THE DEVIL IS IN THE DETAIL: SIMPLE PROJECTIONS OF ATMOSPHERIC CARBON

ECONOMETRICS GAMES CASE B REPORT

TEAM 4

Abstract

Models which link atmospheric carbon concentrations to emissions are crucial to understand both the projected level of concentration in the future, as well as emission reduction policies needed for certain desirable concentration pathway. This paper builds one such model based on the Global Carbon Budget Framework through a simple statistical model. It then further breaks down emission into regional level, and predict future pathways for each regions separately. Predictions for carbon concetration are striking: the developing world, especially Asia, is projected to be responsible for most anthropogenic emission, whereas North America and Europe would see their level trending downwards. Our work further utilizes the RCP scenarios to predict what emission would look lilke under different climate scenarios. To keep the world from warming up not more than 1.5^oC, every regions of the globe would need to reduce their emission substantially by the end of the 21st century and come back to the 20th century level. On the other hand, if there is no control and emissions rise significantly worldwide, the globe is guaranteed to warm by 4.5^oC. In terms of policy prescription, the developing world needs to be put under more restrictive carbon limit than that given by the Kyoto Protocol, while the rich world, due to their role in importing carbon through trade, must formulate certain carbon-based tariffs and encourage clean technology adoption in the rest of the world. Finally, we utilize our model to capture the relationship between emissions and GDP in Australia, and use the emissions pathways under the baseline and 4 RCP scenarios to predict GDP. The bottom line: with current economic technology, to achieve desirable emission level of RCP 2.6, the economy will be shrinked considerably - a loud call for the maximal adoption of carbon-non-intensive production technology and more climate leadership.

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1 Introduction

According to the UN Framework Convention on Climate Change, the level of emission mitigation for each country should depend on “equity” and be “in accordance with their common but differentiated responsibilities and respective capabilities” (UNFCCC, 1992). The Kyoto Protocol was implemented with this idea in mind: developed countries are given an emission limitation for the period 2008 to 2012, with the usual base year being 1990. Developing countries, on the other hand, do not have emission commitments they must adhere to because of the need for development (UNFCCC, 1998). Given this fact, it is a natural step to investigate carbon emission at some dissaggregate level.

Our paper extends further our statistical model previously used to predict carbon concentration and emission level using the Global Carbon Project framework (Allen et al., 2018). The model utilises simple univariate time-series techniques to extrapolate fossil fuel and land-use change emissions. Equations for land and ocean sinks are augmented to the system, and allowed to react to the level of atmospheric carbon concentration. The key identifying assumption used to overcome endogeneity between atmospheric carbon growth and biosphere sink is a simple timing restriction – sinks only react to lagged concentration levels. The equations for emissions and sinks are coupled with identities, including the global carbon budget, and projections are estimated using stochastic simulation.

We then breaks down emission by geographical regions and model their growth up to the year 2100. The result is striking: Asia is projected to be responsible for about 60% of global emission by the end of this century, while emission from Europe and North America steadily decline - to level below that of 1960 for the former and 1980 for the later. Every other regions of the globe is expected to increase their emission, though their share of total emission remains stable due to the upwards climb in aggregate carbon atmospheric concentration.

The different RCP scenarios provides some strong implications for regional emissions based on the expected concentration pathways. For the strictest case, RCP 2.6, where the planet is only allowed to warm up by 1.5^oC, every regions in our model must reduces their emission level significantly. For all of them, the end of the 21st century must see a return to carbon emission level of the 20th one - a tall order, given the requirement for development across the world. On the other hand, the catastrophic case of RCP 8.5 that projects a warming up of 4.5^oC occurs when carbon control is so weak that every region emits more carbon than they already have. This scenario is one of strong population growth, weak adoption of climate policy and climate leadership.

Country-level analysis of emissions give us a more detailed picture of the global climate scene, and a potential to formulate specific policies - including distribution scheme for required emission reductions - on combating carbon emission. However, it is vital to then take into account the effects of international trade: on a territory/production basis, Europe’s and US’ emissions may have been stabilizing or even downward trending. A look at consumption-based and net transfer emissions reveal the “offloading” of emissions from many countries to others, through exporting and importing products. Further analysis using more than territorial-based emission data is needed to craft truly effective carbon emission policies.

Nevertheless, it is possible to prescribe certain distribution scheme in terms of responsibility for emission reduction. In light of the expected strong role developing countries will play in emitting carbon within this century, the Kyoto Protocol’s spirit must be modified: we must formulate certain reduction limits for these nations. On the other hand, given the implied trade in carbon from the goods and services trade, the developed world must discourage carbon-intensive production from source nations. Possible policies include carbon-based tariffs and encouragement of clean energy adoption.

Finally, we link emission level to GDP for the case of Australia and use projection for the former to predict the latter until 2100. Under the five different emission scenarios (baseline, and 4 RCP scenarios implied by the corresponding carbon concentration level), GDP diverge widely. It will grow well into the future under the catastrophic RCP 8.5 scenario, whereas to achieve the RCP 2.6 one with 1.5^oC change in temperature, GDP would srhink remarkably. The implication is that to implement a desirable climate policy and attenuates climate change, massive policies changes would be required that in turns depend on strong climate leadership and climate techonlogy.

2 Literature Review

Peters et al. (2011) explores the role of international trade in explaining cross-country emission differences. They note that from 1990 to 2008, CO_2 emissions in developed countries have stabilized, yet those in developing countries have doubled. The analysis using a trade-linked global database for CO_2 emission found that most developed countries have increased their consumption-based emissions faster than territorial (production) emissions - supporting the hypothesis that the divergent emission trends are partly the result of a transfer of emissions between exporting developing countries and importing developed ones. In particular, the emission transfers from non-Annex B to Annex B countries have grown by 17% per year on average. Sector-wise, 40% of emissions from the production of traded products come from energy-intensive industries (cement, steel, pulp and paper,...). This rate is stable between 1990 and 2008. In contrast, non-energy-intensive manufacturing (textiles, electronics, furniture, cars,...) is accounted for a growing share, from 24% in 1990 to 30% in 2008.

In the same country-level emission framework, Hertwich & Peters (2009) explicitly model the trade link effects using a fully coupled multiregional intput-output model. Average per capita footprint varies from just over 1 t per person per year in certain African countries and Bangladesh to 28 t per person/year in the US. In terms of emission from producing consumption goods, indirect impacts from the supply chain are more important than the direct impacts in the household. At lower level of income, food and services are important contributor while for higher level, mobility and the consumption of manufatured goods account for the largest greenhouse gas emissions.

3 Data

This paper utilizes country-level emission statistics provided by the Global Carbon Project (Le Quéré et al., 2018) - specifically, CO_2 emissions in million tons of carbon per year for 213 countries and territories, and certain country groupings. We only utilize territorial emissions - that is, emission produced within a country's jurisdiction, either for domestically consumed or exported good and services.

Territorial emissions are emissions produced within a country's jurisdiction. Emissions may be produced on goods and services for either domestic consumption or for export. Consumption emissions, on the other hand, are those inferred from goods and services consumed within a country - so they may include either domestically produced or imported products. Linking these two concepts is emission transfers, which is emissions from products for exports net that of emissions from imported products. Conceptually, then:

Territorial (production) emissions = domestic products + export products

Consumption emissions = domestic products + import products

Emissions transfers = export products - import products

In principle, “when the reported territorial emissions are adjusted for net emission transfers, a consumption-based emission inventory is obtained” (Peters et al., 2011)

The dataset for Industrial Production Index is taken from the OECD Data website (OECD, 2019). We use the yearly time series for OECD countries group, EU 28, and a few specific country of interest. The index was created with a value of 100 in 2015.

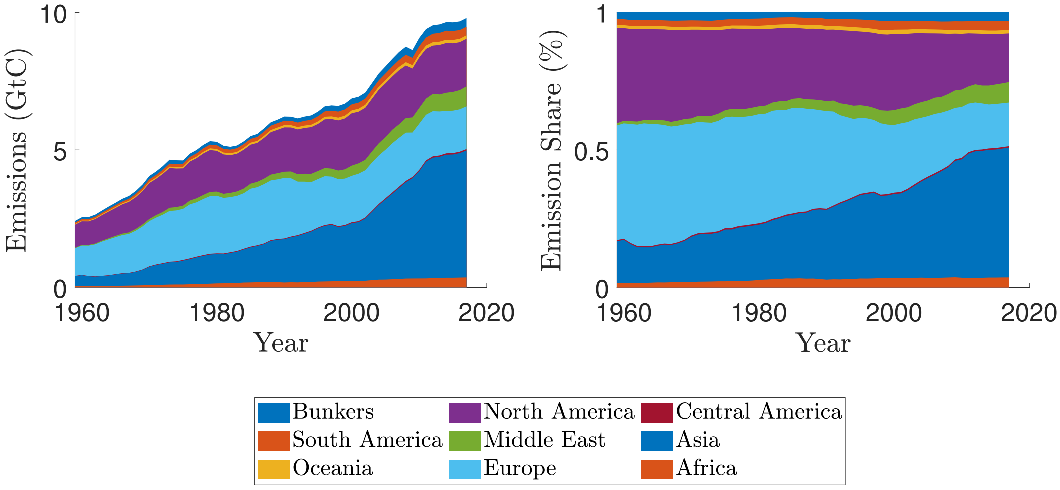

Figure 1: Fossil Fuels and Cement Production Emissions (GtC) and Shares (%) by Region

Figure 1 shows the fossil fuel emission level and share by region over time. Overall there have been a global increase in carbon emission level, with Asia having the largest growth: from around 15.12% to 47.13%. The share from other developing regions have either been increasing or stabilizing. Africa’s share rose from 1.6% to 3.7%, Central America’s has been stable around 0.5%, the Middle East’s went from 0.7%, and South America went from 2% to 3%. Of course, given an increasing global emission level, this implies every developing regions have saw their emission levels rising over the period of interest. Developed regions’ shares, on the other hand, have either decline or been stable: North America saw its share fell from 34% to 17%, Oceania’s fluctuates around 1% while Europe’s plummeted from 41% to 15%. The share of bunker has not changed much beyond 3%.

