BROOKINGS DISCUSSION PAPERS IN INTERNATIONAL ECONOMICS

No. 160

LONG RUN PROJECTIONS FOR CLIMATE CHANGE SCENARIOS

Warwick J. McKibbin, David Pearce
and Alison Stegman

April 2004

Warwick J. McKibbin is a professor in the economics department of the Research School of Pacific and Asian Studies at the Australian National University (ANU), a non-resident Senior Fellow in the Economic Studies Program at the Brookings Institution, and a Professorial Fellow at the Lowy Institute for International Policy in Sydney. David Pearce is a Principal Policy Analyst at the Centre for International Economics in Canberra. Alison Stegman is a PhD candidate at the Australian National University in Canberra. The views expressed are those of the authors and should not be interpreted as reflecting the views of other individuals or institutions named above.

Long Run Projections for Climate Change Scenarios[*]

Warwick J. McKibbin**
The Lowy Institute for International Policy, Sydney
Centre for Applied Macroeconomic Analysis, ANU, Canberra
The Brookings Institution, Washington

David Pearce
Centre for International Economics, Canberra

And
Alison Stegman
The Australian National University, Canberra

Revised Draft 23 April 2004

---

[*] This was prepared for the Stanford Energy Modeling Forum workshop on Purchasing Power Parity versus Market Exchange Rates. It has benefited from discussions with Peter Wilcoxen, Barry Bosworth, Ian Castles, Alan Heston, Neil Ferry and many colleagues at the Stanford meeting. We are grateful to the Australian Greenhouse Office and Lowy Institute for financial support. This paper draws on a larger project with Peter Wilcoxen from Syracuse University and extends earlier work that was undertaken jointly with Peter Wilcoxen and Philip Bagnoli of the OECD. The views expressed in the paper are those of the authors and should not be interpreted as reflecting the views of the Institutions with which the authors are affiliated including the trustees, officers or other staff of the Brookings Institution.

**Send correspondence to Professor Warwick J McKibbin, Economics Division, Research School of Pacific & Asian Studies, Australian National University,ACT 0200, Australia. Tel: 61-2-61250301, Fax: 61-2-61253700, Email: warwick.mckibbin@anu.edu.au.

Long Run Projections for Climate Change Scenarios

ABSTRACT

The prediction of future temperature increases depends critically on the projections of future greenhouse gas emissions. Yet there is a vigorous debate about how these projections should be undertaken and how reasonable is the approach of the *Special Report on Emissions Scenarios* (SRES) published by the Intergovernmental Panel on Climate Change (IPCC) which forms the basis of nearly all recent analyses of the impacts of climate change. In particular there has been significant criticism by Ian Castles and David Henderson regarding the plausibility of some scenarios.

This paper explores a range of methodological issues surrounding projecting greenhouse emissions over the next century. It points out that understanding future emissions, requires a framework that deals with the sources of economic growth and allows for endogenous structural change. It also explores the role of "convergence" assumptions and the debate regarding the use of purchasing power parity (PPP) measurement versus market exchange rate (MER) measurement of income differentials. Using the G-Cubed multi-country model we show that emission projections based on convergence assumptions defined in MER terms, are 40% higher by 2100 than emissions generated using a PPP comparison of income differentials between economies. This result illustrates the argument by Castles and Henderson that the use of MER convergence assumptions will likely overestimate emissions projections, taking many other issues as given. However it is not clear what this means for the SRES projections given that it might be argued that in some models in the SRES, there could be endogenous changes in technology that will offset this result. We do not have access to those models to explore this issue and can only show what this particular assumption implies in the G-Cubed model. It is also ambiguous exactly what was done in the SRES report regarding convergence assumptions in some scenarios.

Either way these results do not imply that climate change is not an issue but that there is a great deal of uncertainty about future climate projections and it is very unhelpful to presume that all futures are equally likely. In order to deal with this we also propose as a better guide to policymakers a methodology that calculates probabilities for future projections rather than the approach of SRES which is based on storylines without any assessment of plausibility. It is unfortunate that some analyses of the impacts of future climate change are based on the extreme outliers from the SRES without any understanding of the probability of these outcomes. This alternative approach could be done using the economic approach proposed in the G-Cubed model as outlined in this paper, or it could be done with the existing range of SRES scenarios to better inform the debate on likely future greenhouse scenarios.

Contact author: Professor Warwick McKibbin
Email warwick.mckibbin@anu.edu.au

JEL classification: C50, C68, F01, F43, Q54, Q56

Keywords: Climate change, Kyoto Protocol, G-Cubed, model, projections, SRES, PPP versus MER

1. Introduction

Background

Everyone wants accurate, or at the very least, understandable, projections of future climate change. While the need is clear, providing the projections is considerably more difficult. The crucial starting point for any climate projections are the projections of emissions of greenhouse gases, which themselves depend on the various human activities (mostly, but not entirely, energy related) that generate the emissions. While converting these emissions to temperature and climate change is the domain of atmospheric and meteorological sciences, generating the emission predictions is the domain of the sciences of human activity, most notably economics.

Of the various attempts to generate emissions projections for input into climate models, the IPCCs *Special Report on Emission Scenarios* (IPCC 2000), or SRES, is probably the most comprehensive and visible, and as a result has attracted considerable critical analysis. Some of this critique focuses on the approach to uncertainty adopted by the SRES (see, for example, Schneider, 2001). Other aspects of the critique have focused on the apparently high economic growth rates in some of the scenarios and the ways in which this may have emerged (see Castles and Henderson, 2003a and 2003b). Indeed, of the many critiques of the SRES, the Castles and Henderson critique has generated considerable public attention through its subsequent publication in relatively popular media.

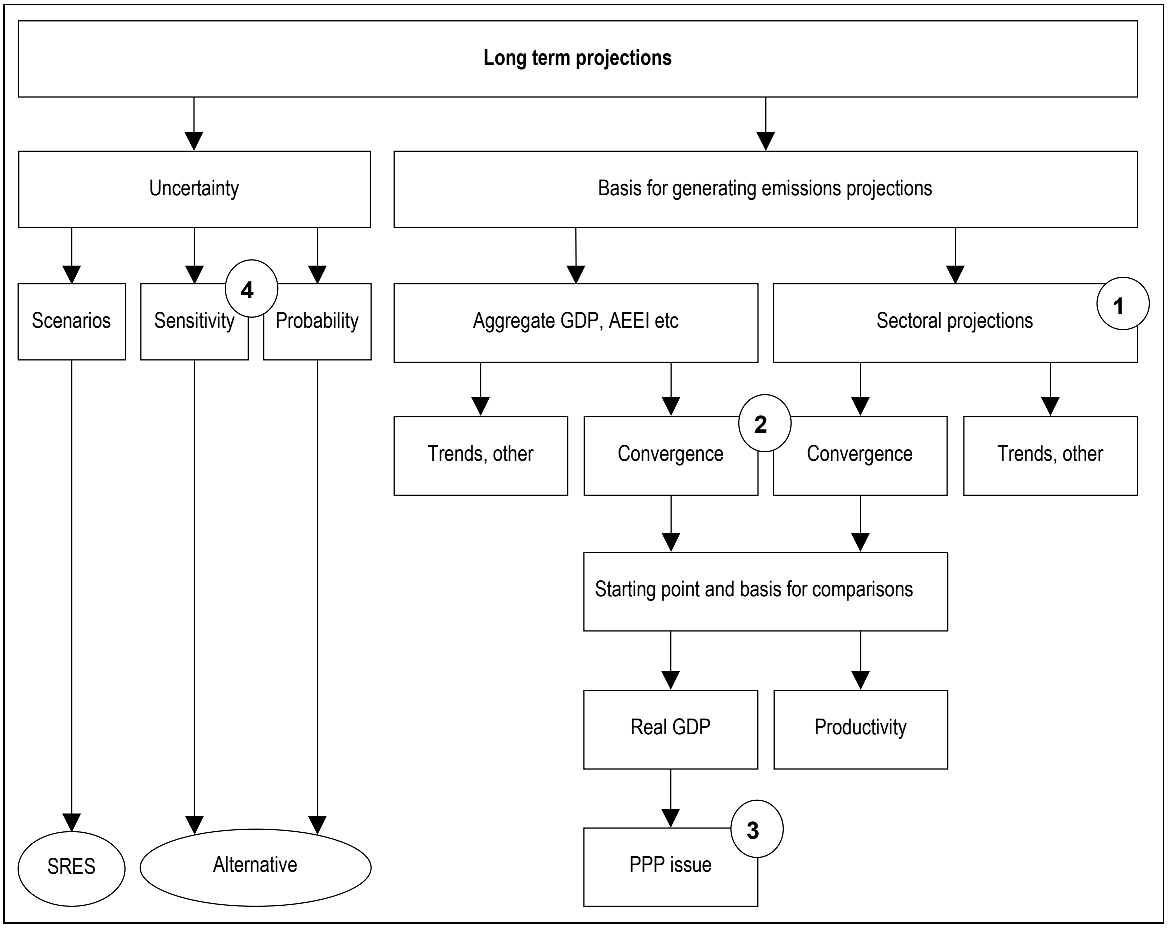
It is important that these areas of critique are carefully examined and understood. It is also crucial that the broader methodological issues surrounding such projections are also clearly delineated. As the economics is the first link in a chain of analysis that leads to climate predictions, it is crucial that economists use the best possible analysis for their part of the job.

This paper sets out some of the methodological issues that arise when attempting to project emissions over the long time frames necessary for climate predictions. In particular, we are concerned with:

- the analytical issues behind designing projections exercises;
- understanding the sources of economic growth;
- examining the role of the idea of 'convergence' in generating economic growth projections;
- considering the role of 'purchasing power parity' (PPP), versus market exchange rates (MER) in understanding economic growth and implementing particular convergence models (the basis of the Castles and Henderson critique)
- making suggestions about a fruitful approach to uncertainty when projecting emissions.

Structure of the paper

This paper covers a number of different areas of discussion. The overall logic of the discussion is illustrated in the following figure. There are two broad sets of issues in generating long term projections, the underlying basis for the projections and the treatment of uncertainty. Looking at the basis for projections, these could be done at an aggregate level or at a sectoral level. Our first concern is with discussion the importance of a sector basis for projections.



Either aggregate or sectoral approaches could use a variety of source of underling drivers, trends other expectations and so on. One possibility is to use convergence as a way of generating projections. Our second concern is to discuss convergence issues. One of these issues is the starting point and the basis for comparisons in convergence models. One option is to use convergence of underlying productivity. Another option is to use real GDP per capita comparisons. If GDP is the basis, then a potential PPP issue arises. Our third concern is to discuss these PPP issues and their implications.

Our fourth concern relates to the treatment of uncertainty in long run projections. While the SRES adopted a scenario approach, there are other alternatives which we briefly consider.

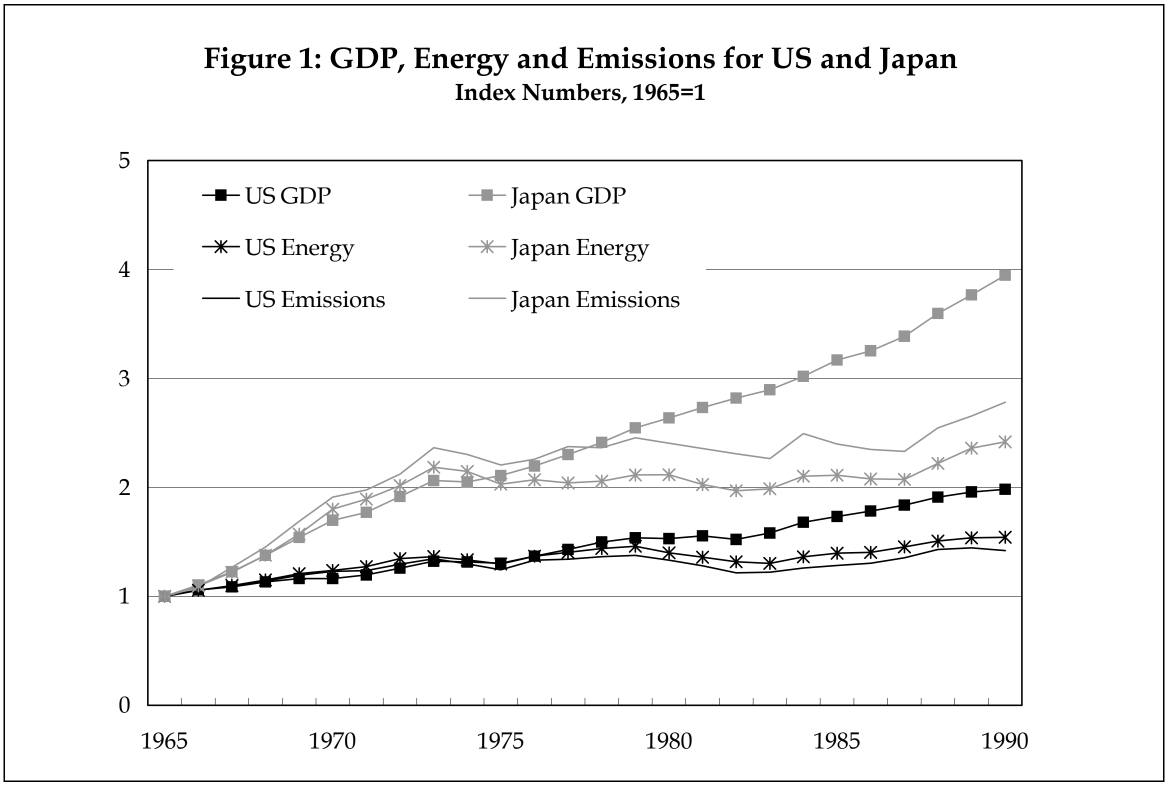
Overview of findings

It is, of course, very difficult to predict the long run evolution of global economic growth. The task is made more difficult, particularly in the context of emissions projections, in that it is not just the rate of growth that matters, but the composition of that growth and its geographical location. It is for the same projected rate of aggregate economic growth over the coming century to be associated with a wide range of emissions profiles. The driver is not growth per se, but the sources of that growth.

