

PolitoCliDyn: first-order carbon cycle LiveScript

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Code, with extensions, of the paper:

E.Canuto, D.Mazza and C. Novara, Projection of the airborne CO₂ concentration by land/ocean absorption dynamics and fossil-fuel reserve depletion, *Environmental Modelling & Assessment*, 2024

Acronyms

AFOLU agriculture, forestry and other land use

CAT Climate Action Tracker (data source)

CC carbon cycle

CD carbon dioxide (CO₂)

CliDyn Climate Dynamics

FF fossil fuel (oil, natural gas=methane, coal and lignite)

GCP Global Carbon Project (data source)

IIASA International Institute for Applied Systems Analysis (data source)

IPCC Intergovernmental Panel on Climate Change (data source)

LTI linear time invariant

MAGICC Model for the Assessment of Greenhouse Gas Induced Climate Change (data source)

NaN denotes, in the code Tables, either a quantity of no interest or non computable

OWID Our-World-in-Data (data source)

ppm ratio between amount of CD moles and amount of dry air moles in a given volume, reported as a part per million (concentration unit)

ppm/y part per million per year (CD concentration rate unit)

Polito Politecnico di Torino

RMS root mean square

std standard deviation

SSP Shared Socioeconomic Pathway (future emission scenario)

[Gm³ = 10⁹ m³] square brackets denote measurement units

Summary

A first-order LTI dynamics of the mean global carbon cycle is identified through global airborne CD concentration data [ppm] and reconstructed FF emissions [ppm/y] since 1850. FF emission history is projected to the future,

constrained by predicted proven FF reserves (oil, natural gas and coal). In turn, the data-fit CC dynamics, driven by the projected emissions, forecast the future airborne CD concentration. Comparison is made with CAT, IIASA, IPCC and MAGICC predictions. Discrepancies are shown recoverable by first-order quadratic dynamics.

Input data

They are arranged into subfolders of **PolitoCliDyn_InData**.

- 1) **CAT**, projected airborne CD concentration data from Climate Action Tracker, see Part III, Fig.11
- 2) **GCP**, historical CD emission data from Global Carbon Project, to be used in Part I and Part III. See Part I, Figs. 2 to 3, and Part III, Figs. 1 and 2
- 3) **IIASA**, projected CD emission data from International Institute for Applied Systems Analysis, to be used in Part III and Part IV. See Part III, Fig. 12 and Part IV, Fig. 5
- 4) **IPCC Tables**, projected airborne CD concentration data from the Intergovernmental Panel on Climate Change, to be used in Part IV, see Figs. 5 to 7. Only a subset of the projection files have been employed.
- 5) **MAGICC**, projected CD emission and airborne CD concentration data from the online Model for the Assessment of Greenhouse Gas Induced Climate Change, to be used in Part IV (only SSP 460), see Fig. 8
- 6) **OWID**, historical fossil-fuel proven reserves, consumption and CD emissions by fuel data, from Our-World-in-Data, to be used in Part II, see Figs. 2 to 4
- 7) **Scripps Research**, historical airborne CD concentration data to be used in Part I, see Fig. 1 to 3.

CAVEAT: users are suggested to save a copy of PolitoCliDyn_InData. Any change may produce unexpected results and/or code failure. The code is only protected against missing or renamed files, when the folder PolitoCliDyn_OutData has reached convergence (see below 'Output data'). File not found is signaled, the relevant Part exits, but LiveScript keeps running based on either PolitoCliDyn_OutData or default values.

Output data

A) Numerical data are arranged in PolitoCliDyn_OutData (xlsx and mat files).

- 1) **CDFitParameterTable_PartI** (mat and xlsx) contains for each item of the rolling regression (ParamFitx, x=1 to 151 in the mat file, x=1,11,...,151 in the xlsx file), a parameter table of the three regression (difference, integral, cumulative) results: mean values, std, residuals and statistical indices. ParamCommon contains common data to regressions. The mat file is read in Part IV for building CD concentration projections. CAVEAT: if renamed or deleted, Part IV exits unless Part I has been previously run.
- 2) **CDFitTimeTable_PartI** (mat and xlsx) contains the time profiles (TimeFitx, x=1 to 151 in the mat file, x=1,11,...,151 in the xlsx file) of the raw CD concentration data, estimate and residuals of the three regressions. History contains the historical time profiles of the airborne CD concentration and the CD emission by fossil fuel combustion. Historical CD data are read in Part IV from mat file. CAVEAT: if renamed or deleted, Part IV exits unless Part I has been previously run.

3) **RollingFitTable.mat** contains the initial times of the rolling time regressions to be used in Parts I, III and IV. CAVEAT: if renamed or deleted, Part III and IV exit unless Part I has been previously run..

4) **PredReserve_PartII.mat** contains a table of three columns with the predicted reserves and std of oil, gas and coal, to be read in Part III. CAVEAT: if renamed or deleted, Part III exits unless Part II has been previously run.

5) **FFEInitTab_PartIII.mat** contains for each fuel (third coordinate from 1 to 3), for each bound (mean, upper and lower, column from 1 to 9) and for each regression (row from 1 to 151), the most recent estimates by `fminsearch` of the Meixner parameters (amplitude [ppm/y], time constant [y] and peak time [y]). The row order is mean parameters, upper bound parameters, lower bound parameters. A richer set of results of the regressions $x=1,11,\dots,151$ can be found in the sheets `Parameters iFit=x` of `FFEFitParameterTable_PartIII.xlsx`.

CAVEATS: 1) the estimates change by changing `tEndUser`. 2) If either deleted or renamed, default internal values are employed and `tEndUser` is set to about 2200. The anomaly is signaled and the file is rebuilt.

6) **FFEPriorStd_PartIII.mat** contains the most recent measurement std to be used in each regression. The measurement std is reconstructed a posteriori from the estimate residuals. It depends on each regression, but not on time. CAVEAT: if renamed or deleted, the anomaly is signaled, internal default values are employed, `tEndUser` is set to about 2200 and the file is rebuilt.

7) **FFETotPredictionTable_PartIII.mat** contains for each regression (`Totx`, $x=1$ to 151), the total emission profiles (mean, upper bound, lower bound) of fossil fuels (columns 2, 3 and 4). The first column is the time [y]. The emission profiles include historical data and projections. The profiles are read and used in Part IV. CAVEAT: if deleted or renamed, Part IV exits unless Part III has been previously run.

8) **FFEPredictionTable_PartIII.xlsx** contains in the sheets `Projection iFit=x` the time profiles of each fuel CD emission for the projections $x=1,11,\dots,151$.

9) **CDPredictionTable_PartIV.xlsx** contains in the sheets "Projection `iFit=x`" the mean, upper and lower time profiles of the airborne CD concentration for the projections $x=1,11,\dots,151$.

B) Plot images are saved in `PolitoCliDyn_Figures` (png images).

CAVEAT: the code has been tested to converge from an empty `PolitoCliDyn_OutData`, in absence of `PolitoCliDyn_InData` anomalies. Users are suggested to ascertain convergence, after having saved the package folder. Convergence occurs when the `fminsearch` iterations of Part III (`logSearch=1`) become horizontal lines (2 steps for oil and gas, 3 steps for coal), under `szIter=500`, `tSelfFit=1950` and `tEndUser=2200`. Convergence must be restored after changing `tEndUser`.

User input

CAVEAT: even if the range of the numerical sliders and spinners is changed by users, the code value is forced within the default range. When the user value is out of the default range, a warning signals that the user value has been corrected .

```
% ACTION: section to be run first
szIter=500;
```

```

tSelfFit = 1950;
uBandProb = 0.9;
tEndUser = 2200;
userGraphs = 1;
logSearch = 1;
% ACTION: users to change mlxFolder name to their own
mlxFolder="E:/Dati/ProjectResearch/CarloNovara/Climate/Code/
PolitoCliDyn_1stOrderCC_code/PolitoCliDyn_1stOrderCC_Main";
try
    cd(mlxFolder);
catch
    error('WARNING: LiveScript halts, check mlxFolder name!');
end
CheckLiveScriptFolder;

```

```

PolitoCliDyn: 1st order CC: checking Live Script folder
DONE: PolitoCliDyn_1stOrderCC_LiveScript.mlx found
DONE: Live Script folder

```

```

userInputToggleFun;

```

```

PolitoCliDyn: 1st order CC: saving user input data
DONE: ../PolitoCliDyn_OutData/userInputToggle.mat has been created

```

szIter=max number of fminsearch iterations

The positive integer szIter is the variable factor of the maximum number of iterations of the MATLAB function fminsearch, equal to szIter x size of unknowns. The fixed range is 500 to 800. The least value is the fminsearch default.

tSelfFit=selected regression

The positive integer tSelfFit represents the initial regression year ,whose results are plotted and written in the LiveScript. The fixed range is 1940 to 1980. CAVEAT: the uncertainty band in Fig.1 of Part IV significantly increases from 1940 to 1980 in agreement with Fig.7 of Part I.

uBandProb=uncertainty band

The positive real uBandProb is the total probability of the uncertainty bands plotted by colored shades around result variables. The fixed range is 0.9 to 0.9973. The least value corresponds to the "very likely" band of IPCC documents. A 3σ - band corresponds to uBandProb = 0.9973. Please notice that some uncertainty bands are by default plotted as 3σ -bands.

tEndUser=projection end time

The next choice concerns Part III and Part IV. The Boolean logtEnd toggles the user choice (=1) of the end time (tEndUser) of the projection in Part III of the finite-reserve CD emissions and in Part IV the projection of airborne CD concentration. The fixed range is 2150 to 2250. The default value, 2200, balances past and future.

userGraphs=saving graphical plots

The Boolean userGraphs toggles saving (=1) graphical plots as png images in the the folder ..\PolitoCliDyn_Figures. The files are named by PartX_Fig_Y_Day_Month_Year.png and are replaced by successive daily runs. Folder cleaning along several days as well as daily saving is left to users. Undocked Matlab images can be cleared by `close all` in the Command Window.

logSearch=plot of fminsearch iterations

The Boolean logSearch toggles the semilogy plot of the fminsearch iterations (=1) of the different code parts:

- 1) Part I: difference and integral regressions selected by tSelfFit
- 2) Part II: the three regressions (oil, gas and coal) that estimate the proven reserve upper limit
- 3) Part III: the three regressions (mean, upper and lower final reserve) for the three fossil fuels (oil, gas and coal), which estimate and project the finite-reserve CD emission profiles
- 4) Part IV: the two regressions (difference and integral) that estimate the parameters of the first-order quadratic equation from IPCC data.

CheckLiveScriptFolder

If called from the right LiveScript folder, adds sub-folders to Matlab search path.

userInputToggleFun=saving user parameters

If called from the right LiveScript folder, the set of user parameters is saved, allowing Run Section

Parti I

The first-order LTI state equation

$$\dot{x}(t) = -k(x(t) - \underline{x}) + u(t), x(t_0) = x_0,$$

with unknown parameters $k [y^{-1}]$, pole, and $\underline{x} [ppm]$, pre-industrial airborne CD equilibrium, is identified through global data of the CD annual mean concentration $x(t) [ppm]$ and of the annual FF by-combustion emission $u(t) [ppm y^{-1}]$ (Figs. 1 to 3). A rolling-time regression (Fig.7), $t_0 \leq t \leq t_p$ is performed by progressively, year-by-year, shifting the initial time $t_0 \geq 1850 y$ toward the present $t_p = 2020 y$, until permitted by a statistical F-test, which defines the *red forbidden region* of Fig.8 ($t_0 > 2000 y$, forbidden t_0 in Table 1). The *pink not recommended region* is found by the residual RMS in Fig.9. Users can select, within the *selection region*, the initial time $1940 \leq t_0 \leq 1980$ (tSelfFit in the User Input section, SelfFit tInit in Table 1) of the regression, whose results are graphically shown in Figs. 4 to 6 and in Tables 2 to 4. The estimated equilibrium $\hat{\underline{x}}$, if close (see Fig. 7) to the pre-industrial estimate from historical data, plays the role of an implicit test of coherence between raw data and model. As a check, regression is repeated twice by fitting both the airborne CD concentration rate (*difference fit*) and the CD concentration raw data (*integral fit*). As a further check, the model identified by the *difference fit* is integrated (*cumulative fit*). Residuals are compared in Fig.6.

Part I run

```
CheckLiveScriptFolder;
```

```
PolitoCliDyn: 1st order CC: checking Live Script folder  
DONE: PolitoCliDyn_1stOrderCC_LiveScript.mlx found  
DONE: Live Script folder
```

```
Init_LiveScript;  
PolitoCliDyn_1stOrderCC_PartI;
```

```
-----  
PolitoCliDyn: 1st order CC, airborne CD prediction, Part I
```

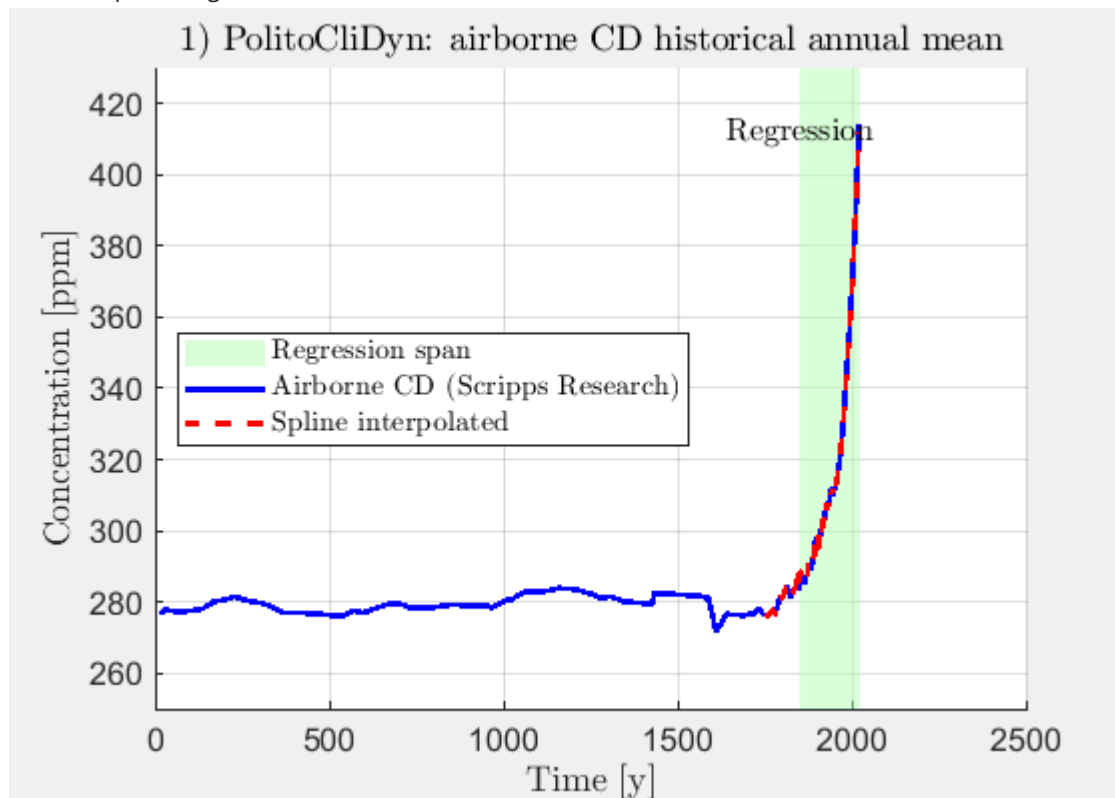
Table 1: User input and actual (corrected) data

Type	Ind.era t0	Forbidden t0	Selfit tInit	RoI fit step	RoI fit size
{'Actual'}	1.8500e+03	2.0000e+03	1.9500e+03	1.0000e+00	1.5100e+02
{'Input' }	NaN	NaN	1.9500e+03	NaN	NaN

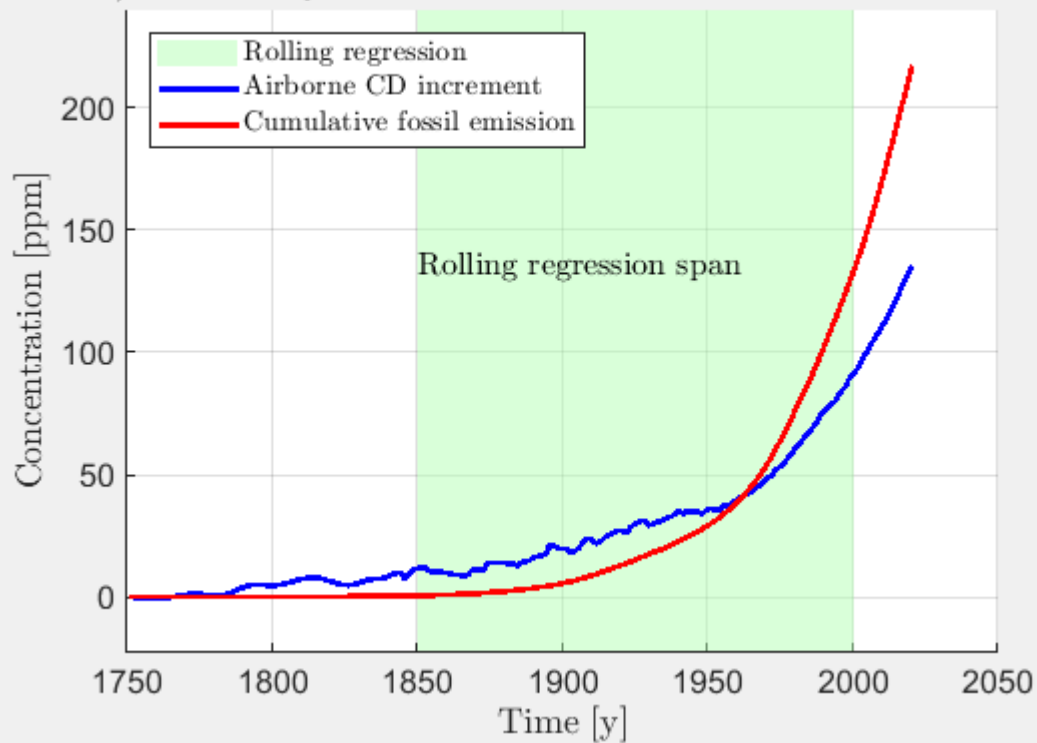
```
Part I: reading CD emission data (GCP)
```

```
Part I: reading airborne CD concentration data (Scripps Research)
```

