A Macro Time Series Model of the Carbon Cycle

(Version 2.0)

Abstract

In order to project the effect of fossil fuel CO_2 emissions on global temperature we need to project not just those emissions but also future global atmospheric CO_2 concentration. A model of the effect of fossil emissions on the carbon cycle should be in the context of the natural emissions and absorption. Thus we need time series data on gross CO_2 emissions and absorption by land and sea. There appears to be a lack of any such data, however we do have data on net absorption by land and sea. Here we provide proxy series to assist with projections. Existing research provides estimates of the natural carbon fluxes at specific points in time. These are first used here to provide linear interpolations, which are then used together with the net flows to form estimates of the natural gross flows. The series are the used to estimate the parameters of a carbon cycle based on the natural stocks and flows. The performance of the model is evaluated over the historical period. Finally the model equations are used to project estimates to 2060. Various alternative scenarios are presented The results suggest that global temperatures can be stabilised .[1]

Since pre-industrial times, fossil fuel emissions have added about 45 percent more carbon dioxide to the atmosphere. Atmospheric CO_2 concentration is the major determinant of global temperature increase. The higher CO_2 concentration has led to an increase in global temperature of over 1 degree C. How much do emissions need to be reduced to stabilize temperature?

Currently about half fossil fuel emissions are added to the atmosphere and half are absorbed by the earth. So we would expect fuel emissions should be at least halved to stop atmospheric concentration increasing. However the planet naturally emits and absorbs more than twenty times the volume of annual fossil fuel emissions. We need to understand these dynamics, and how they may change, to be confident about any projection of global temperatures.

Relevant time series data are available from the *Global Carbon Budget* (GCB), see Friedlingstein et.al.2023, and its associated Global Carbon Project (GCP) *Data Supplement*. These data are meticulously compiled from a multitude of scientific observations. Global annual data are provided from 1959 gigatonnes of carbon (GtC), which include fossil fuel emissions, land use change emissions, atmospheric changes and land and ocean sinks. These sinks represent the net result of the natural absorption and emissions of CO_2 from the land and sea.

The gross flows are not directly observable and result from a wide geographic and seasonal distribution of absorption and outgassing. We need estimates of them because any attempt to project global trends based only on the net flows would be problematic. Net flows provide

[1] I would like to acknowledge comments on an earlier draft of this paper provided by Josep Canadell of the Global Carbon Project.

insufficient information on which to base a carbon cycle model. Any estimates of the gross flows will necessarily differ from the unknown actual flows. However acting as proxy variables against which the known fluxes are calibrated, they will still provide a useful tool on which to derive projections of the known net fluxes.

The Carbon Cycle

A further source of useful information on the carbon cycle is *Climate Change 2021: The Physical Science Basis, Chapter 5*, IPCC, (Ch5, Canadell, et.al.). There, following diagram was presented:

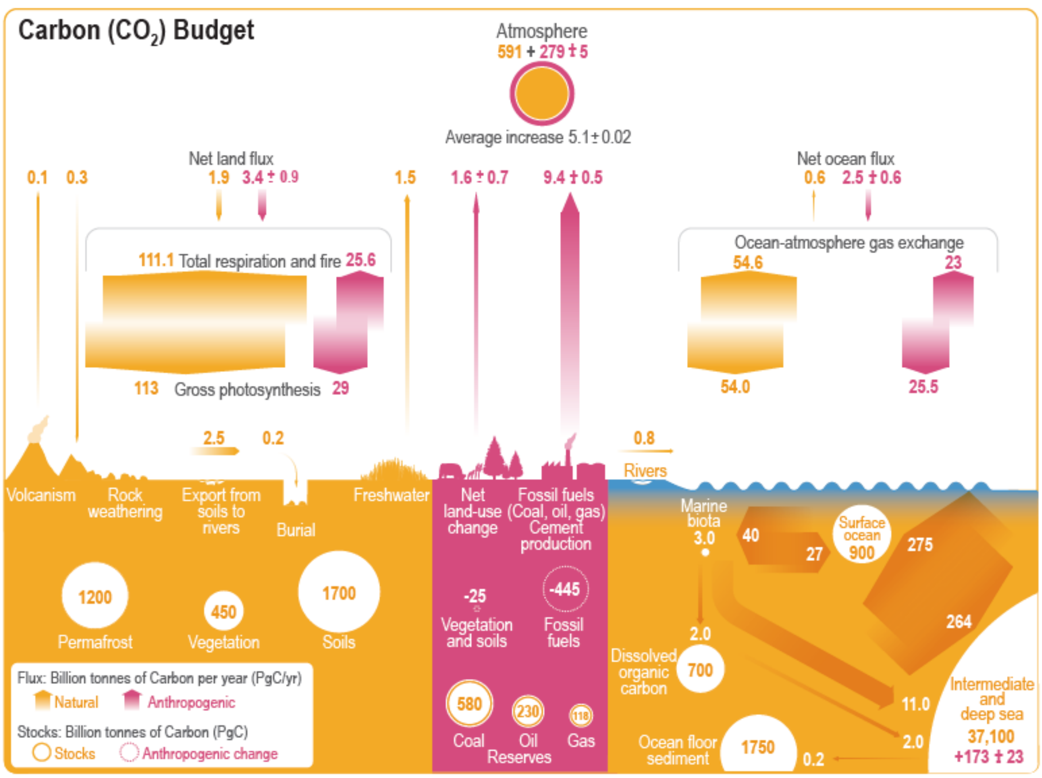

Figure 1. The Carbon Cycle and changes since pre-industrial times. (Source: Ch5 Fig 5.12)

The yellow arrows are fluxes (flows) and the circles are reservoirs (stocks) in GtC and represent the situation in pre-industrial times. The pink figures represent anthropogenic changes and relate to the period 2010-2019. This figure shows the land and sea gross flows to and from the atmosphere at two points in time. This information provides the basis for an initial estimate of time series for the gross flows.

The following steps have been taken:

- Use emissions data to establish a base date for interpolation
- Generate linear interpolations of the gross flows.
- Generate time series based on linear benchmarks modified to be consistent with the known GCP net flows.
- Use these to formulate and estimate a global carbon cycle model.

The first step in this process is to estimate a straight line approximation to the linear section of the emissions data 1950 to 2019. This results in an equation:

$$F_E = -237.755 + 0.122629 \text{ Year} \qquad R^2\ .9849 \qquad (1)$$

$$(-65.16) \qquad (66.70) \qquad \text{t values}$$

where F_E is estimated fossil fuel emissions. The following is a graph of this relationship:

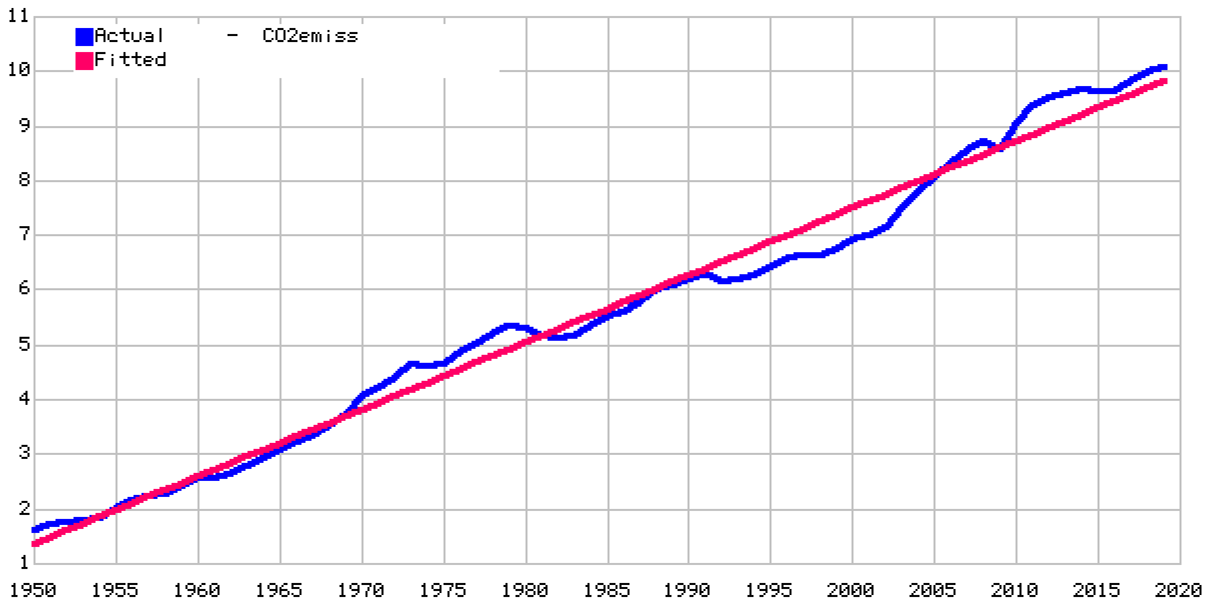

Figure 2. Actual fossil fuel emissions and a linear approximation (GtC/year)

Solving equation (1) for F_E=0 gives Year=1938.75. Therefore most of the observed changes in the carbon cycle reported in Ch5 would have occurred if the fossil fuel emissions had increased in a linear manner starting in 1939. As depicted, the increase in emissions is approximately linear over this period. Therefore it is reasonable to assume that the resulting effect on natural carbon flows would also be approximately linear over this period. Hence for linear interpolation and extrapolation, we may assume that the yellow figures in Ch5 refer to 1939 and the red figures to 2015. We may thus create linear time series for relevant carbon cycle variables.

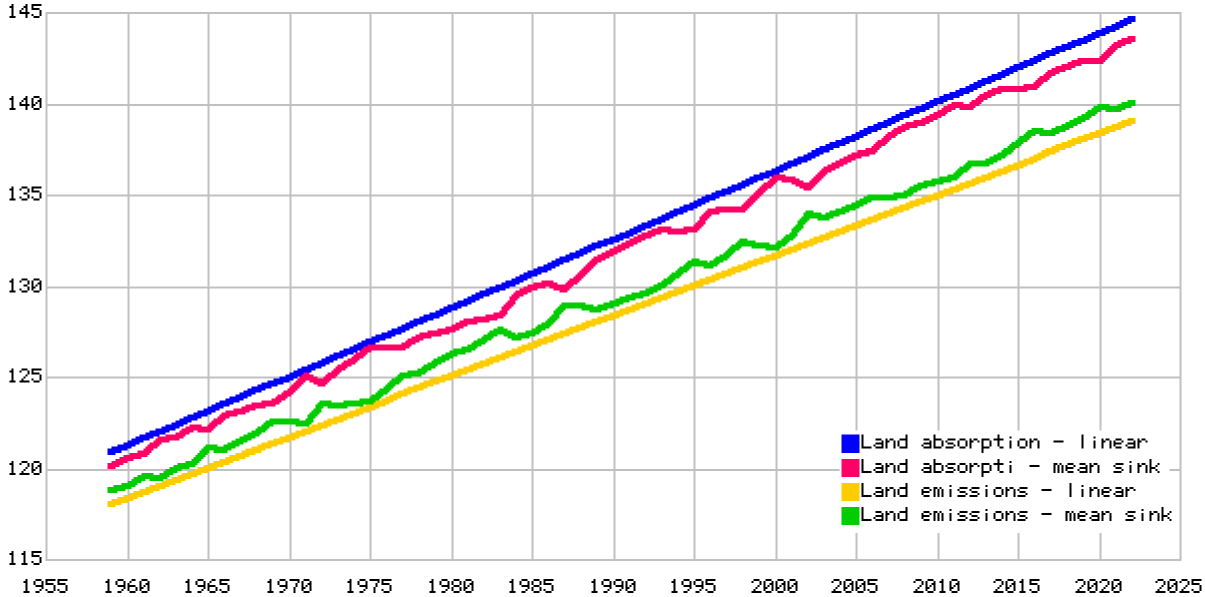

Figure 3. Linear and adjusted series for land absorption and emissions (GtC/year)

The Ch5 data suggests that land gross absorption 2010-2019 would be 142.0 and emissions 136.7. These numbers have been used to set the linearization for 2015, while the pre-industrial numbers are based in 1939. The Carbon Budget net sink data are then applied to the mean of the gross absorption and emission trends. The results are shown in Figure 3.