There are different methodologies for predicting future carbon emissions. One of the key issues in looking forward is how history is understood since this is critical to different views of how to project the future. Figure 1[1] shows the paths of real GDP (in domestic units), energy use (in BTU) and carbon emissions for the United States and Japan from 1965 to 1990 plotted as an index equal to unity in 1965. A dominant feature of this figure is that emissions, energy use and real GDP tended to follow a common trend until 1972 (although in Japan emissions rise faster than economic growth before 1972). When the OPEC oil price shocks dramatically changed the price of energy in 1972, there was a shift in the relationship with GDP growth continuing on a slightly different trend but energy use and emissions rising much less quickly. How is this historical experience interpreted? Energy models, which dominate the long run projections literature, tend to represent this as autonomous energy efficiency improvements (AEEI)[2]. This is an increase in energy efficiency of roughly 1% per year. Economists on the other hand see this as structural change induced by changes in relative prices. To be sure there is also a change in technology induced by higher energy prices but this is not autonomous in a behavioral sense. In projecting forward it is critical how this historical experience is built into the projections. In our view it is not sufficient to attribute this change to AEEI, but rather to attempt to further decompose and understand it.

---

1 Adapted from Figure 1 in Bagnoli et al (1996).



In this paper we set out the methodology for undertaking long run projections used in the G-Cubed multi-country economic model. We illustrate how different assumptions about economic growth at the individual sector level can have large implications for the economy wide economic growth and economy wide carbon dioxide emissions from burning fossil fuels. We compare this with the methodology followed by the models that produced the SRES scenarios for the IPCC.

As part of our analysis we examine the magnitude of the consequences of the Castles and Henderson critique of the SRES by generating a baseline projection from the G-Cubed model based on our usual growth convergence assumptions using a PPP measure of initial gaps between countries. To explore whether the different assumptions about growth

---

2 See Manne and Richels (1992) for an overview of the concept of AEEI.

projections make any difference to the emissions projections, we then regenerate these projections assuming MER based gap between economies. In G-Cubed, the difference in emission outcomes turns out to be substantial. If developing countries grow more quickly over a century (because the potential for 'catch-up' is larger in the MER case), then the income and expenditure of both developing countries and developed countries rise. This causes an increase in energy use and a rise in carbon emissions globally- not just in developing countries.

We find that by 2050 the projection of emissions from fossil fuels use based on the MER measures of GDP gaps is 22% higher than our base projection (using PPP) and by 2100, projected emissions are 40% higher than baseline emissions. About half of the higher emissions are generated from countries that are classed as developing in 2002 and about half from industrial economies. These numbers are almost 3 times those found in Manne and Richels (2003) who undertake a similar exercise. There are a number of reasons for these differences, which are open to debate. We do not change assumptions about exogenous technological developments caused by higher growth except those generated by relative price changes. Others might argue that higher economic growth would lead to faster AEEI and therefore emissions change by less. This is an open question. We also have much greater international interdependence between countries through trade and capital flows than the Manne and Richels study. The greater the positive spillovers from growth in developing countries to growth in industrial countries the larger the emissions, taking all other things equal.

Although the results we find are significant, they cannot be directly applied to the SRES approach. Firstly, it is not clear that the SRES actually based any or all of the projections in the study on a standard growth convergence model, despite spending considerable space summarizing that literature. In many of the models used in the SRES the entire economy is summarized by the exogenous path for GDP growth and emissions growth is driven by technology. GDP plays a minor role except as the scale variable. Indeed it is likely that the projections of emissions in the SRES were undertaken by the modelers before the chapter on economic growth was even written, because the economics of growth doesn't really play an important role given the underlying methodology of the models used.

If the modelers in the SRES used market exchange rate GDP differentials but the rate of convergence from the PPP convergence models then there is a problem as argued by Castles and Henderson (2003a) and as we illustrate in this paper. If the SRES models used an MER based convergence model by adjusting the rate of convergence to be consistent with the MER approach then there is still a problem because there is no evidence of convergence of GDP per capita in MER terms. This is why the growth convergence literature that has been published since the development of PPP GDP data and does not use market exchange rates. Secondly there is also no evidence of convergence between MER and PPP exchange rates so in our opinion there is no way to go from a PPP convergence model to a MER convergence model.

However, it may just be that the models did something completely different to what is suggested in the SRES report. One alternative that likely underlies some of the projections is that the concept of convergence is implemented by specifying a gap between $US incomes per capita at the start of the projection period and an arbitrary gap between $US incomes per capita at the end of the projection period. The problem with this approach is that it relies on the evolution of the real exchange rate between countries to be able to say anything about the underlying drivers of growth at the sectoral level within a country. Many of the models used do not have the real exchange rate modeled and therefore cannot back out the underlying drivers of growth within a country for driving real economic growth. Even this approach would suffer from the same critique that income gaps measured in $US at different points in time cannot be used to derive underlying economic growth.

While it is possible that some of the SRES scenarios contain growth rates that are higher than would be case if PPP had been used in comparing base GDP, it does not follow in these scenarios that lower GDP growth would translate to lower emissions. We illustrate in this paper that the relationship between emissions and GDP depends on the relative importance of various sources of growth. It is possible to have a model with growth drivers and parameters setting that result in GDP and emissions moving in opposite directions.

Despite the debate on PPP versus market exchange rates and whether this affects the SRES predictions of future emissions profiles, there is a deeper debate that needs to be undertaken on the overall world view that drives the models underlying the SRES type exercises of predicting more than 100 years into the future. It is clear that there are alternative approaches (such as the sectoral approach of G-Cubed) of generating emission profiles. Given the inherent uncertainty of projecting the future clearly a suite of approaches should be considered in future work on projecting greenhouse emissions. There is enormous uncertainty over the likely path of emissions, let alone how this will impact on climate outcomes. The policy implications are that whatever is done should take this uncertainty fundamentally into consideration.

The PPP 'controversy' arises in the context of one particular approach to forecasting (the use of some notion of convergence). Even if this issue is resolved, there remains many more fundamental issues to be considered and discussed between modelers and policy makers.

2. Some Theoretical Considerations

a. Source of Economic Growth[3]

To project growth, it is important to first understand the ultimate sources of growth. A considerable amount of work has been undertaken on growth theory in recent years, and our general understanding of the drivers of growth has improved considerably.

At an abstract level there are four sources of growth within an economy: (1) increases in the supply of labor, capital and other inputs; (2) increases in the quality of these inputs, (3) improvements in the way inputs are used (technical change); and (4) improvements in the way that inputs are allocated across industries. For the world economy as a whole, a fifth source of growth is reallocation of inputs among countries. The first three effects can be illustrated with a simple model. Suppose an industry can be represented by the following Cobb-Douglas production function:

$$Y_t = A_t(F_t K_t)^{\beta}(G_t L_t)^{\gamma}(J_t E_t)^{\sigma}(H_t M_t)^{(1-\beta-\gamma-\sigma)}$$

where: Y_t is output at time t; K_t, L_t E_t and M_t are inputs of capital, labor, energy and materials; β, γ and σ are parameters; A_t is a coefficient reflecting the overall level of productivity; and F_t, G_t, J_t and H_t coefficients capturing the quality of each input.[4] This expression can be transformed into a relationship between growth rates by differentiating with respect to time and dividing through by Y_t. The result is shown below, where lower case variables represent the rates of growth of the corresponding upper case variables:

---

3 This section draws heavily on Bagnoli, McKibbin and Wilcoxen (1996).

4 Coefficients F, G, J and H could also be interpreted as biases in the pattern of technical change. A more general specification would allow for both improvements in factor quality and biases in technical change. Empirically, it would be difficult to distinguish the two effects. One approach would be to form a panel data set from time series data for a large number of industries and then estimate productivity growth rates imposing the restriction that biases be industry specific and improvements in factor quality be the same across industries.

$$y = a + \beta(f + k) + \gamma(g + l) + \sigma(j + e) + (1 - \beta - \gamma - \sigma)(h + m)$$

Output growth will thus be a weighted sum of overall productivity growth (*a*), increases in the quantity of factors (*k*, *l*, *e* and *m*), and increases in factor quality (*f*, *g*, *j* and *h*). The weights in the sum are parameters of the production function.[5]

A more general expression can be obtained by relaxing the assumption that the production function is Cobb-Douglas. Suppose the production process may be represented by a constant returns to scale function *Q* which depends on the level of technology, *A*, and quality-adjusted inputs of capital, labor and materials:

$$Y_t = Q(A_t, F_t K_t, G_t L_t, J_t E_t, H_t M_t)$$

If firms minimize costs taking prices as given it is straightforward to show that the rate of output growth will be given by:

$$y = \left(\frac{1}{Q}\frac{\partial Q}{\partial A}\right)a + S_K(f + k) + S_L(g + l) + S_E(j + e) + S_M(h + m)$$

where the first term on the right hand side is called the rate of total factor productivity (TFP) growth, and S_K, S_L, S_E and S_M are the shares of capital, labor energy and materials in total costs. This expression is similar to the Cobb-Douglas case except that the weights in the sum are now cost shares instead of production function parameters. In fact, the Cobb-Douglas function is a special case in which the cost share of each input can be shown to be equal to the corresponding parameter. The main difference between the two expressions is that the general case is nonparametric: decomposition of the growth rate does not depend on estimates of production function parameters. Moreover, observations of the rates of growth

---

5 This is a generalization of Solow (1957). For a survey of recent papers which use less restrictive production or cost functions, see Dewiert (1992). Maddison (1987) presents a broad survey of the productivity literature.

of inputs and outputs cannot be used to estimate parameters of the production function since no parameters are identified. For the purposes of analyzing growth, however, this is not a liability.[6]

As an empirical matter, decomposing output growth into its constituent pieces is a difficult task. For many industries, measuring the rate of output growth *y* is fairly straightforward: the quantity produced in one year is compared to the quantity produced the previous year. However, determining the source of the growth requires very careful accounting to measure the quality-adjusted rates of growth of factor inputs. Any errors in measuring inputs will cause the rate of total factor productivity growth to be misstated.

It is worth emphasizing the last point: studies of the sources of growth use the equation above to determine total factor productivity growth (*tfp*) *as a residual* after accounting for other factors:

$$tfp = \left(\frac{1}{Q} \frac{\partial Q}{\partial A} \right) a = y - S_K (f + k) - S_L (g + l) - S_E (j + e) - S_M (h + m)$$

Any error in the measurement of input growth rates will cause *tfp* to be measured incorrectly. Denison (1962), Christensen and Jorgenson (1969), and others have emphasized that careful accounting for quality adjusted growth of inputs leaves little residual growth to be attributed to improvements in total factor productivity.

Jorgenson (1988) has shown that for the economy as a whole there is also another potential source of growth: reallocation of resources between industries. To see this, consider an economy with two sectors, *X* and *Y*. If the overall productivity of labor in sector *X* is higher than it is in sector *Y* (say because of prior technical change), a shift in final demand from *Y* to *X* shifts primary factors from *Y* to *X* and will result in growth of total output. This occurs even if there is no concurrent productivity growth in the individual sectors. The effect is even more pronounced if the composition of demand shifts toward sectors which have

---

6 This approach is due to the pioneering work of Denison and is sometimes called ‘growth accounting’. See Denison (1974, 1979, 1985) for much more refined examples of this style of analysis.

productivity growth rates that are higher than average.

Thus, in order to project the world economy over a number of decades into the future we would need underlying projections of each country's labor force, capital stock, materials inputs, changes in factor quality and changes in product demand patterns. Many of these will lead to changes in relative prices and thus change the structure of each region's economy. Moreover, the evolution of each country's capital stock will be an endogenous result of domestic and foreign investment decisions. In order to combine all of these projections, capture the effects of relative price changes, and project the future path of the capital stock you need a disaggregated intertemporal general equilibrium model.

b. Sources of emissions growth

The evolution of GDP will likely but not necessarily be related to the path of carbon emissions. Because energy use is both an input and output in the process of generating GDP, the path of energy use will be determined from the bottom up. GDP growth is determined by the path of input use and technology. Just having a view of aggregate GDP growth does not mean that carbon emissions are residually determined. Bagnoli, McKibbin and Wilcoxen (1996) shows how a given path of GDP for an economy can yield very different profiles of energy use and carbon emissions depending on the sources of growth behind GDP.

It is natural to an economist to form a global projection of GDP by projecting underlying sectoral productivity growth, efficiency improvements and population or labor force growth and then incorporate these into a model with endogenous decisions on other inputs such as energy use, materials use and capital accumulation to build up the economy wide projection for GDP growth. The emissions projection which accompany this growth projection are determined by the sectoral use of fossil fuels in energy generation that are the outcome of the decisions of firms and households.

c. Convergence of Economic Growth Between Countries

Ideally the projection of economic growth within countries would be determined within the context of each country since as we have shown above the drivers of growth are many and varied. However because our understanding of technical change is incomplete, it is useful to incorporate as much of the observed empirical relationships between growth rates across countries as possible. One of these issues is the observation that various measures such as income per capita or technology in sectors across countries tend to "catch up" to the leading country. Thus although it is desirable to focus on the sources of growth within each country it is nonetheless important to take into account the issue of convergence across countries. This section examines the theoretical basis for assumptions of convergence in GDP per capita levels and provides a brief review of the empirical evidence on income convergence.

