = '$CH_4$ GWP*'
    df = pd.DataFrame([e_co2_eq, e_co2_eq_star]).T
    df.index.name = 'Years'
    return df
```

Plot

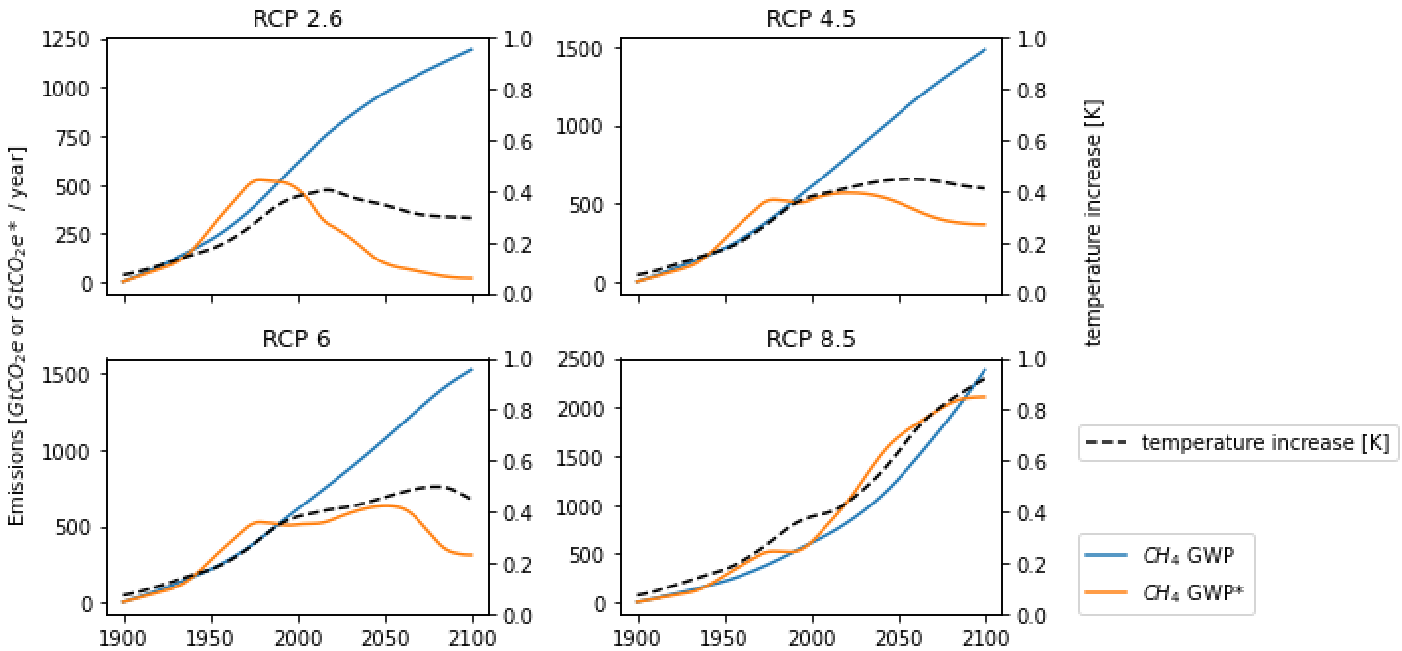
In [76]:

```
from matplotlib import pyplot as plt

def plot_one(ax, name, path, make_df, temp_increases):
    start_year=1900
    end_year=2100
    df = make_df(path, start_year=start_year, end_year=end_year)
    ax1 = df.cumsum().plot(ax=ax, title=name, legend=None)
    ax2 = ax1.twinx()
    ax2.set_ylim((0, 1))
    temp_increases[start_year:end_year].plot(ax=ax2, color='black', style='--',
                                              label='temperature increase [K]')
    return ax1, ax2

def plot_all(rcp_scenarios,  make_df=make_gwp_df):
    temperatures = calc_temp_increase()
    fig, subs = plt.subplots(2, 2)
    fig.set_size_inches(10, 5)
    subs_flat = subs.flat
    for name, path in rcp_scenarios.items():
        sub = next(subs_flat)
        ax1, ax2 = plot_one(sub, name, path, make_df=make_df,
                            temp_increases=temperatures[name])
    ax1.legend(loc=(1.2, 0))
    ax2.legend(loc=(1.2, 0.6))
    fig.text(0.75, 0.5, 'temperature increase [K]', rotation='vertical')
    fig.text(-0.01, 0.25, 'Emissions [$GtCO_2e$ or $GtCO_2e*$ / year]', rotation='vertical')
    fig.tight_layout()
```

Plot all

In [77]:

```
plot_all(rcp_scenarios, make_df=make_gwp_df)
```



GWP* improved

$$E_{CO_2\text{-}we*} = [r * \frac{\Delta E_{SLCP}}{\Delta t} * H + s * E_{SLCP}] * GWP_H$$

Flow term - Response to emission rate

$$r * \frac{\Delta E_{SLCP}}{\Delta t} * GWP_H$$

Stock term - Long-term equilibration to past increase in forcing (memory)

$$s * E_{SLCP} * GWP_H$$

- Linear regression: r = 0.75, s = 0.25

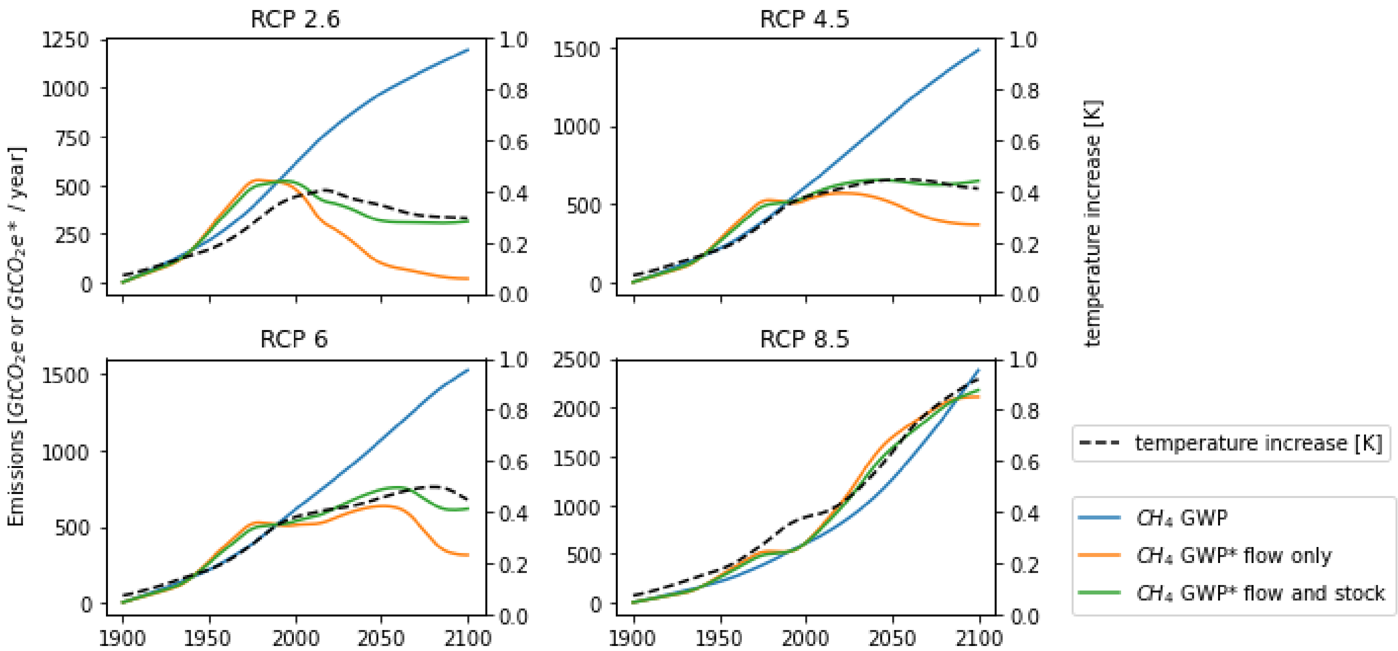
Calculate modified GWP* too

In [78]:

```
def make_gwp_df_mod(file_name, start_year=1765, end_year=2500, base_year=1765, r=0.75, s=0.25):
    emissons = read_data(file_name)
    start_index = start_year - base_year
    end_index = end_year - base_year + 1
    e_co2_eq = (emissons * GWP100_CH4)[start_index:end_index]
    e_co2_eq_star = calc_gwpstar_emissions(emissons)[start_index:end_index]
    # here's the meat
    e_co2_eq_star_mod = r * e_co2_eq_star + s * e_co2_eq
    e_co2_eq.name = '$CH_4$ GWP'
    e_co2_eq_star.name = '$CH_4$ GWP* flow only'
    e_co2_eq_star_mod.name = '$CH_4$ GWP* flow and stock'

    df = pd.DataFrame([e_co2_eq, e_co2_eq_star, e_co2_eq_star_mod]).T
    df.index.name = 'Years'
    return df
```

Plot again

```
In [79]: plot_all(rcp_scenarios, make_df=make_gwp_df_mod)
```



Conclusions

- Quantification with Python programming can help to understand how climate modeling works
- Many open source tools available
- Often code is very "result-oriented", lacking basic sw engineering principles
- Improving this code can help improve scientific outcome