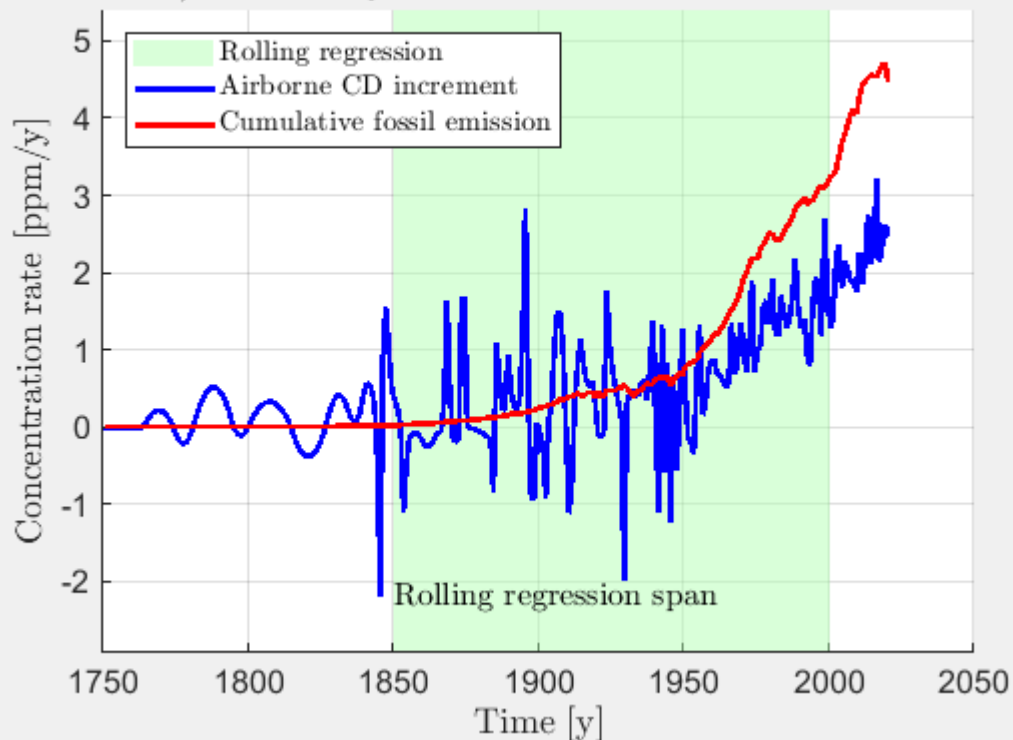
```
Part I: plotting raw data
```



2) PolitoCliDyn: CD increment and cumulative FF emission



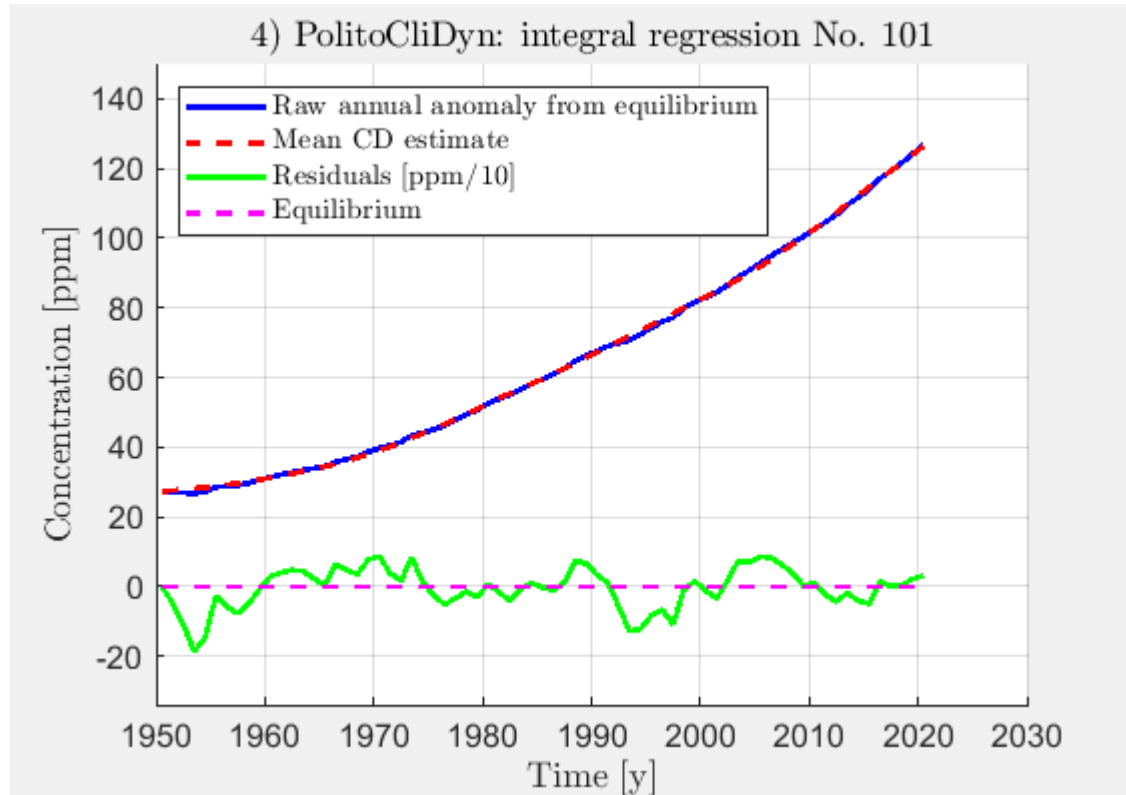
3) PolitoCliDyn: airborne CD rate and emission

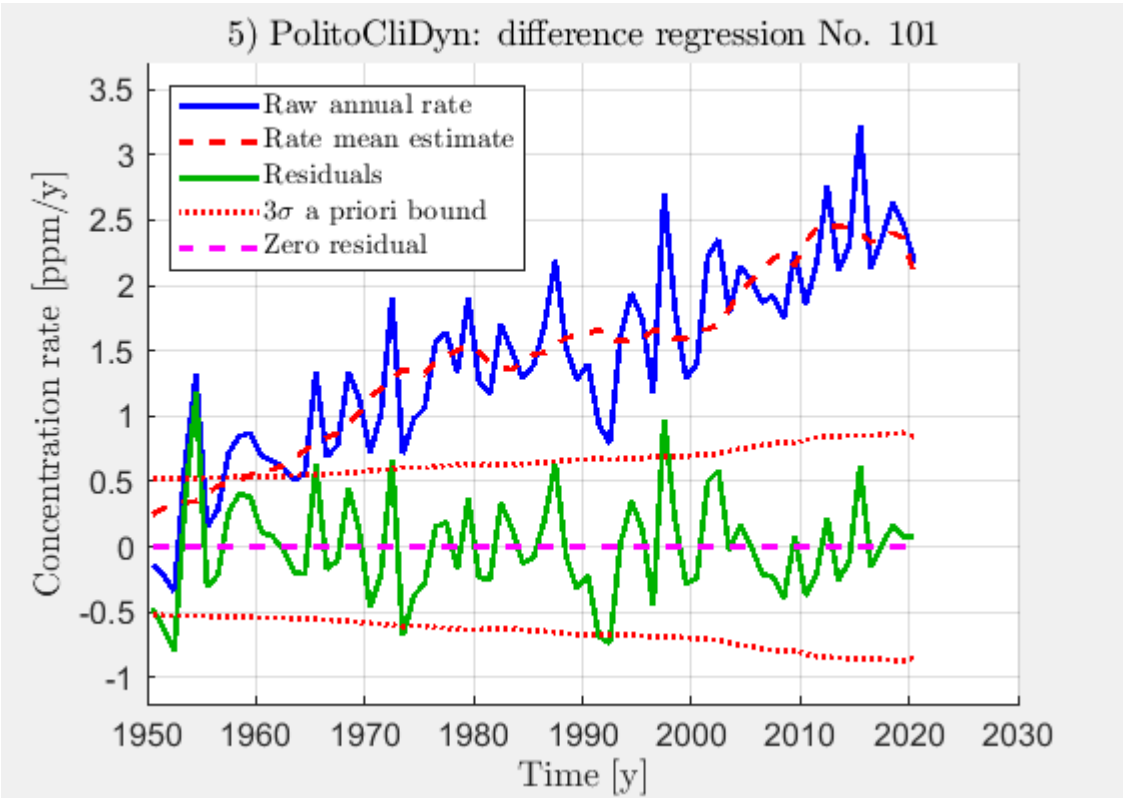


Part I: regression tables to command window
 Part I: regression tables to file
 Part I: regression time profiles to file
 Part I: rolling regression
 Fit step=1, initTime=1850
 Part I: integral regression
 Part I: difference regression
 Part I: cumulative check and residual offset

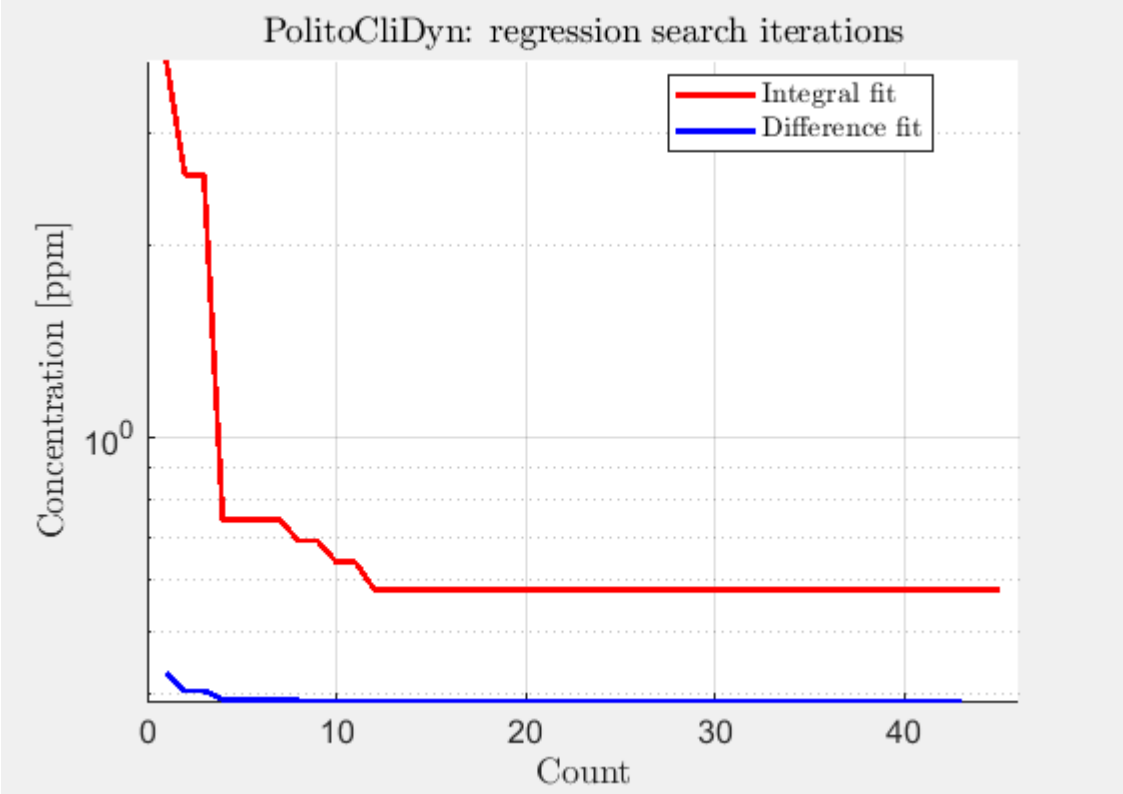
Part I: writing time profiles and parameters into spreadsheet files

Fit step=11, initTime=1860
Fit step=21, initTime=1870
Fit step=31, initTime=1880
Fit step=41, initTime=1890
Fit step=51, initTime=1900
Fit step=61, initTime=1910
Fit step=71, initTime=1920
Fit step=81, initTime=1930
Fit step=91, initTime=1940
Fit step=101, initTime=1950





Part I: plotting regression iterations



Part I: SELECTED, tables of selected regression

Table 2: Airborne CD common parameters

Type	Init. time	Atm. std	Emis. std(%)	Unknowns	Hist. Equil.	Raw RMS
{'Common'}	1.9500e+03	1.2000e-01	5.0000e+00	2.0000e+00	2.7962e+02	3.0131e+01
{'Std' }	NaN	NaN	NaN	NaN	2.9745e+00	NaN

Table 3: Airborne CD results, regression No. 101

Regression	Equilibrium	Pole	tau	Input scale	Res. mean	Res. RMS
{'Integral' }	2.8525e+02	1.8891e-02	5.2934e+01	9.9061e-01	-5.0578e-02	5.7907e-01
{'Difference' }	2.8457e+02	1.8580e-02	5.3823e+01	9.9077e-01	-1.1688e-05	3.8752e-01
{'Cumulative' }	2.8432e+02	1.8580e-02	5.3823e+01	9.9077e-01	-4.8525e-03	5.8758e-01
{'St. deviation' }	3.5429e-01	1.6846e-03	4.8800e+00	NaN	NaN	NaN
{'Std/est.(%)' }	1.2450e-01	9.0668e+00	9.0668e+00	NaN	NaN	NaN

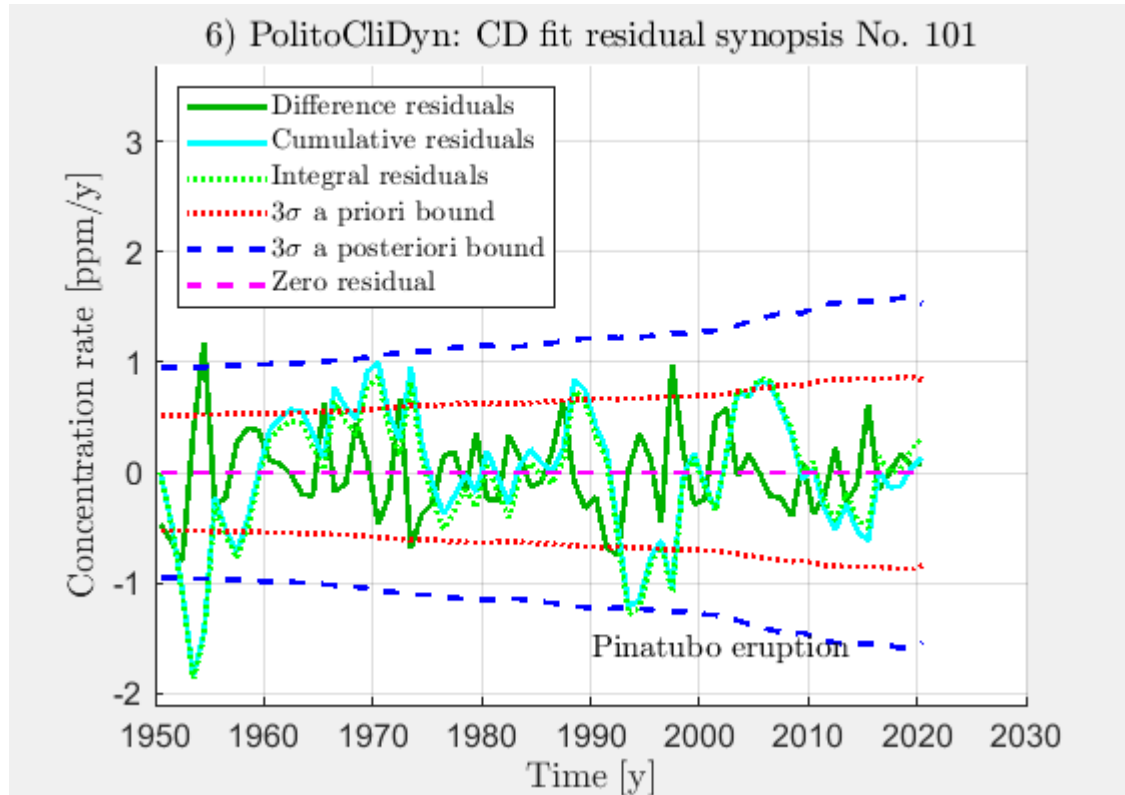
Table 4: Airborne CD residual statistics, regression No.101

Regression	Total SS	Residual SS	log10(1-R2)	Samples
{'Integral' }	3.0131e+01	5.7907e-01	-3.4326e+00	7.1000e+01
{'Difference' }	7.4064e-01	3.8752e-01	-5.6262e-01	7.1000e+01