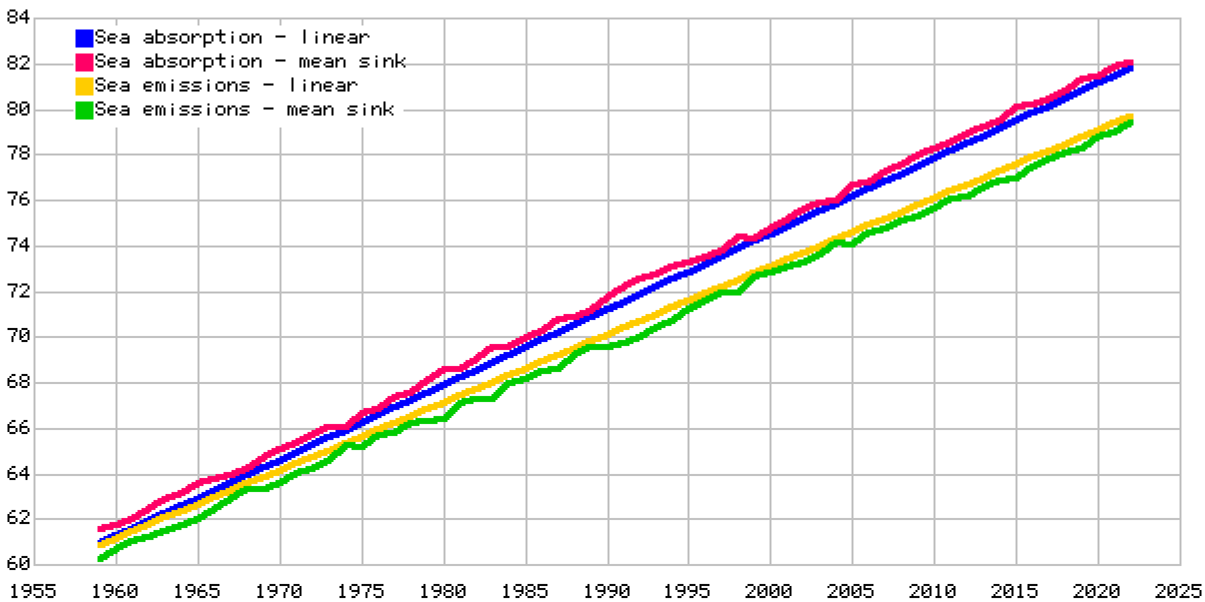

Figure 4. Linear and adjusted series for sea absorption and emissions (GtC/year)

The Ch5 data suggest that sea gross absorption 2010-2019 would be 79.5 and emissions 77.6. These are the numbers that have been set for 2015 in the linearization. The Carbon Budget net ocean sink data have then been applied to the trend mean. The results are shown in Figure 4.

Note that for land, the Carbon Budget net land sink data is less in 2015 than what would be expected given the Ch5 chart, however for the sea, the Carbon Budget net ocean sink is slightly greater than what would be indicated. The Carbon Budget data used here has been proportionally adjusted to eliminate the budget imbalance. This does not account for the land net difference.

A model of the carbon cycle

Consider a theoretical model of the carbon cycle, linking these variables:

$S_A = \alpha_{A0} + \alpha_{A1} A_K + \alpha_{A2} T$	Sea absorption = f (air stock, temperature)
$S_E = \alpha_{E0} + \alpha_{E1} S_K + \alpha_{E1} T$	Sea emissions = f (sea stock, temperature)
$S_D = \alpha_{D0} + \alpha_{D1} S_K$	Deep sea sequestration =f (sea stock)
$\Delta S_K = S_A - S_E - S_D + R$	Change in sea stock
$\Delta A_K = S_E - S_A + L_E - L_A + L_U + F_E$	Change in air stock
$L_A = \alpha_{A0} + \alpha_{A1} A_K + \alpha_{A2} T$	Land absorption = f (air stock, temperature)
$L_E = \alpha_{E0} + \alpha_{E1} L_K + \alpha_{E2} T$	Land emissions = f (land stock, temperature)
L_U	Land use change emissions (external)
F_E	Fossil fuel emissions (external)
$\Delta L_K = L_A - L_E - L_U - R - L_T$	Change in land stock
R	Rivers
L_T	Land transfers n.e.c.

The flows in this model are determined in relation to the relevant stocks together with temperature as an additional explanatory variable. Stocks are determined by accumulation of the flows. Fossil fuel and land use change emissions are external inputs to the model.

Various estimates of land and sea carbon storage in GtC are given in Ch5 Figure 5.25. The GCP Estimate from these charts has been digitised and provides the data for S_K and L_K, using the initial values of 2150 GtC for the land stock and 900 GtC for the sea stock.

Data for deep sea sequestration are given by

$$S_D = S_A - S_E + R - \Delta S_K$$

Data for changes in the land stock not elsewhere accounted for are given by

$$L_T = L_A - L_E - L_U - R - \Delta L_K$$

We thus have a coherent data set which we may use to estimate the postulated model parameters.

Sea absorption and emissions

The primary determinants of absorption of CO_2 by the sea from the air are changes in the partial pressure of CO_2 and temperature. This is the first equation of our theoretical model. An equation representing the parameters of this relationship is:

$$S_A = 0.2905 + 0.0941\ A_{K-1} \qquad R^2\ .9814 \qquad (2)$$

(0.2294) (56.80) t values

where S_A is estimated sea absorption, A_{K-1} is atmospheric stock, lagged. Temperature has been excluded as it had the wrong sign and is highly correlated with atmospheric concentration. The coefficient indicates that a one Gt increase in atmospheric carbon will result in a 0.09 Gt increase in oceanic carbon. Lagged air stock is used to avoid issues with simultaneity. A graph of the fitted values from this equation is as follows:

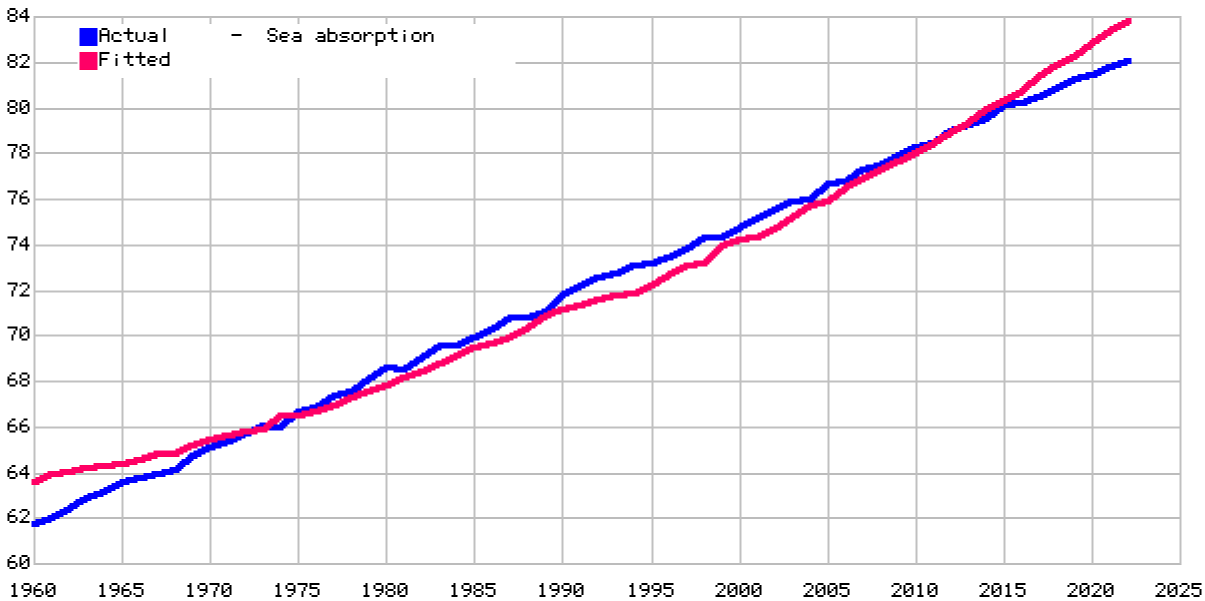

Figure 5. Sea absorption: actual and as fitted by regression equation

Sea emissions are related to the stock of oceanic carbon and temperature. This equation is estimated as follows:

$$S_E = 0.06689\ S_{K-1} + 9.80\ T_{-1} \qquad R^2\ .9501 \qquad (3)$$

(277.6) (19.56) t values

This indicates that annual emissions are about 7 percent of the stock of oceanic carbon and that a one degree increase in temperature gives rise to 10 Gt of additional emissions, or about 1 percent of the sea stock. This is consistent with known effect of temperature on the solubility of carbon dioxide in sea water. Note that here we are using air temperature as a proxy for sea temperature.

A graph of the fitted values from this equation is as follows:

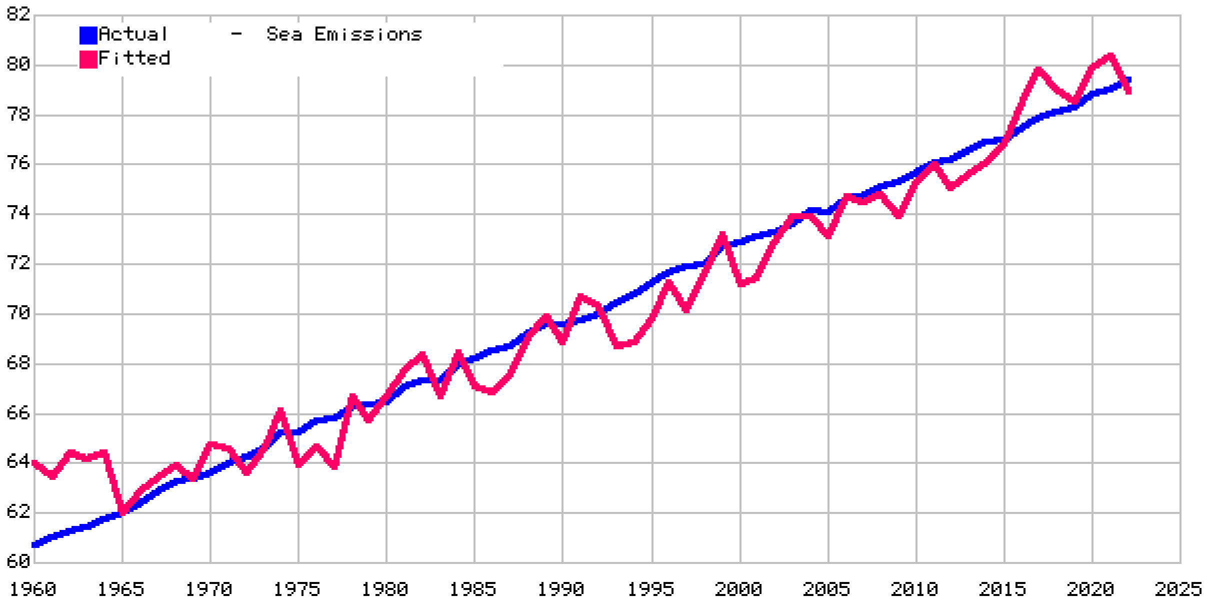

Figure 6. Sea emissions: actual and as fitted by regression equation

The inclusion of temperature in the emissions equation gives rise to the corresponding volatility in the fitted values. We do not suggest that the outgassing necessarily follows this pattern, but the equation does capture at least some of the known effect of temperature, which counteracts the effects of increased partial pressure of carbon dioxide.