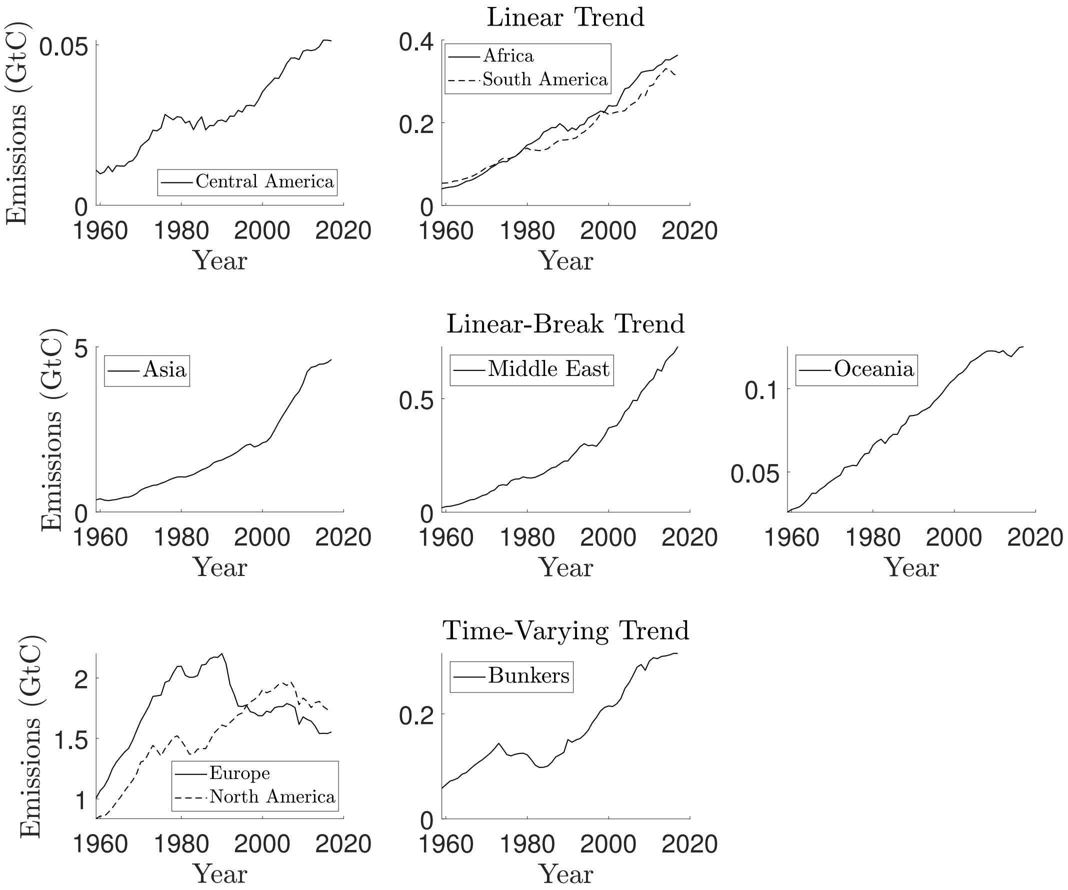

Figure 2: Emissions by Country (grouped by trend type (row) and scale)

Figure 2 groups the regional emission trends by their time series properties. Africa, South and Central America has an upwards linear trend, with the first two series tracing each others fairly closely. Asia, the Middle East and Oceania all have linear trend with a break in them: Asia's break comes in 2002, Middle East in 2004, while Oceania 2009. The former two breaks seem to reflect an acceleration of emission growth, possibly connected to accelerated industrialization in the 21st century for these regions. The location and test for structura breaks was found by using a Quandt-Andrews unknown breakpoint test. In the last group are Europe, North America, and the bunker series. The first two series initially grew, but then change non-monotonically and seem to have either stabilize or decline from 2000. The emission from bunker has been increasing overall, but with time-varying trend.

To formally test for the emission time series' statistical properties, we use a Dickey-Fuller test on the unit root null hypothesis and present the results in Table 1. For each regional emission series, we test them at their level and their first difference. Overall, for every level series, we cannot reject the null hypothesis of there being an unit root at 5% significant level. However, the test on most first difference series reject the unit root hypothesis at the same significant level, with the exception of Central and North America.

Table 2 presents the results from the Quandt-Andrews Unknown Breakpoint Test. The null hypothesis is the tested series has no breakpoints within 15% trimmed data. As shown in Figure 2, the Asia, Middle East and Oceania series all seem to have linear-break trend.

Table 1: Dickey-Fuller Test of the Emission from Fossil Fuels by Region

Dickey-Fuller test	Null Hypothesis: unit root	
Emissions by region	t-statistic	p-value
Africa	-1.978	0.601
First difference	-7.409	0.000
Asia	1.042	1.000
First difference	-3.591	0.041
Central America	-1.381	0.854
First difference	-2.881	0.178
Europe	-2.045	0.564
First difference	-5.372	0.000
Middle East	0.696	1.000
First difference	-9.124	0.000
North America	-1.540	0.803
First difference	-3.225	0.090
Oceania	-3.380	0.066
First difference	-7.263	0.000
South America	-2.855	0.185
First difference	-3.636	0.036
Bunkers	-1.311	0.875
First difference	-5.234	0.000
Statistical Difference	1.133	1.000
First difference	-10.444	0.000

3.1 New Variables Definition

The share of emission for region r in the set of region R in year t is defined as

$$\frac{Emission_{r,t}}{\sum_{i \in R} Emission_{i,t}}$$

And the timepaths of these share were depicted in Figure 1.

4 Empirical Strategy and Model Specification

4.1 Baseline Model

In this section, we present a simple model for forecasting ofthe growth in atmospheric carbon dioxide. We begin by considering the the flow budget constraint given by

$$G_t = E_t^{FF} + E_t^{LUC} - S_t^L - S_t^O$$

where E^{FF} and E^{LUC} refer to emissions from fossil fuels and changes in land use respectively, whereas S^L and S^O refer to the absorption of carbon dioxide into the land and ocean respectively (known as land and ocean *sinks*). In this specification, G_t refers to the atmospheric growth in carbon dioxide. Therefore,

Table 2: Quandt-Andrews Unknown Breakpoint Test

Null Hypothesis: No breakpoints within 15% trimmed data		
Emissions by region	t-statistic	p-value
Africa	3.060	0.278
Maximum LR F-statistic (2002)		
Asia	4.865	0.038
Maximum LR F-statistic (2002)		
Central America	1.643	0.810
Maximum LR F-statistic (1998)		
Europe	3.469	0.184
Maximum LR F-statistic (1980)		
Middle East	12.706	0.000
Maximum LR F-statistic (2004)		
North America	7.428	0.001
Maximum LR F-statistic (2008)		
Oceania	4.788	0.041
Maximum LR F-statistic (2009)		
South America	3.920	0.113
Maximum LR F-statistic (2009)		
Bunkers	4.420	0.064
Maximum LR F-statistic (2009)		

if we define C_t as the atmospheric concentration of carbon dioxide, then

$$\begin{aligned} C_t &= C_{t-1} + G_t \\ &= C_0 + \sum_{j=1} G_j \end{aligned}$$

In this simple model, we suppose that the *sink* at any time is related to the atmospheric carbon concentration in the previous period. For the ocean sink, including a single lagged term improved the fit.

$$S_t^L = \beta_0^L + \beta_1^L C_{t-1} + e_t^L$$

and

$$S_t^O = \beta_0^O + \beta_1^O C_{t-1} + \beta_2^O S_{t-1}^O + e_t^O$$

where β_1^L and β_1^O are the sink *rates* (or efficiency) for land and ocean sinks, respectively. Modelling sinks as a function of atmospheric concentration is inspired by the data evidence and the previous studies. First, estimating the above two equations reveal significant correlation between sink and concentration and give a decent goodness of fit. Meanwhile, the sink rate is the main objective of previous studies (Bennedsen et al., 2018), and its sign is of academic dissensus.

In order to forecast the growth in carbon concentration, we require forecasts of the emissions, which will imply forecasts of the sinks in future periods through the total concentration of carbon. The key identification assumption of this model is that the sink rates are determined by past atmospheric carbon concentrations. We justify this assumption by noting that the concentration has a smooth trend in the levels rather than flow.

For E_t^{LUC}, we specified an AR(2) model, as suggested by the AIC, thus,

$$E_t^{LUC} = \delta_0 + \delta_1 E_{t-1}^{LUC} + \delta_2 E_{t-2}^{LUC} + \varepsilon_t^2$$

Our model for emissions is decomposed into regional emissions paths. Emissions from each region exhibit a distinct trend and so we adapt a univariate model for each individually. Firstly, augmented Dickey-Fuller rests for unit roots show that we cannot reject the null hypothesis of a unit root in levels, but we can reject it in differences for most regions (Table 1).[1] As such, we specify our models in first-differences.