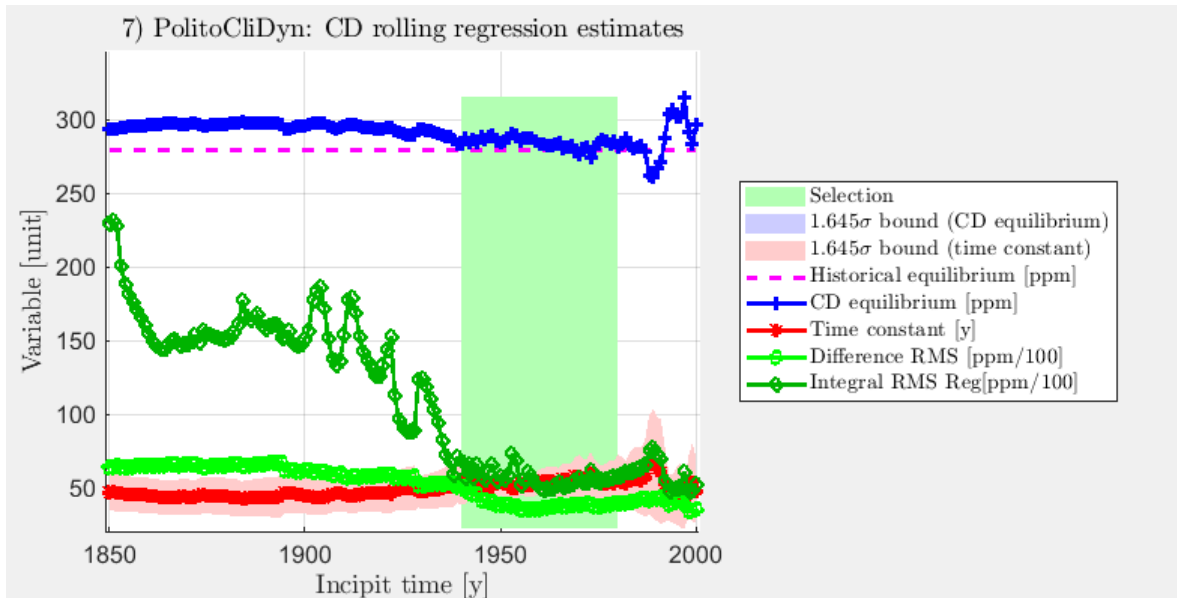
Table 5: F-test and thresholds, regression No. 101

Variable RMS[ppm]	Explained RMS[ppm]	F-test	99.9% threshold	99% threshold
6.6778e-01	5.5074e-01	1.4887e+02	1.1799e+01	7.0114e+00

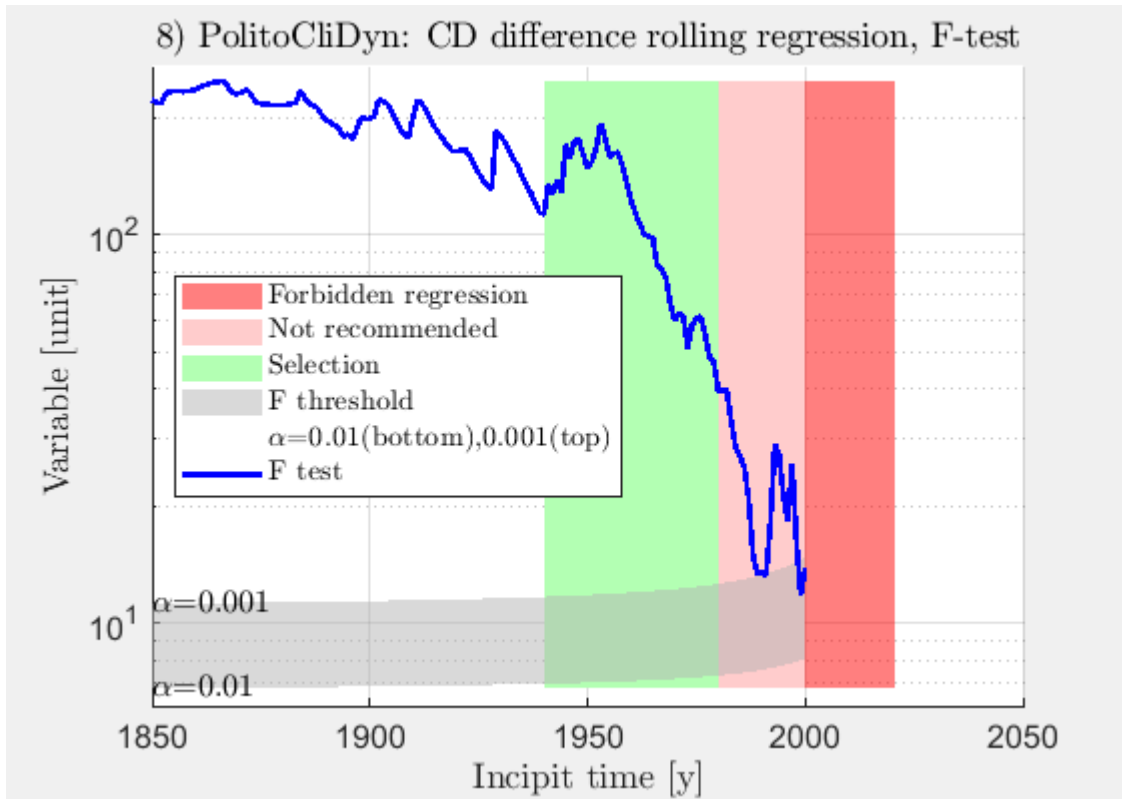
Part I: SELECTED, plotting residual synopsis



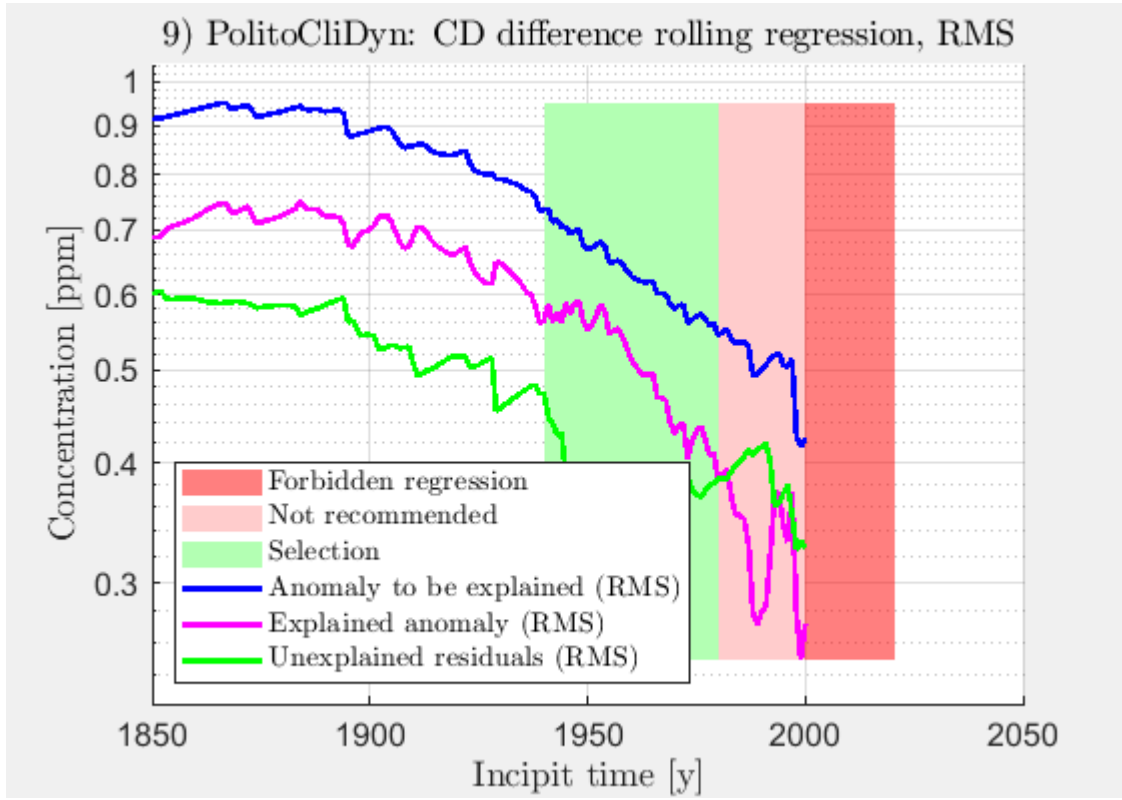
Fit step=111, initTime=1960
Fit step=121, initTime=1970
Fit step=131, initTime=1980
Fit step=141, initTime=1990
Fit step=151, initTime=2000
Part I: rolling regression figures
plotting rolling regression parameters



plotting rolling regression F-test



plotting rolling regression RMS



End of Part I

Part II

Fossil-fuel future proven reserves $r(t)$, $t \geq t_0$ are predicted by the asymptotic upper limit r_∞ of

$$r(t) = r_\infty - (r_\infty - r_0) \exp(-s(t)^n), s(t) = \frac{t - t_0}{\tau}, r(t_0) = r_0$$

Unknown parameters τ, r_∞, n and their std are estimated from historical data (OWID) of the fuel proven reserves (oil, natural gas and coal). Shale oil and natural gas are not included. Historical and predicted reserves are reported in Fig. 2 and Table 1 under different volume/mass units: $[\text{Gm}^3 = 10^9 \text{m}^3]$ applies to oil, $[\text{Tm}^3 = 10^{12} \text{m}^3]$ applies to natural gas and $[\text{Pg} = 10^{15} \text{g}]$ to coal. The exponent $n > 1$, expressing progressive difficulties in reserve finding and proving, balances the asymptotic margin $r_\infty - r(t_p)$, $t_p = 2020$ y and the reserve uncertainty (see Fig. 1). Volume and mass units are scaled to CD concentration [ppm], by fitting historical data of fuel consumption to those of fuel CD emission (OWID) (see Figs. 3 and 4). Table 2 reports the predicted reserves in [ppm] units and the relevant scale factors.

Part II run

```
CheckLiveScriptFolder
```

```
PolitoCliDyn: 1st order CC: checking Live Script folder
DONE: PolitoCliDyn_1stOrderCC_LiveScript.mlx found
DONE: Live Script folder
```

```
Init_LiveScript;
```

PolitoCliDyn: 1st order CC, airborne CD prediction, Part II

Table 1: User input and actual (corrected) data

Type	Ind.era t0	Forbidden t0	SelfFit tInit	RoI fit step	RoI fit size
{'Actual'}	1.8500e+03	2.0000e+03	1.9500e+03	1.0000e+00	1.5100e+02
{'Input' }	NaN	NaN	1.9500e+03	NaN	NaN

Part II: reserve prediction tables

Part II: reserve prediction and prediction dynamics exponent search

Part II: oil reserve prediction (no shale oil)

Reading fossil-fuel reserve data

Regression and prediction

Uncertainty band and plot

Part II: natural gas reserve prediction (no shale gas)

Reading fossil-fuel reserve data

Regression and prediction

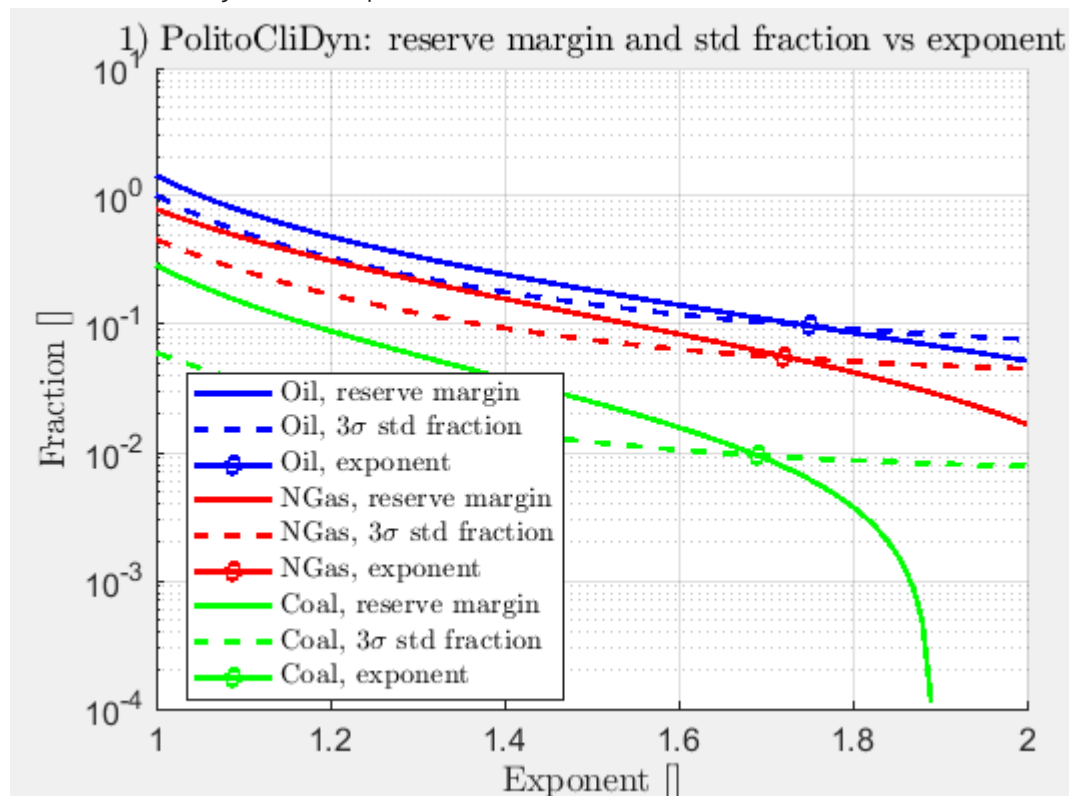
Uncertainty band and plot

Part II: coal and lignite prediction

Reading fossil-fuel reserve data

Regression and prediction

Uncertainty band and plot



Part II: plotting fuel reserve prediction iterations

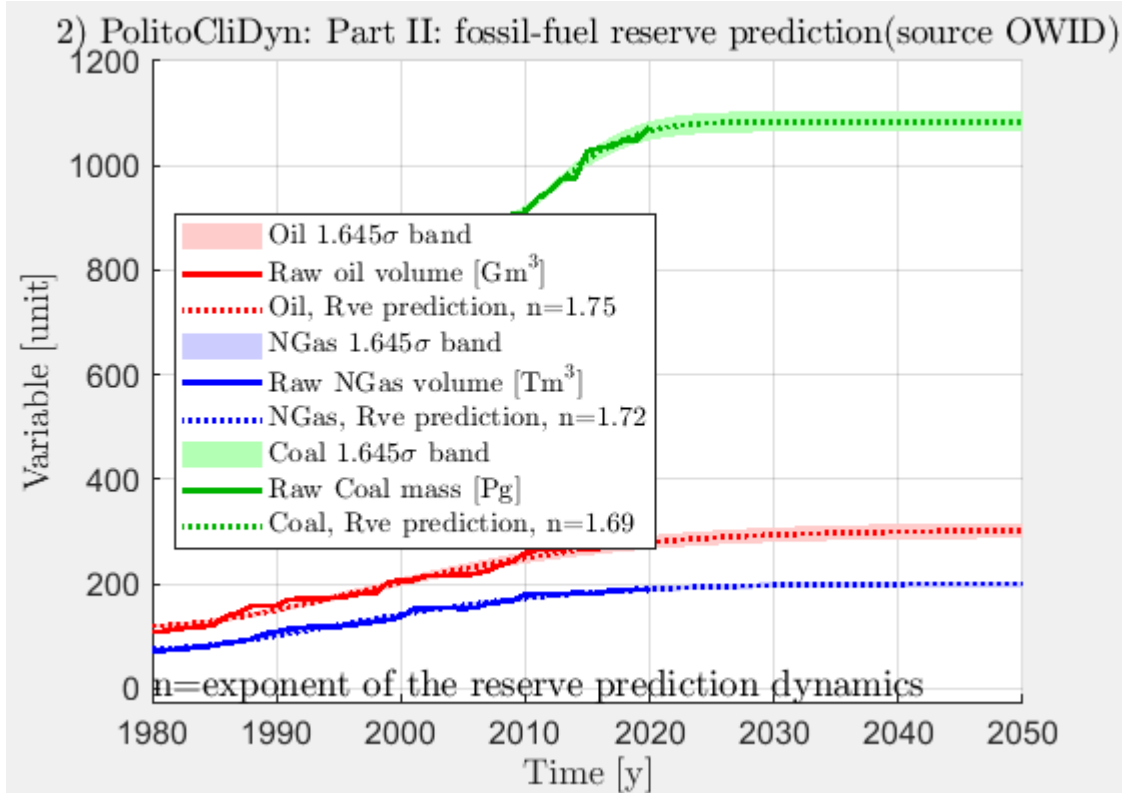
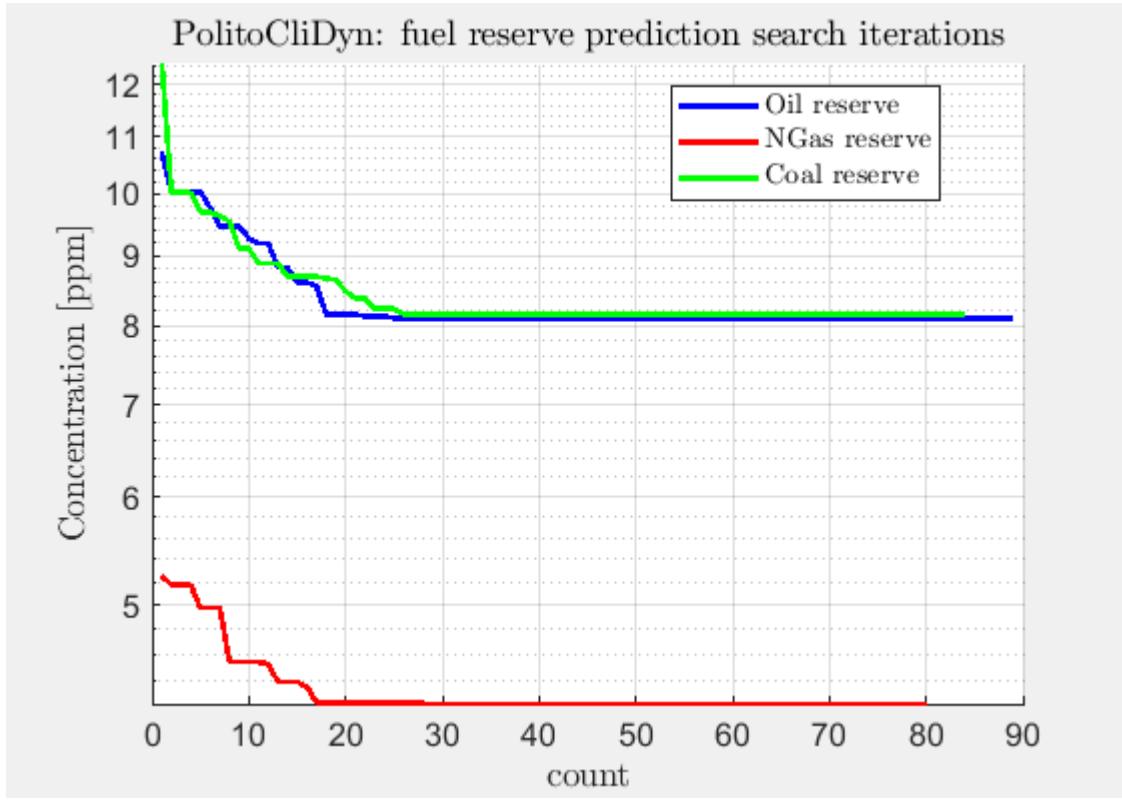