Studies of convergence often distinguish between conditional and unconditional convergence. Conditional convergence refers to convergence that exists as long as certain characteristics across the sample remain the same. Unconditional convergence does not require this restriction. The concept of convergence itself is often defined in different ways. Defining convergence and using the appropriate concept is an important consideration in convergence studies.

i. Neoclassical Growth Theory and Convergence

The neoclassical growth models of Ramsey (1928) and Solow (1956) suggest that there is an inverse relationship between the growth rate of income or output per capita and the initial starting level (Sala-i-Martin, 1996a). Sala-i-Martin and Barro (1992) argue that if countries are similar with respect to preferences and technology then poor countries tend to grow faster than rich countries and "there is a force that promotes convergence in levels of per capita product and income" (p224).

Sala-i-Martin (1996a) uses a simple neoclassical growth model to show that the speed of adjustment parameter, β, is positive. The higher β the greater the response of the average growth rate to the difference between the initial level of output per effective labour unit and the steady state value. The model implies *conditional* convergence in that *for a given steady state*, the growth rate is higher the lower the initial level of output per effective labour unit. This type of convergence is often referred to as conditional β convergence.

The neoclassical growth model does not predict *unconditional* convergence. Poor countries are predicted to grow faster than rich countries only if they share the same steady state characteristics.

The production function in neoclassical growth models is usually specified using 'effective labour units'. In the application of neoclassical growth theory, however, differences between per capita and per effective labour unit specifications are usually ignored as are differences between output and income specifications.

ii. Empirical Evidence on Convergence

Empirical research on convergence has received considerable attention in the economic literature. Most of this research is concerned with the distribution of income per capita (living standards) and, to a smaller extent, the distribution of output per worker or per hour worked (productivity).

The literature is not uniform in its approach to convergence analysis and alternative measures of convergence have important implications for the definition of convergence and its existence. Four broad approaches to convergence analysis can be identified in the literature: beta convergence, sigma convergence, time series (co-integration) analysis, and distributional analysis. We provide a brief description of these alternative approaches below. Sala-i-Martin (2002) and Quah (1995a) also provide summaries of the alternative approaches to convergence analysis.

Beta convergence refers to the existence of a negative relationship between the growth rate of income per capita (or the variable of interest) and the initial level. That is, a situation where poor countries tend to grow faster than richer countries. The implication is that poor countries will eventually 'catch-up' to the income levels of richer countries. Papers by Sala-i-Martin (see, for example, 1996a, 1996b, 2002) and Sala-i-Martin and Barro (1991, 1992) have been particularly influential. In a series of papers they document a consistent and robust finding of conditional convergence across countries and unconditional convergence across regions within a country with a speed of convergence coefficient of 2 percent. Sala-i-Martin concludes that "the estimated speeds of convergence are so surprisingly similar across data sets that we can use a mnemonic rule: *economies converge at a speed of about two percent per year*" (1996b, p1326). As discussed above, the speed of adjustment coefficient, β, measures the speed at which countries converge to their steady state. Only if countries converge to the same steady state does convergence across countries in an absolute or unconditional sense exist. Whilst Sala-i-Martin and Barro find evidence of unconditional convergence across regions within a country, this type of analysis also imposes restrictions since it only examines regions within a country where steady states are likely to be similar.

Sigma convergence refers to a reduction in the spread or dispersion of a data set over time. Beta convergence is a necessary condition for sigma convergence, but it is not a sufficient one (Quah (1995a) and Sala-i-Martin (1996b) provide a formal algebraic derivation of this result). Some researchers have argued the relative merits of the beta and sigma approaches to convergence analysis (see, for example, Quah (1995a)). Sala-i-Martin, however, argues that "the two concepts examine interesting phenomena which are conceptually different … both concepts should be studied and applied empirically" (pp 1328-1329, 1996b).

The distributional approach to convergence analysis was developed in a series of papers by Quah (see 1995a, 1995b, 1996, 1997, 2000). Quah (1995a) argues that cross sectional regression approaches to convergence analyse "only average behaviour" (p 15) and are uninformative on a distribution's dynamics because they "only capture 'representative' economy dynamics" (p 16). Quah argues that "to address questions of catch-up and convergence, one needs to model explicitly the dynamics of the entire cross-country distribution" (1995b, p1). He proposes a dynamic distributional approach to convergence analysis and applies his techniques to a number of alternative theoretical specifications. Quah's approach has been influential because it has applications in a wide range of research areas (see Overman and Puga (2002) for an application to regional unemployment).

The times series approach to convergence analysis is based on the assumption that forecasts of income differences converge to zero in expected value as the forecast horizon becomes arbitrarily long. If the differences between countries' income per capita levels contains either a non zero mean or a unit root then the convergence condition is violated (Bernard and Durlauf, 1995, 1996).

In general, there is little evidence for unconditional convergence of income per capita or productivity levels when a large cross section of countries is considered (see Sala-i-Martin (1996b) for β and σ convergence analyses, Quah (1995b) for a distributional analysis, and Bernard and Durlauf (1995) for a time series analysis).

The evidence for alternative forms of conditional convergence is stronger (see Quah (1995b, 1997) and Sala-i-Martin (1995)), although there is considerable debate about the appropriate interpretation of these results.

The neoclassical growth model predicts *conditional* (beta) convergence: initially poor countries will grow faster than initially rich ones assuming they are converging to the same steady state. In practice, countries differ in many respects including their levels of technology, propensities to save, and population growth rates (Sala-i-Martin, 1996a). Whilst analyses of conditional β convergence may be useful in examining the *speed* at which countries converge to their steady states, they do not provide empirical support for a closure of the income gap:

"only if all countries converge to the *same steady state* does the prediction that poor economies should grow faster than rich ones holds true" (Sala-i-Martin, 1996a, p1027). Likewise, conditioning in distributional analyses of convergence (as undertaken by Quah (1997)) may be useful in understanding the distribution of income across countries but the sense in which convergence exists in these studies is restrictive.

Although the evidence in favor of *unconditional* income convergence across countries is weak, the analyses provide useful information that can be used in economic projections. Empirical analyses of productivity convergence at the sectoral level are limited (see Barro and Sala-i-Martin (1991) and Bernard and Jones (1996a, 1996b)) and the growth convergence literature gives some useful guidance for formulating projections of sectoral productivity growth. However it is critical to measure the initial gaps correctly. The rate of growth of either sectoral productivity or income per capita or whatever is assumed to converge across countries depends critically on this initial gap. This is because with a constant rate of closing of the gap, the larger the initial gap, the higher the rate of growth required to close to gap by the constant factor each year. Thus the way the initial gap is measured is fundamental. This is why there is a debate on the difference between PPP and MER measures of economic variables across countries.

d. PPP versus Market Exchange Rates

International comparisons of national income (and other aggregates) require that income levels across countries are expressed in a common unit. The simplest way to convert income levels expressed in different currencies is to use exchange rates. Exchange rate based conversions of international Gross Domestic Product (GDP) are easy to calculate and available from the OECD's National Accounts (http://www.oecd.org) database and the World

Bank's World Development Indicators (http://www.worldbank.org). There are, however, a number of problems that arise with the use of exchange rates as conversion factors. Exchange rates reflect the relative purchasing powers over *traded* goods and services. They may be useful for the comparison of domestically produced traded goods and services. They are not appropriate for the international comparison of volume measures that include production for domestic consumption, such as output and productivity. The use of exchange rates in such situations leads to a traded sector bias. Exchange rate conversions tend to understate the real incomes of poorer countries and overstate the degree of inequality between countries because they ignore the lower cost of living that is typically observed in poorer economies (Dowrick, 2001). Furthermore, exchange rates are not solely determined by relative prices. They are increasingly influenced by speculative capital movements and therefore expectations and, as a result, may be too volatile to be used reliably as conversion factors.

Castles and Henderson (2003b) have strongly argued the case against the use of market exchange rates as conversion factors:

"[Market exchange rate] valuations across countries, since they do not measure quantity differences, have no place in international comparisons of output or real expenditure, nor in constructing measures of the growth of output or real expenditure that extend across national boundaries" (p420)

There is therefore a need for appropriate conversion factors that eliminate differences in price levels and allow reliable international volume comparisons of output. The most widely used conversions factors that attempt to account for price level differences are purchasing power parities (PPPs). PPPs are designed to only reflect differences in the volume of goods and services between countries. The simplest and most well-known example of a PPP is the *Economist's* Big Mac Index. The Big Mac Index compares the price of a similar, if not identical, good (a Big Mac hamburger) between countries. Consider the information published in April 2003 (http://www.economist.com). At this time, a Big Mac in the United States cost, on average, US$ 2.71. In Australia, the price was A$3.00. The PPP for Big Macs between the United States and Australia was therefore 3.00/2.71 = 1.11. Exchange rates at the time suggest a conversion factor of 1.61. Exchange rates do not provide an indication of the relative purchasing power over a wide range of goods and services.

The main source for PPPs over a wide range of goods and services is the United Nations International Comparison Program (ICP) database. The ICP was established in 1968 as a joint venture of the UN and the International Comparisons Unit of the University of Pennsylvania, with financial contributions from the Ford Foundation and the World Bank. In 1970 the comparison included just 10 countries, by 1993 country coverage had increased to 118. The OECD, in collaboration with the Statistical Office of the European Union (Eurostat) has continued to collect price data to estimate PPPs in its member states and currently operates on a three-year cycle. Since 1993, the World Bank has assumed the role of global coordinator for the ICP in non-OECD countries. Through its Development Data Group the Bank coordinates ICP surveys and publishes global PPP data sets.

The ICP 2003-2005 Round is currently being undertaken (see http://www.worldbank.com/data/icp/ for updates).

The resources necessary to construct the ICP database are considerable and there have been significant funding and data collection problems. The ICP recently argued that "data quality has been severely damaged by a lack of timeliness, continuity, consistency and reliability. Without a substantial increase in funding to tackle these problems the ICP will fail, undermining the accurate monitoring of progress towards development goals." (http://www.worldbank.com/data/icp/pdf/ICPbrochure.pdf)

Despite these issues, most researchers agree that the ICP estimates remain the best statistics available for volume comparisons at the disaggregated level (Dowrick, 2001). There remains considerable debate, however, over the appropriateness of alternative *aggregate* PPPs. Aggregate PPPs refer to PPPs that have been aggregated to correspond to broad consumption headings and total GDP. The debate concerns the method by which these aggregate PPPs are calculated. We consider the two most popular aggregation methods, the Geary-Khamis (GK) method and the Elteto, Koves and Szulc (EKS) method, and briefly discuss some of the issues involved in constructing time series from PPP adjusted data.

The Geary-Khamis (GK) method is used to calculate the aggregate volumes (real GDP and its expenditure categories) at constant international prices in the Penn World Tables (PWT) and is advocated by Maddison (1995, 2001).

The GK method involves comparing each country to the characteristics of the overall group of countries. International prices are constructed by taking a weighted average over all countries in the group, where the weights correspond to output shares. The GK international price reference vectors for N goods, p_{wi}, and the corresponding Paasche PPPs for K countries, P_k, are calculated by solving the following system of $N + K$ simultaneous equations:

$$p_{wi} = \sum\nolimits_{j=1}^{K} \left(\frac{p_{ji}}{P_j} \frac{q_{ji}}{\sum\nolimits_{r=1}^{K} q_{ri}} \right) \quad \forall\ i = 1, \ldots, N$$

$$P_k = \frac{\sum\nolimits_{i=1}^{N} p_{ki} q_{ki}}{\sum\nolimits_{i=1}^{N} p_{wi} q_{ki}} \quad \forall\ k = 1, \ldots, K$$

The advantage of using the GK aggregation method is that it is additive. Because the GK method compares all countries using a single price vector, the quantity indices for GDP expenditure components will add to the quantity index for total GDP. This property is extremely useful for comparisons at various levels of aggregation. However, fixed or constant price indices, as constructed by the GK method, suffer from substitution bias:

"As relative prices change, utility maximizing agents substitute expenditure away from relatively more expensive goods towards relatively cheaper goods. Comparisons based on a single price vector ignore this fact." (Hill, 2000, p151).

Hill recognises that there is also a 'producer' substitution effect that works to offset this 'consumer' substitution effect but argues that "in practice, at least at the level of GDP, the consumer substitution effect always dominates the producer substitution effect … [which] is the reason why Laspeyres price and quantity indexes almost always exceed their Paasche counterparts." (p 152)

The tendency for substitution bias is often referred to as the Gerschenkron effect (see Gerschenkron (1951), Hill (2000)). It implies that the GK method, and additive PPP methods in general, have a systematic tendency to overestimate the quantity index for countries whose relative prices differ substantially from the reference price vector.

The GK method gives greater weight to the price vectors of larger countries when constructing the international reference price vector. As a result, international prices largely reflect the prices in relatively rich countries (Nuxoll (1994) argues that the ICP international prices most closely resemble the prices of Hungary), the relative per capita income of poorer countries is overstated, and the degree of inequality tends to be understated.

Hill (2000) examines the extent of substitution bias in the GK method by undertaking a comparison of bilateral GK indexes with corresponding Fisher indexes[7]. Hill finds "clear evidence of substitution bias in the results of Geary-Khamis PPP based international comparisons. In some cases, the Geary-Khamis results underestimate per capita income differentials across countries by as much as a factor of two." (p160)

---

7 The Fisher index is a superlative index that closely approximates the underlying price and quantity index (Hill, 2000).The Fisher Index is not transitive, however, and is therefore not appropriate for multilateral comparisons.