Our baseline specification is an AR(2) model, estimated with Newey-West HAC standard error correction.

$$\Delta E_t^i = \alpha_0 + \alpha_1 \Delta E_{t-1}^i + \alpha_2 \Delta E_{t-2}^i + \varepsilon_t^{E,i}$$

We then test the model for unknown breakpoints using the Quandt-Andrews test (2). We find evidence of structural breaks in the constant (i.e. linear trend in levels) for Asia, Middle East and Oceania and so include a dummy variable in these models equal to one after the year corresponding to the peak LR F-statistic. However, some of these breaks occur late in the sample and so strongly influence the projections with estimates based on only a few observations. We lag the dummy variable by three years to attenuate this issue marginally.

Finally, some of the regions exhibit emissions dynamics beyond simple breaks in linear trends. For Europe, North America and Bunkers we estimate a time varying intercept model on the first-difference. This is estimated in a state space framework with the latent intercept following a random walk.

$$\Delta E_t^i = \mu_t^i + \epsilon_t^{E,i}$$

$$\mu_t^i = \mu_{t-1}^i + \epsilon_t^{\mu,i}$$

The final estimate of the intercept represents the the linear trend of emissions in the projections. The variance estimates for the state equations allow the the intercept to exhibit a relatively large amount of variation, thus meaning the projections are highly influenced by the last portion of the sample. We restrict the variance of the state equation – effectively setting the signal-to-noise ratio – to reduce some of the variation in the intercept. The variance of the measurement equation is restricted to be fifty times larger than the state equation. This effectively becomes a low frequency filtering model.

This approach assumes that each region is independent and does not model regional spillovers. In fact, the data on territorial emissions capture certain regions transferring emissions to others via international trade (taken up further in the Discussion section). In addition, regional emissions may respond to common global factors, which are not captured in this approach.

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[1] However, we cannot reject the test in differences for Central America. Visual inspection and the size of emissions from this region suggest a simple approach will suffice without overdue influence on the system.

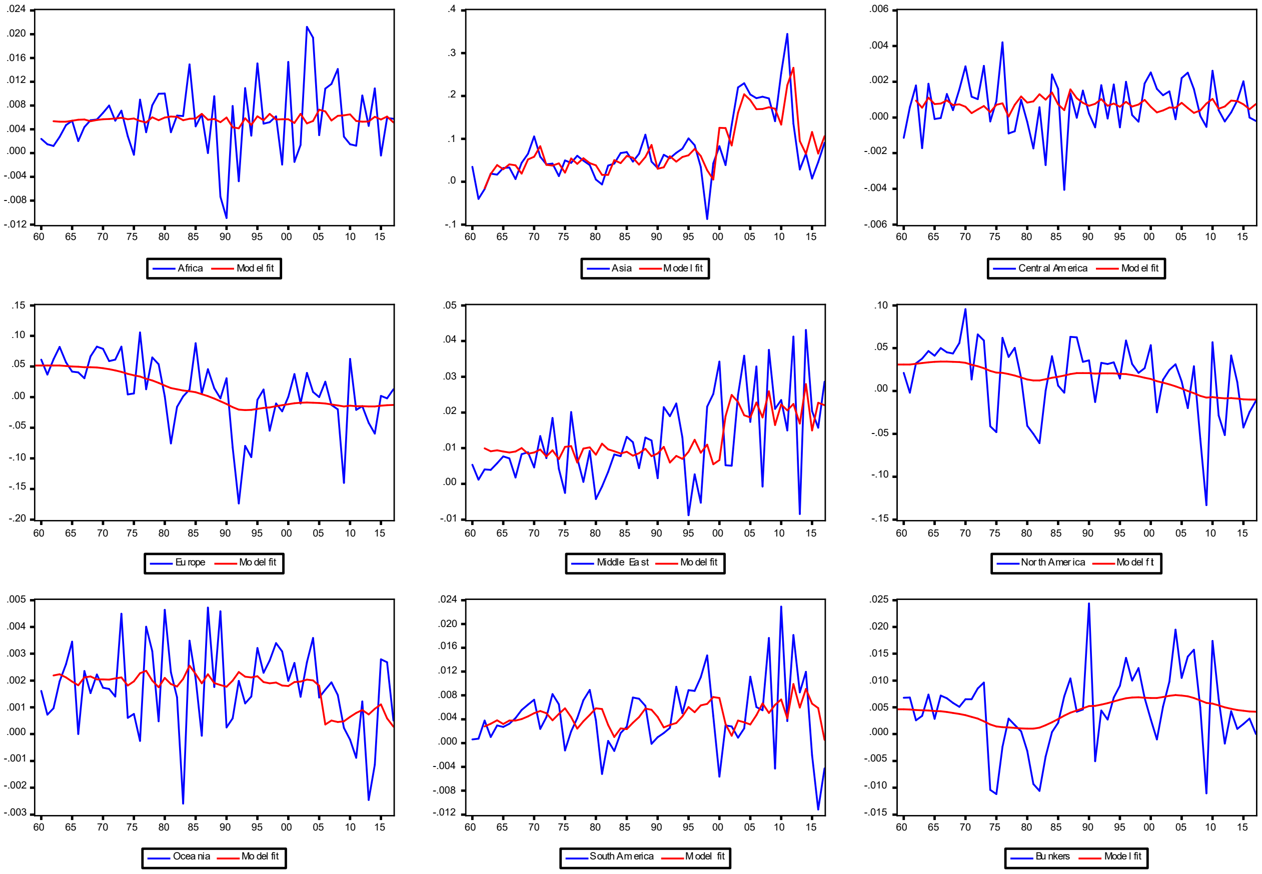

Figure 3: Territorial emissions sample data and model fit

To summarise, the forecast model is given by:

(1) Forecast the emissions:

(a) $\hat{E}^{LUC}_{t+1} = \delta_0 + \delta_1 E^{LUC}_t + \delta_2 E^{LUC}_{t-1}$

(b) $\Delta\hat{E}^i_{t+1} = \alpha_0 + \alpha_1 \Delta E^i_t + \alpha_2 \Delta E^i_t$

(c) $\hat{E}^i_{t+1} = E^i_t + \Delta\hat{E}^i_{t+1}$

For each region i.

(d) $\hat{E}^{TOT}_{t+1} = \sum_{i=1}^{9} \hat{E}^i_t$

(2) Forecast sinks:

(a) $\hat{S}^L_t = \beta^L_0 + \beta^L_1 C_{t-1}$

(b) $\hat{S}^O_t = \beta^O_0 + \beta^O_1 C_{t-1} + \beta^O_2 S^O_{t-1}$

(3) Forecast growth using the flow budget constraint:

(a) $\hat{G}_{t+1} = \hat{E}^{FF}_{t+1} + \hat{E}^{LUC}_{t+1} - \hat{S}^L_{t+1} - \hat{S}^O_{t+1}$

(4) Calculate carbon dioxide stock for next period forecasts:

(a) $C_{t+1} = C_t + \hat{G}_{t+1}$

We note that the specification here assumes independence of shocks. As discussed in Ballantyne (2015), if this assumption were to not hold, the results may potentially be different. The parameter estimates for this model are given below

	Point Est.	Std. Err.	t-stat	p-value
δ_0	0.413	0.136	3.027	0.004
δ_1	0.460	0.132	3.471	0.001
δ_2	0.221	0.124	1.788	0.080
β_0^L	0.486	0.350	1.386	0.171
β_1^L	0.011	0.002	5.132	0.000
β_0^O	0.164	0.058	2.827	0.007
β_1^O	0.662	0.102	6.489	0.000
β_2^O	0.003	0.001	3.107	0.003

Table 3: Parameter Estimates

All specifications use Newey-West HAC standard error corrections. The system of equations is projected stochastically, with 1,000 pertubations which are used to generate the standard errors.

To reverse engineer the projection for territorial emissions from the RCP scenarios, we need to make some adjustments to the model. As in Case A, we can back out projections for total territorial (fossil fuel) emissions from the RCP projections for atmospheric carbon growth. However, this gives us the sum of all regions and we need to disaggregate this into portions generated by each region. We do this by modelling the shares of total emissions each region accounts for.[2]

We estimate time varying intercept models on the first-difference of regional shares, maintaining the variance restriction imposed in the similar models above.

$$\Delta S_t^i = \zeta_t^i + \epsilon_t^{S,i}$$

$$\zeta_t^i = \zeta_{t\;1}^i + \epsilon_t^{\zeta,i}$$

The projection of emissions share for any region must be constrained between zero and one; however, projecting using the final intercept estimate may result in shares outside this region. We adopt an ad hoc solution by decaying the intercept (linear trend in levels) at a rate of 5 per cent per year over the projections. The results show that Asia and the Middle East continue growing as shares of emissions, but this tapers off after 30 years to settle at around 60 and 10 per cent of total emissions. This corresponds to Europe and the US continuing to decline as shares of emissions, settling at around 10 per cent each. Note that Bunkers is estimated as the residual of one minus the other regional shares.

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[2] For simplicity, we omit the statistical discrepancy and use shares of total emissions taken as the sum of our nine regions. The statistical discrepancy exhibits a reasonable amount of serial correlation and so a thorough analysis should factor this in.