Table 2: Reserve regression results

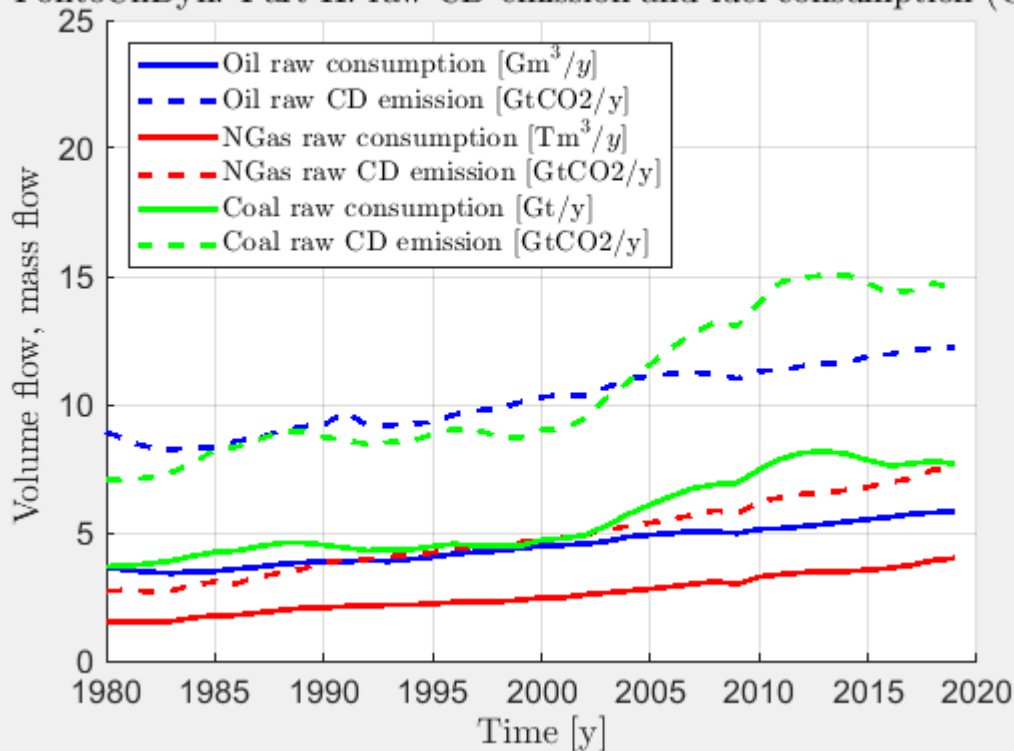
Units: Gcm=Giga cubic metre, Tcm= Tera cubic metre, GtC = Giga tons of carbon, GtCO₂ = Giga tons of CO₂

Fuel type	As. reserve	Amplitude	Time const.[y]	Exponent	Samples	Raw/resRMS
{'Oil [Gcm]' }	3.0289e+02	1.8277e+02	2.6384e+01	1.7500e+00	4.1000e+01	5.4003e+01
{'Std [Gcm]' }	8.9711e+00	8.1146e+00	1.5987e+00	0.0000e+00	0.0000e+00	8.1019e+00
{'NGas [Tcm]' }	2.0102e+02	1.2490e+02	2.3636e+01	1.7200e+00	4.1000e+01	3.8703e+01
{'Std [Tcm]' }	3.5066e+00	3.1874e+00	9.3241e-01	0.0000e+00	0.0000e+00	4.2347e+00

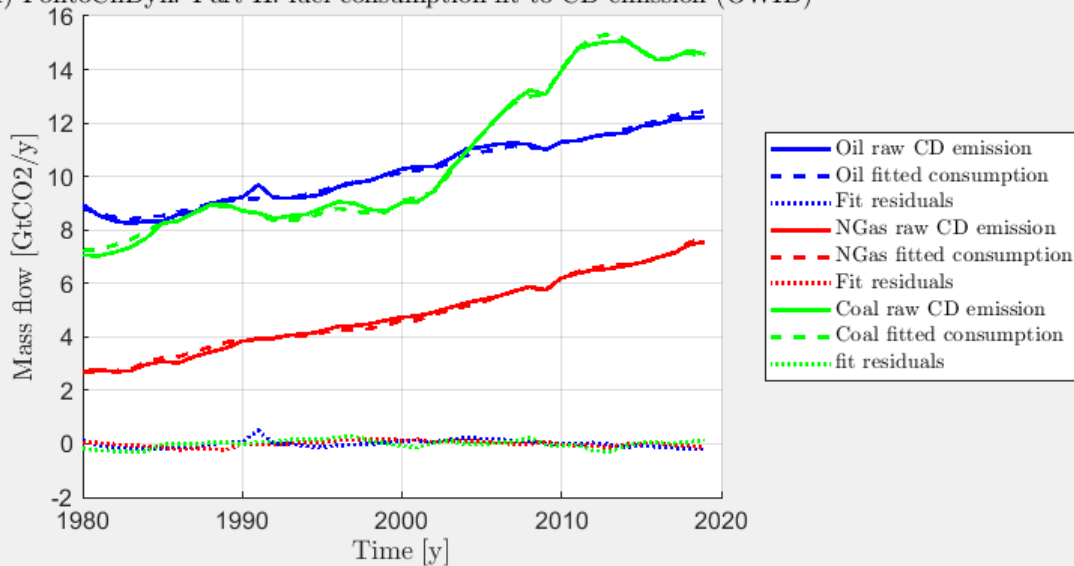
{'Coal [GtC]'} }	1.0843e+03	1.8839e+02	7.2126e+00	1.6900e+00	1.3000e+01	5.9600e+01
{'Std [GtC]'} }	1.1961e+01	1.0984e+01	6.5012e-01	0.0000e+00	0.0000e+00	8.1561e+00

Part II: fuel consumption unit to CD emission unit (Source:OWID)

3) PolitoCliDyn: Part II: raw CD emission and fuel consumption (OWID)



4) PolitoCliDyn: Part II: fuel consumption fit to CD emission (OWID)



Part II: reserves and uncertainty

Table 3: Predicted reserves

Fuel type	Bias [GtCO2]	Scale[GtCO2/unit]	Reserve[GtCO2]	Samples	Raw/resRMS [GtCO2]
{'Oil [unit=Gcm]'} }	2.6626e+00	1.6778e+00	5.1083e+02	4.0000e+01	1.2565e+00
{'Std [GtCO2]'} }	1.3601e-01	2.9915e-02	2.4248e+01	NaN	1.4080e-01
{'Fraction'}	5.1079e-02	1.7830e-02	4.7468e-02	NaN	9.8217e+02
{'NGas [unit=Tcm]'} }	-3.1634e-01	2.0015e+00	4.0203e+02	4.0000e+01	1.4411e+00
{'Std [GtCO2]'} }	6.2589e-02	2.3406e-02	1.1786e+01	NaN	1.0630e-01
{'Fraction'}	-1.9786e-01	1.1694e-02	2.9317e-02	NaN	2.2670e+03
{'Coal [unit=GtC]'} }	6.1346e-01	1.7985e+00	1.9508e+03	4.0000e+01	2.7639e+00
{'Std [GtCO2]'} }	8.8100e-02	1.5262e-02	3.8150e+01	NaN	1.4813e-01

End of Part II

Part III

The historical measurements (GCP) of CD emission by fuel combustion $\check{c}(t), t \leq t_p$ [ppm y^{-1}] of each fuel, oil, natural gas and coal (see Figs.1 to 2) are projected into the future by means of the bell-shaped curve (the *Meixner curve*)

$$\check{c}(t) = \frac{a \exp(\beta \sigma(t))}{\cosh(\sigma(t))} + \tilde{c}(t), \sigma(t) = (t - s)\tau^{-1}, t_0 \leq t \leq t_p$$

$$\hat{c}(t) = \frac{a \exp(\beta \sigma(t))}{\cosh(\sigma(t))}, t_p < t < t_{\text{end}}, r_{\infty} = r(t_p) + \int_{t_p}^{t_{\text{end}}} \hat{c}(\eta) d\eta + \tilde{r}$$

up to the measurement errors $\tilde{c}(t)$ and \tilde{r} . The Meixner curve is the product of three factors accounting for *amplitude* (a), *skewness* (the exponential function), *shape and location* (the hyperbolic cosine) of past and future CD emissions, where $t_0 \geq 1850$ y, $t_p = 2022$ y, and $2150 \leq t_{\text{end}} \leq 2250$ y is the free end-time of the prediction, to be chosen by users. To be simple and robust (see Figs. 5 to 10), the exponent of the skewness term has been set to zero, $\beta = 0$, implying bell-shape symmetry. Skewness appears to be weakly identifiable, due to highly fluctuating and just increasing raw data (left leg of the bell-shaped curve).

The unknown parameters and their std (see Table 1) are fit on historical emissions and predicted reserve (Fig. 3). As in Part I, a rolling-time regression has been implemented for recording fit fluctuations and divergence (see Figs. 5 to 10). The *forbidden region* (red region in figures) is imposed by the F-test (Fig. 11) for $t_0 > 2000$ y as in Part I and the same applies to the *not recommended region* (pink in the figures). As a check, the reserve residual \tilde{r} is shown in Fig.10 to stay within the a priori reserve uncertainty (see Part II). The selected fit is constrained to be the same as in Part I (see Figs. 3 and 4). Amplitude and times of the projected emissions are in Table 2.

Figs.11 and 12 compare the prediction of the finite-reserve total emission with those of CAT and IPCC (retrieved from IIASA). The closest IPCC prediction is that of the SSP 2-4.5, where 2 denotes the class of the scenarios and 4.5 the net radiative forcing [Wm^{-2}] at 2100 y, which perturbs the energy equilibrium of the Earth's biosphere and consequently the climate.

Part III run

```
CheckLiveScriptFolder;
```

```
PolitoCliDyn: 1st order CC: checking Live Script folder
DONE: PolitoCliDyn_1stOrderCC_LiveScript.mlx found
DONE: Live Script folder
```

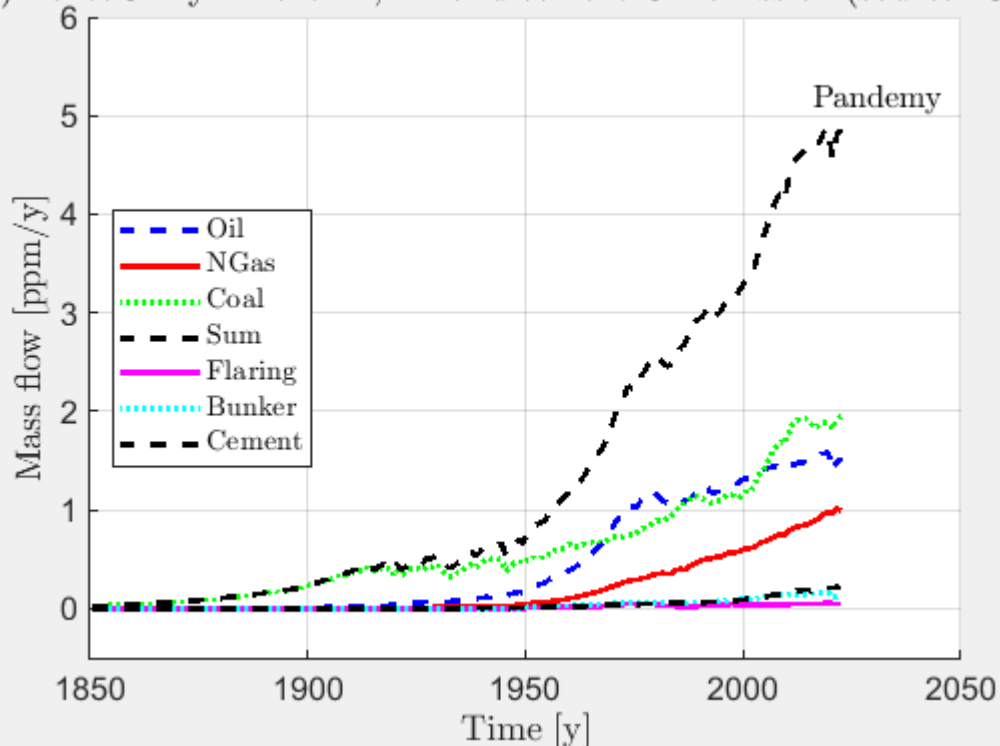
```
Init_LiveScript;
PolitoCliDyn_1stOrderCC_PartIII;
```

```
PolitoCliDyn: 1st order CC, airborne CD prediction, Part III
```

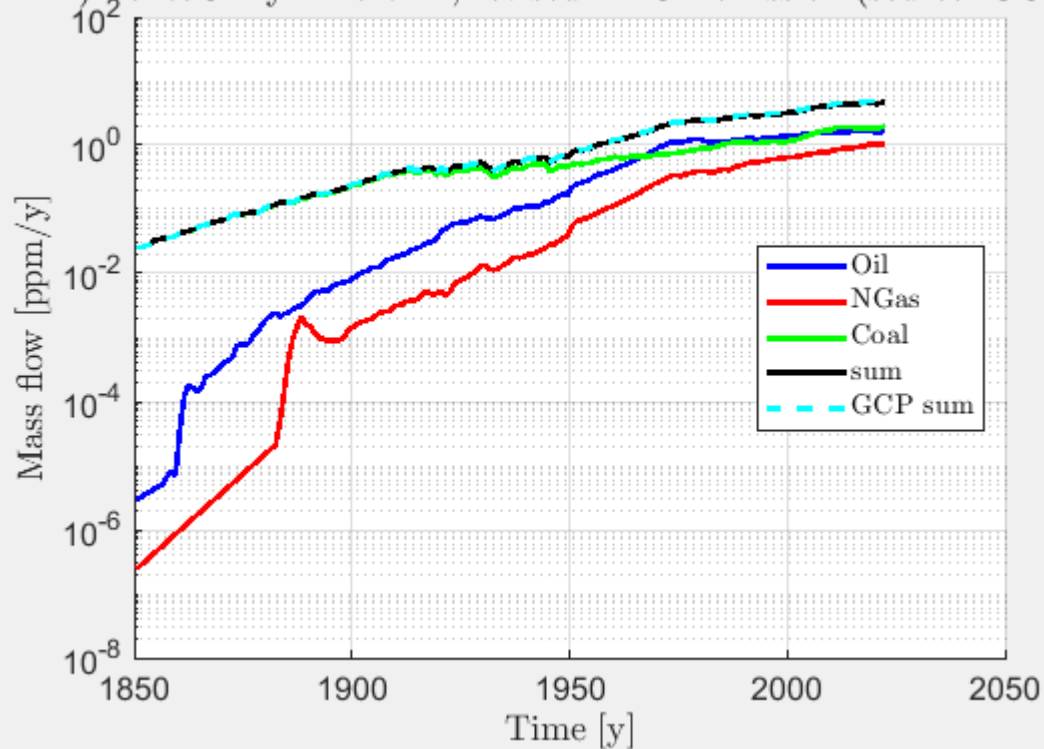

Table 1: User input and actual (corrected) data

Type	Ind.era t0	Forbidden t0	SelfFit tInit	RoI fit step	RoI fit size
{'Actual'}	1.8500e+03	2.0000e+03	1.9500e+03	1.0000e+00	1.5100e+02
{'Input' }	NaN	NaN	1.9500e+03	NaN	NaN