Dowrick and Quiggin (1997) argue that GK measures (and constant price measures in general) are not only subject to substitution bias, but that they "do not allow a utility interpretation inasmuch as they can contradict the rankings given by the application of revealed preference tests" (p42).

Dowrick (2001) argues that, although the GK method is successful in reducing the traded sector bias that results from exchange rate comparisons, the GK method imparts "a substantial degree of substitution bias. … [The] typical level of substitution bias in the GK measure … is around ten percentage points; in some cases the magnitude of the bilateral bias approaches fifty percentage points." (p15)

Furthermore, because the degree of substitution bias may be changing over time, analyses of convergence are also affected. Dowrick and Quiggin (1997) examine the degree of substitution bias in quantity measures of GDP in 1980 and 1990. They find that measures of convergence over the period 1980 to 1990 are significantly affected by the choice of aggregation method. Additive measures (such as GK) are found to exhibit significant substitution bias, but the extent of bias decreased over the sample period, leading to the conclusion that "constant price measures systematically confuse the convergence of true GDP with the convergence of prices" (p 62). As a result, convergence analyses based on additive measures tend to understate the extent of true quantity convergence when the reference price vector reflects the prices of relatively rich countries.

The cross-country sample used in Dowrick and Quiggin is restricted to 17 OECD countries and, as such, the results on convergence need to be interpreted within the context of their sample selection. Nevertheless, the important finding that convergence results are affected by the choice of aggregation method has important implications for empirical convergence analyses based on broader samples.

The OECD provides PPP estimates for GDP and various final expenditure components calculated using the Elteto, Koves and Szulc (EKS) method (OECD, 1993). Following the procedure of the PWT, the OECD originally used the GK method of aggregation. In 1993, in recognition of the existence of Gerschenkron effects in GK PPP estimates, the OECD began using the EKS method to obtain PPPs for expenditure components and GDP and they continue to publish limited GK results.

The EKS method involves taking the geometric mean of bilateral Fisher price indexes and is free from the type of substitution bias suffered by the GK method (Hill, 2000). The EKS price index for country k is calculated as (Hill, 2000):

$$P_k = \left(\prod_{j=1}^{K} P_{jk}^F \right)^{\frac{1}{K}}$$

where

$P_{jk}^F = \sqrt{P_{jk}^P P_{jk}^L}$ is the Fisher price Index

$P_{jk}^P = \dfrac{\sum_{i=1}^N p_{ki} q_{ki}}{\sum_{i=1}^N p_{ji} q_{ki}}$ is the Paasche Price Index

$P_{jk}^L = \dfrac{\sum_{i=1}^N p_{ki} q_{ji}}{\sum_{i=1}^N p_{ji} q_{ji}}$ is the Laspeyres Price Index

The choice between alternative conversion approaches is far from clear. The literature survey presented above suggests that the GK method suffers extensively from substitution bias. Because of the existence of the Gerschenkron effect, the OECD considers EKS results appropriate "for comparisons across countries of the price and volume structures of individual aggregates such as … GDP" (OECD, 1993, p4). The EKS method is the "main method used by the OECD-Eurostat PPP Programme" (OECD, http://www.oecd.org/faq/0,2583,en_2649_34357_1799281_1_1_1_1,00.html#1799267)

EKS results, however, are not additive. The property of additivity is desirable when the analysis of various expenditure components is required and the OECD states that "GK results are considered to be better suited to the analysis of price and volume structures across countries" (OECD, 1993, p4).

Maddison (1995) prefers GK results for all comparisons including those involving aggregates such as GDP. As discussed above, the GK method weights countries according to their output shares, whereas the EKS method involves equal country weights. Maddison states: "I see no point in equi-country weighting systems which treat Luxemburg and the USA as equal partners in the world economy, so I have a strong preference for the Geary-Khamis approach" (Maddison, 1995).

Despite the debate over aggregation methods, PPPs are regarded as the preferred conversion factor for international comparisons of output and productivity. The United Nations System of Nations Accounts (1993) explicitly states that

"When the objective is to compare the volumes of goods or services produced or consumed per head, data in national currencies must be converted into a common currency by means of purchasing power parities and not exchange rates. It is well known that, in general, neither market nor fixed exchange rates reflect the relative internal purchasing powers of different currencies. When exchange rates are used to convert GDP, or other statistics, into a common currency the prices at which goods and services in high-income countries are valued tend to be higher than in low-income countries, thus exaggerating the differences in real incomes between them. Exchange rate converted data must not, therefore, be interpreted as measures of the relative volumes of goods and services concerned." (http://unstats.un.org/unsd/sna1993/toctop.asp)

The preference for PPPs over exchange rates applies to comparisons of output levels and to comparisons of growth rates where conversion factors are required. For economic growth comparisons between countries, domestic growth rates (based on real GDP in domestic currencies rather PPP adjusted GDP) are appropriate and recommended by the OECD (http://www.oecd.org/dataoecd/50/27/1961296.pdf). Growth comparisons between regions, however, require a weighting system and PPPs are the most appropriate conversion factor for the output weights: "measuring the growth of output in a number of countries grouped together, or across the world as a whole, the appropriate country weights – the measures of comparative real size of these different economies in some agreed base period – are PPP-based values" (Castles and Henderson, 2003b, p418).

Growth rate comparisons are an important concern when constructing time series based on PPP adjusted data. ICP data is only available for 'benchmark' years. GDP time series are usually created by using a combination of ICP data and national accounts growth rates (see Hill (2003) for a survey of alternative methods). An important property of the resulting time series is that the PPP GDP growth rates are consistent with country national accounts growth rates. The benchmark data used in the PWT is modified to ensure consistency but Hesten, Summers and Aten (2001) argue that the procedure is difficult to implement and suggest that the spanning tree approach proposed by Hill (2003) (which involves chaining bilateral comparisons) may provide a useful alternative. They describe how the spanning tree approach could be used in the PWT and promote this as "a priority area of research" (p100).

In Table 1 we highlight some of the issues discussed above with illustrative examples.

Table 1 illustrates the effects of using alternative aggregation methods. While the GK and EKS methods give different results, they are much closer to each other than they are to market exchange rate conversions. Thus despite the aggregation issue, the use of PPP however constructed gives a much better picture of the underlying income difference than the market exchange rate measure.

Table 1: Alternative Conversion Factors

		Conversion Factor				
		Ratio to United States			Ratio to EKS	
		Exchange Rate	EKS	GK	Exchange Rate	GK
GDP Per Capita ($US)	Belgium	0.86	0.80	0.82	0.96	1.00
	Denmark	1.07	0.79	0.84	1.20	1.03
	France	0.90	0.77	0.81	1.03	1.01
	Germany	0.97	0.76	0.78	1.13	0.99
	Greece	0.36	0.44	0.49	0.71	1.08
	Ireland	0.55	0.57	0.59	0.85	1.01
	Italy	0.70	0.72	0.74	0.86	0.99
	Luxembourg	1.29	1.13	1.15	1.02	0.99
	Netherlands	0.83	0.72	0.76	1.02	1.03
	Portugal	0.35	0.49	0.55	0.64	1.10
	Spain	0.50	0.55	0.57	0.81	1.01
	United Kingdom	0.67	0.70	0.70	0.85	0.98
	Austria	0.94	0.79	0.79	1.06	0.98
	Finland	0.68	0.64	0.67	0.94	1.02
	Sweden	0.87	0.69	0.71	1.12	0.99
	Switzerland	1.37	0.95	0.99	1.28	1.01
	Iceland	0.95	0.77	0.81	1.09	1.02
	Norway	0.99	0.78	0.86	1.11	1.06
	Turkey	0.12	0.22	0.26	0.48	1.13
	Australia	0.66	0.71	0.74	0.81	1.01
	New Zealand	0.52	0.64	0.65	0.72	0.99
	Japan	1.38	0.83	0.90	1.47	1.05
	Canada	0.78	0.80	0.82	0.87	1.00

Source: OECD (1993), Purchasing Power Parities and Real Expenditures, Volumes I and II

e. Conversion Factors and Income Convergence Assumptions

The choice between using market exchange rates or PPPs to convert GDP clearly has a significant impact on international income level and growth comparisons. How and why this might affect projections of future emission levels depends on the assumptions that underlie the projection model. If income convergence assumptions are an important determinant of economic growth rates, as they appear to be in the SRES scenario families A1 and B1 (summarized below), then accurately measuring the income gap becomes an important consideration.

The rate of growth in a convergence model will be determined by the size of the initial gap, the rate of change of the frontier, and the assumed degree of convergence.

In looking at arguments for and against the use of PPP exchange rates when making inter-country comparisons, this is a tendency to confuse PPP the hypothesis (that price bundles across countries will tend to equalise) with PPP the empirical technique (in which the value of an equivalent bundle of goods is compared across countries) such as in Manne and Richels (2003). These are very different concepts and it is unfortunate that they have the same name. If the hypothesis of PPP held, then there would be no issue in the use of either PPP or MER exchange rates in developing some form of convergence model, because there would be a unique relationship between relative prices and the exchange rate between countries.

As we have illustrated, empirical comparisons of prices show convincingly that the hypothesis of one price does not hold over the history of the last 50 years or so. That is, PPP exchange rates and market exchange rates are not the same. Further there is no observed tendency for these to move in any systematic way relative to each other and more particularly there is no evidence that they tend to converge over time. Sure it is possible to construct a model where there is a relationship between PPP and MER holds and assume that one can always be converted easily into the other so that it can be seen purely as a “numeraire choice”. But that doesn’t mean it is a useful assumption to base real world analysis on.

Because the hypothesis of PPP does not hold in any current data set, there can be no empirical basis for using it as an assumption in constructing a model of the evolution of prices and quantities. In particular, the fact that PPP and MER estimates can be significantly different for some countries over time means that the choice of the appropriate exchange rate (PPP or MER) at the starting point matters. It also matters over time because if there is no systematic relationship between MER and PPP exchange rates then they can’t lead you to the same point at some arbitrary point in the future. For example, the appreciation of the US dollar between 1982 and 1985 by 50% in real and nominal terms shows that neither the real or nominal exchange rates during this period were useful in comparing the relative size of the US and European economies. A convergence model starting in 1982 would clearly lead to a very different world in 2050 than a model starting in 1985.

Now consider the argument that it is perfectly reasonable to specify a scenario defined as some relationship in MER terms between the incomes of industrialized economies and developing countries at some point in the future. If there is an underlying convergence of income measured in PPP terms but there is no relationship between PPP and MER then there can be an infinite number of growth paths in MER terms between now and 2100 including perhaps one in which there is no convergence because of a trend in the MER. You can of course assume that there is a relationship between PPP and MER and make the problem disappear but without anything but wishful thinking as a basis.

3. The G-Cubed Approach to Long Run Projections

a. The G-Cubed Model

The G-Cubed model outlined in McKibbin and Wilcoxen (1999), is ideal for undertaking global projections having detailed country coverage, sectoral disaggregation and rich links between countries through goods and asset markets. A number of studies—summarized in McKibbin and Vines (2000)—show that the G-cubed model has been useful in assessing a range of issues across a number of countries since the mid-1980s.[8] A summary of the model coverage is presented in Table 2. Some of the principal features of the model are as follows:

- The model is based on explicit *intertemporal* optimization by the agents (consumers and firms) in each economy[9]. In contrast to static CGE models, time and dynamics are of fundamental importance in the G-Cubed model.

- In order to track the macro time series, however, the behavior of agents is modified to allow for short run deviations from optimal behavior either due to myopia or to restrictions on the ability of households and firms to borrow at the risk free bond rate on government debt. For both households and firms, deviations from intertemporal optimizing behavior take the form of rules of thumb, which are consistent with an optimizing agent that does not update predictions based on new information about future events. These rules of thumb are chosen to generate the same steady state behavior as optimizing agents so that in the long run there is only a single intertemporal optimizing equilibrium of the model. In the short run, actual behavior is assumed to be a weighted average of the optimizing and the rule

---

[8] These issues include: Reaganomics in the 1980s; German Unification in the early 1990s; fiscal consolidation in Europe in the mid-1990s; the formation of NAFTA; the Asian crisis; and the productivity boom in the US.

9 See Blanchard and Fischer (1989) and Obstfeld and Rogoff (1996).

Table 2: Overview of the G-Cubed Model

Regions
United States
Japan
Australia
Canada
New Zealand
Europe
Rest of the OECD
China
Brazil
Mexico
Rest of Latin America
Oil Exporting Developing Countries
Eastern Europe and the former Soviet Union
Other Developing Countries
Sectors
Energy:
(1) Electric Utilities
(2) Gas Utilities
(3) Petroleum Refining
(4) Coal Mining
(5) Crude Oil and Gas Extraction
Non-Energy:
(6) Mining
(7) Agriculture, Fishing and Hunting
(8) Forestry/ Wood Products
(9) Durable Manufacturing
(10) Non-Durable Manufacturing
(11) Transportation
(12) Services
(Y) Capital Good Producing Sector

of thumb assumptions. Thus aggregate consumption is a weighted average of consumption based on wealth (current asset valuation and expected future after tax labor income) and consumption based on current disposable income. Similarly, aggregate investment is a weighted average of investment based on Tobin's q (a market valuation of the expected future change in the marginal product of capital relative to the cost) and investment based on a backward looking version of Q.