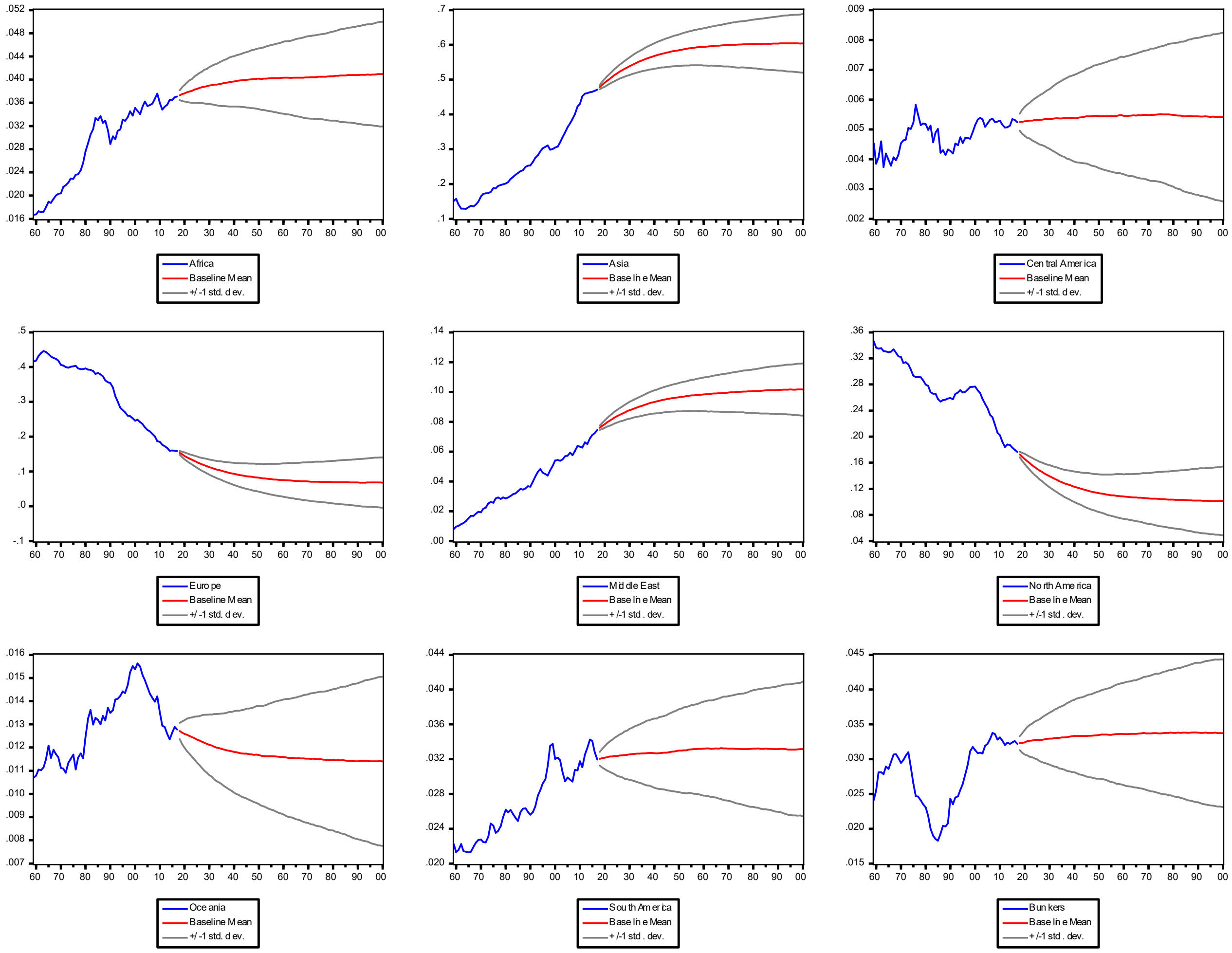


Figure 4: Fraction of total territorial emissions, sample data (1959–2017) and projections (2018–2100)

5 Results

5.1 Regional Analysis of Territorial Emissions

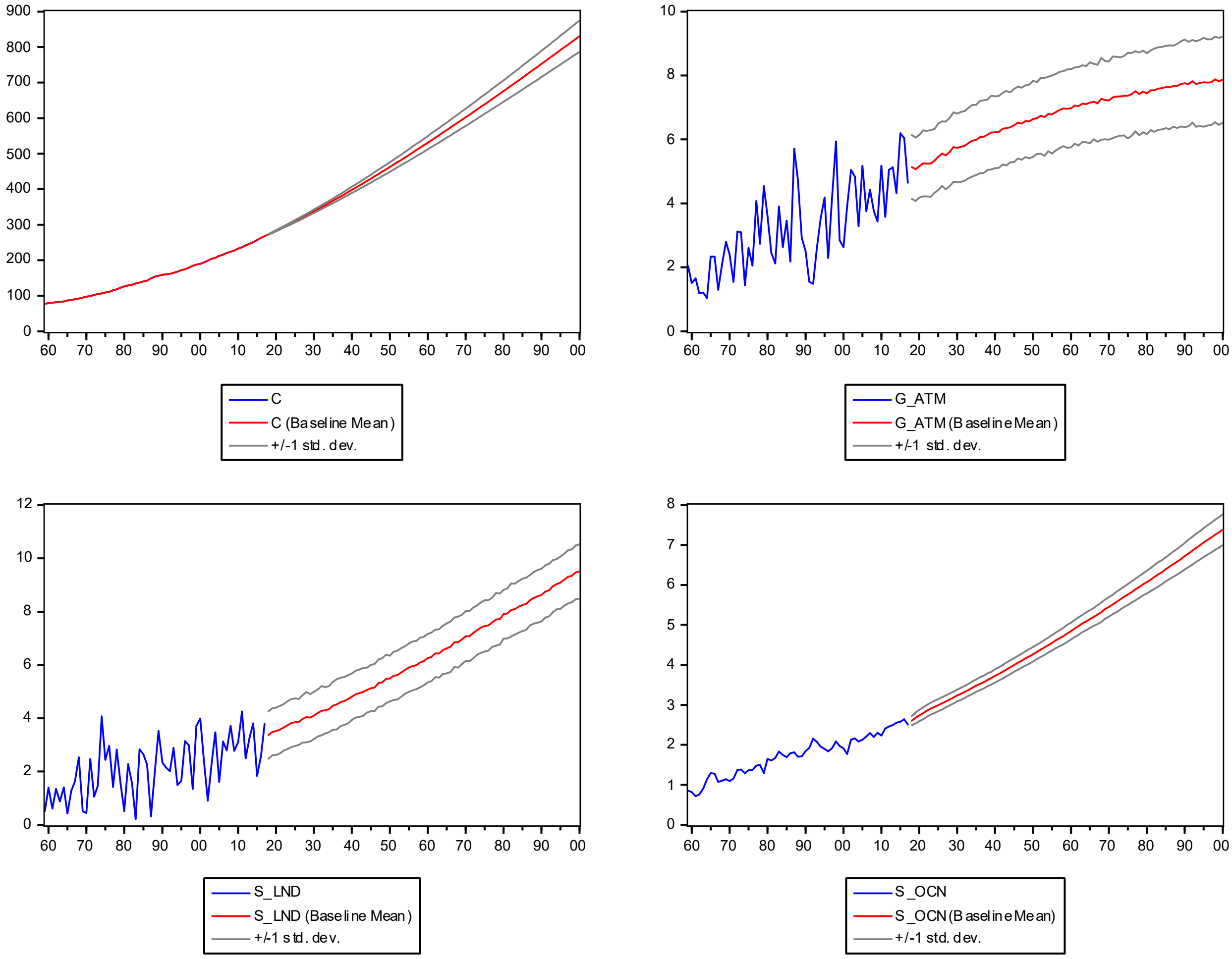


Figure 5: Atmospheric carbon concentration and growth, land and ocean sinks, sample data (1959–2017) and projections (2018–2100)

Using our baseline model, we predict the future aggregate level of atmospheric carbon concentration, growth, and the yearly carbon sink amounts in Figure 5. As noted in our Case A report, carbon concentration is projected to grow unbounded, but the growth rate flattens out over time due to sink levels being forecasted to grow along with lagged concentration level.