Land absorption and emissions

In the next stage of our estimation of our theoretical model is to use the CH5/GCP based data for land absorption (gross photosynthesis), which starts at 120 Gt/year and increases by 29. Intuitively we would expect this to increase with temperature but this was not the case in the estimation, and temperature was excluded. The estimated equation is:

$$L_A = 51.123 + 0.10628A_{K-1} \qquad R^2\ .9814 \qquad (4)$$

(35.76) (56.79) t values

where L_A is estimated sea absorption, A_{K-1} is atmospheric stock, lagged The coefficient indicates that about 10 percent of atmospheric CO_2 is absorbed by the land annually. .

A graph of the fitted values from this equation is as follows:

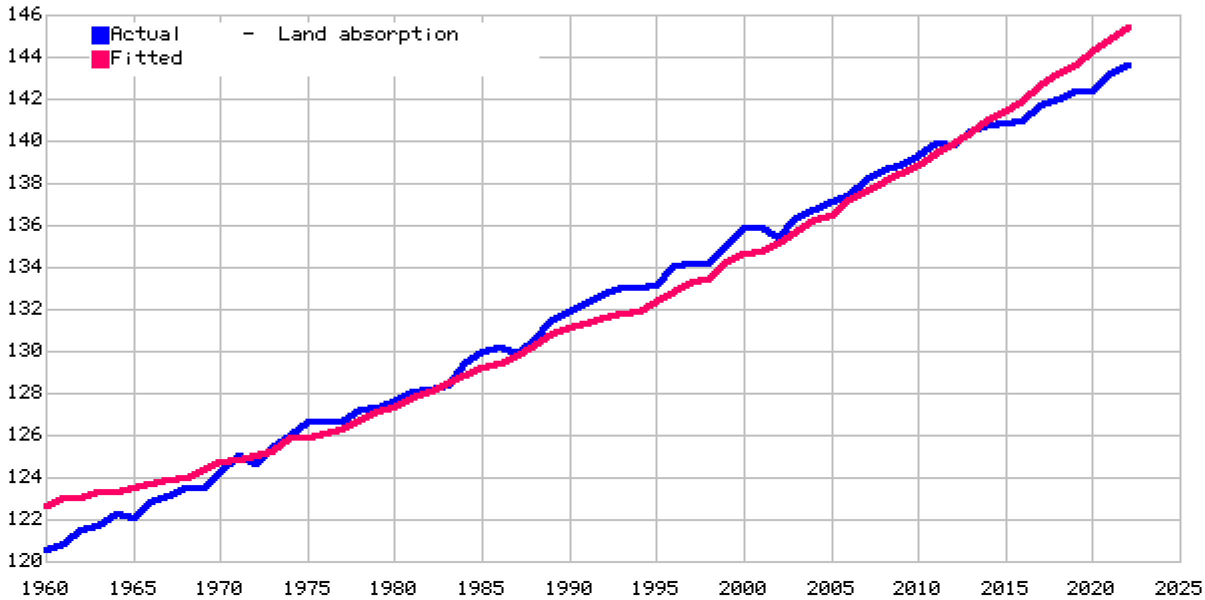

Figure 7. Land absorption: linear and as fitted by regression

Land emissions in our theoretical model are assumed to be a function of the land stock and temperature. These increase from 111 in pre-industrial times and 119 at the start of our estimation period to 137 in 2015.

The parameters of our theoretical model of land emissions have been estimated. The results are:

$$L_E = 0.05893\, L_{K-1} + 15.298\, T_{-1} \qquad R^2\ .9061 \qquad (5)$$

(346.28) (20.41) t values

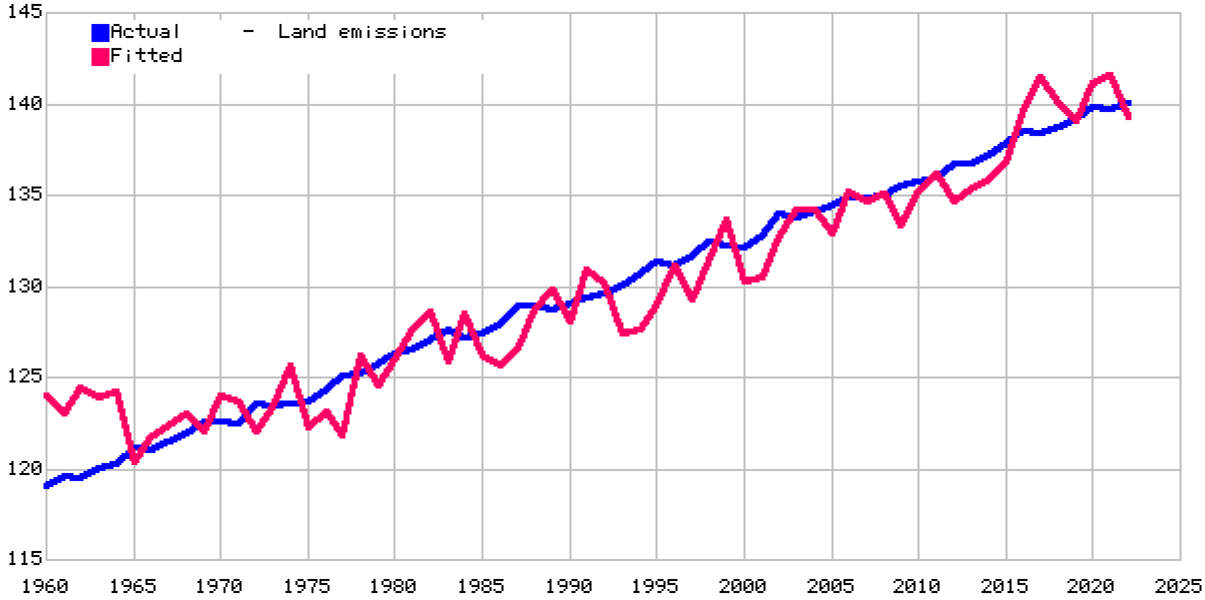

Figure 8. Land emissions: actual and as fitted by regression equation

The fitted values reflect the volatility arising from the temperature component. The temperature coefficient indicates that a one degree rise in temperature results in a 15.3 Gt/year increase in land emissions. The land stock coefficient indicates that 6 percent of increases in land carbon are emitted.

Equations for deep sea sequestration S_D and residual land transfers L_T have also been estimated. All carbon transfers are thus accounted for, and the theoretical model as postulated, can operate as a simulation model in which only fossil fuel emissions F_E and land use change emissions L_U are exogenous.

Comparison with other studies

The section in Ch5 that deals with linear feedback analysis (5.4.5.5) proposes to decompose changes in land carbon storage (ΔC_L) and changes in ocean carbon storage (ΔC_O) into contributions arising from warming (ΔT) and increases in CO_2 (ΔCO_2) as follows:

$$\Delta C_L = \beta_L \, \Delta CO_2 + \gamma_L \, \Delta T$$

$$\Delta C_O = \beta_O \, \Delta CO_2 + \gamma_O \, \Delta T$$

where β_L (βo) and γ_L (γo) are coefficients that represent the sensitivity of land (ocean) carbon storage to changes in CO_2 and global mean temperature respectively.

It is possible to interpret this in a way relating to the published GCB data where ΔC_L and ΔC_O are the land and sea net sinks and the other variables as published. However applying regression analysis to such a model does not yield anything useful and the temperature coefficients have the wrong sign. This is why it is necessary to separate the net sinks into gross absorptions and emissions.

We are yet to devise a simulation experiment with our model that could provide comparable results to those presented in relation to the proposed decomposition.. However it may be possible to interpret our estimated equations in a way that may provide a comparison with other models.

The atmospheric stock coefficient in equation (2) in 2015 implies a contribution to sea absorption of 81.9 GtC given an atmospheric load of 870 GtC. Total sea absorption in 2015, as per Ch5 Figure 5.12 is 79.5 GtC. The ratio, 0.97 (79.5/81.9) could be taken as an estimate of β_O. The temperature coefficient in equation (3), 9.8, could be taken as an estimate of γ_O.

The atmospheric stock coefficient in equation (4) in 2015 implies a contribution to land absorption of 92.5. Total land absorption in 2015, as per Ch5 Figure 5.12 is 142 GtC. The ratio, 1.54 (142/142) could be taken as an estimate of β_l. The temperature coefficient in equation (5), 15.3, could be taken as an estimate of γ_L. The signs of the γ estimates may be reversed because emissions have a negative effect on stocks.

These estimates of the β and γ parameters are not dissimilar to those reported foe other models.

Dynamic projection of atmospheric changes 1995-2022

The above behavioural equations for the four fluxes, i.e. land and sea emissions and absorption have been estimated. These equations are all defined in terms of the relevant stocks of carbon in the air, sea and land. The land and sea stocks can be computed as the cumulated net fluxes.

This system has been used as a dynamic simulation model to compute atmospheric changes over the historical period from 1959 to 2022, using 1958 starting values. Actual data has been used for land use emissions L_U, and fossil fuel emissions F_E. These are the only components exogenous to the dynamic simulation. The results are shown in the following graphs.

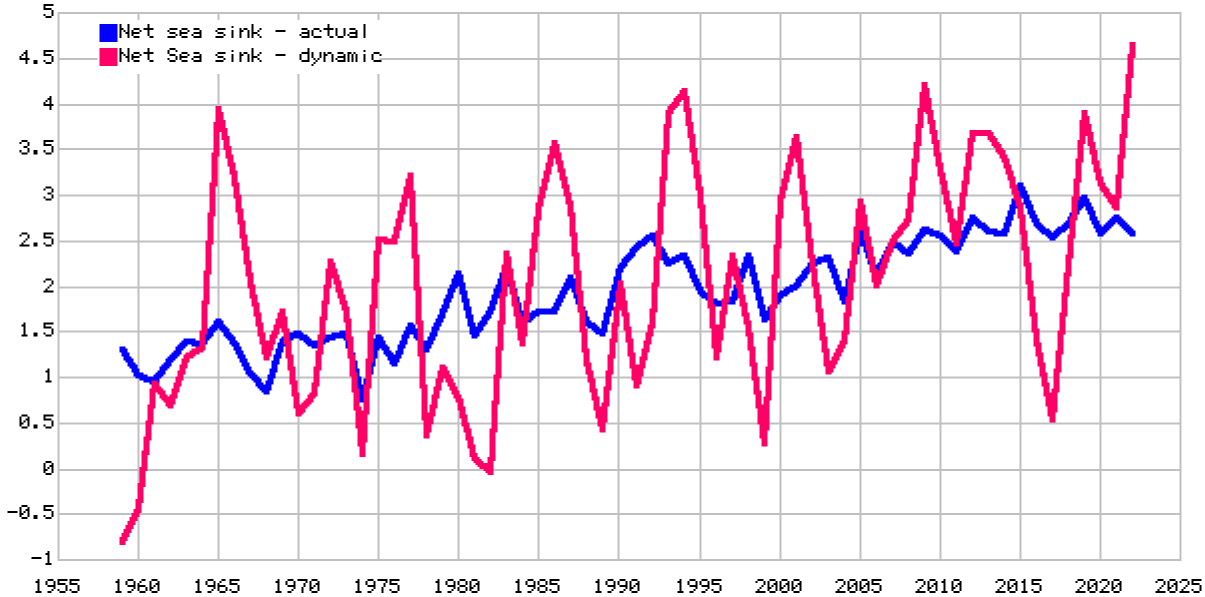

Figure 9. Sea net absorption: actual and projected

Due to the volatility of temperature, which is incorporated into the sea emissions projections, the net absorption, calculated as gross absorption less emissions, is much more variable than apparent in the Carbon Budget ocean sink data as seen in Figure 9. Similarly in Figure 10, computed net land absorption is more volatile than is apparent in the Carbon Budget land sink data. However in both cases, the trend is similar to the actual data.