- There is an explicit treatment of the holding of financial assets, including money. Money is introduced into the model through a restriction that households require money to purchase goods.

- The model also allows for short run nominal wage rigidity (by different degrees in different countries) and therefore allows for significant periods of unemployment depending on the labor market institutions in each country. This assumption, when taken together with the explicit role for money, is what gives the model its "macroeconomic" characteristics. (Here again the model's assumptions differ from the standard market clearing assumption in most CGE models.)

- The model distinguishes between the stickiness of physical capital within sectors and within countries and the flexibility of financial capital, which immediately flows to where expected returns are highest. This important distinction leads to a critical difference between the *quantity of physical capital* that is available at any time to produce goods and services, and the *valuation of that capital* as a result of decisions about the allocation of financial capital.

As a result of this structure, the G-Cubed model contains rich dynamic behavior, driven on the one hand by asset accumulation and, on the other by wage adjustment to a neoclassical steady state. It embodies a wide range of assumptions about individual behavior and empirical regularities in a general equilibrium framework. The interdependencies are solved out using a computer algorithm that solves for the rational expectations equilibrium of the global economy. It is important to stress that the term 'general equilibrium' is used to signify that as many interactions as possible are captured, not that all economies are in a full market clearing equilibrium at each point in time. Although it is assumed that market forces eventually drive the world economy to a neoclassical steady state growth equilibrium, unemployment does emerge for long periods due to wage stickiness, to an extent that differs between countries due to differences in labor market institutions.

b. The G-Cubed Projection Approach

As with the growth accounting framework outlined in section 2, the assumptions about the inputs into growth projections are from the fundamental sources of growth in the G-Cubed approach. There are two key inputs into the growth rate of each sector. The first is the economy wide population projection. The second is the sectoral productivity growth rate. In Bagnoli et al (1996) we modeled economy wide productivity and then used the historical experience of differential growth across sectors to apportion the aggregate productivity projections to each sector within an economy.

We now assume that each sector in the US will have a particular rate of productivity growth over the next century. We then assume that each equivalent sector in each other country will catch up to the US sector in terms of productivity, closing the gap by 2% per year. The initial gaps are therefore critical for the subsequent sectoral productivity growth rate. We follow a two step process in determining the initial size of the gap. The first step is to specify the gap between all sectors and the US sectors equal to the gap between aggregate PPP GDP per capita between each country and the US. We can't easily use sectoral PPP gap measures because these are difficult to get in a consistent manner and with a wide enough coverage for our purposes. Thus the initial benchmark is based on the same gap for each sector as the initial gap for the economy as a whole. If we then have evidence that a particular sector is likely to be closer to or further away from the US sectors than the aggregate numbers suggest, we adjust the initial sectoral gaps attempting to keep the aggregate gaps consistent with the GDP per capita gaps. We then assume that productivity growth in each sector closes the gap between that sector and the equivalent US sector by 2% per year. The productivity growth is calculated exogenously to the model. We then overlay this productivity growth model with exogenous assumptions about population growth for each country to generate two of the main sources of economic growth.

Given these exogenous inputs for sectoral productivity growth and population growth, we then solve the model with the other drivers of growth, capital accumulation, sectoral demand for other inputs of energy and materials all endogenously determined. Critical to the nature and scale of growth across countries are these assumption plus the underlying assumptions that financial capital flows to where the return is highest, physical capital is sector specific in the short run, labor can flow freely across sectors within a country but not between countries and that international trade in goods and financial capital is possible subject to existing tax structures and trade restrictions.

Thus the economic growth of any particular country is not completely determined by the exogenous inputs in that country since all countries are linked through goods and asset markets.

Carbon emissions are determined in the model by the amount of fossil fuels (coal, oil, natural gas) that are consumed within each country in each period. These primary factors are endowed within countries but can also be traded internationally subject to transportation costs (captured implicitly through the elasticities of substitution between each good in the model). Thus economic growth can occur within a country, without any particular pattern implied for energy use. The pattern on energy use will be dependent on the underlying inputs into the growth process. The illustration in figure 1 of the change in energy use relative to GDP after the oil price shocks of the early 1970's would be explained in this approach by a substitution away from energy into the other inputs of capital and labor. This could be achieved both within sectors as well as by changing the composition of sectors in aggregate GDP with services (less energy intensive) becoming a larger share of the economy than energy intensive manufacturing sectors. There can also be some technological change that is part of this story.

In order to illustrate the importance of sectoral productivity growth figures 2 through 5 show the patterns of GDP growth and emission of carbon when we change assumptions about productivity growth at the sectoral level. We change productivity growth in each sector, on a sector by sector basis, by 1% per year for 50 years. Each figure contains 13 groups of two bars. Each group along the horizontal access is the sector in which the increase in productivity growth occurs. Sector Y at the end of the chart is the sector that produces capital goods. In figure 2 we show the percentage deviation of both emissions and GDP as a result of the productivity growth in sector i. For example, if sector 9 (durable manufacturing) experiences more rapid productivity growth we see that by 2020, GDP will be approximately 1.1% higher than otherwise and emissions will be 1% higher. Yet in sector 10 (non-durable manufacturing) we see that real GDP will be 0.5% higher but emissions will be lower. This occurs because producers substitute away from energy use in sector 10 when productivity rises. We see that in the services sector (sector 12) there is almost double the GDP impact relative to the increase in emissions. In each of the energy sectors (1 to 5) higher productivity growth has almost no impact on GDP yet leads to significant increases in economy wide emissions. This is not because of emissions from those sectors, but because productivity growth reduces the relative price of these sectors output (i.e. various forms of energy) which causes other sectors and final demand to substitute into energy and thus raise emissions.

Figure 3 shows the results for the same sectors for the same shocks but with results in 2050 rather than 2020. It is interesting that the ratios of GDP to the change in emissions moves around between 2020 and 2050. This partly reflects the way in which higher wealth generated by productivity growth in some sectors leads to changes in spending patterns across the economy which changes overall emissions.

Figures 4 and 5 show the same style of results but this time for China as a result of changes in US productivity growth by sector. This demonstrates the spillovers from growth in the US to growth and emissions in a developing country. It is interesting that although the US experienced 4 % higher GDP by 2020 as a results of productivity growth in sector 12 (services), this spills over to China as a rise in GDP of 0.6% by 2020. This illustrates the importance of international linkages in the G-Cubed model. Secondly notice that the increase in emissions is much larger (1%) in China relative to the GDP increase. This partly reflects the higher emission coefficients in China as well as the higher growth from the US being into higher expenditure on higher energy intensive products in China (less on services and more on energy and energy intensive manufacturing). Note that the spillover of growth in the US in the capital producing good (sector Y) to China is negative. This is because capital flows into the US away from China as the cost of capital goods fall in the US. Therefore both GDP and emissions falls in China for this particular type of productivity growth.

Figure 2: Percentage Change in US Emissions and Real GDP by 2020
For a 1 percent rise in US sector i productivity growth

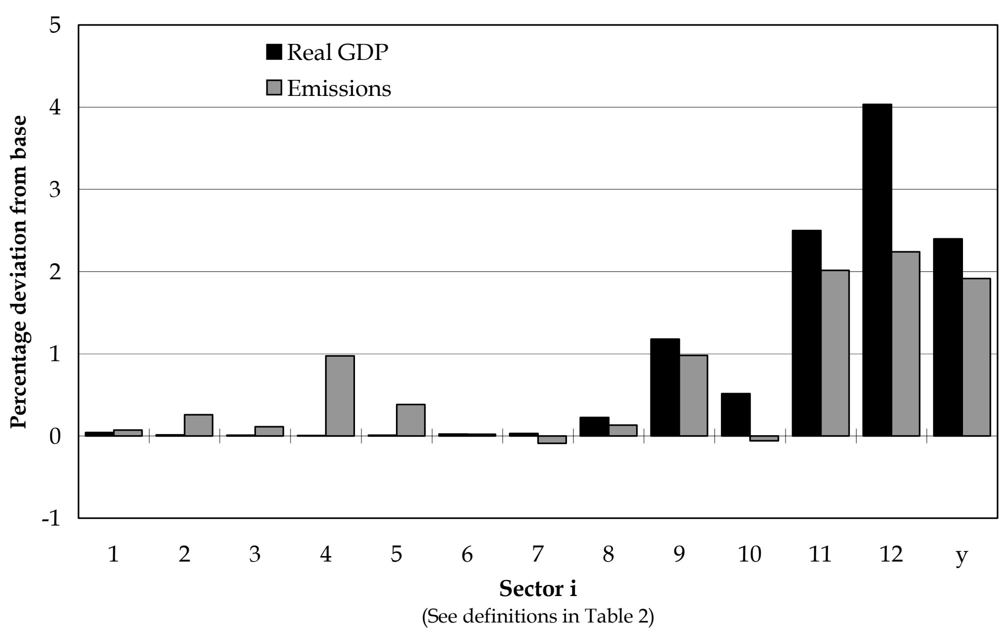
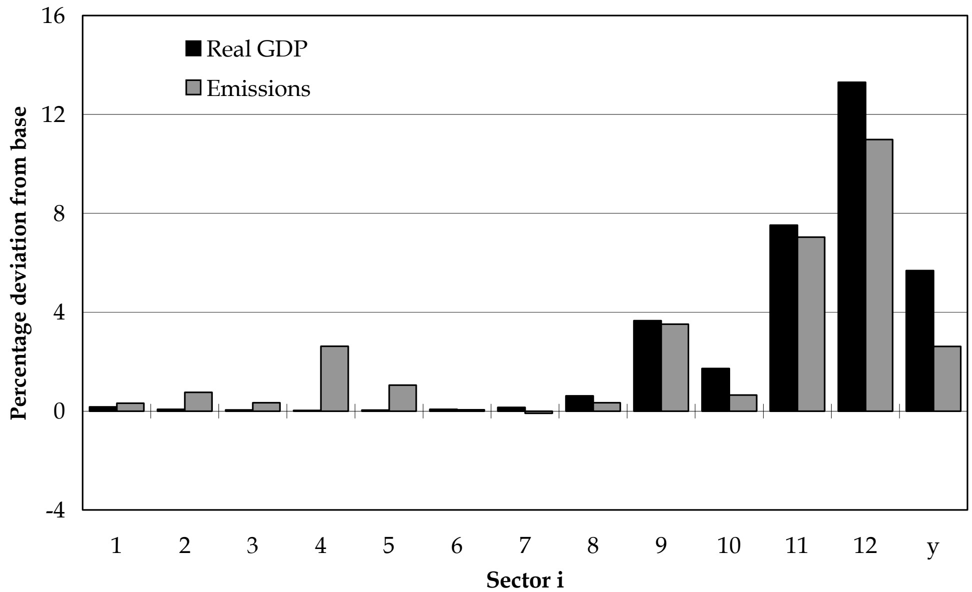


Figure 3: Percentage Change in US Emissions and Real GDP by 2050

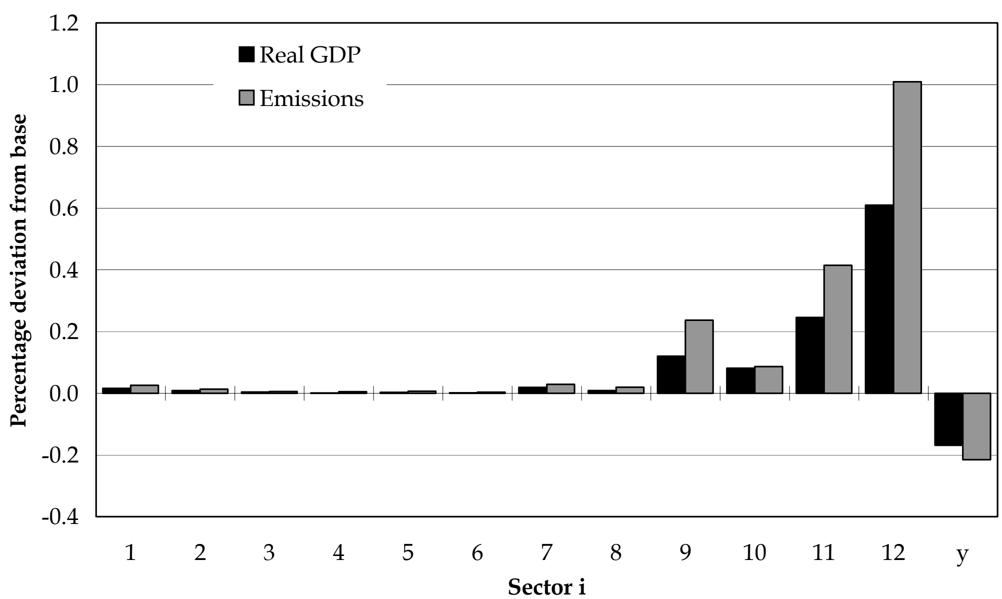
For a 1 percent rise in US sector i productivity growth



(See definitions in Table 2)

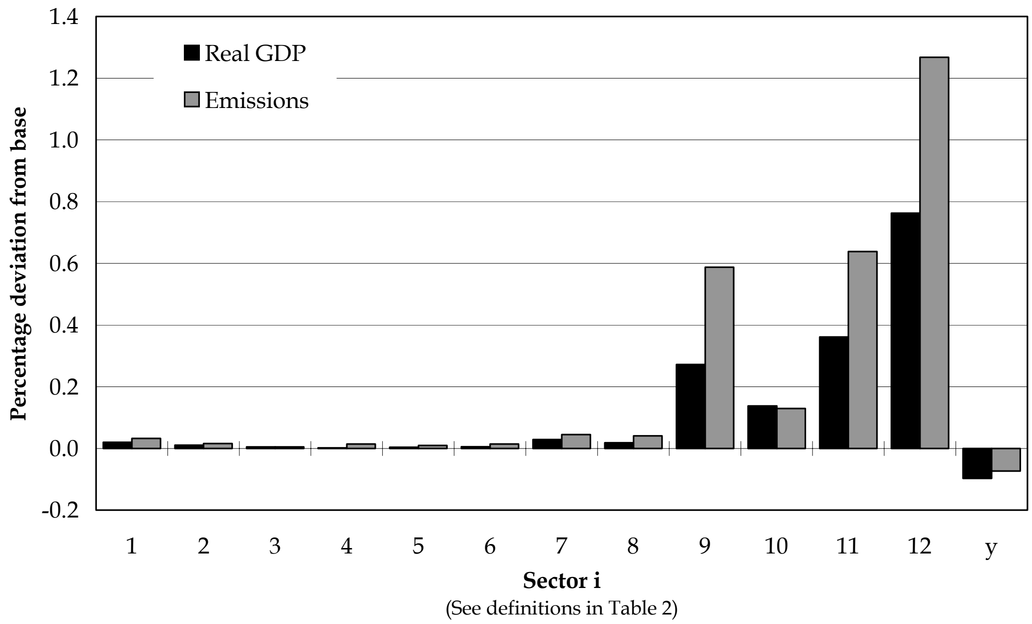
Figure 4: Percentage Change in China Emissions and Real GDP by 2020

For a 1 percent rise in US sector i productivity growth



(See definitions in Table 2)

Figure 5: Percentage Change in China Emissions and Real GDP by 2050
For a 1 percent rise in US sector i productivity growth



These various results clearly show that there is no simple relationship between GDP and emissions when the fundamental drivers of growth are taken into account, and when the full range of economic interactions between regions is allowed (both trade and capital flows). This shows the importance of getting at the fundamental drivers of economic growth (productivity or technical change, along with population) rather than using an aggregate proxy, such as GDP.