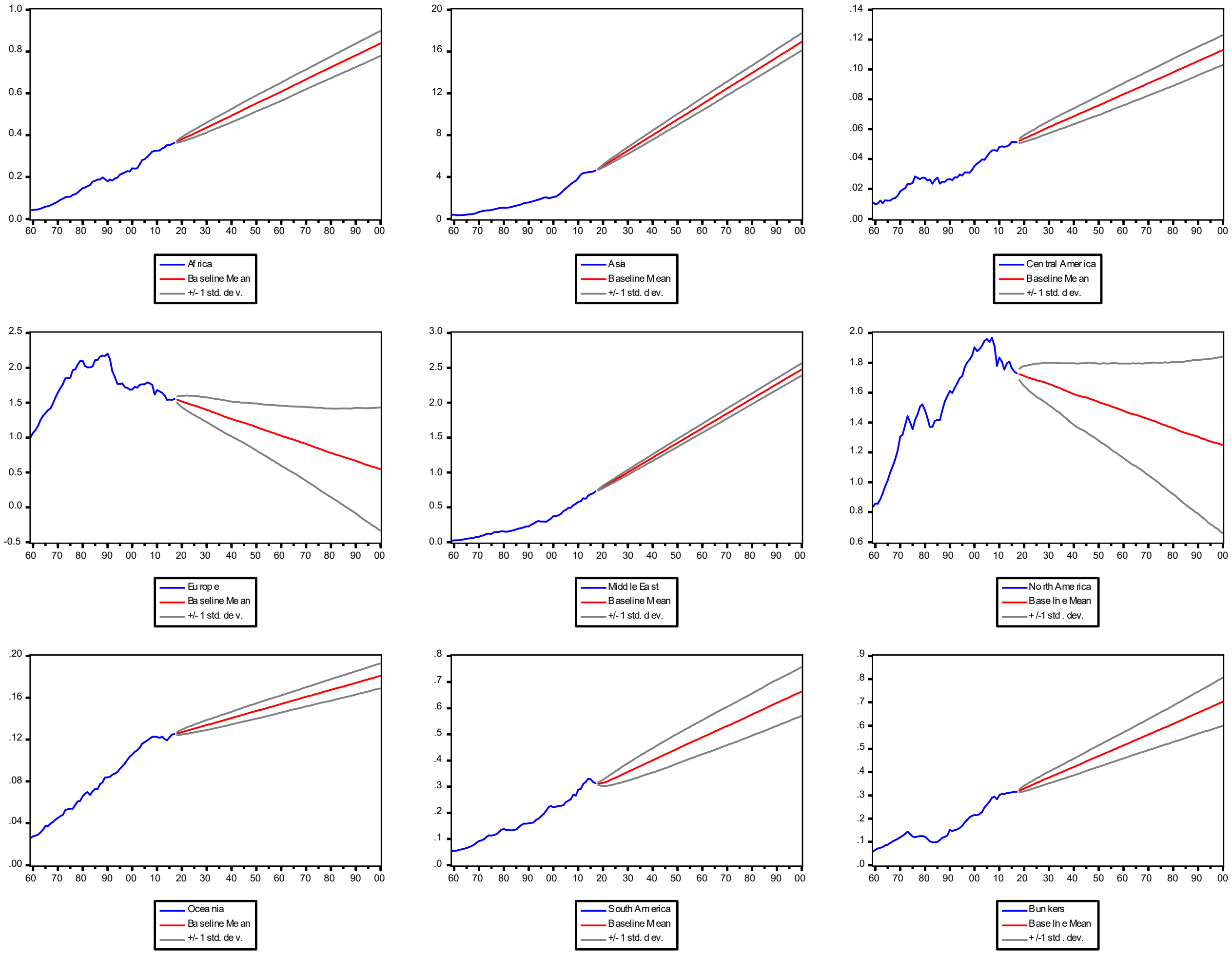


Figure 6: Regional territorial emissions (fossil fuels and cement production), sample data (1959–2017) and projections (2018–2100)

Extending the baseline results, Figure 6 and 4 present the projection for each region's future emissions up to the year 2100 - in level and share. The developing world - that is, Africa, Asia, the Middle East, Central and South America - is expected to see emissions climbing upwards until the end of the century. By 2100, the highest-emitting region by far will be Asia, more than all other regions combined, with around 50% to 70% attributable to it. In fact, the increase in total emission level is so high that for every other regions with increasing level, their shares will actually be flat-lining. For the developed regions, the story is inverse: Europe and North America will see their emission pathways heading downwards. The only exception is Oceania, which will also climb up in emission level. Regardless, all three regions should see their share declining over time. Emission from aviation and shipping are also expected to rise.

5.2 Regional Analysis of RCP Scenarios

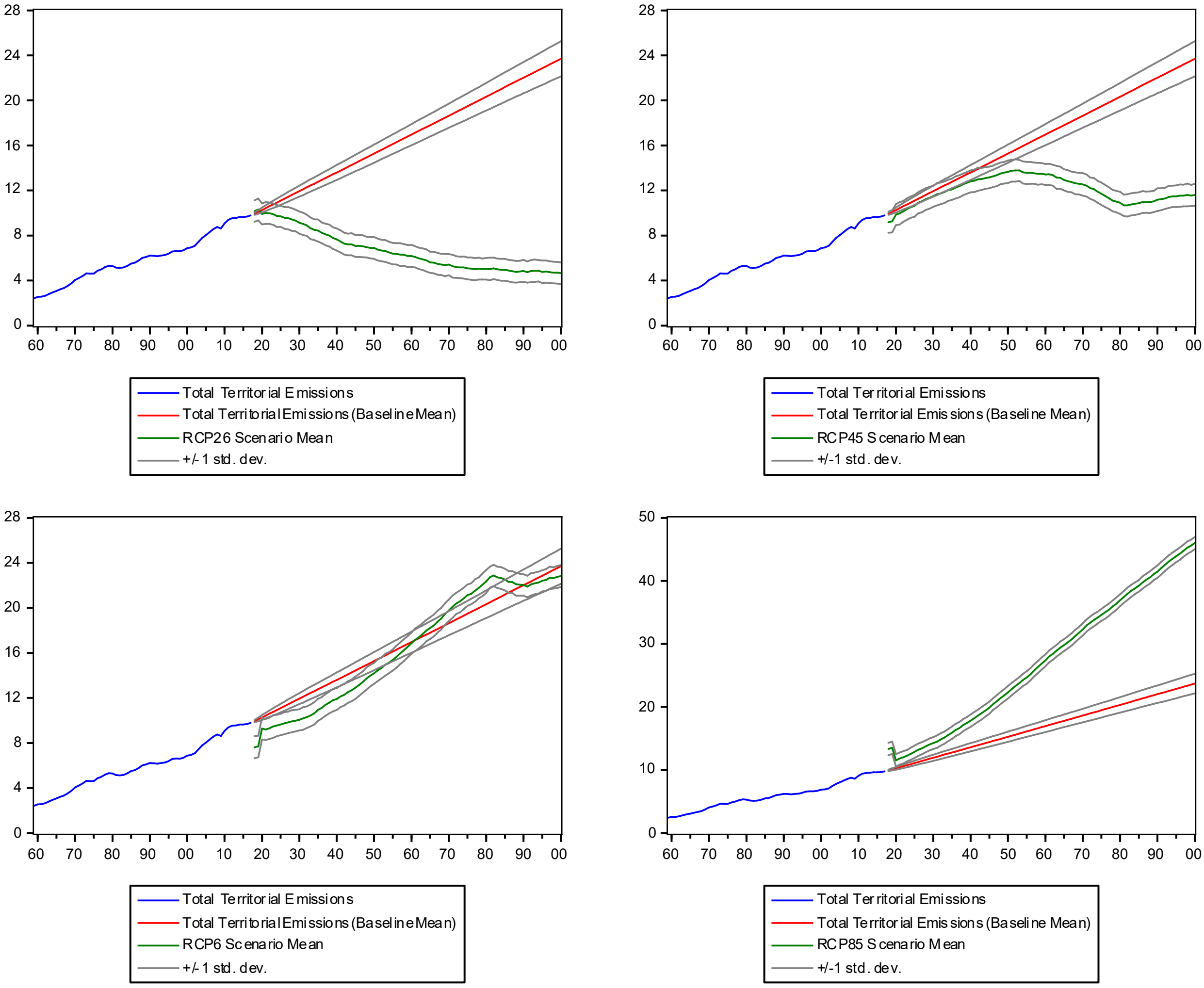


Figure 7: Atmospheric carbon growth under different RCP scenarios, sample data (1959–2017) and projections (2018–2100)

Figure 7 depics the projected aggregate emissions under different RCP scenarios, in comparison to the projected current mean. RCP 26, with the planet warming up by only 1.5^oC, requires a substantial reduction in emission towards the 1960 level by 2100. The two intermediate scenario places a laxer constraint on emission, with RCP 6 seeming to fit our projected current mean the most. The catastrophic situation of RCP 8.5, with increasing temperature of 4.5^oC, occurs when emission spirals out of control and accelerate its upwards trajectory.

We break down the projected emissions for the four scenarios by region under Figure 8, 9, 10, and 11. Under the strictest case, RCP 2.6, not only would total emissions need to fall, every region need to cut down on emission level. Europe and North America will have to converge to below historical (1959) level by 2100. All developing regions and Oceania must also cut down their emission pathways, with the aim of reaching mid to late 20th century carbon emission level by 2100. Emission from aviation and maritime shipping will also need to be reduced.

For RCP 4.5 and RCP 6.0, most regions will see some rise in emissions, with the exception of Europe and North America. Noticeably, the emission increase in RCP 4.5 is forecasted to flattens out and even slightly decline for all regions at around 2060. Nevertheless, emission level will still be higher than they are at 2018 level across all regions save for Europe and North America. RCP6, which was noted under the aggregate emission projection to most closely follow the projected current mean, is similar to RCP 4.5.

The catastrophic case of RCP 8.5 happens when every regions increase their emission to the end of the 21st century. The combination of accelerated increase in emission among developing regions, and the pick-up in emission among developed ones, would ultimately bring atmospheric carbon concentration to a level guaranteeing a 4.5^oC increase in global mean temperature.