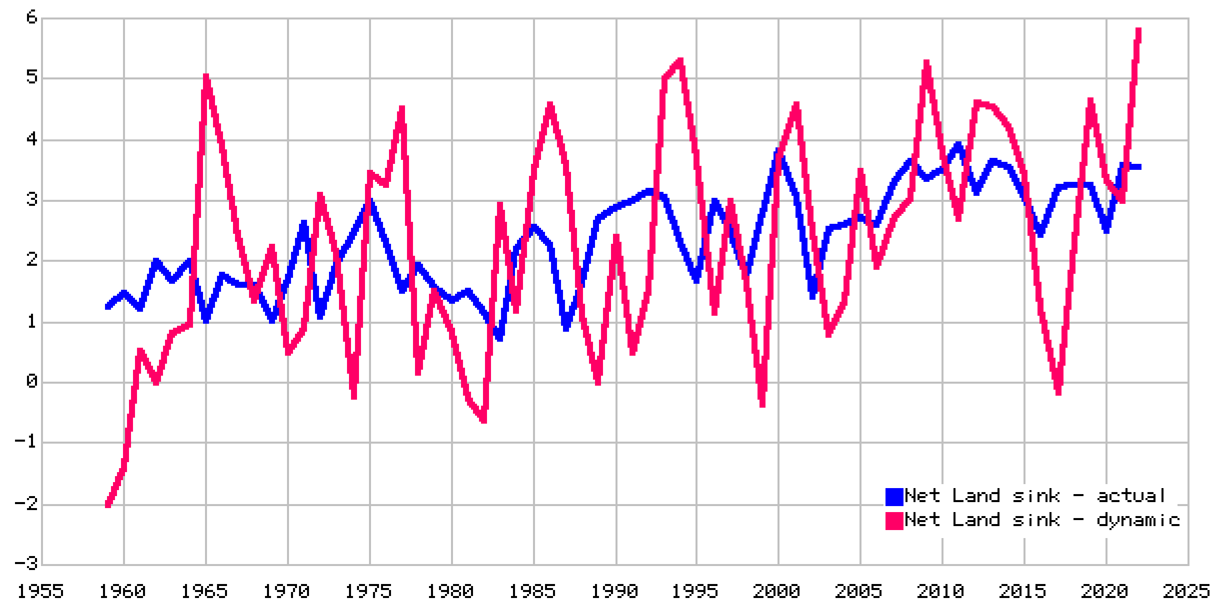

Figure 10. Land net absorption: actual and projected

Sea and land stocks are computed from the projected net sinks, allowing for deep sea sequestration, rivers, and other land transfers.

$$S_K = S_{K-1} + S_A - S_E - S_D + R$$
$$L_K = L_{K-1} + L_A - L_E - L_U - R - L_T$$

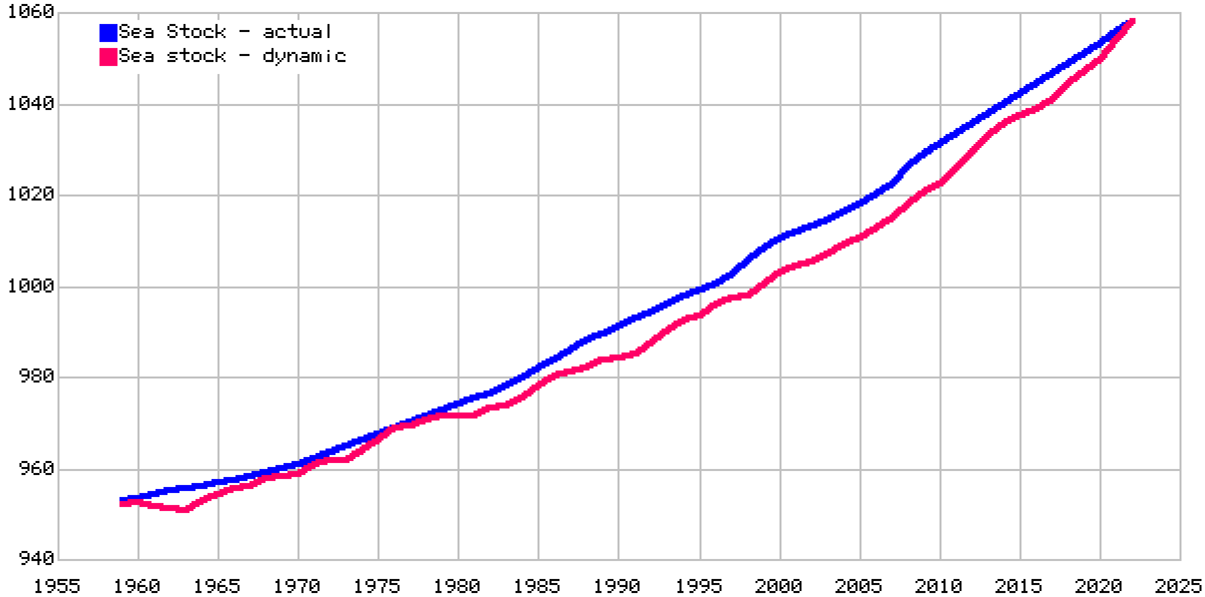

Figure 11. Sea stock: actual and projected

The dynamically computed sea stock tracks the actual sea stock quite well as shown in Figure 11. Similarly, in Figure 12, the computed land broadly stock replicates the actual land stock.

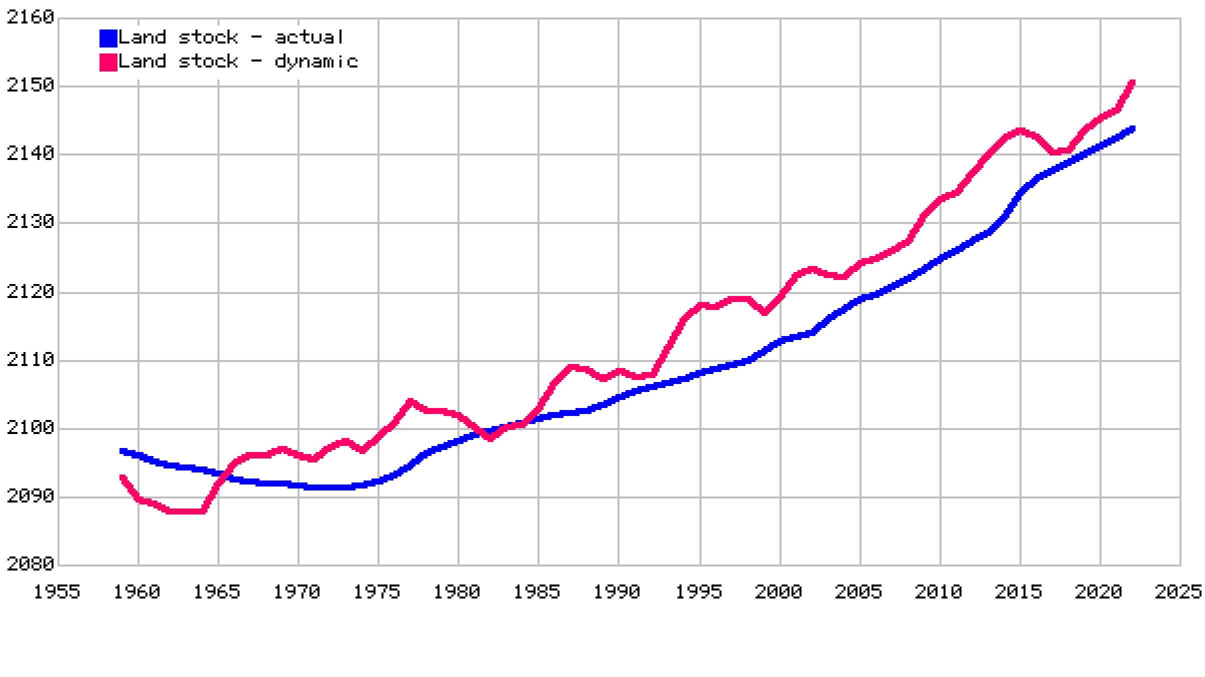

Figure 12. Land stock: actual and projected

Finally, we can compute changes in atmospheric carbon as per the equation:

$$A_K = A_{K-1} + S_E - S_A + L_E + L_U + F_E - L_A$$

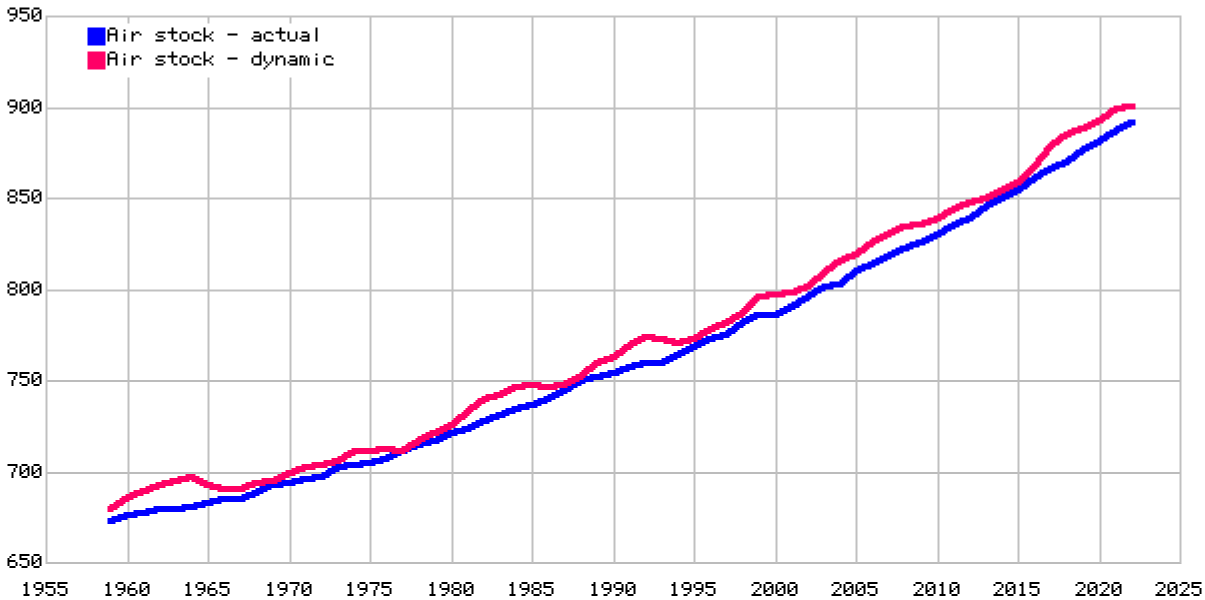

Figure 13. Dynamically computed atmospheric carbon, 1959-2022

The results appear to justify the methodology, in that whereas the imputed gross fluxes may have a somewhat indeterminate relationship with the unknown actual fluxes, the fact that they are estimated based on actual data for atmospheric carbon and temperature, is reflected back in that they are able to regenerate the historical atmospheric series well. This inspires some confidence that the equations will perform reasonably over the forecast period.