It is important to note that in the default approach used in the G-Cubed model, the initial gaps between countries are calibrated using initial real income comparisons between the US and other regions. These real income comparisons need to reflect the quantity of production and so to make the comparison we use PPP and not market exchange rates for the reasons outlined above. This is clearly the theoretically correct approach when using G-Cubed. This form of calibration, however, is not fundamental to our approach but is the result of data availability and convenience.

It is interesting to note that the G-Cubed model has a ‘PPP issue’ because of the particular default approach we take to our convergence model. This is not, however, a fundamental feature of G-Cubed itself. Indeed, PPP issues do not arise elsewhere in the model, because as a well specified economic model G-Cubed tracks relative prices and quantities and tells a detailed story about nominal and real exchange rates.

Another challenge in the G-Cubed approach is defining which country is on the frontier. We use the US in our default approach, but we could easily adjust this assumption for particular sectors as empirical evidence became available.

4. The IPCC SRES Projection Approach

This section provides a brief overview of the emission projections documented in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) (2002). The IPCC was established by the World Meteorological Organization (WMO) and the United Nation’s Environmental Program (UNEP) to “assess the scientific, technical and socio-economic information relevant for the understanding of human-induced climate change” (IPCC, 2000). The SRES developed a range of emission scenarios that were designed to provide “input for evaluating climatic and environmental consequences of future greenhouse gas emissions and for assessing alternative mitigation adaptation strategies” (IPCC, 2000).

The report covers four regions: OECD90 (all countries that belonged to the Organization of Economic Development (OECD) as of 1990), REF (countries undergoing economic reform - East European countries and the Newly Independent States of the former Soviet Union), ASIA (all developing countries in Asia) and ALM (developing countries in Africa, Latin America and the Middle East). OECD90 corresponds to UNFCC (1992) Annex II countries. REF includes non Annex II, Annex I countries. OECD90 and REF are categorised as industrialised regions (IND) and ASIA and ALM are categorised as developing (DEV).

The SRES highlights the interdependency between what they regard as the major driving forces of future emissions. According to the SRES, the main driving forces of future greenhouse gas trajectories are “demographic change, social and economic development, and the rate and direction of technological change” (2000, p5).

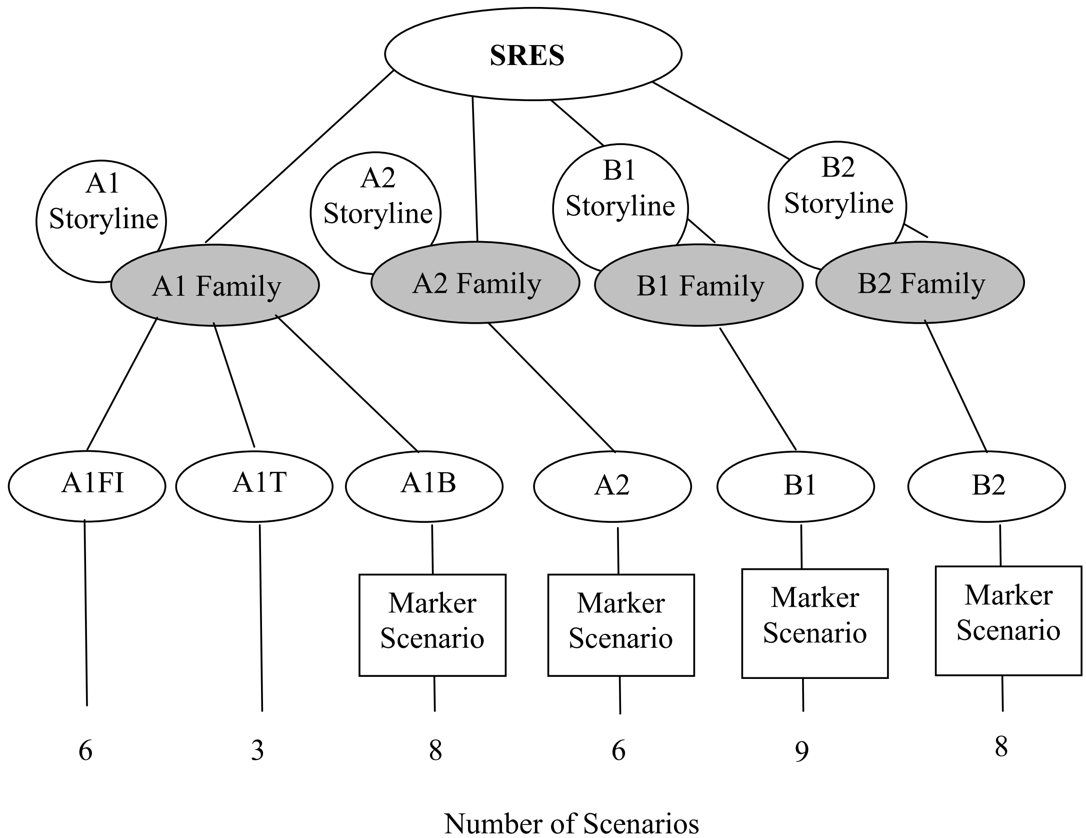
To represent a range of driving forces and resultant emissions the SRES considers four “qualitative storylines” called “families”: A1, A2, B1, and B2. From these four families, 40 alternative scenarios are developed in 6 scenario groups. Each scenario group has an illustrative scenario (6) and each family has a marker scenario (4). This structure is illustrated in Figure 6.

The SRES scenarios were designed to “cover a wide spectrum of alterative futures to reflect relevant uncertainties and knowledge gaps” (2000, p24) and to “cover as much as possible of the range of major underlying ‘driving forces’ of emissions scenarios” (2000, p24).

The **A1 storyline** includes “very rapid economic growth, global population that peaks in the mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies” (SRES, 2000, p4). Economic convergence among regions is a major underlying theme of the scenario family. The three scenario groups in the A1 family are differentiated by their technological emphasis: fossil fuel intensive (A1F1), non-fossil energy sources (A1T), or a balance across sources (A1B).

The **A2 storyline** describes “regionally orientated” economic development and relatively slow economic growth per capita and technological change (compared with the other storylines). “The underlying theme is self-reliance and preservation of local identities” (SRES, 2000, p5).

Figure 6: SRES Scenario Structure

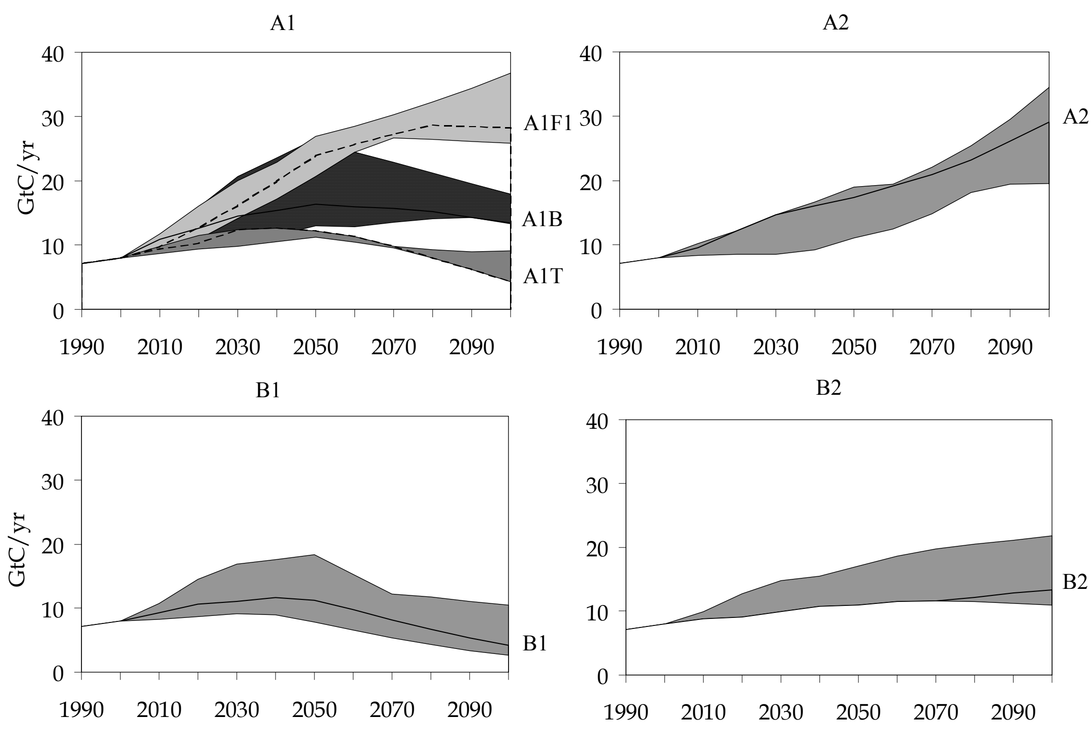


The **B1 storyline** describes "a convergent world" ("efforts to achieve equitable income distribution are effective" (SRES, 2000, p182)) with a population structure as in the A1 storyline, "but with rapid changes in economic structures towards a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies" (SRES, 2000, p5). There is an emphasis on "global solutions" and "improved equity".

The **B2 storyline** emphases "local solutions", continuously increasing population (at a rate lower than in the A2 storyline), "intermediate" levels of economic growth and "less rapid and more diverse technological change than in the B1 and A1 storylines" (SRES, 2000, p5).

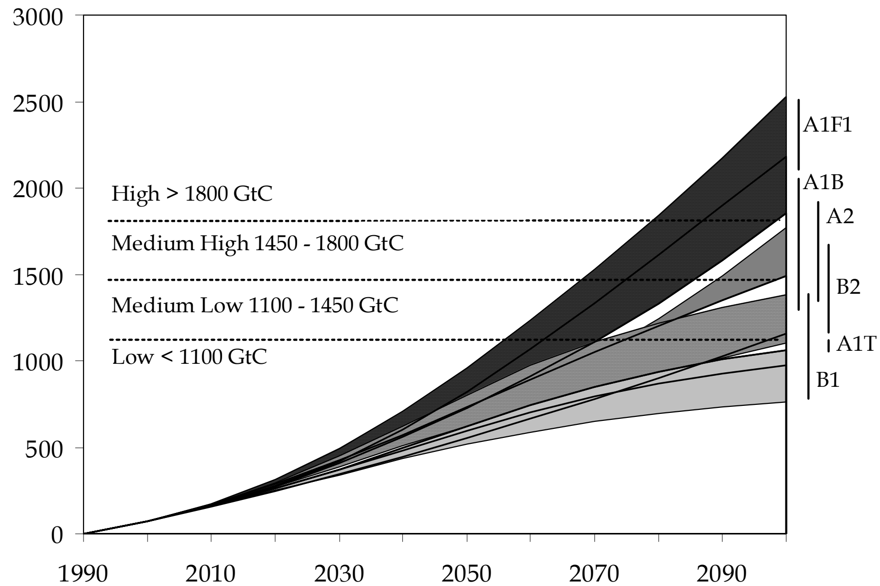
Figures 7 and 8 demonstrate the range of global annual CO_2 emissions and cumulative CO_2 emissions for each of the SRES storylines. It is important to recognise that although the emission projections documented in the SRES include environmental policies, they do not include "explicit policies to limit greenhouse gas emissions or to adapt to the expected global climate change" (2000 p172). They therefore represent outcomes in the absence of direct climate change policies.

Figure 7: Total Global Annual CO_2 Emissions



Source: IPCC (2000) Appendix VII. Marker Scenarios shown as solid lines

Figure 8: Total Global Cumulative CO_2 Emissions



Source: IPCC (2000) Appendix VII. Marker Scenarios shown as solid lines

Cumulative SRES carbon emissions range from 800 GtC (gigatonnes of carbon) to over 2500 GtC with a median of about 1500 GtC.