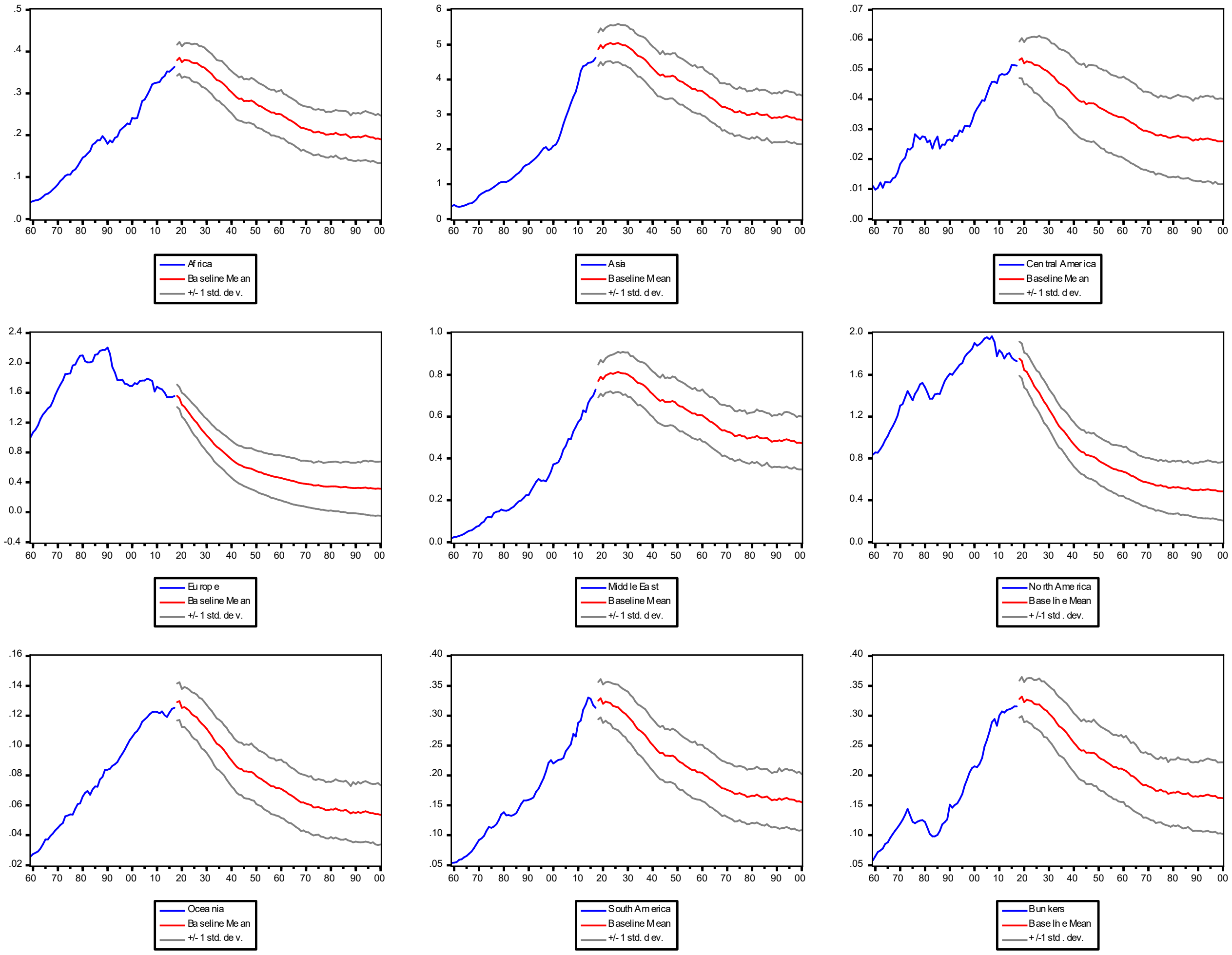


Figure 8: Territorial emissions implied under RCP2.6 scenario, sample data (1959–2017) and projections (2018–2100)

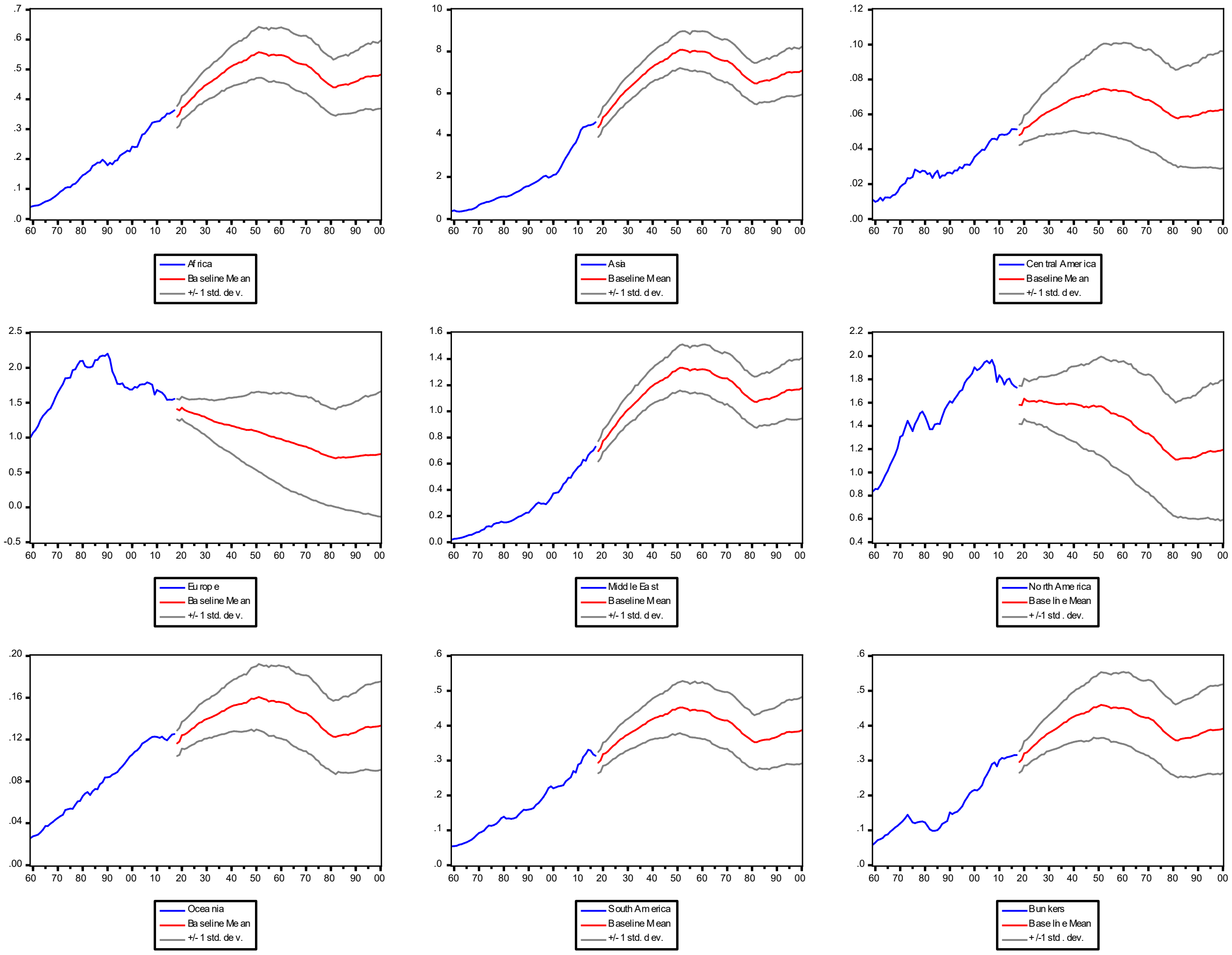


Figure 9: Territorial emissions implied under RCP4.5 scenario, sample data (1959–2017) and projections (2018–2100)

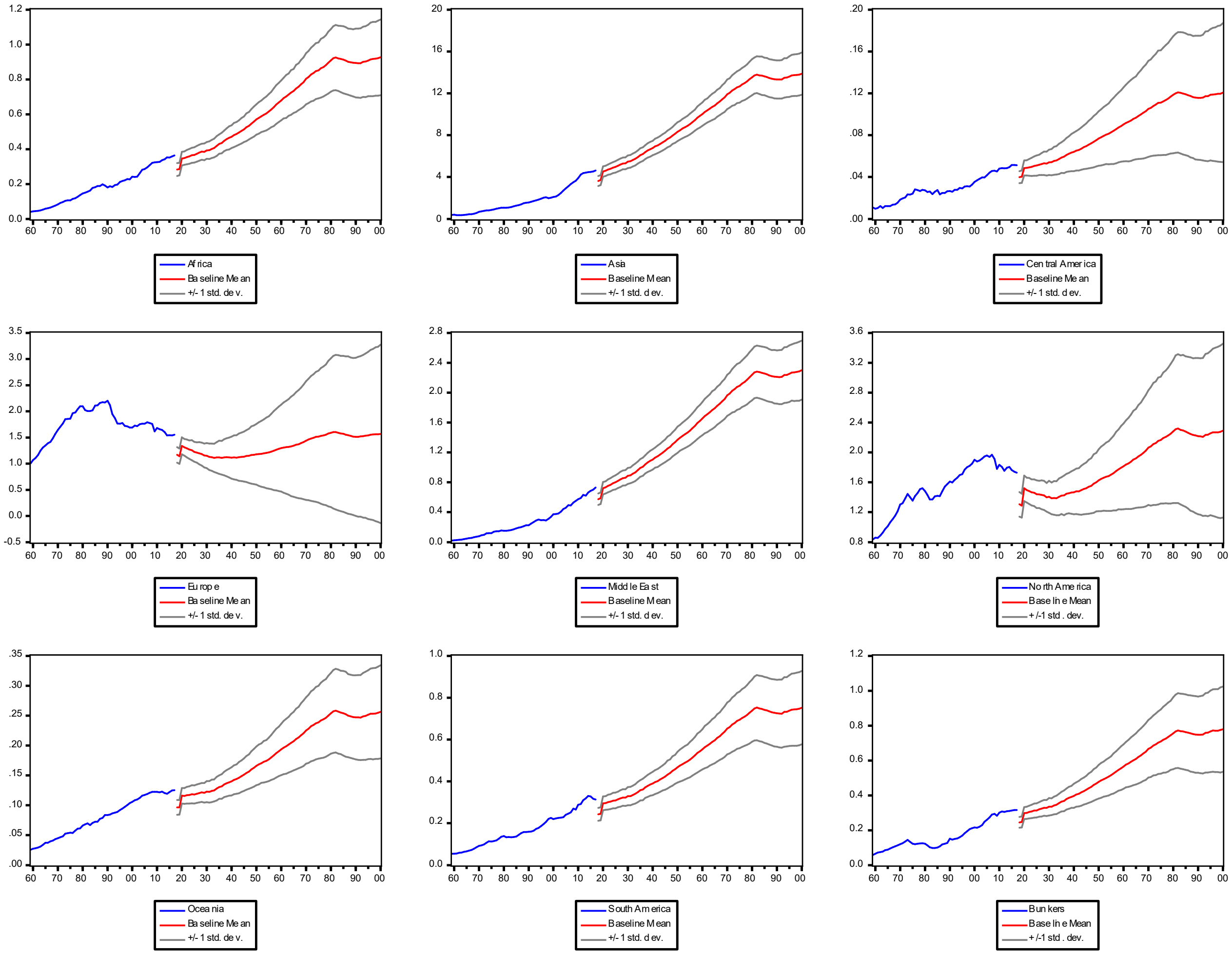


Figure 10: Territorial emissions implied under RCP6 scenario, sample data (1959–2017) and projections (2018–2100)