1) PolitoCliDyn: Part III, FF and cement CD emission (source: GCP)



2) PolitoCliDyn: Part III, revised FF CD emission (source: GCP)



Part III: reading reserve data

Part III: Meixner fit tables to file

Part I: selected fit time profiles to file

Part III: rolling regression and prediction with Meixner curve

```

Fit step=1, initTime=1850
Fit step=11, initTime=1860
Fit step=21, initTime=1870
Fit step=31, initTime=1880
Fit step=41, initTime=1890
Fit step=51, initTime=1900
Fit step=61, initTime=1910
Fit step=71, initTime=1920
Fit step=81, initTime=1930
Fit step=91, initTime=1940
Fit step=101, initTime=1950

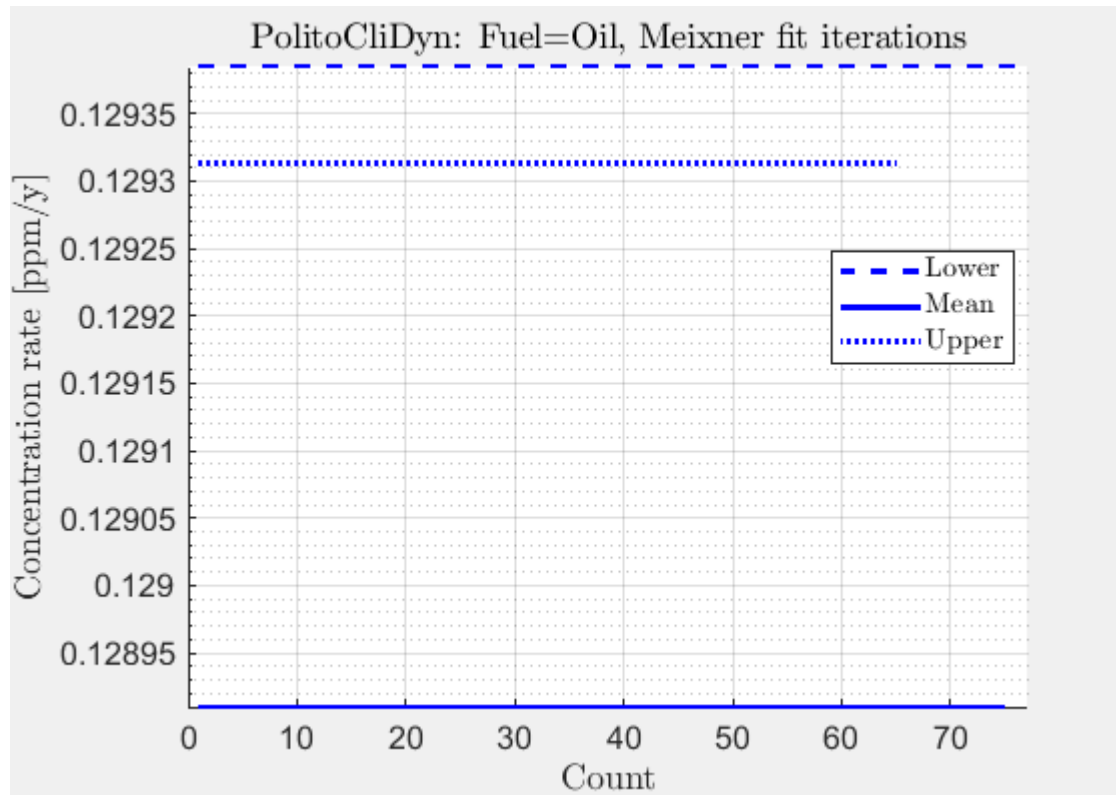
```

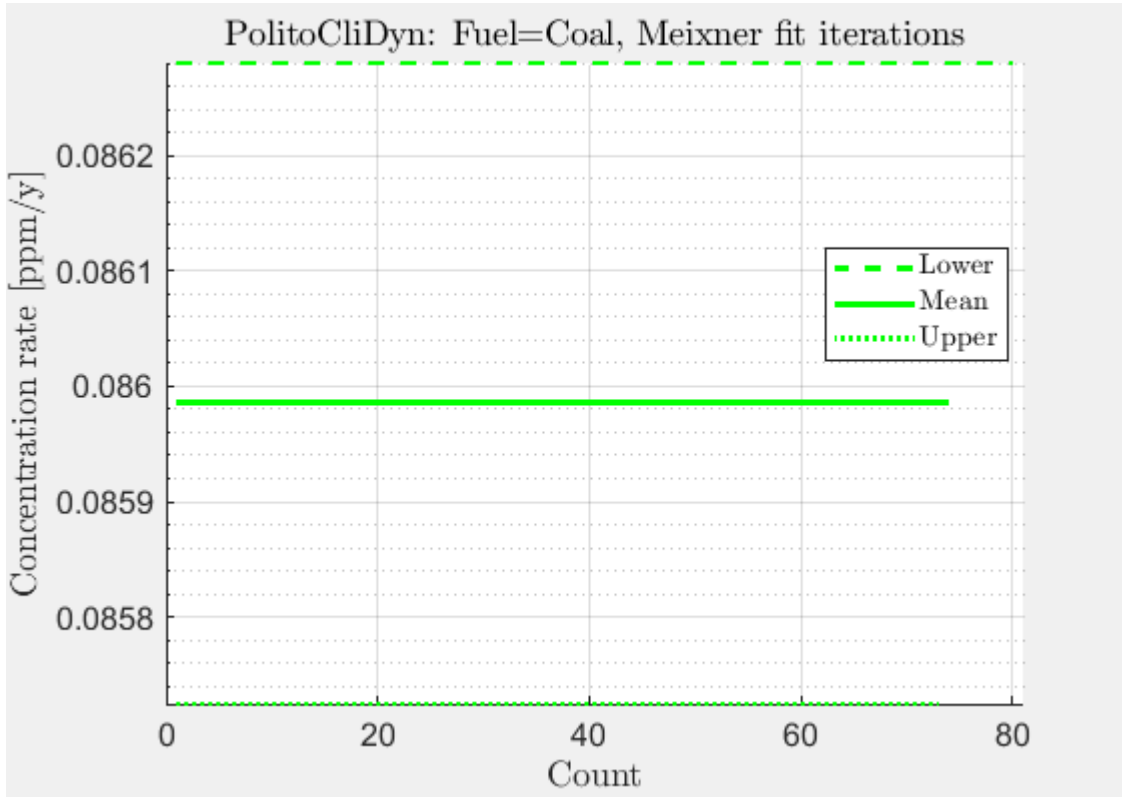
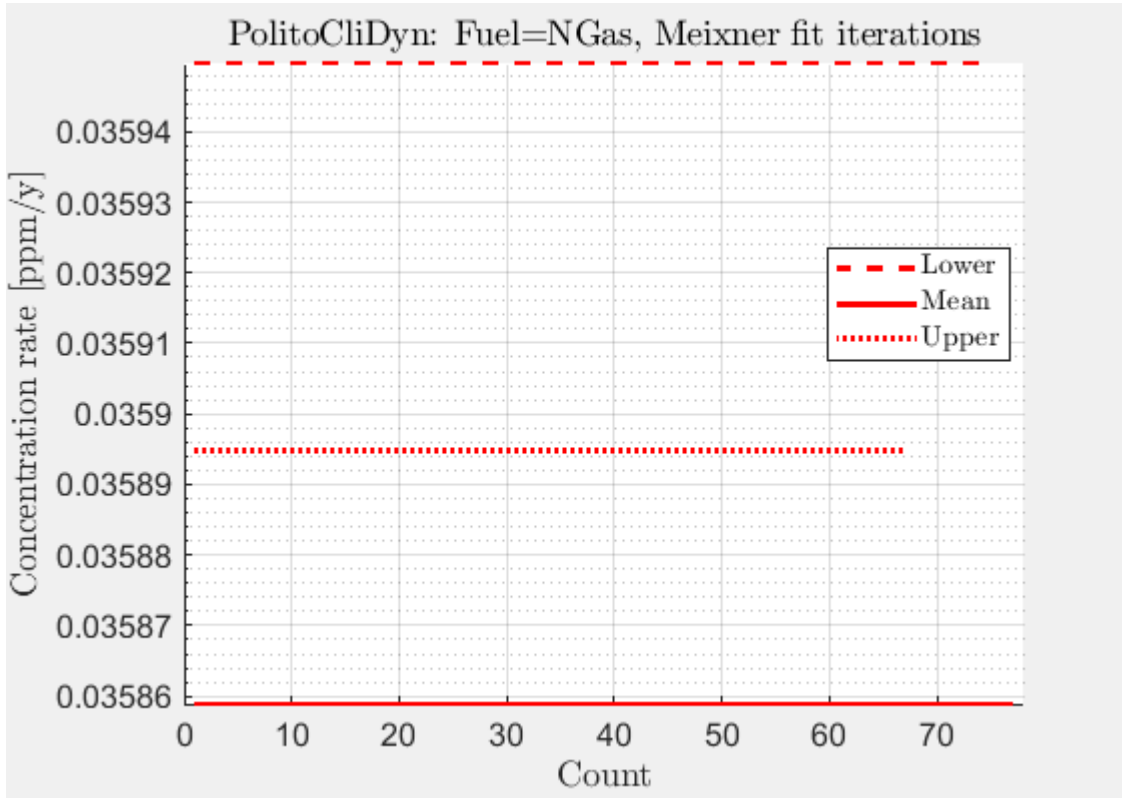
SELECTED FIT

```

iFuel=1, iBound=1, Fit initTime=1950, Fit Error =1.293855e-01
iFuel=2, iBound=1, Fit initTime=1950, Fit Error =3.594975e-02
iFuel=3, iBound=1, Fit initTime=1950, Fit Error =8.628026e-02
iFuel=1, iBound=2, Fit initTime=1950, Fit Error =1.289102e-01
iFuel=2, iBound=2, Fit initTime=1950, Fit Error =3.585892e-02
iFuel=3, iBound=2, Fit initTime=1950, Fit Error =8.598534e-02
iFuel=1, iBound=3, Fit initTime=1950, Fit Error =1.293135e-01
iFuel=2, iBound=3, Fit initTime=1950, Fit Error =3.589477e-02
iFuel=3, iBound=3, Fit initTime=1950, Fit Error =8.572524e-02

```





Part III: SELECTED, tables of selected regression

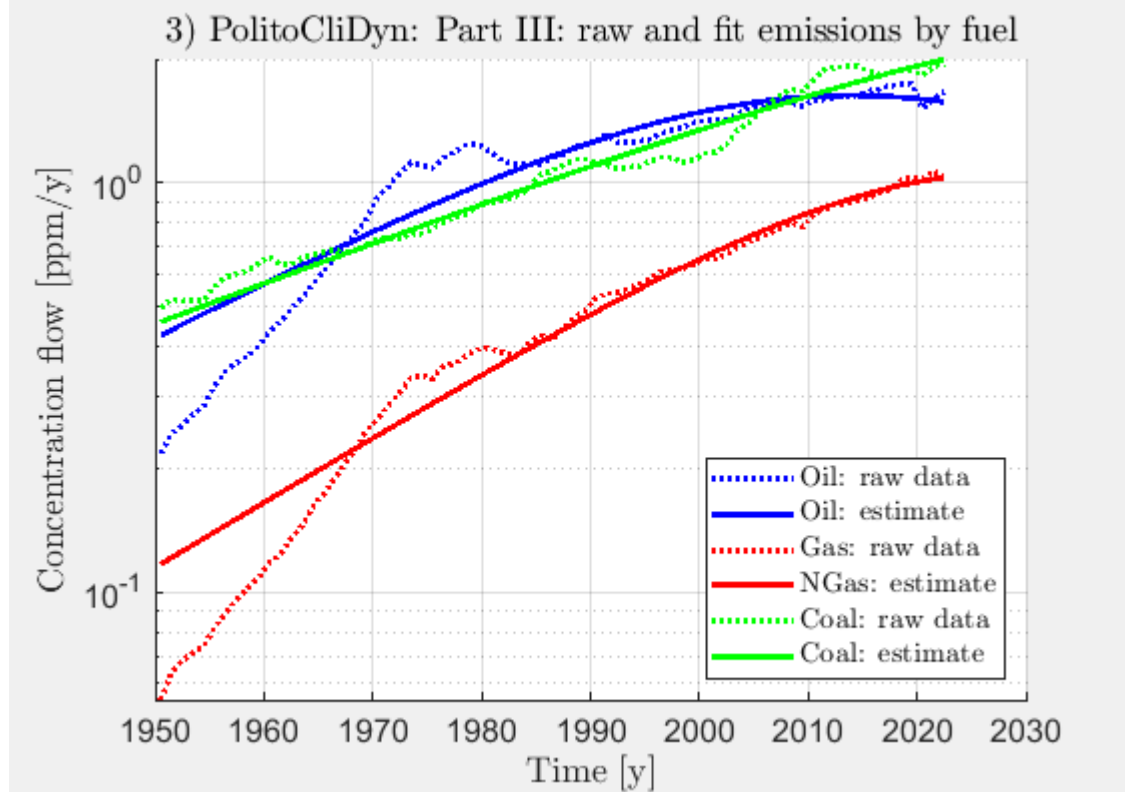
Table 2: fuel emission fit parameters by Meixner curve

Fuel/bound	Amplitude	Time const	Peak time	Ampl std	Tau std	Time std	Res RMS
{'Oil down' }	1.6254e+00	3.0309e+01	2.0125e+03	2.6223e-02	5.5851e-01	4.9594e-01	1.2973e-01
{'Gas down' }	1.0445e+00	2.6796e+01	2.0281e+03	1.0803e-02	3.2757e-01	1.8325e-01	3.6124e-02
{'Coal down' }	2.5809e+00	4.3027e+01	2.0546e+03	3.9221e-02	8.5298e-01	4.5507e-01	8.6354e-02
{'Oil mean' }	1.6330e+00	3.1328e+01	2.0139e+03	2.6425e-02	5.9084e-01	4.9863e-01	1.2893e-01

{ 'Gas mean' }	1.0604e+00	2.7170e+01	2.0291e+03	1.1025e-02	3.3476e-01	1.8166e-01	3.5902e-02
{ 'Coal mean' }	2.6291e+00	4.3310e+01	2.0559e+03	4.0084e-02	8.6317e-01	4.7593e-01	8.6053e-02
{ 'Oil up' }	1.6420e+00	3.2316e+01	2.0153e+03	2.6988e-02	6.3040e-01	5.0565e-01	1.2959e-01
{ 'Gas up' }	1.0761e+00	2.7510e+01	2.0301e+03	1.1346e-02	3.4440e-01	1.8207e-01	3.6010e-02
{ 'Coal up' }	2.6777e+00	4.3578e+01	2.0572e+03	4.0951e-02	8.7306e-01	4.9747e-01	8.5788e-02

Table 3: CD emission projections, peak values and times

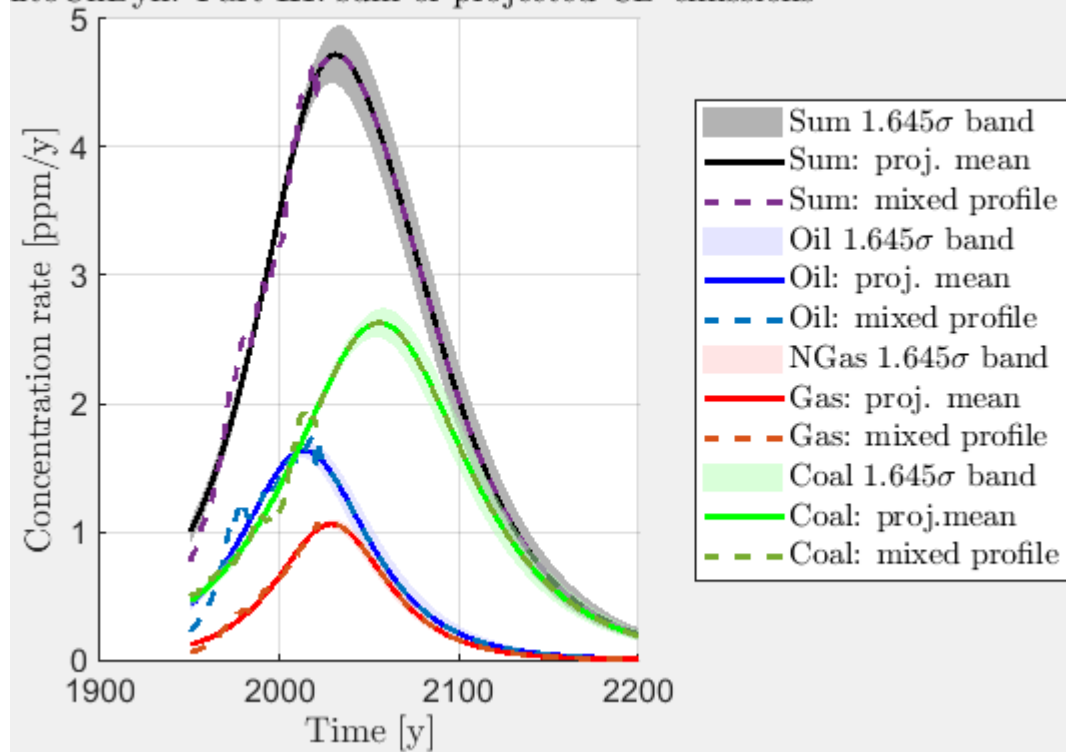
Fuel	Max	Min	Max time	Min time	RawVarRMS	ExtVarRMS
1.0000e+00	1.6869e+00	1.5982e+00	2.0165e+03	2.0145e+03	4.5537e-01	4.1785e-01
2.0000e+00	1.0948e+00	1.0574e+00	2.0305e+03	2.0295e+03	2.9852e-01	2.9040e-01
3.0000e+00	2.7454e+00	2.6108e+00	2.0585e+03	2.0565e+03	4.6173e-01	4.6023e-01