Global temperatures and CO_2

Global temperatures are closely related to atmospheric carbon dioxide. It is not the only factor but for forecasting purposes atmospheric carbon provides our best indicator.

A theoretical model may be proposed as

$$T = \alpha_0 + \alpha_1 A_P$$

where T is the global temperature anomaly and A_P is atmospheric CO_2 ppm.

This model has been estimated using NASA data 1958-2022 as

$$T = -3.32018 + .010271 A_P \qquad R^2\ .9247 \qquad (6)$$
$$(-25.04) \quad (27.82) \qquad \text{t values}$$

This means that 92% of the variation in temperature can be explained by the variation in atmospheric CO_2. The t values indicate the coefficients are statistically significant. A 100 part rise in ppm will cause a 1.02 degree rise in temperatures. The actual and fitted values are as follows.

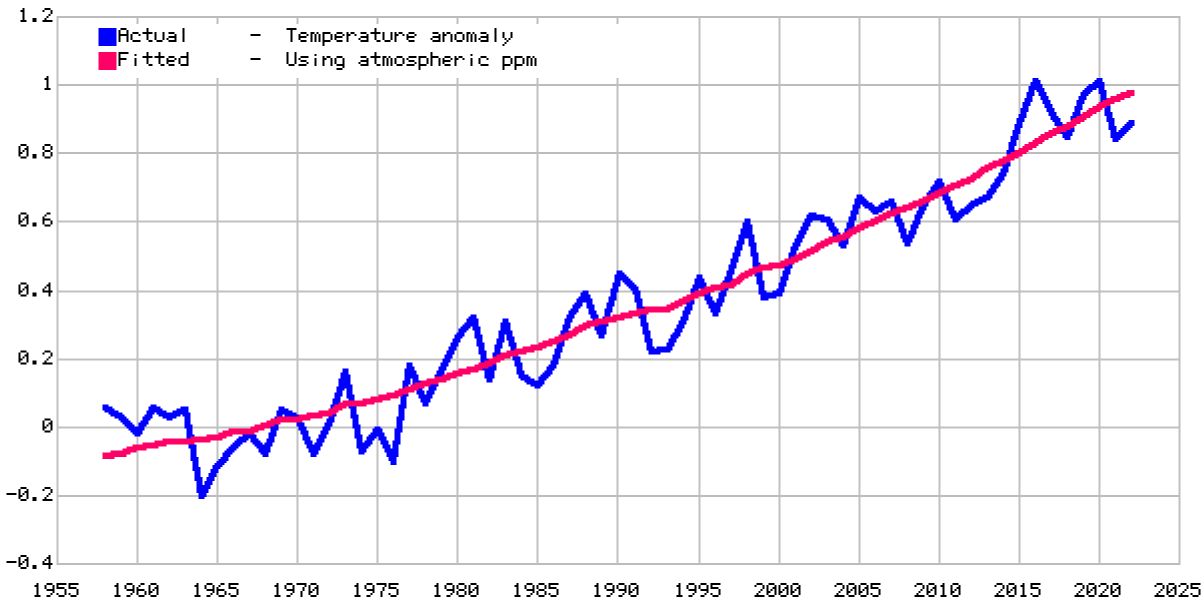

Figure 12. Global temperature and atmospheric CO_2 ppm

As can be seen from the graph annual temperatures are quite volatile. Our projections of temperature will not capture this but will provide a long term guide, at least based on current conditions. To obtain projections of atmospheric carbon 2023-2060 we use our behavioural equations starting from the actual values for 2022. The accepted conversion factor is 1 ppm = 2.124 GtC.

Projection of emissions

In order to form projections of atmospheric carbon we use external projections of land use change emissions and of fossil fuel emissions. The former has no trend and is of lesser magnitude and can be essentially assumed to slowly decline. For the latter we use fossil fuel emissions projections from Macro Elasticity Trade Link Model (Meltrade).

This is a multi-country macroeconomic model of global trade and resources. It was first described at UN Project Link (See Perkins 2007). It has since been updated and re-estimated and is now in operational mode. The baseline assumption is that emissions can be halved by 2040. The projections for emissions are as in Figure 13.

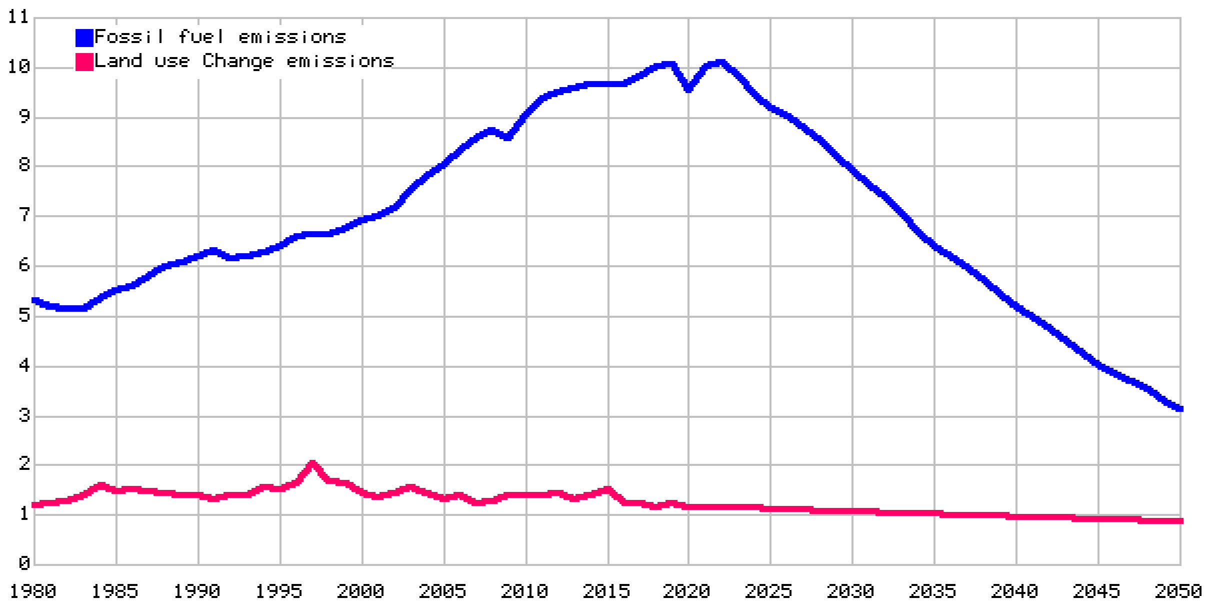

Figure 13. Emissions projections to 2060 (GtC)

The Meltrade model is based on UN National Accounts data and energy related data published by the US Energy Information Administration. Emissions are linked to country based fossil fuel consumption. The model does not yet incorporate analytics related to substitution of renewable energy, but rather uses percentage-wise assumptions of declines in fossil fuel consumption. The model then matches production of coal oil and gas to consumption, subject to the availability of reserves; balances total world production and consumption; equates supply and demand within each country such that production plus imports equals consumption plus exports; and balances total world imports and exports by fuel.

The projections for coal, oil and gas are shown in Figure 14. Total emissions by country of fuel consumption, for the ten largest emitters are shown in Figure 15.

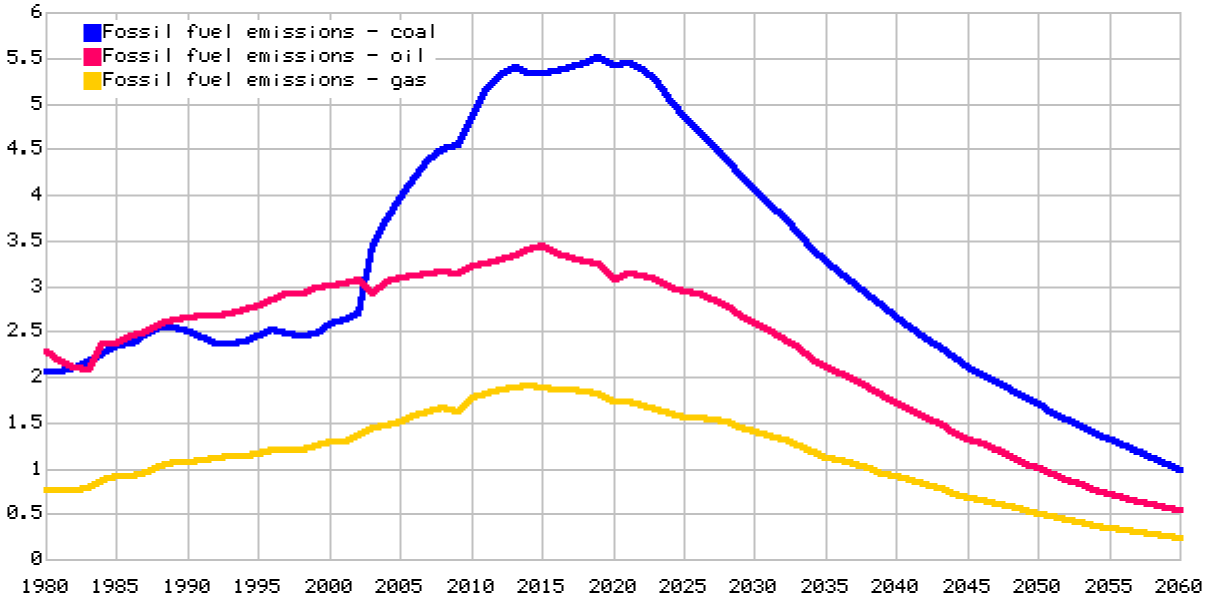

Figure 14. Fossil fuel emissions by fuel: projections to 2060 (GtC)

These projections rely heavily on the assumption that China will substantially replace its use of coal by renewables. Current indications are that a massive transformation is indeed taking place.

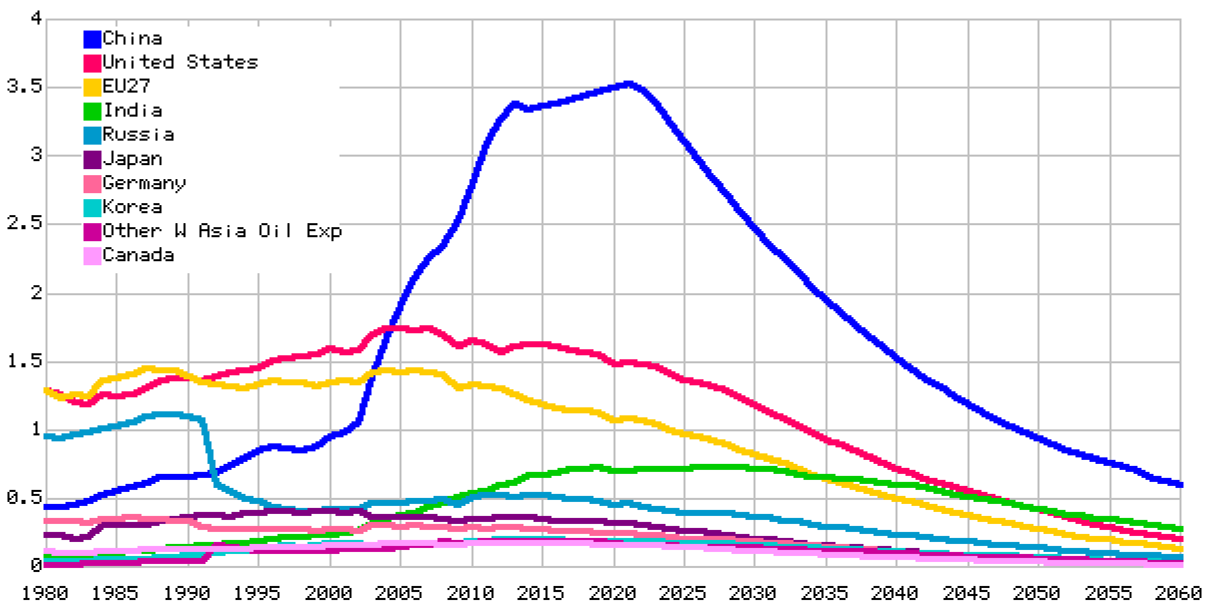

Figure 15. Fossil fuel emissions – 10 largest countries: projections to 2060 (GtC)

Carbon cycle projections

Total natural planetary absorption is currently now about half the level of emissions. If emissions are halved by 2040 then atmospheric concentration will be stabilised. This is apparent in the model results.