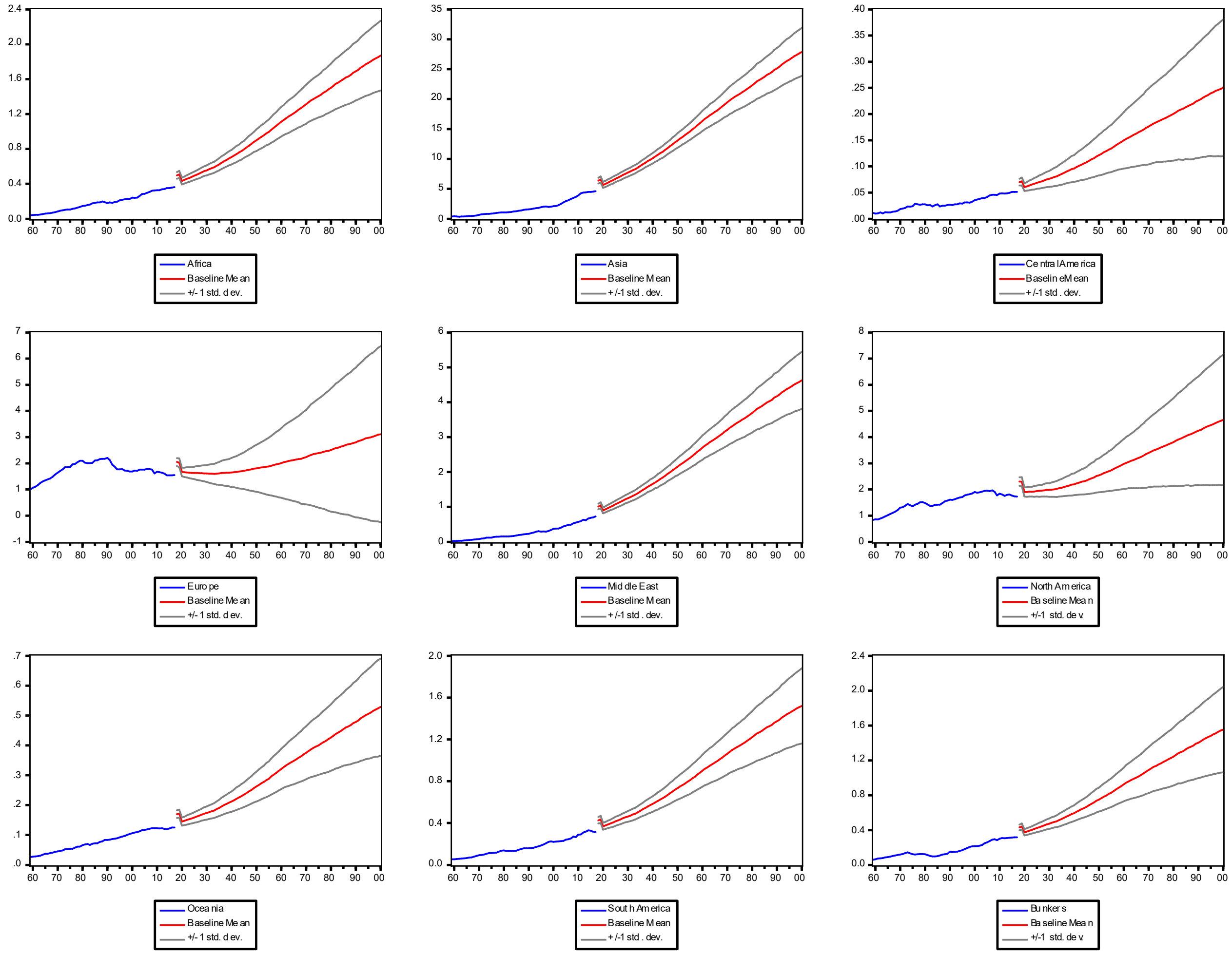
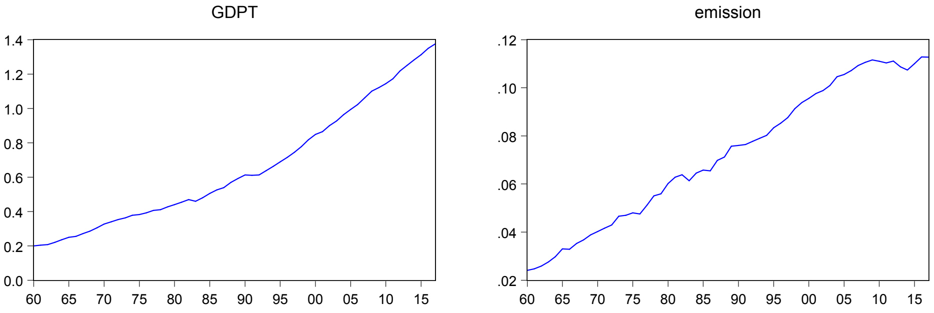


Figure 11: Territorial emissions implied under RCP8.5 scenario, sample data (1959–2017) and projections (2018–2100)

5.3 Relationship Between GDP and Emissions

In this section, we focus on estimating the relationship between the economic activity and emissions in Australia. First, we consider a time plot of the GDP and emissions, where it is clear that both have strong upward trends.



Using an Augmented Dickey-Fuller test, we find strong evidence for both series having unit roots (p-values of 0.9985 and 0.9580, respectively), indicating that the series have stochastic trends. Therefore, regressions of the from

$$E_t = \beta_0 + \beta_1 GDP_t + \varepsilon_t$$

are likely to be spurious. Since it is likely that both emissions and GDP have common underlying drivers, e.g. economic growth, industries, exports...etc., these series are likely to be cointegrated (having common stochastic trends). Using the Johansen cointegration test, we find evidence for at least one cointegrating relationship (p-value of no cointegrating relationships is 0.0148) in the presence of a linear time trend. The cointegrating relationship is given by

$$GDP_t = 19.65E_t \quad 0.04103t$$

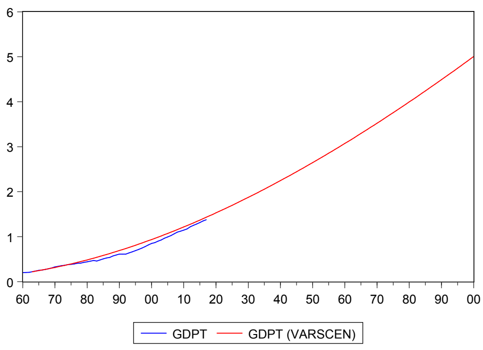
where GDP_t is measured in trillions of USD (deflated to 2010) and the E_t are measured in GtC. This implies that for, in the long run, for each trillion of dollars of GDP increase, emissions will go up by approxmiately 19.65 GtC. The appropriate framework to use in this case would be the vector error correction model (VECM) given by

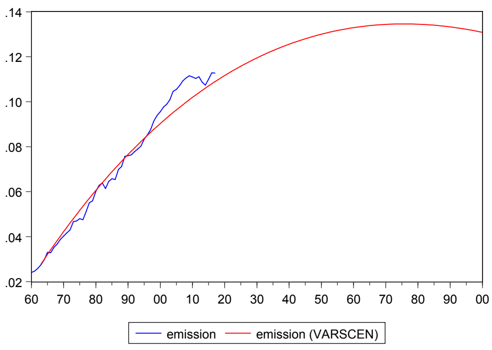
$$\Delta X_t = A_0 + \alpha\beta' X_{t\ 1} + \sum_{j=1}^{p\ 1} \Gamma_j \Delta x_{t\ j} + \varepsilon_t$$

where β is the cointegrating vector implied by the above cointegrating relationship and $X_t = (GDP_t, E_t)'$. We can think of the VECM as simply a VAR in the first difference augmented by the cointegrating (long run) relationship. Using the AIC, we select a lag length of 2. Therefore, the parameter estimates are given by

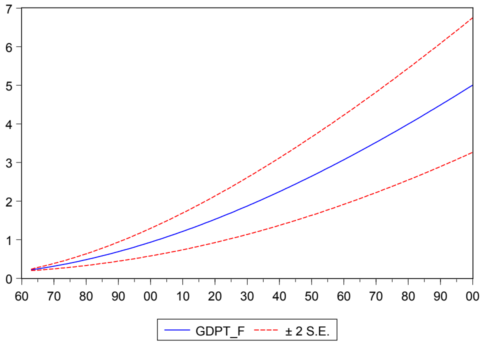
Co-efficient	ΔGDP_t equation	ΔE_t equation
Constant	0.0189 (0.00421)	0.000875 (0.00079)
α	0.0262 (0.0097)	0.0290 (0.0289)
Γ_1 for $\Delta GDP_{t\ 1}$	0.2117 (0.1382)	0.0290 (0.0288)
Γ_1 for $\Delta E_{t\ 1}$	0.0319 (0.1531)	0.01166 (0.1425)
Γ_2 for $\Delta GDP_{t\ 2}$	0.6330 (0.7576)	0.0478 (0.1452)
Γ_2 for $\Delta E_{t\ 2}$	1.5215 (0.7718)	0.0478 (0.1452)

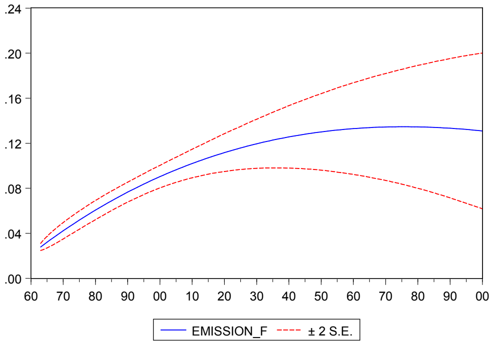
Using the VECM, we can forecast out the future paths of GDP and emissions. The following figures presents the paths for both GDP and emissions out to 2100.