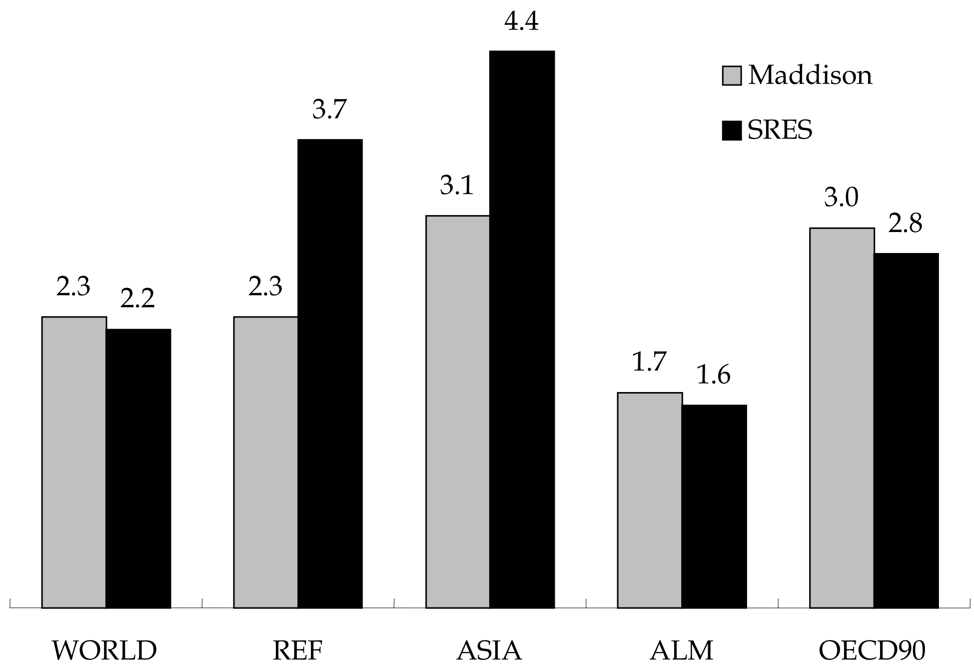
The SRES highlights the finding that scenarios with different driving forces can exhibit similar emissions and scenarios with similar driving forces can exhibit different emissions. The SRES were designed to "be transparent" and "reproducible" (2000 p25). However, the relationship between alternative driving force assumptions and projected emissions is far from clear. The SRES recognises that there is a need for the "main driving forces, and underlying assumptions" to "be made widely available" (p47). Until this is completed it is difficult to critically assess the usefulness of the SRES emission projections. Many of the underlying assumptions and methods used in the SRES have been criticised (see, for example, Castles and Henderson (2003a, 2003b)). Some of these issues have been discussed in the preceding sections.

Figures 9 and 10 contain PPP adjusted data sourced from Maddison (2003) and exchange rate adjusted data from the SRES. Maddison's GDP PPPs are calculated using the GK method of aggregation. These estimates are used because Maddison's data are quoted within the SRES (and are therefore well-known to the SRES authors) and because they provide the comprehensive country coverage needed to undertake comparisons with the SRES regions.

Figure 9 compares the historic income per capita growth rates presented in the SRES with growth rates calculated on a PPP basis. The historical growth rates used in the SRES are considerably different to Maddison's estimates for the REF and ASIA regions.

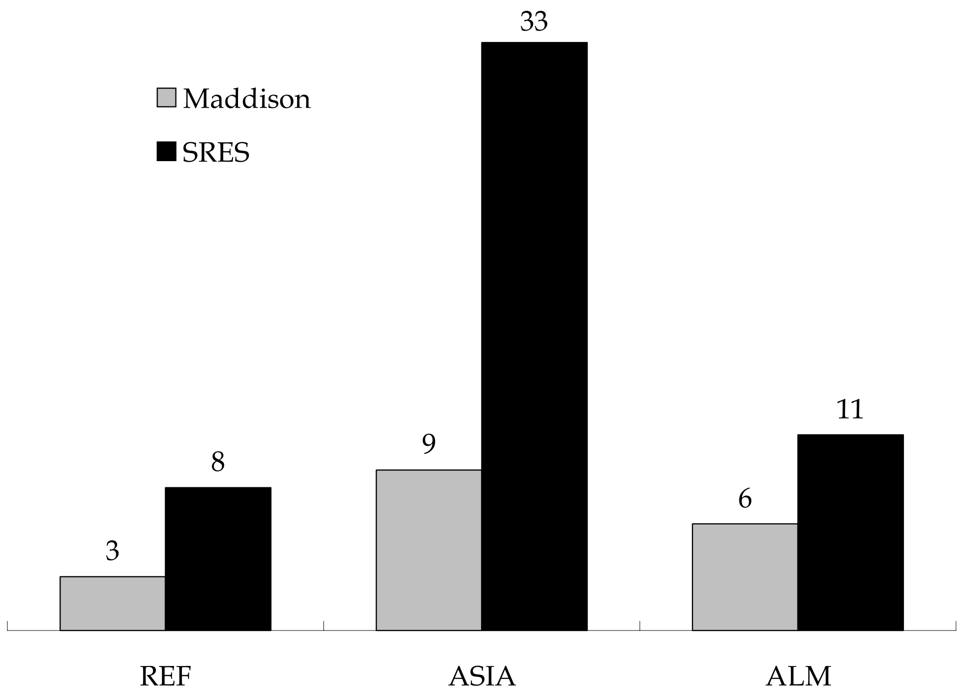
Figure 10 compares the regional income per capita ratios used in the SRES with estimates based on Maddison's data set. Income per capita in each of the three regions is compared to the income per capita level in the OECD90 region in 1990. The SRES data substantially overstates the level of inequality for all three regions.

Figure 9: Income Per Capita Growth Rates (% per year) 1950-1990



Source: SRES Table 4-7, Maddison (2003)

Figure 10: Income per Capita, Ratio of OECD90 to Other Countries 1990



Source: SRES Table 4-6 (the midpoint of the range is used), Maddison (2003)

These comparisons are important because they illustrate the magnitude of the difference between PPP based and MER based estimates of output and economic growth. As is set out in the UN's *System of National Accounts* (the professional standard for national accounting) when the objective is to compare the volume of goods and services produced between countries, PPP conversions and not market exchange rates should be used.

a. Convergence and Economic Growth in the SRES

The SRES represents, in part, the IPCC's response to the evaluation of its previous scenario exercise undertaken in 1992, the IPCC IS92 Emissions Scenarios. The evaluation recommended changes to a number of the key assumptions regarding the driving forces of future emissions. In particular, it was suggested that the impact of convergence in income levels between developed and developing countries be considered. As a consequence, convergence in income per capita levels represents one of the driving forces in the SRES and is a major theme of the SRES scenario analysis.

As outlined in the previous section explicit convergence assumptions characterise the SRES A1 and B1 scenario families. For this reason we focus on these scenarios and, in particular, the marker scenarios from these families.

Whilst convergence in income per capita is a central theme of the A1 and B1 scenario families, the convergence assumptions that characterise the SRES scenarios do not appear to be limited to income per capita. The SRES report uses the terms “economic convergence” and “convergent world” in describing the A1 and B1 storylines and the B1 family includes technology convergence, economic structure convergence, and education convergence assumptions. SRES assumes a negative relationship between income per capita and final energy intensities and, as with income per capita, energy intensities are assumed to converge in the A1 and B1 scenarios.

The SRES does not provide an explicit description of the convergence models used in the A1 and B1 scenarios. The only way to examine the convergence assumptions is to analyse the historical and projected growth rates that appear in the report. Table 3 summarises the historic economic and income per capita growth rates used in the SRES and the projected growth rates for the A1 and B1 marker scenarios. Table 4 contains historical and projected income per capita ratios across the SRES regions for the A1 and B1 market scenarios.

The information in Table 4 illustrates the convergence assumptions that characterise the A1 and B1 families. The ratio of the poorest region in 1990 (ASIA) to the richest region (OECD90) is projected to increase from 0.02-0.03 to 0.66 in the A1 marker scenario and to

0.45 in the B1 market scenario over the period 1990 to 2100. In the A1 marker scenario the catch-up is a byproduct of "rapid economic development and fast demographic transition" (2000, p197). In the B1 marker scenario, the reduction in income inequalities is due to "constant domestic and international efforts" (2000, p200).

Table 3: SRES Growth Rates

	1950-1990	1990-2050		1990-2100	
		A1	B1	A1	B1
Economic Growth Rates (% per year)					
OECD90	3.9	2.0	1.8	1.8	1.5
REF	4.8	4.1	3.1	3.1	2.7
IND	3.9	2.2	1.9	2.0	1.6
ASIA	6.4	6.2	5.5	4.5	3.9
ALM	4.0	5.5	5.0	4.1	3.7
DEV	4.8	5.9	5.2	4.3	3.8
WORLD	4.0	3.6	3.1	2.9	2.5
Income Per Capita Growth Rates (% per year)					
OECD90	2.8	1.6	1.5	1.6	1.2
REF	3.7	4.0	3.0	3.3	2.8
IND	2.9	2.0	1.7	1.9	1.5
ASIA	4.4	5.5	4.8	4.4	3.9
ALM	1.6	4.0	3.5	3.3	3.0
DEV	2.7	4.9	4.2	4.0	3.5
WORLD	2.2	2.8	2.3	2.7	2.2

Source: SRES Tables 4-5, 4-7.

Table 4: SRES Income Per Capita Ratios (Ratio to OECD90)

	1990	2050		2100	
		A1	B1	A1	B1
OECD90	1.00	1.00	1.00	1.00	1.00
REF	0.11-0.15	0.58	0.29	0.92	0.65
ASIA	0.02-0.03	0.30	0.18	0.66	0.45
ALM	0.06-0.12	0.35	0.27	0.56	0.56
DEV/IND	0.05-0.08	0.36	0.28	0.62	0.55

Source: SRES Table 4-6

The SRES appears to consider a situation in which steady states across countries are converging so that the distinction between conditional and unconditional convergence disappears. As argued above, whilst there is a large body of literature in support of the existence of various forms of conditional convergence there is little evidence of unconditional aggregate convergence. Even if steady state characteristics across countries were to converge, the empirical literature suggests that the rate of convergence in income per capita would be very slow. The SRES authors acknowledge that "it may well take a century (given all other factors set favourably) for a poor country to catch-up to levels that prevail in the industrial countries today, never mind the levels that might prevail in affluent countries 100 years in the future" (p 123).

5. Some Illustrative Implications of The Alternative Approaches

a. Effect of lower GDP growth in the SRES

Castles and Henderson (2003a, 2003b) suggest that if PPP adjusted data were used in the SRES, the projected economic growth rates would be lower and so would the projections of emission levels.

An examination of the effect on emission projections of changing the economic growth assumptions in the SRES requires knowledge of the assumed relationship between economic growth and emissions in the SRES scenarios. This information is not provided in the SRES. The authors of the SRES argue that the relationship between economic growth and emissions is complex and involves the (endogenous) interrelationships between economic growth, population changes, and changes in emissions intensity.

Consider the following equation know as the IPAT identity (Ehrlich and Holdren, 1972):

$$\text{Impact} = \text{Population} \times \text{Affluence} \times \text{Technology}$$

which can be expressed as

$$\text{Emissions} = \text{Population} \times \text{GDP per capita} \times \text{Emissions per GDP}$$

$$E \quad = \quad P \quad \times \quad GDPPC \quad \times \quad I \quad \text{(Emissions Intensity)}$$

If population growth (*p*), GDP per capita growth (*gdppc*) and growth in emissions intensity (*i*) are independent then the IPAT identity can be approximated by a linear expression in growth rates:

$$e = p + gdppc + i$$

and changes in income per capita growth would result in corresponding changes in emissions growth. While this relationship appears to indicate that GDP should move with emissions, it is, in fact, quite misleading. Emissions intensity and GDP are closely related, particulalrly because the drivers of GDP growth may themselves be the same factors that drive changes in emissions intensity.

With endogenous right hand side variables, the relationship between changes in income per capita growth and emissions growth becomes more complicated.

We can examine the factors determining emission intensity, and the relationship between emissions and GDP by considering a simple CES production model. Assume that aggregate output is a CES function of energy (*E*) and other factors (*O*, which would include labour and capital). Let P_E be the price of energy and let P_O be the price of other inputs. Further, assume that energy is itself a CES composite of an emitting technology (*EM*) and a non emitting technology (*NE*). Let P_{EM} be the price of the emitting energy source and P_{NE} be the price of the non emitting source. With appropriate choice of parameters, this simple setup could represent a variety of styles of models.

Expressing variables in percentage changes (and ignoring any changes in population), we can write:

$$\begin{aligned} emis = gdp \ &+ \ p_{EM}\,(\sigma_1 S_{EM}(S_E - 1) - \sigma_2\,(1 - S_{EM}\,)) \\ &+ \ p_{NE}\,(\sigma_1 S_{NE}(S_E - 1) - \sigma_2\,(S_{NE}\,)) \\ &+ \ \sigma_1 S_O p_O \end{aligned} \qquad (5.1)$$

where σ_1 is the elasticity of substitution between the energy bundle and other inputs; σ_2 is the elasticity of substitution between energy types; S_E is the share of energy in total output; S_O is the share of other inputs in total output; S_{EM} is the share of emitting energy in total energy and S_{NE} is the share of non emitting energy in total energy.