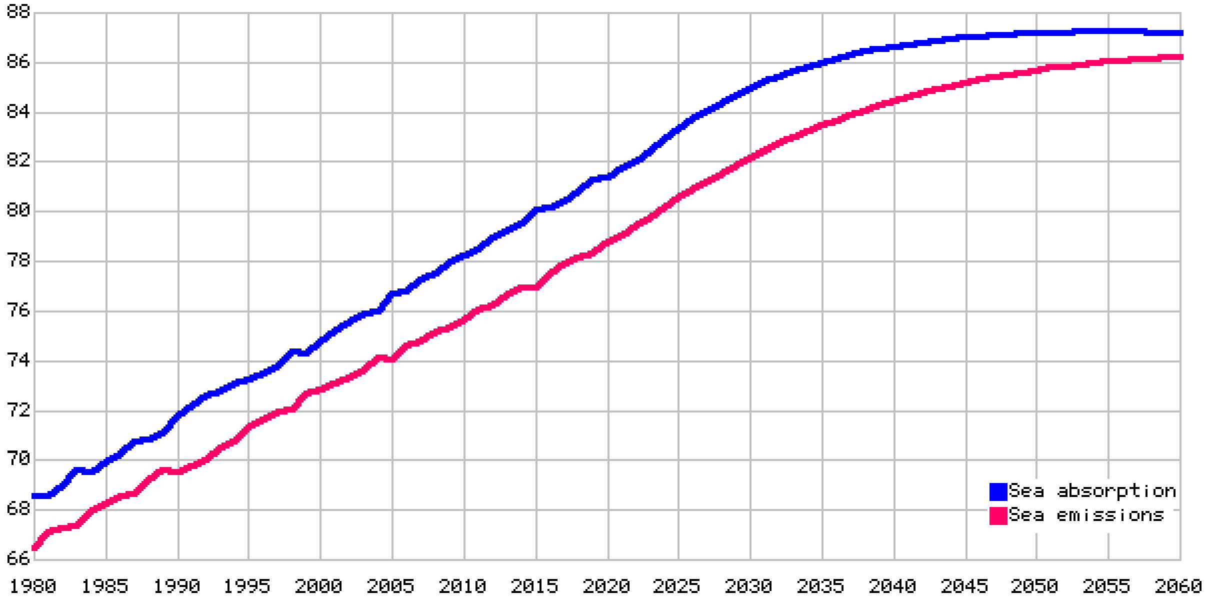

Figure 16. Sea absorption and emissions; projections to 2060 (GtC)

As the level of atmospheric concentration stabilises, so do the levels of absorption.

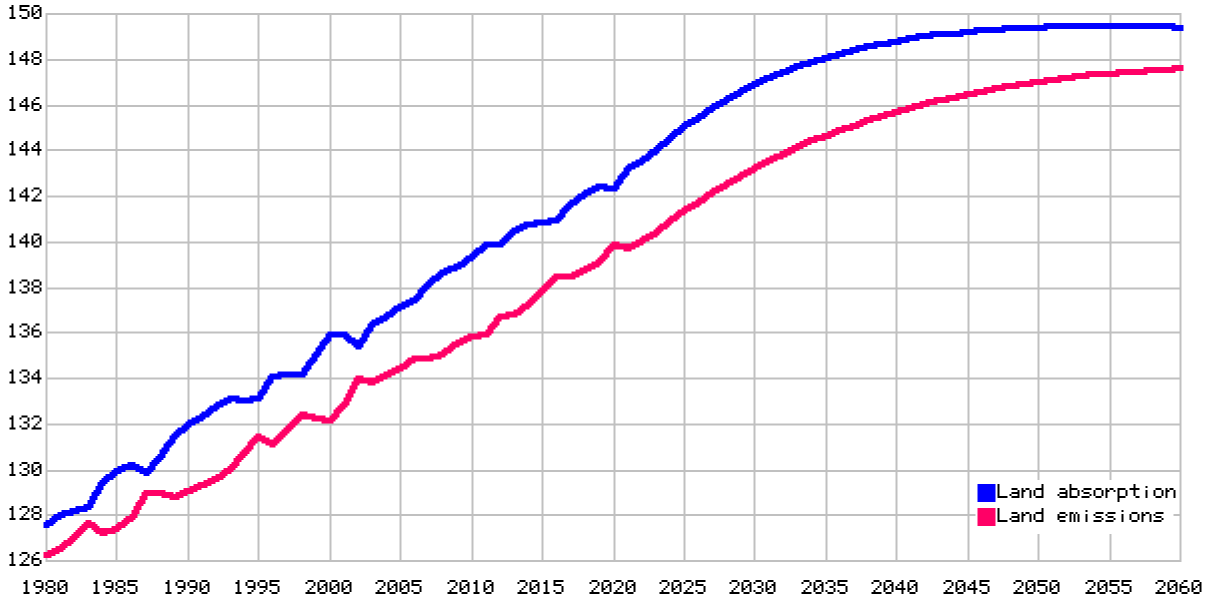

Figure 16. Land absorption and emissions: projections to 2060 (GtC)

The level of natural emissions also rises more slowly, as the uptake of carbon in the land and sea slows, but not as much as the slowdown in absorption, so that net absorption falls.

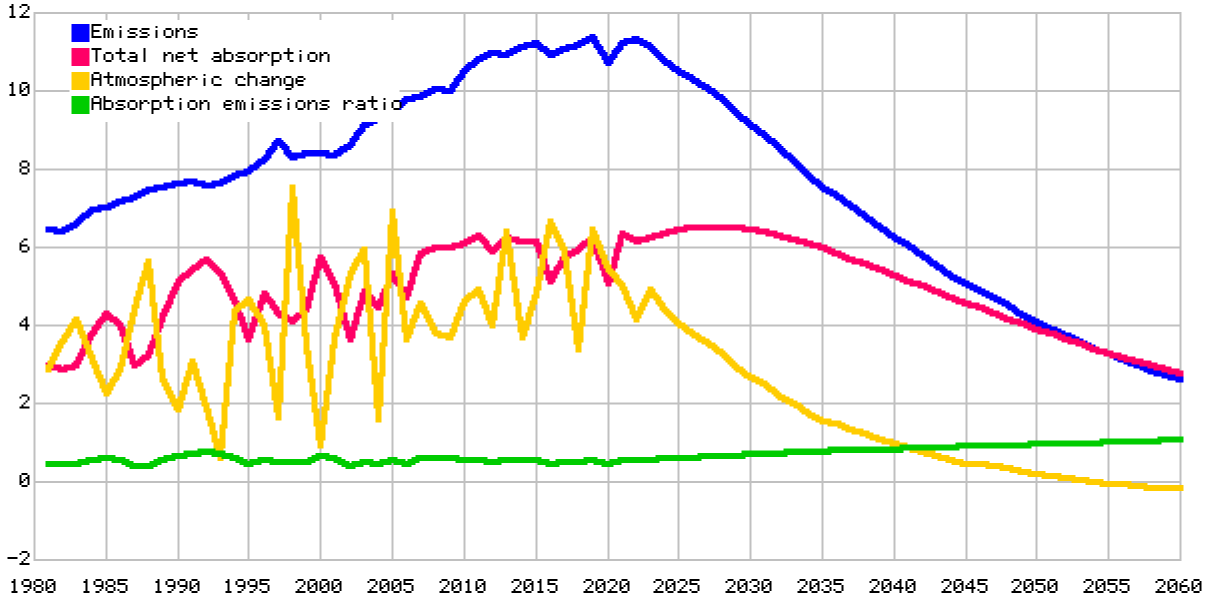

Figure 17. Emissions and net absorption: projections to 2060 (GtC)

While emissions and absorption remain in balance, there is little change in atmospheric CO_2. This means that temperatures remain at elevated levels.

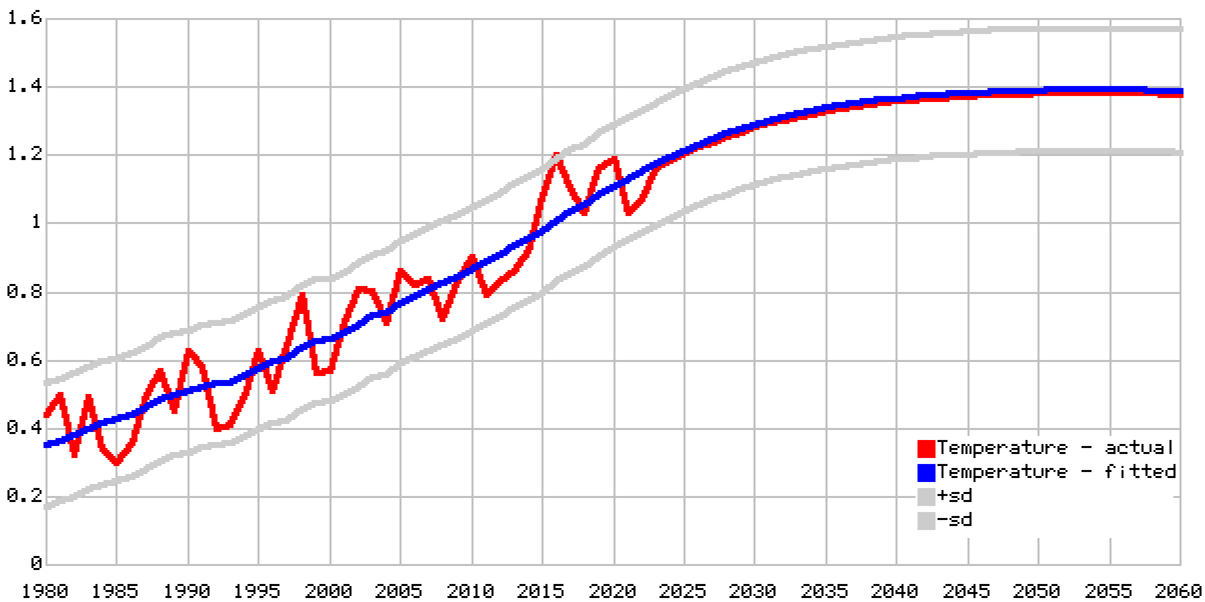

Figure 18. Temperature projections to 2060 (GtC)

NASA measures temperatures relative to the average 1951-1980 level. The most commonly used temperatures are quoted relative to the 1850-1000 average, which is 0.18 degrees higher. This is what is shown in Figure 18. Average temperatures level off at about 1.4 higher than pre-industrial levels. There is considerable variability in the annual measurements, which we can expect to continue. Figure 18 also shows the average ± one standard error of regression as per equation 6.

These results show that if we can halve emissions by 2040, we may be able to keep the average temperature rise to less than 1.5 degrees. However given annual variability, there is about a 15 percent chance that the temperature will exceed 1.5 degrees of warming in any given year.