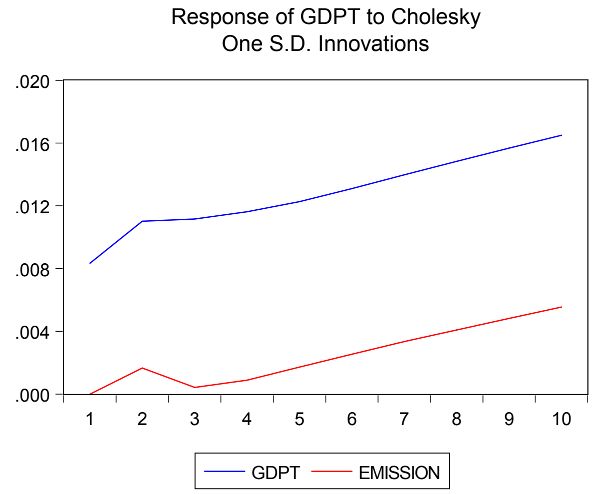


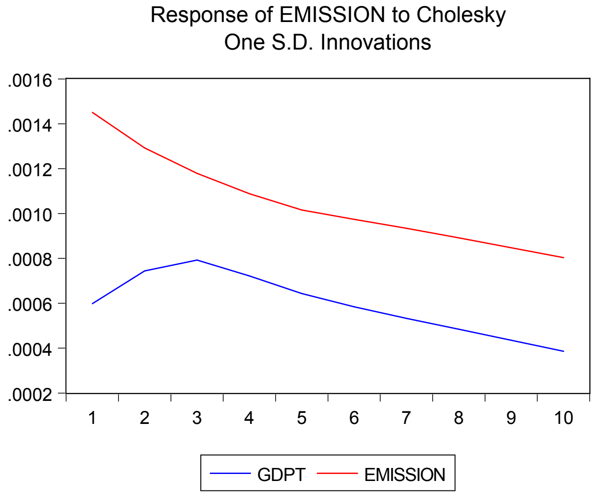
We also present the forecasts with 95% confidence intervals.



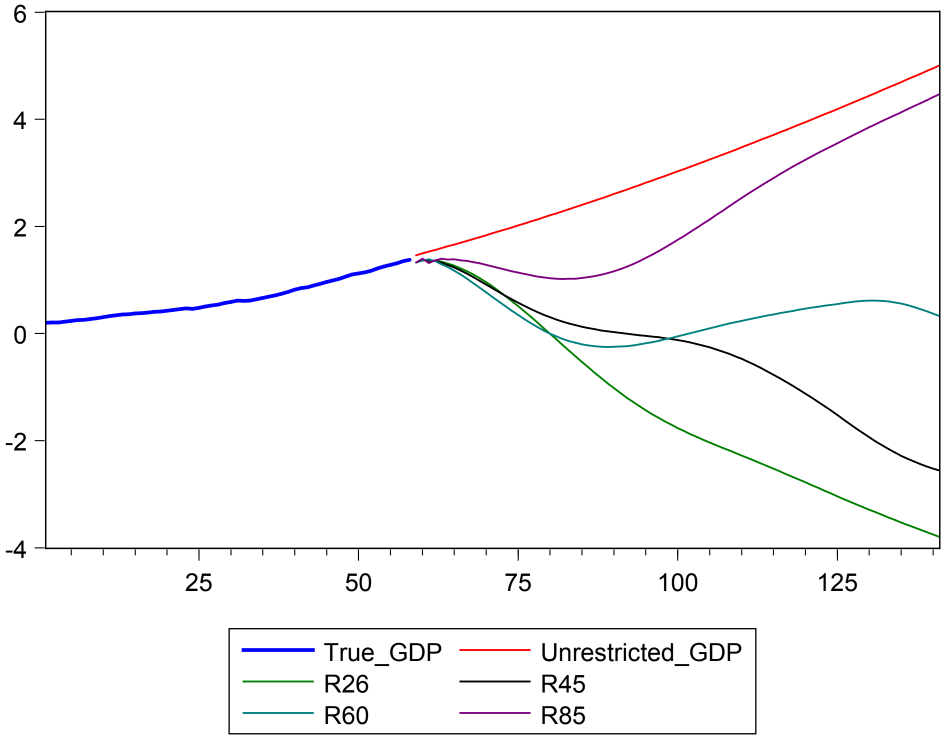


From this model, we can also estimate impulse response functions for the VECM model.


Response of GDPT to Cholesky One S.D. Innovations


Response of EMISSION to Cholesky One S.D. Innovations

From the impulse response functions, we see that the effect of emissions on GDP is permanent, not transitory due to the error correcting relationship. Furthermore, we also find similar types of relationship in the other direction. Next, we consider the GDP path under the different RCP scenarios. From the forecasts of GDP, we can see that under RCP85, the GDP path is quite similar to the unrestricted baseline forecast. However, under all other RCP scenarios, the Australian GDP is predicted to fall. As is expected, with the RCP26 scenario, the decline is fastest, with all three scenarios predicting negative GDPs by 2100.



6 Discussion

Our model predicts an increase in global carbon atmospheric concentration to 2100, and was extended to analyze regional patterns. The feedback mechanism modelled between sink level and lagged concentration level was estimated to be positive, implying the ocean and ground captures more carbon as concentration level rises. This attenuating force is responsible for a slowing down of the increase in atmospheric concentration growth rate, and holds back carbon concentration level.

Our findings on regional territorial emissions are interesting, as it projects different trajectories for regions that correlate with development level. For the period from 2018 towards 2100, Europe and North America are expected to be pulling their emission level downwards - Europe towards level below that seen in 1959, and North America to 1980 level. In contrast, all the developing regions will raise their emission level, with Asia being responsible for more emissions than every other groups' combined in 2100. Note that this divide is in line with the framework set out in the Kyoto Protocol (UNFCCC, 1998), where richer nations are given targets to limit their emission while poorer ones are not. Thus, this may be taken as evidence that the framework is "working" - in fact, we may follow up with the question of when to "wean" poorer countries off the no limit path.

However, this disaggregate level discussion on carbon emission must take into account the international trade background. The data we utilize contain territorial emissions, that is, emissions created within the jurisdiction of a nation - either for products to be consumed domestically or exported. Nations that seem to be lowering their emission level can, in fact, be “exporting” carbon emissions to others that are producing goods and services for them. Peters et al. (2011) and Hertwich & Peters (2009) have noted that this can explain the discrepancy between observed trend for the rich and poor world’s carbon emissions. China is the largest emitter of CO_2 emissions with the territorial-based inventory, with the US coming in second, yet when we switch to a consumption-based inventory this ranking is reversed.

Policy prescriptions then depend on how big the component of carbon trade is in the global carbon market. With the territorial-based measurement, we expected the developing world to contribute progressively more carbon to the atmosphere, which calls into question the framework set out in the Kyoto Protocol of not subjecting them to limit control. However, even the developed world must be able to lower emission level considerably if we want to achieve the concentration level prescribed by RCP 2.6. However, if we are convinced that transfer of carbon is significant, then developed countries have a responsibility to rein in importation of carbon-intensive products. One possible step to attenuate the problem then is to create carbon-based tariffs, or facilitate clean, low-carbon technology transfer from the rich world to the poor one.

Our model also captures the relationship between GDP and emission for Australia, and then use the pathways for the latter under basic and different RCP scenarios to predict the former. What’s noticable is that under the baseline or RCP 8.0 scenario, GDP is expected to grow well to around 4 trillion $ by 2100 but under the most restrictive one, RCP 2.6, the economy will collapse. Thus, to implement the desirable climate scenario major changes to political leadership and climate technologies are required. Note, however, that these predictions depends on a predicted close relationship between GDP and emission. Forecasts of such complex relationship over this whole century must be taken with some levels of warranted skepticism.

7 Conclusion

Anthropogenic carbon emission is the major driver in atmospheric carbon concentration and global warwming. Understanding the link between emission and concentration, then, in order to predict both variables for the future is vital. Our model was built with such intention in mind, basing itself on the Global Carbon Budget framework (Allen et al., 2018). It incorporates the difference in emission between the world’s region and provide some striking as well as fruitful predictions.

The developing world - most noticabely Asia - will be responsible for the majority of the world’s carbon emission to 2100, while emission levels for Europe and North America will decline significantly. The policy implication is significant: the Kyoto Protocol gave developing countries considerble leeway, which needed to be called into question. However, given that developed countries import significant level of goods and services with carbon embedded, they must also be called into actions. Specifically, they should implement carbon-based tariffs and encourage clean technology adoption the world over to reduce climate change.

We further extend our results by predicting emission requirement under different RCP scenarios, and Australia’s GDP level until 2100 under the predicted emissions. The safest scenario for our planet requires massive reduction in emission across the globe, whereas letting emission grows out of control is catastrophic for the planet. The prediction for GDP in Australia implies that current technology and climate leadership there is not enough to achieve the emissions required for climate safety.

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