Fit step=111, initTime=1960
Fit step=121, initTime=1970
Fit step=131, initTime=1980
Fit step=141, initTime=1990
Fit step=151, initTime=2000

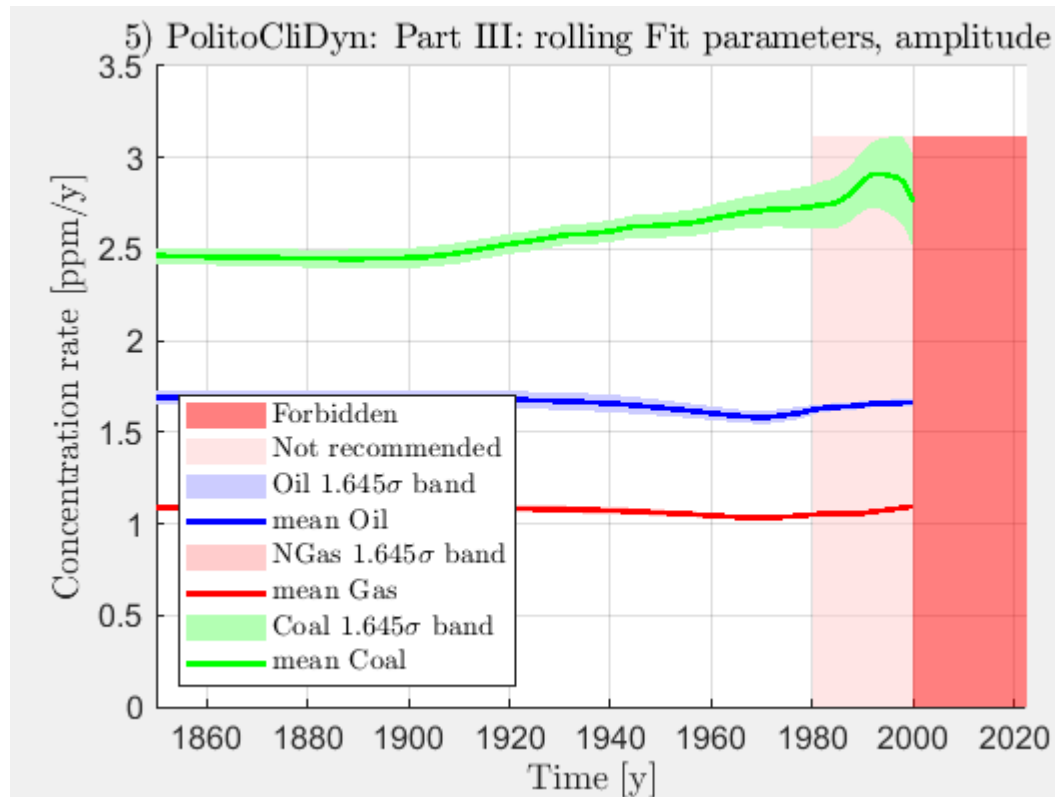
Part III: end of rolling regression
Part III: writing mean parameters into spreadsheet files
Part III: sum of the selected projected CD emission by fuel

litoCliDyn: Part III: sum of projected CD emissions

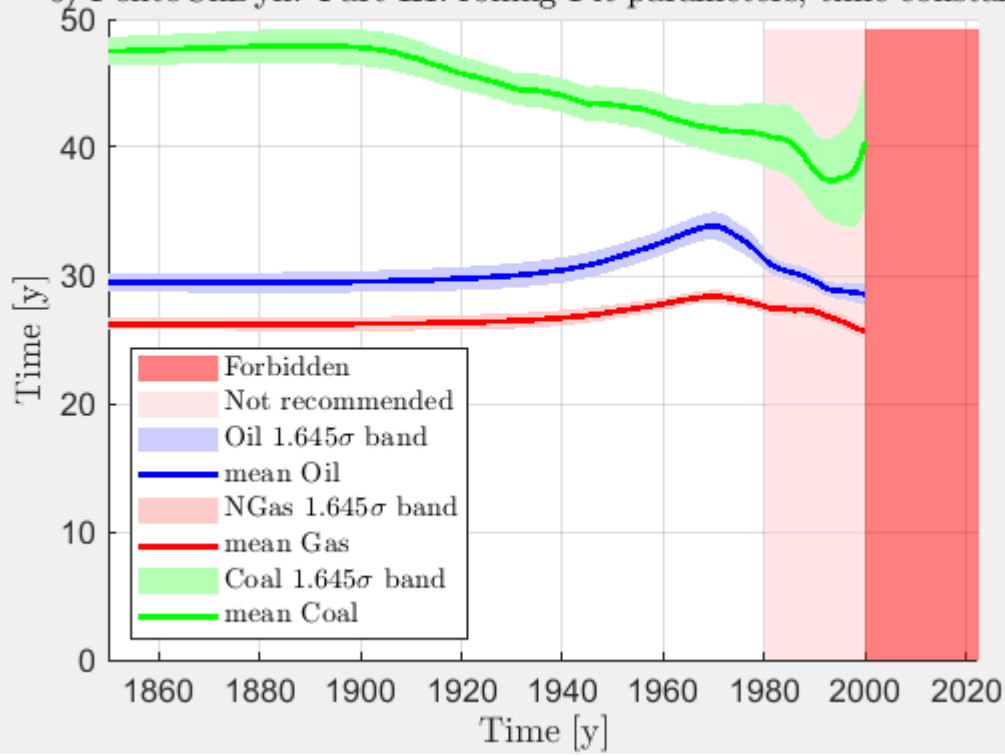


Part III: saving residual RMS as apriori std and optimal init unknowns

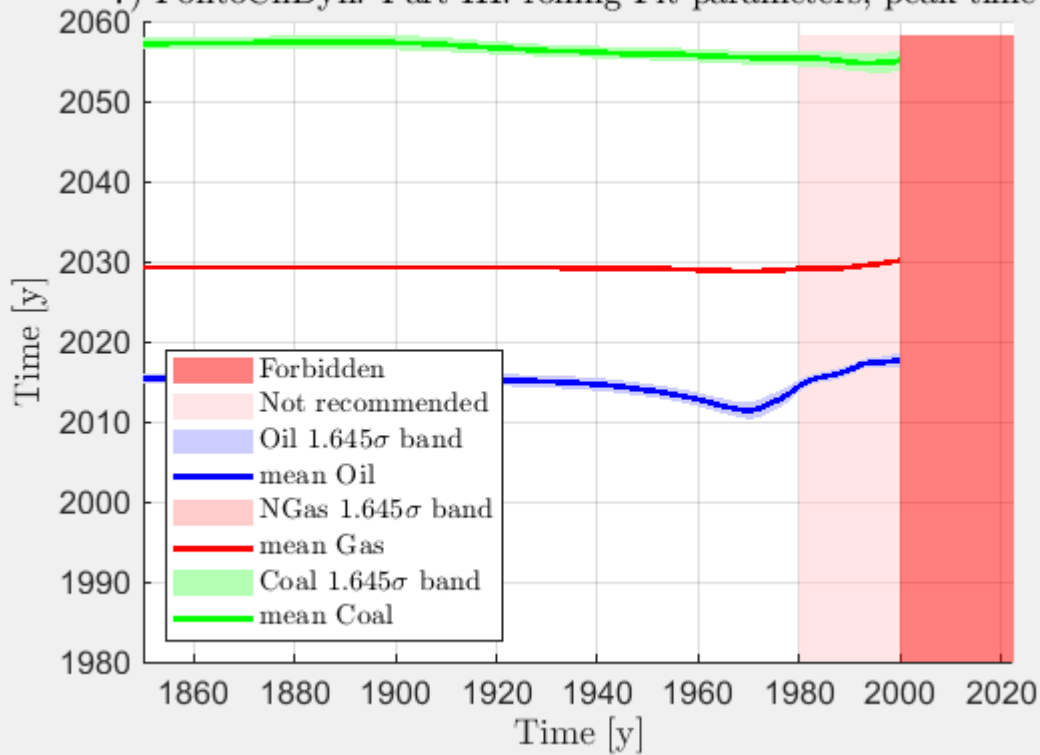
Part III: plotting rolling regression parameters

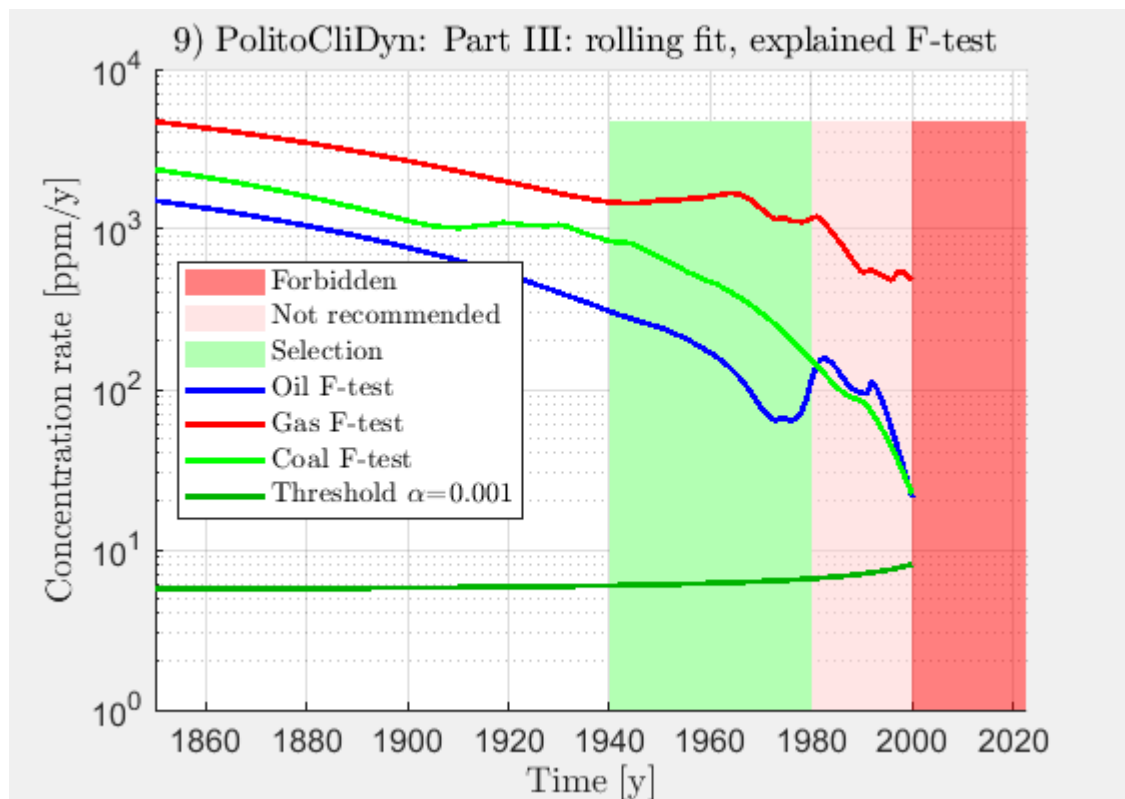
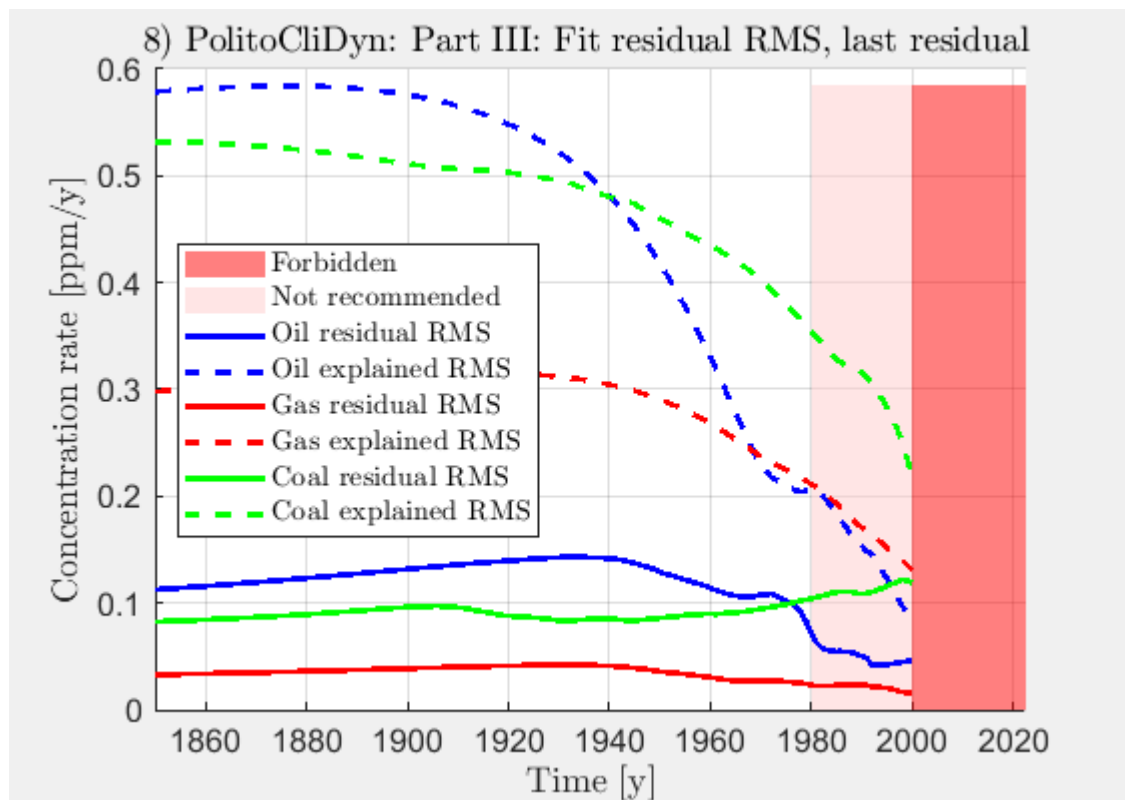


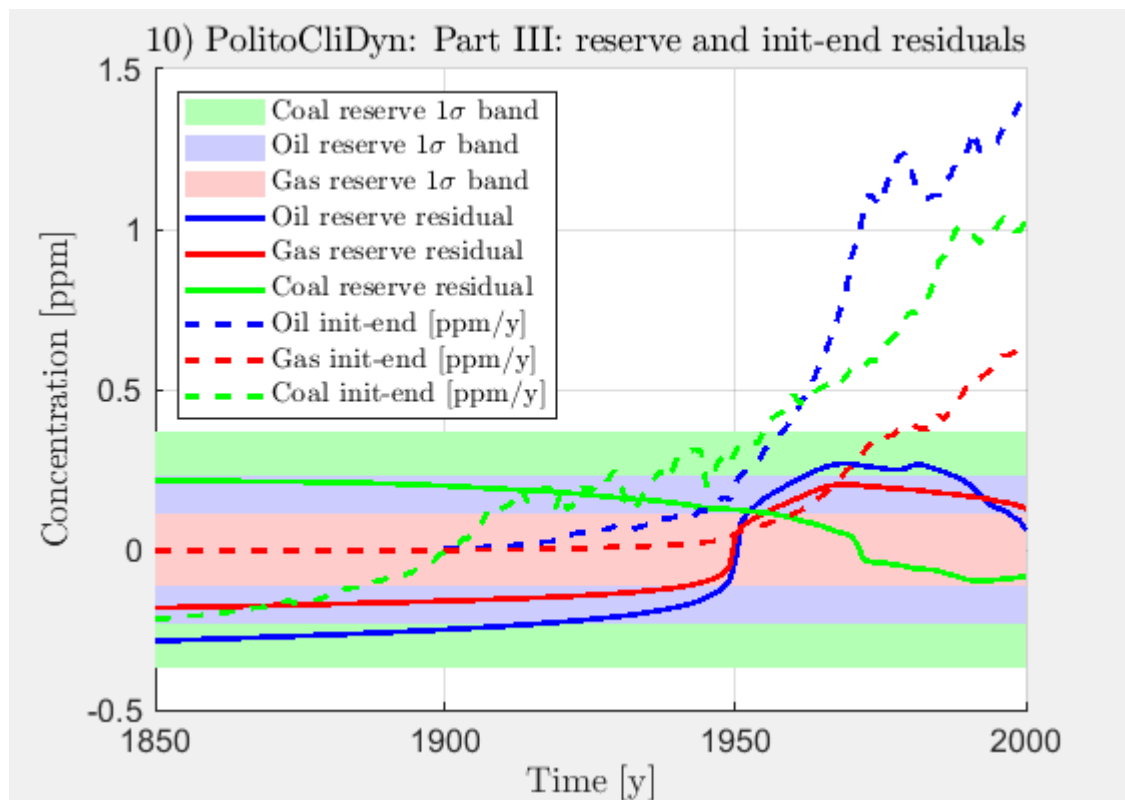
6) PolitoCliDyn: Part III: rolling Fit parameters, time constant