Alternative scenarios

To what extent are the above results dependent upon the modelling assumptions and parameters? The structural model, based on the natural flows, which rise in response to the fossil fuel emissions, has a plausible theoretical basis. The model parameters are an artefact of the data set used. It is therefore instructive to investigate the effects of changing some of the parameters. Table 1 shows the results of several tests.

Alternative parameter tests	**2040**	**2060**
Projected temperature – baseline	1.38	1.39
Reduce temperature emissions coefficients by 50%	1.31 (-4.3%)	1.33 (-4.6%)
Increase atmosphere absorption coefficients by 50%	1.29 (-6.0%)	1.31 (-6.3%)
Increase land burial and sea sequestration each by 0.5 GtC/year.	1.33 (-3.6%)	1.32 (-5.3%)
Higher emissions scenario – halved by 2050	1.44 (+4.3%)	1.54 (+10.8%)

Table 1. Alternative model parameters and assumptions

The approach adopted is to perform alternative projections from 2023 to 2060 and to compare the results with the original projections. While the profiles of all the variables change, the key output is temperature rise. The effects on temperature are compared in the years 2040 and 2060. From the current 1.07, the projected temperature at these dates is 1.38 and 1.39, The peak is 1.40 in 2054.

The gap between absorption and emissions narrows. One reason for this aspect of model behaviour is the positive effect of temperature on emissions. The temperature coefficient is 9.8 for sea emissions and 15.3 for land emissions. The first alternative projection is one in which the values of these parameters are halved (reduced by 50%). This means that emissions do not rise as much, and more carbon is retained in the sea and land. The effect of this change is to reduce to ultimate rise in temperature by about 0.06 degrees or 4.6%. The same pattern is observed, whereby temperatures stabilise at about 1.33 degrees, but do not fall substantially. Were these parameters to be increased, an analogous increase in temperatures would be observed.

In the absorption equations, the coefficients of atmospheric concentration are 0.09 for sea and 0.10 for land. In the second alternative projection, these coefficients are increased by 50%. This means that again, more carbon is retained in the land and the sea. The effect is to reduce the ultimate temperature rise by about 0.08 degrees, or 6.3%. An analogous result would occur if the coefficients were decreased.

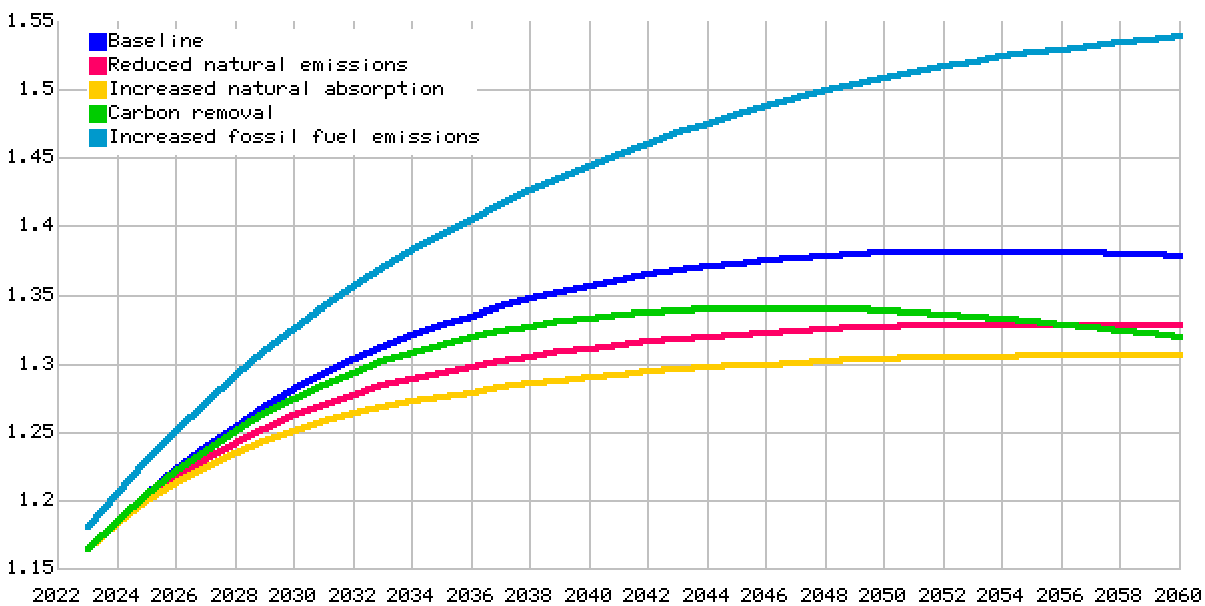

Figure 18. Alternative projections of temperature: 2023 to 2060 (GtC)

What we observe in the above experiments is that when fossil fuel emissions are reduced to the level of natural absorption, atmospheric concentration and temperatures stabilise, but do not fall substantially. This is because the additional carbon is still being retained in the system apart from the small amount of deep sea sequestration.

The planet's absorption of CO_2 increases as atmospheric concentration rises, but lags behind emissions. Such is the situation with stocks and flows when the flow is only a small part of the stock. When emissions fall to meet the planet's increased absorption however, both emissions and absorption, fall in tandem. The fraction absorbed does not rise above 1. The atmospheric concentration largely persists. This model outcome would not necessarily be expected *a priori*.

The third experiment increases the amount of removal of carbon from the system. Currently in the model this is about 0.8 GtC/year. This value arises from the net difference between net flows and stock changes that are apparent in the data. In the alternative projection, an additional 1 GtC/year is removed, half from the land stock (burial) and half from the sea stock (deep sea sequestration).

The results show that this increase in carbon removal decreases the temperature rise in 2040 by 0.05 degrees. In this case temperatures peak in 2045 and then fall, by 0.01 degrees in 2060.

In the final alternative projection, a different profile of emissions is used, in which fossil fuel emissions are only halved by 2050 instead of 2040. In this case, temperature reaches 1.54 by 2060 and is still increasing.

The alternative projections are shown in Figure 19. What we can see from these experiments is that despite quite substantial changes in the parameters, of 50%, the resultant changes in the final temperature are relatively small, only 5% or 6%. We may therefore conclude that the results are quite robust with respect to the parameter estimates.

We may also observe from the projections that reduction in temperature will depend on carbon removal and that substantial efforts would be necessary to achieve only a gradual reduction. Failure to reduce emissions however, has a substantial effect on increasing temperature, as shown by the high emissions projection.

Conclusion

In order to project global temperatures over time, it is appropriate to use annual data. Given that atmospheric CO_2 is the main determinant of temperature, it is important to consider not just the changes in net fluxes that give rise to atmospheric changes, but the structure behind the natural flows that the injection of fossil fuel carbon has disrupted.

A model based on global flows is a simplification of disparate geographical processes. A model where natural flows are related to the magnitude of the stocks from which they emanate would seem to be at least a minimal starting point. To achieve this, it was necessary to construct series representing the natural flows, using the available evidence. Against these, the parameter estimates are calibrated, making the link back to known atmospheric concentration plausible. It is unlikely that any alternative reconstruction of the natural flow data would make any substantial difference to the results.

All the historical data represent a phase in history in which fossil fuel emissions have risen. The projections however, relate to a future in which fossil fuel emissions fall. How much reliability can we attach to the results?

At all times the carbon budget holds, i.e. all carbon in the system is accounted for. The model seems robust. Given that the estimated relationships hold, the model results at least provide a statement of what is mathematically indicated under the new circumstances of emissions reduction, within the given standard error.

An economic model of country-by-county emissions from coal, oil and gas consumption provides the emissions projections on which the carbon cycle outcomes are based. The results are based on the plausible assumption that emissions can be halved by 2040. This is driven by the massive deployment of renewable energy. However these energy forms are not easily compatible with base-load power sources and large amounts of storage capacity are required.

Global temperatures have risen 0.2 degrees over the last decade. Given the reduction in emissions, the finding from this analysis is that warming can be limited to a further 0.2 degrees over the next decade and a half. However this degree of warming will persist for a long time.

A finding that temperature increases can be limited to an average of less than 1.5 degrees gives some hope that catastrophic sea level rises can be avoided. However the probability of extreme weather events increases a faster rate than average temperatures.

In particular years, the temperature may be significantly above trend. What tipping points may be triggered in these circumstances requires further analysis.

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Appendix: Fossil fuel emissions by country of consumption and production

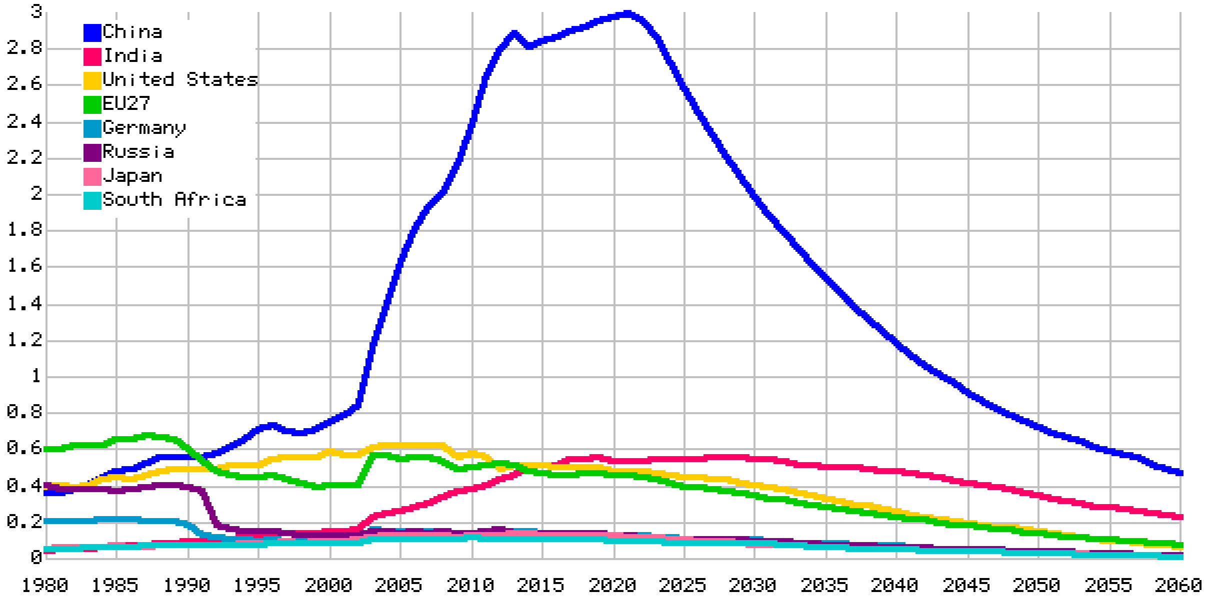

Figure A1. Emissions from coal (GtC) - 8 largest consumers

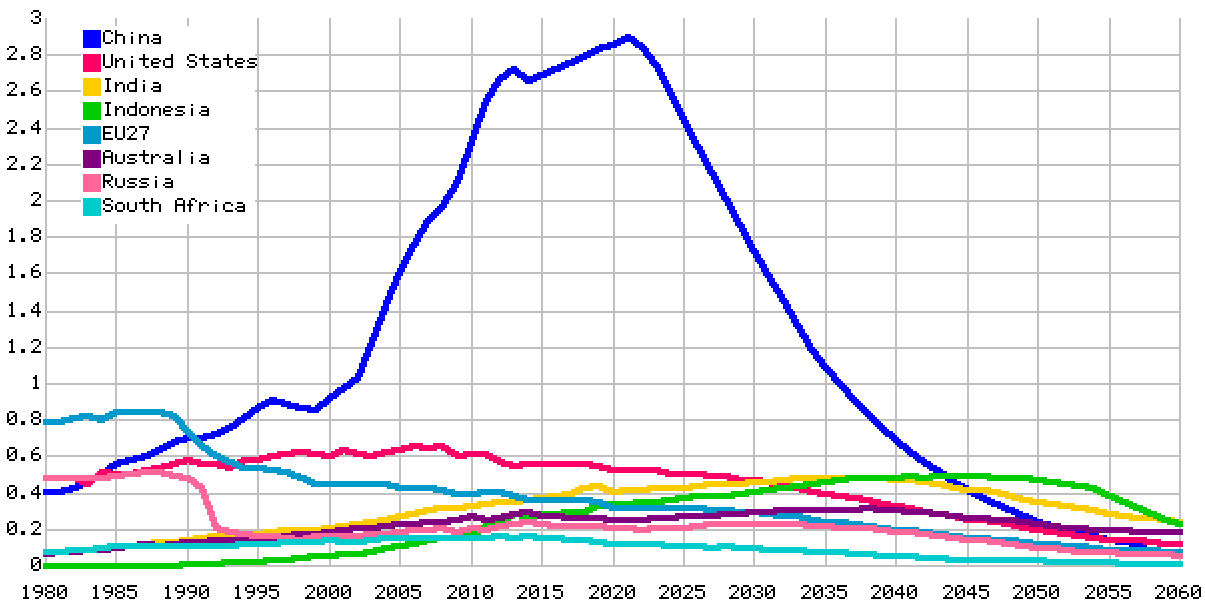

Figure A2. Emissions from coal GtC - 8 largest producers

China is by far the biggest coal producer and consumer, as shown in Figures A1 and A2.

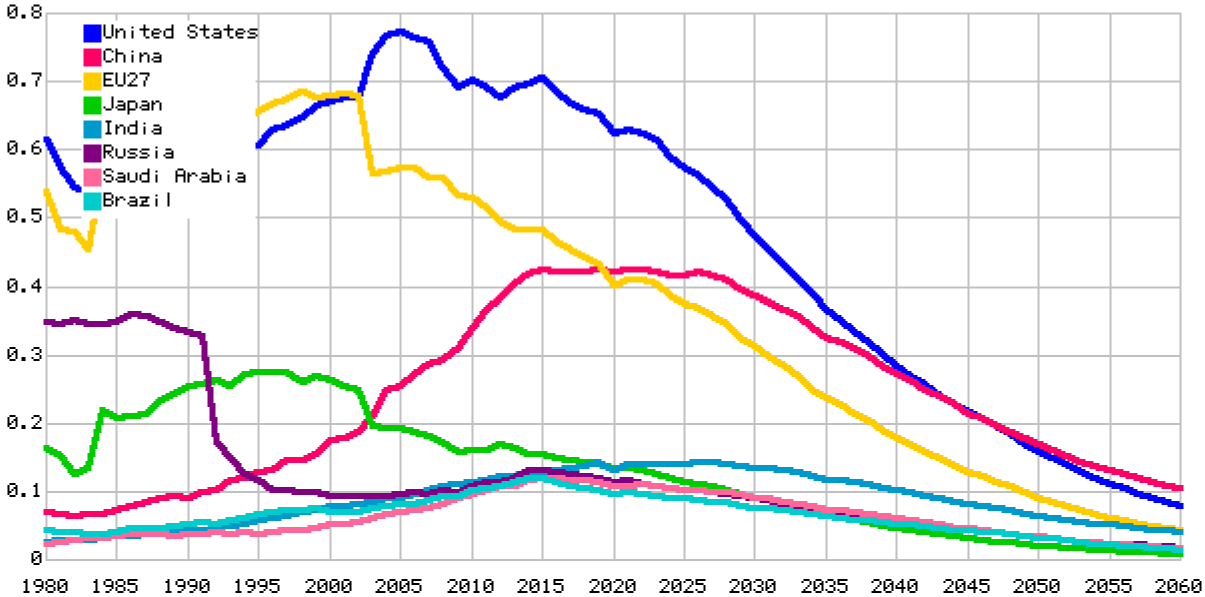

Figure A3. Emissions from oil (GtC) - 8 largest consumers

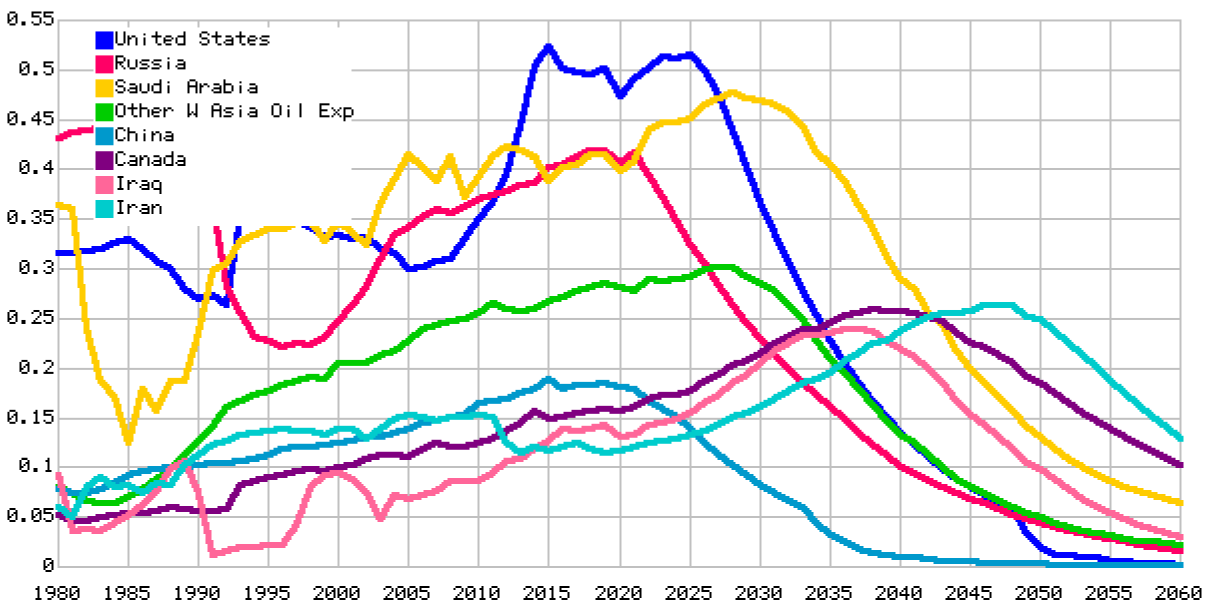

Figure A4. Emissions from oil (GtC) - 8 largest producers

The United States is currently the largest oil producer and consumer. The trajectory regarding Saudi Arabia is uncertain, and depends on the uptake of electric vehicles.

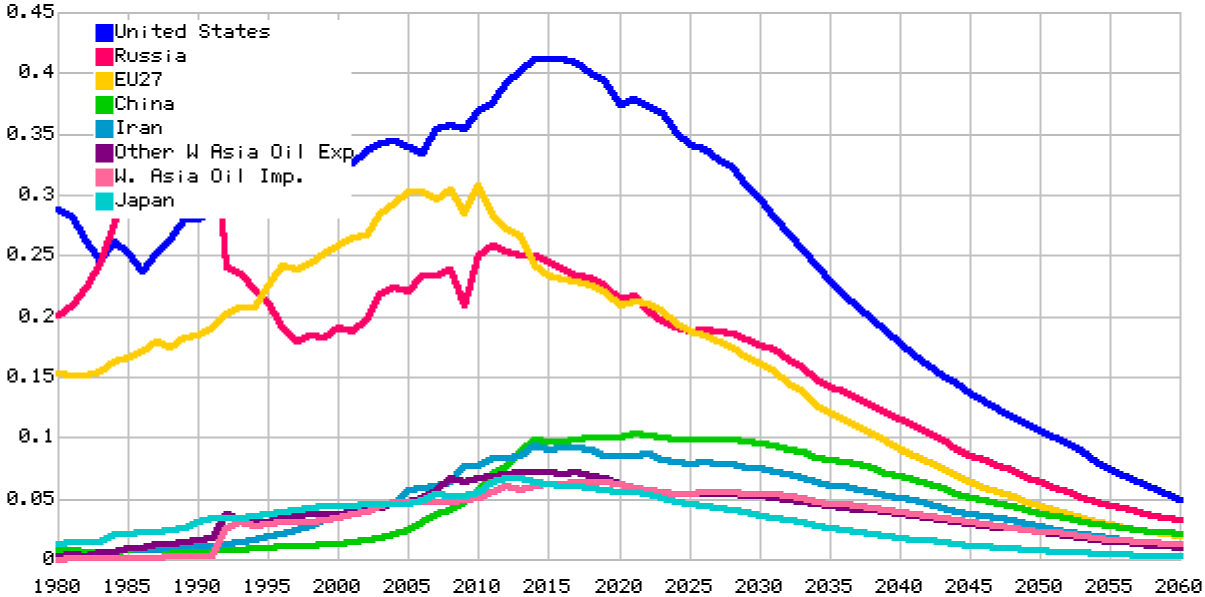

Figure A5. Emissions from gas (GtC) - 8 largest consumers

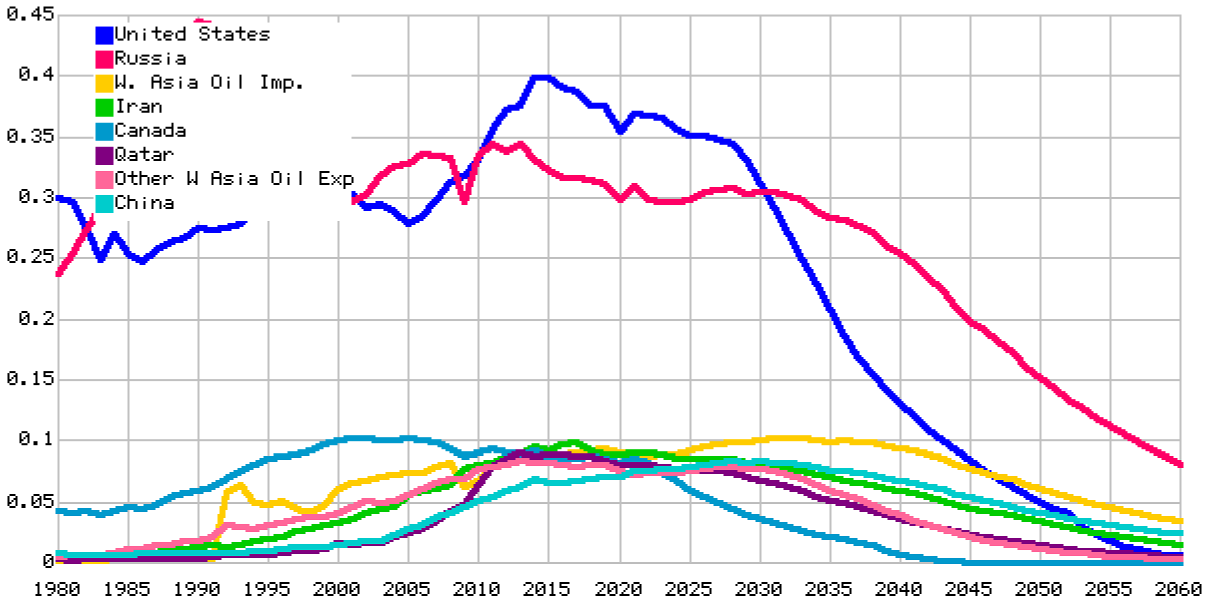

Figure A6. Emissions from gas (GtC) - 8 largest producers

The United States and Russia are the largest gas producers, however the projections for Russia do not include the effect of sanctions due to Russia's invasion of Ukraine.