7) PolitoCliDyn: Part III: rolling Fit parameters, peak time

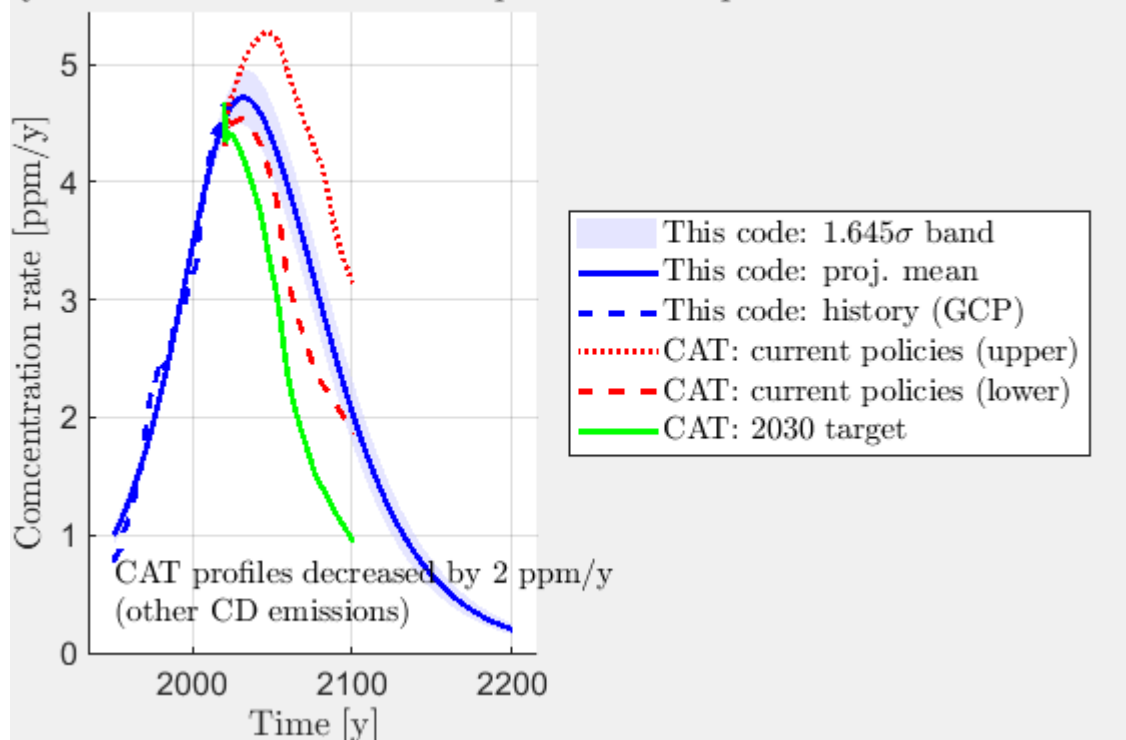






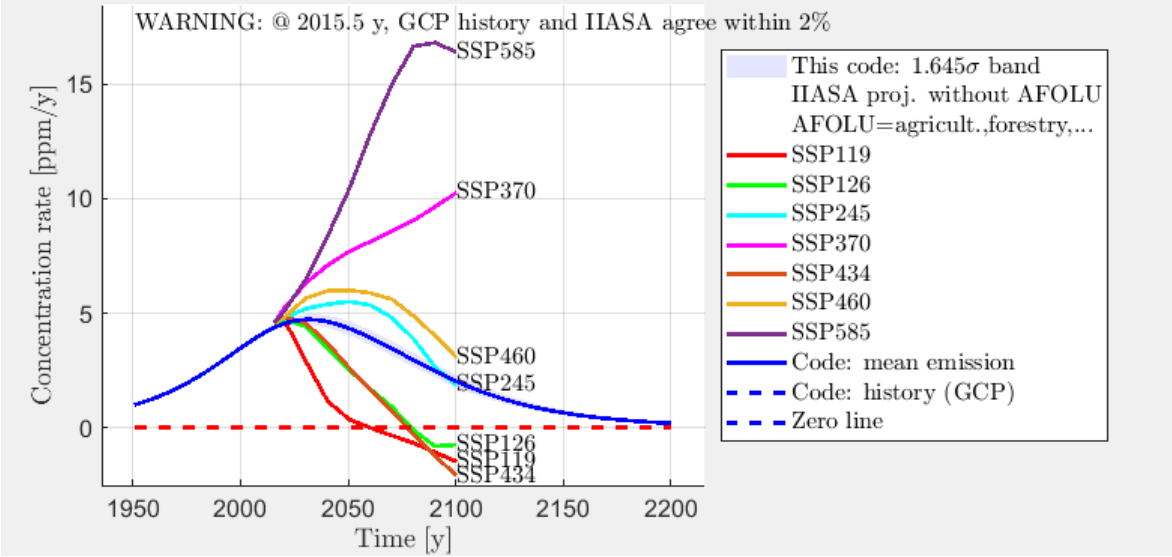
Part III: comparison with CAT (Climate Action Tracker) profiles

PolitoCliDyn: Part III: CD emission compared to CAT profiles



Part III: comparison with IIASA emission profiles

12) PolitoCliDyn: Part III: CD emission compared to IIASA profiles



End of Part III

Part IV

The prediction of the total finite-reserve emission $u(t) = \hat{c}(t)$ is applied to the first-order state equation of Part I for projecting the airborne CD concentration $\hat{x}(t), t > t_p$ (Fig.1). A rolling-time projection (see Figs. 3 and 4) is again implemented by progressively changing the integration initial time $t_0 \geq 1850$ y. The initial time t_{SelfFit} that has been selected by users for graphical plotting and tabulating results (see Figs. 1 and 2), remains the same. Fig. 2 shows graphically the *integration's coherence*. The numerical rate $\Delta \hat{x}(t) = u(t) - \Phi_{\text{LO}}(t)$ [ppm y⁻¹] of the projected CD concentration is reconstructed by the difference between the total emission $u(t)$ and the flow $\Phi_{\text{LO}}(t)$ to land and ocean. Here, the reconstruction error is just *numerical* (see Fig. 2 and Table 2). Rolling-time projection features, like peak time and amplitude of the CD concentration, are coherent with those of the total emission projection in Part III, showing divergence in the pink and red regions.

Fig. 5 compares code results with the IPCC projections driven by the CD emissions in Fig. 12 of Part III. A significant fact is the increasing SSP245 projection (cyan) at 2150 y versus the decreasing finite-reserve projection of the code (blue), notwithstanding the rather close shape of the SSP245 emission (cyan, Fig. 12 of Part III) to the code projection. Fig. 6 shows a diverging discrepancy between the IIASA CD emissions of Fig. 12 of Part III, when integrated by the first-order LTI state equation of Part I (solid lines) and the corresponding IPCC projections of Fig 5 (dashed lines). At first sight, different dynamics have been employed for integrating the projected CD emissions.

To shed light on the issue, the first-order LTI state equation of Part I is added with a quadratic term of the CD concentration anomaly $\delta x(t) = x(t) - \underline{x}$ as follows

$$\dot{x}(t) = -k(x(t) - \underline{x}) + q(x(t) - \underline{x})^2 + u(t), x(t_0) = x_0.$$

As in Part I, the equation is fit to measurements, here IPCC projections and IIASA emissions, in three ways: 1) the *difference* fit employs concentration rates (not in figures), 2) the *integral* fit employs the IPCC concentrations

in Fig 5, 3) the *cumulative* fit integrates the IIASA emissions with the three unknown parameters k, \underline{x}, q found by the difference fit. The code focuses on the intermediate scenario SSP460 (Fig. 7, orange color, and Table 1). Both IPCC concentration (top of Fig. 7, blue and red) and rate (mid of Fig. 7, cyan and magenta) are tracked with small residuals. Residuals are plotted in Fig. 7, bottom, added to unit, so as to employ a semilogarithmic scale. The nonzero equilibrium $\delta \underline{x} > 0$ (under $k > 0, q > 0$) is unstable (see Table 1). The estimated value of k (the *first-order pole*) is close to the LTI estimate, thus providing a further check of its significance.

In Fig. 8, the *coherence* of online MAGICC projections, in the SSP245 case, is investigated, as done for the code in Fig. 2. The numerical rate $\Delta \hat{x}(t) = -\Phi_{LO}(t) + u(t)$ [ppm y^{-1}] of the projected CD concentration is reconstructed by the difference between the total emission $u(t)$ and the flow $\Phi_{LO}(t)$ to land and ocean, which data are provided by the files May2024_SSP_245_magicc_202405141717.csv (projection results) and rc mip_ssp245_template.csv (CD emissions). The residual difference $\Delta \hat{x}(t) - (-\Phi_{LO}(t) + u(t))$ [ppm y^{-1}] is nonzero with and without the AFOLU term in the CD emission.

Part IV run

```
CheckLiveScriptFolder;
```

```
PolitoCliDyn: 1st order CC: checking Live Script folder
DONE: PolitoCliDyn_1stOrderCC_LiveScript.mlx found
DONE: Live Script folder
```

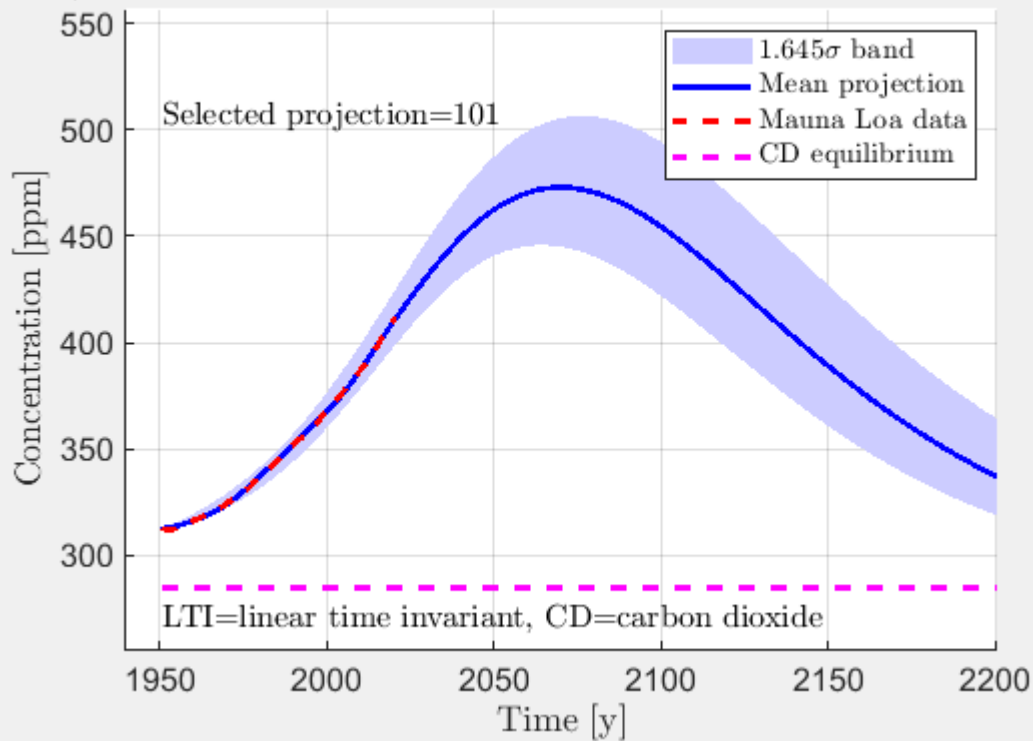
```
Init_LiveScript;
PolitoCliDyn_1stOrderCC_PartIV
```

```
-----
PolitoCliDyn: 1st order CC, airborne CD prediction, Part IV
Part IV: loading user input data and rolling fit timing
Table 1: User input and actual (corrected) data
```

Type	Ind.era t0	Forbidden t0	Selfit tInit	RoI fit step	RoI fit size
{'Actual'}	1.8500e+03	2.0000e+03	1.9500e+03	1.0000e+00	1.5100e+02
{'Input' }	NaN	NaN	1.9500e+03	NaN	NaN

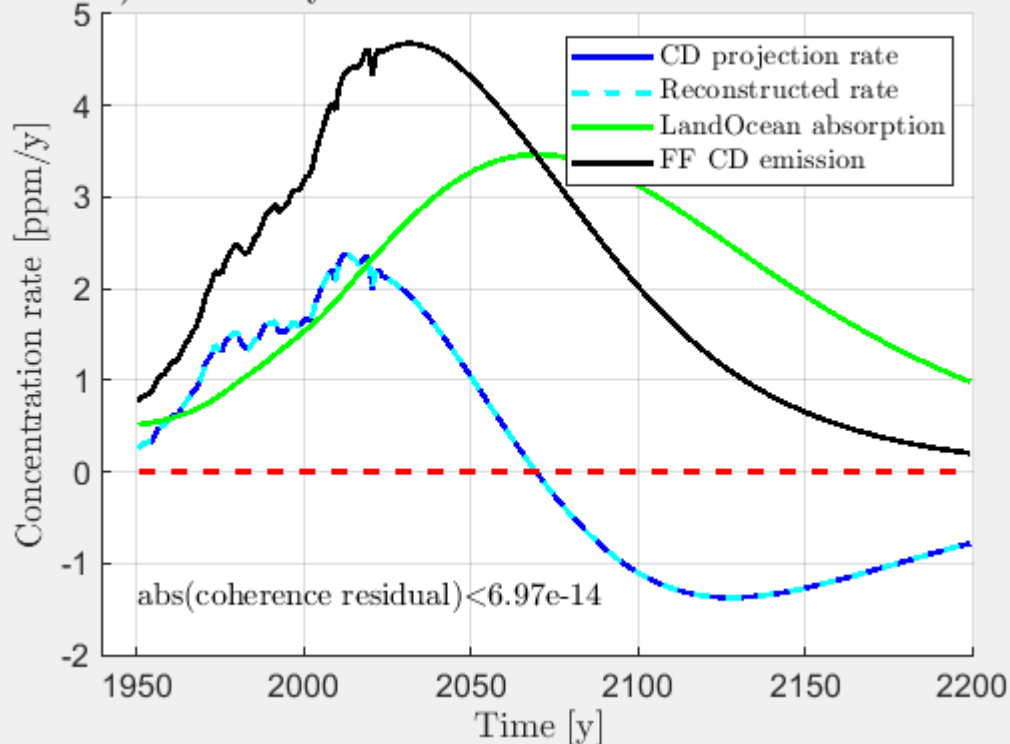
```
Part IV: Airborne CD projection with 1st-order LTI CD dynamics
Fit step=1, initTime=1850
    reading Part I model parameters
    reading predicted Part III FF CD emissions
    reading raw airborne CD concentration
Fit step=11, initTime=1860
Fit step=21, initTime=1870
Fit step=31, initTime=1880
Fit step=41, initTime=1890
Fit step=51, initTime=1900
Fit step=61, initTime=1910
Fit step=71, initTime=1920
Fit step=81, initTime=1930
Fit step=91, initTime=1940
Fit step=101, initTime=1950
    plotting selected CD projection
```

1) PolitoCliDyn: Part IV: CD projection, 1st-order LTI dynamics



checking coherence of airborne CD rate

2) PolitoCliDyn: Part IV: coherence of airborne CD rate



Fit step=111, initTime=1960

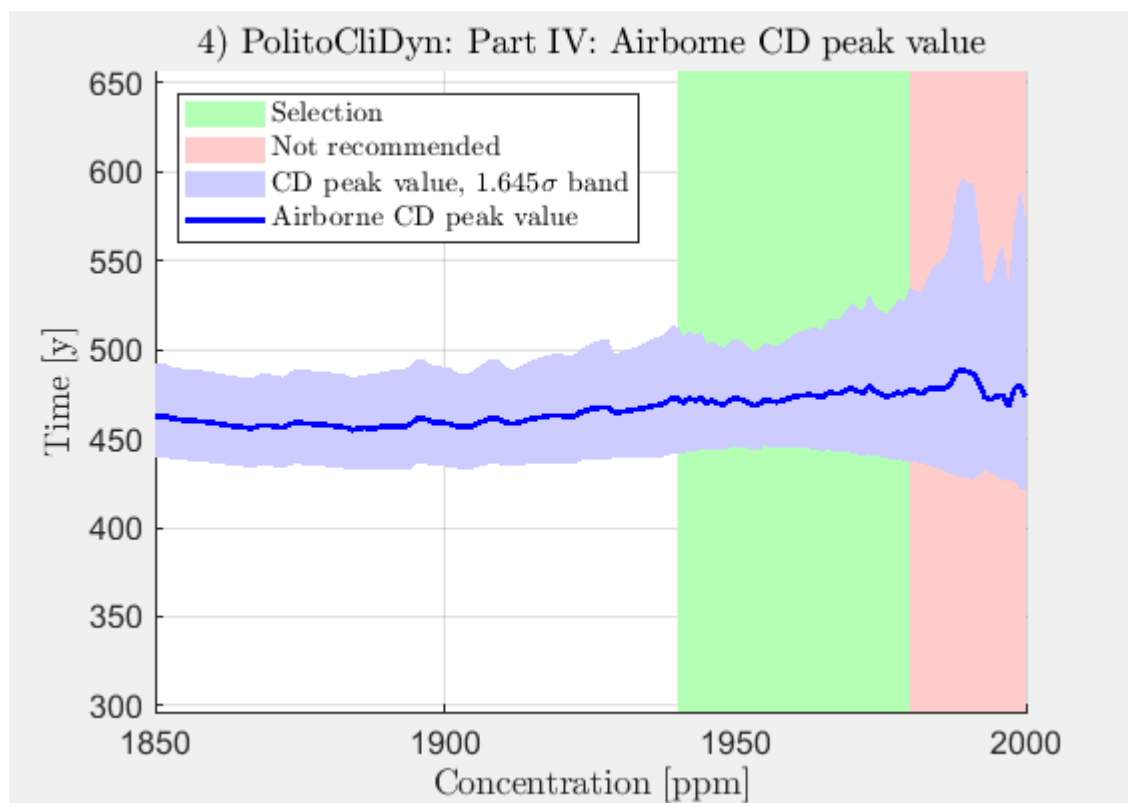
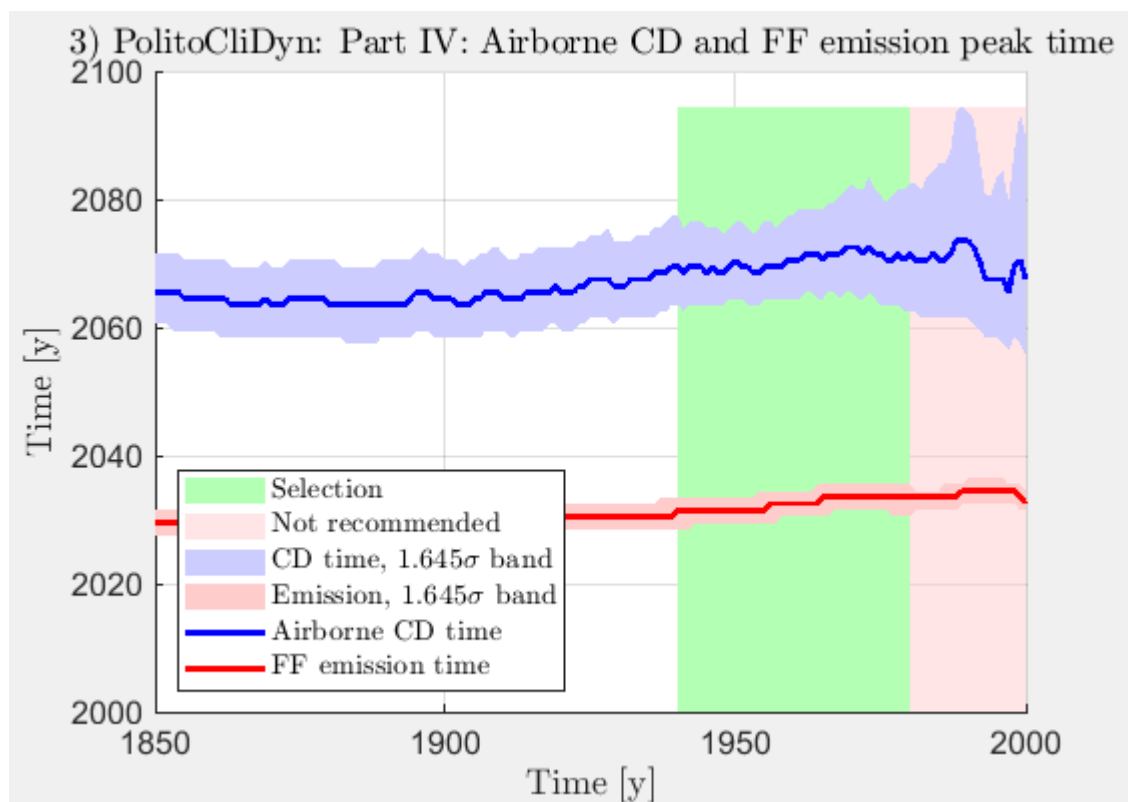
Fit step=121, initTime=1970

Fit step=131, initTime=1980

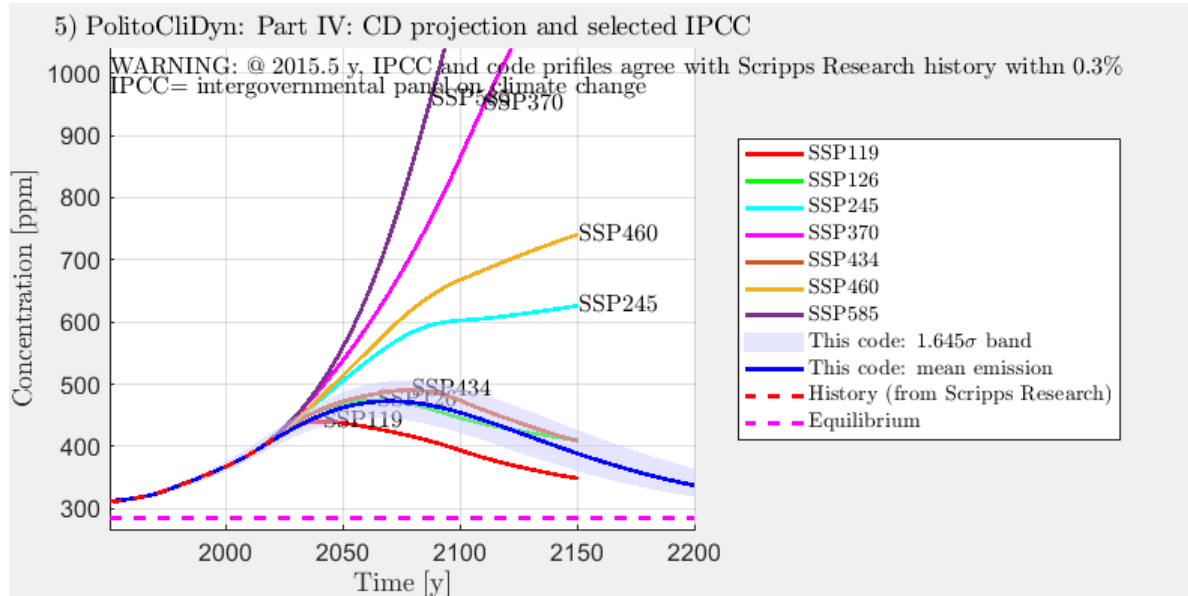
Fit step=141, initTime=1990

Fit step=151, initTime=2000

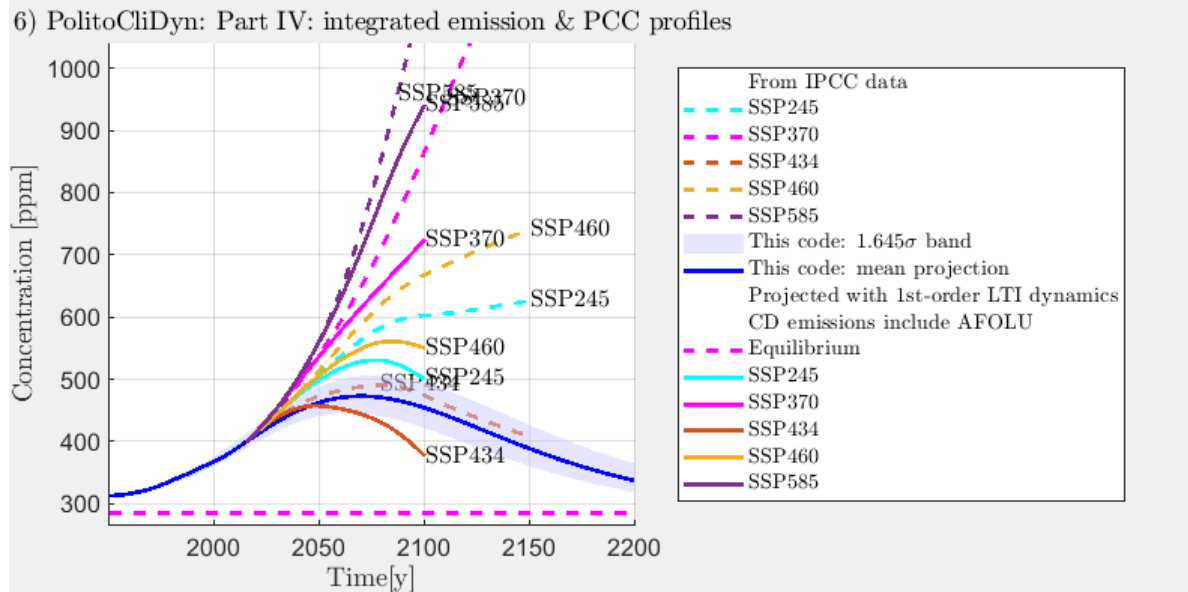
Part IV: airborne CD projection peaks and timing



Part IV: comparison of airborne CD projection with IPCC profiles



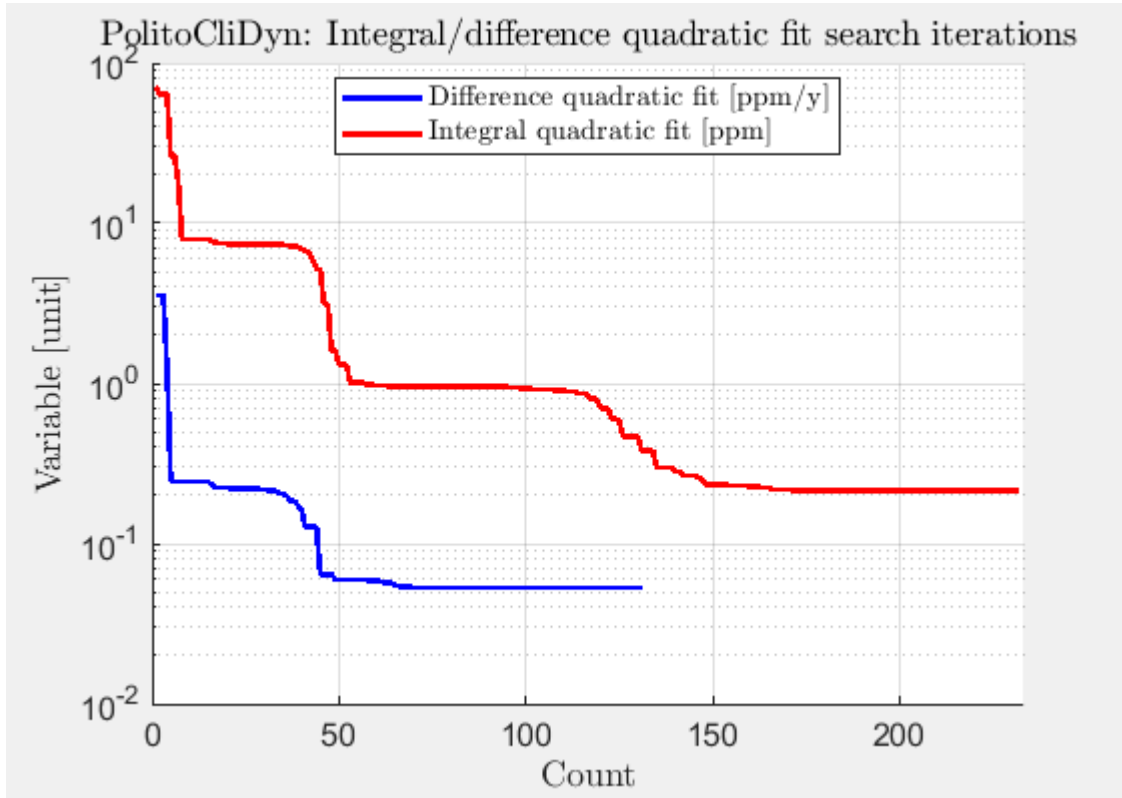
Part IV: recall, fossil fuel CD emissions projections (source: IPCC)
 Part IV: IIASA DC emissions integrated with 1st-order LTI CD dynamics



Part IV: IPCC CD projection rate, CD emission and flow to land/ocean
 Part IV: fitting IPCC CD projections with 1st-order quadratic dynamics

- 1) difference fit
- 2) cumulative fit
- 3) integral fit

Part I: plotting difference and integral quadratic fit iterations



Part IV: plotting fit and residuals, 1st-order quadratic dynamics

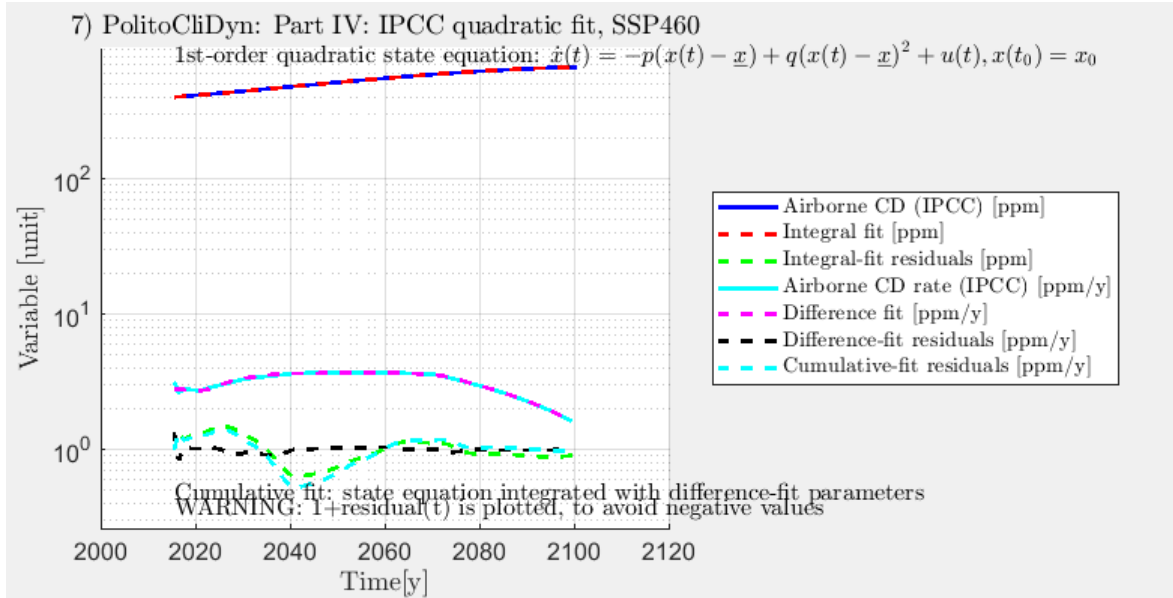
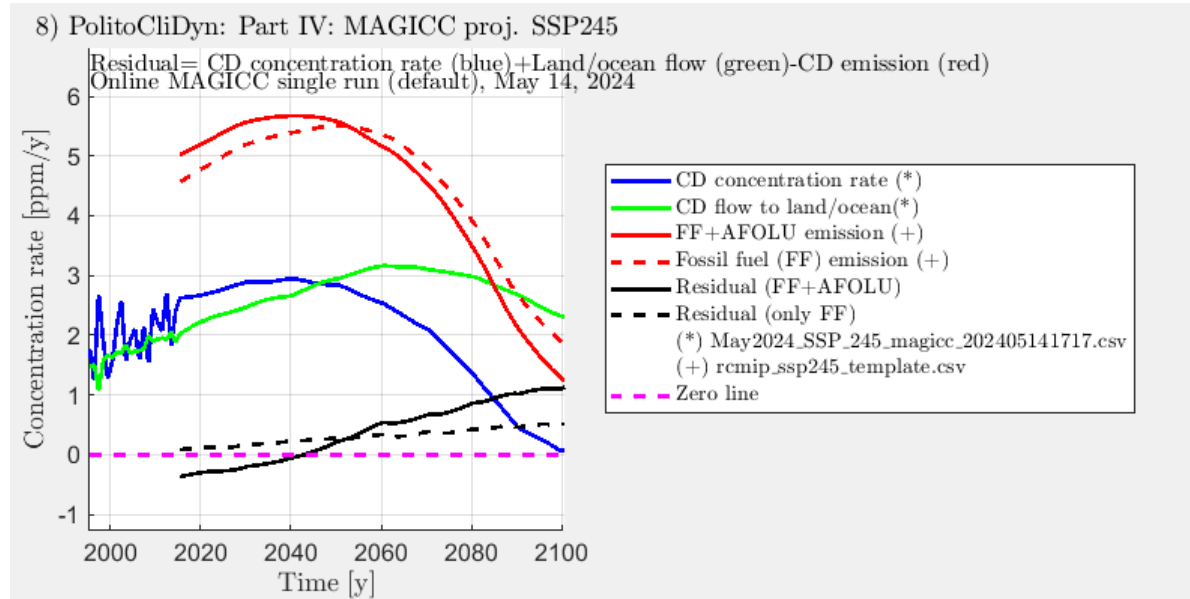


Table 2: 1st-order quadratic equation fit results (IPCC data)

Parameter	Difference[ppm/y]	Cumulative[ppm]	Integral[ppm]	Difference LTI
{'Equilibrium(Eql) [ppm]'	2.4063e+02	2.4063e+02	2.3673e+02	2.9653e+02
{'Pole [1/y]'	1.9985e-02	1.9985e-02	1.9754e-02	2.0807e-02
{'Quadratic[(yxppm)^-1]'	4.0154e-05	4.0154e-05	3.9272e-05	0.0000e+00
{'Unused'	NaN	NaN	NaN	NaN
{'Residual RMS [unit]'	5.3002e-02	2.2693e-01	2.1842e-01	NaN
{'Variable RMS[unit]'	5.9298e-01	8.4096e+01	8.4170e+01	NaN
{'Explained RMS[unit]'	5.9401e-01	8.4087e+01	8.4087e+01	NaN
{'F-test'	3.4058e+03	3.7987e+06	4.1006e+06	NaN
{'0.999 threshold'	5.7111e+00	5.9512e+00	5.9512e+00	NaN
{'Residual mean[unit]'	1.5597e-06	-1.8590e-04	2.0620e-03	NaN
{'Unstable Eql [ppm]'	7.3833e+02	7.3832e+02	7.3973e+02	NaN



End of Part IV