Equation (5.1) shows that the change in emissions depends on the change in GDP plus three other terms which together define emissions intensity. Emissions intensity depends on the changes in the relative prices of energy and non-energy inputs, and emitting and non-emitting energy sources as well as on the ability to substitute between these inputs (and their relative shares in production). Emissions intensity could increase or decline depending on these factors.

Relative input and energy prices will change as a result of the changes in the drivers of growth. For example, productivity improvements in non emitting energy will lead to a decline in its relative price, affecting its use and subsequently emissions intensity.

It is possible for emissions and GDP to move in opposite directions, that is for GDP to increase and for emissions to decline (or vice versa). Put another way, is it possible for changes in emissions intensity to offset changes in GDP in determining emissions?

To address this question, we need to close equation (5.1) so as to relate changes in GDP to changes in price of inputs (or equivalently, to changes in the productivity of inputs). We can close it by assuming a crude reduced form GDP response where GDP is a function of the price of all inputs. This response represents the net effect of changes in labour and capital inputs that result from changes in the productivity of the underlying factors of production. With this assumption (5.1) becomes:

$$\begin{aligned} emis = \; & \gamma(S_O p_O + S_E S_{EM} p_{EM} + S_E S_{NE} p_{NE}) \\ & + p_{EM}\,(\sigma_1 S_{EM}(S_E - 1) - \sigma_2\,(1 - S_{EM})) \\ & + p_{NE}\,(\sigma_1 S_{NE}(S_E - 1) - \sigma_2\,(S_{NE})) \\ & + \sigma_1 S_O p_O \qquad (5.2) \end{aligned}$$

where γ (<0) is a parameter capturing the response of GDP to changes in productivity (represented as prices here).

Equation (5.2) shows that the change in emissions depends on the relationship between the drivers of growth (here represented as the prices of different inputs), the substitution relationships and the overall expansions parameter. With appropriate parameters settings, and exogenous changes in prices, it is possible for emissions and GDP to move in opposite directions. How likely is this, or put another way, for randomly chosen parameter sets, how many of them result in GDP and emissions moving in opposite directions?

In order to check the likelihood of GDP and emissions moving in different directions, we calibrate the simple model above using data from G-Cubed simulate it for a variety of parameter settings. One set of results are set out in figure 11 which plots the likelihood of emissions and GDP moving in opposite directions against the relative importance of non emitting energy productivity changes as a source of growth.

Figure 11: Growth, GDP and emissions

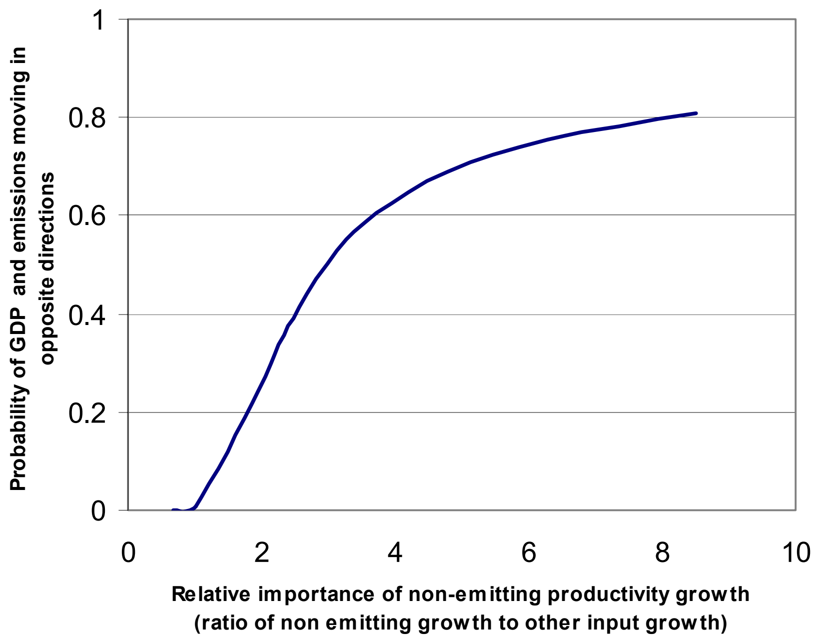


Figure 11 shows that as the relative importance of non-emitting energy productivity improvements as a source of growth increases, the probability that any given parameter set will lead to emissions and GDP moving in opposite directions increases. Thus, the more important clean technology is as a driver of growth, the more likely it is that there will be a parameter set that will cause GDP and emissions to move in opposite directions.

This discussion illustrates three important points. First, understanding the relationship between GDP and emissions requires breaking down the sources of growth and the sources of changes in emissions intensity. Second, while this may be complex in some cases, it is possible to construct back of the envelope models that draw out the key factors. We have used a simple CES model here, but simple versions of more flexible functional forms could be used to represent a wide variety of models. Third, because the relationship between emissions and GDP depends on the sources of growth, it is quite likely that this relationship will differ for the different SRES scenarios.

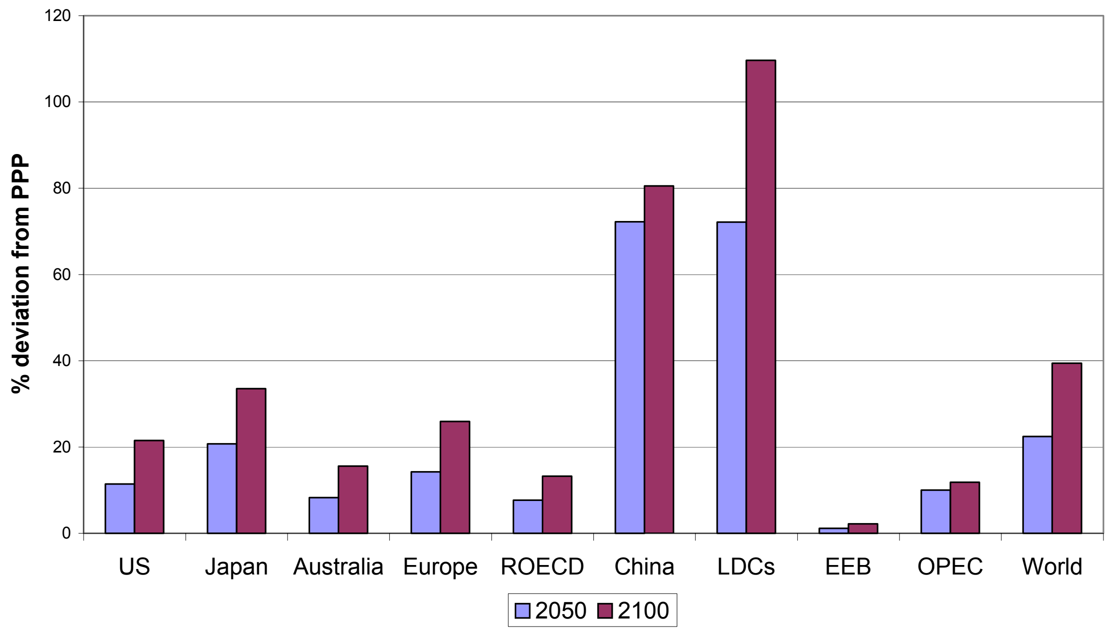
b. PPP versus MER in G-Cubed: an illustration

We now use the G-Cubed model to explore how large the difference between using MER versus PPP initial income levels for emissions over a century. We solve the G-Cubed model under our conventional assumptions of the gaps in productivity growth being related to the overall PPP gaps. We then regenerate the productivity projection by changing the initial gaps for China and LDCs in the model to be based on MER measures of GDP per capital. This implies that we move from gaps of China from 0.2 of the United States to 0.1 of the United States and for developing economies from 0.4 of the United States to 0.13 of the Unites States. That is, for China, the gap relative to the US doubles under the MER approach and for developing economies, the gap more than triples.

The results for the difference in emissions in the MER case versus the PPP case are shown in Figure 11. By 2050 we find that the G-Cubed model produces 21% more emissions than the PPP approach when we base our growth rates on the MER initial conditions. By 2100 this is 40% higher emissions. The impacts on cumulative emissions would be less than this and on temperatures (which depend on cumulative emissions) even less. Nonetheless this is more than 3 times the overestimate found by Manne and Richels (2003). The higher emissions are due to higher emissions in LDCs and China due to higher growth but also due to higher emissions in industrial economies. Stronger growth and a higher marginal product of capital implies that industrial countries sell more to developing countries as well as receiving a higher return on capital invested in these economies. Both of these effects raise emissions and levels of income in non developing economies.

Based on these estimates from the G-Cubed model it seems that the assumptions about the initial levels of income based on MER versus PPP measures are very important for estimates of future carbon emissions. This is a consequence of the particular assumptions we adopt with regards to the convergence model.

Figure 12: Change in Carbon Emissions Market vs PPP 2050 and 2100



6. Storylines versus probabilities

As noted above, the SRES develops a number of different storylines for its analysis, but does not make any judgement about the likelihood of any of these storylines. An important alternative to this approach is to try do develop explicit probability distributions for the key outcomes (such as emissions) from the projections exercise. Such an approach would attach an explicit probability distribution to key model input variables and then use a range of techniques (Monte Carlo analysis, for example) to propagate this uncertainty throughout the model. The result would be a probability distribution for key output variables.

Grubler and Nakicenovic (2001) reject this sort of approach because in their view ‘probability in the natural sciences is a statistical approach relying on repeated experiments and frequencies of measured outcomes ….Scenarios describing possible future developments in society, economy, technology, policy and so on are radically different’ (p.15).

But as Pittock, Jones and Mitchell (2001) point out ‘this frequentist basis for probabilities in predictions of an unknown future is not possible in the earth sciences either, since there will be only one real outcome which cannot be measured now’ (p 249).

Rather, uncertainty analysis in economics and earth sciences requires not a frequentist but a Bayesian approach in which prior assessments of the probability of key input variables are put into an appropriate modelling framework (see the discussion in Malakoff, 1999).

There are a number of possible sources for these prior probability distributions. In terms of key model parameters, they could come from the statistical estimations of the parameters themselves. Alternatively, they could be constructed so as to reflect expert judgements of a particular issue. (This sort of analysis has been used to excellent effect by Nordhaus, 1994, and the various techniques used are described in detail in Morgan and Henrion, 1990).

Whatever the source, uncertainty analysis within a particular modelling framework gives powerful insights into the sources of uncertainty in the model and the drivers of particular modelling results. This insight is unfortunately lacking in the SRES results as presented. It is impossible to tell from the SRES what a small change in assumptions means for the results.

Importantly, probability distributions for emissions could be used as an input into subsequent climate analysis (as undertaken, for example, by Wigley and Raper 2001) to ultimately derive a probability distribution for temperature changes. Such a distribution would be extremely valuable for policy makers, and would assist in planning and policy development. The work by Webster et al. (2003) is an excellent example of how uncertainty analysis can be used in a combined economic and earth systems model. By explicitly modeling uncertainty in emissions as well as other climate factors, they derive an explicit probability distribution for temperature change.

While the probability distributions developed in this way may be imperfect in many regards, it has the advantage of being explicitly derived, with known assumptions that can be tested and challenged. The problem with the current SRES results is that policy makers inevitably overlay their own implicit distributions, which may well be based on political rather than scientific considerations.

7. Summary and Conclusion

Projecting the world economy over long time horizons is challenging. One only has to consider the problems that would have been encountered in 1900 in projecting carbon emissions in the year 2000. Indeed it would have been difficult in 1970 to do well in predicting 2000, given the important structural break in many economic and energy variables resulting from the OPEC oil price shocks. Nonetheless it is important to use the best methodology available to attempt to gain some idea about where carbon emissions might be heading. The mistake would be to rely on the accuracy of these projections for the efficacy of the policy responses that might follow from the predictions. Given the enormous uncertainties in this type of prediction exercise, the policy responses should deal with the uncertainties and the need for flexible responses rather than fixed targets based on projected outcomes[10].

We have outlined the key issues that need to be considered in undertaking long run emissions projections from an economic point of view. Other researchers with an energy or engineering background would tend to focus on technologies rather than economic drivers of growth. Of course, the two are interrelated and poorly understood in practice and there is room for a variety of approaches in the debate. Nonetheless it is important to use best practice when undertaking such a complex task.

In this paper we have illustrated how projections of global economic activity and emissions are undertaken with the G-Cubed multi-country model and how imprecise relationships between economic growth and carbon emissions can be depending on the source of that growth. We have also presented our understanding of the approach in the body of research in the IPCC SRES scenarios. There are a number of differences between the approaches taken in the SRES and the approach we take using the G-Cubed model. These range from the role of economic growth to the implications of technology, autonomous energy efficiency improvements and structural change in understanding future emissions.

We can summarise our findings with the following observations.

- Projecting emissions requires projecting the levels of activities that produce those emissions. For emissions from fossil fuel combustion, this essentially means projecting energy use within the economy as well as projecting the way in which that energy will be generated.
- Both the level of GDP growth, and the relationship between GDP and emissions, will depend on the composition of growth, and the relative importance of the

10 See McKibbin and Wilcoxen (2002) for a long discussion of the range of uncertainties in climate change.

various drivers of economic growth. There is no single aggregate relationship between GDP and emissions, and there is also no single simple measure of AEEI that would mediate between GDP and emissions.

- Rather, the level of emissions depends on the composition of growth. Projecting emissions therefore requires at the least a model that distinguishes between sectors within an economy.
- Within the G-Cubed framework that we use here, the fundamental drivers of growth are population growth and technical change, where this technical change is to be understood at the sectoral level. While there are many ways of projecting technical change at the sectoral level, the default approach that we use with G-Cubed is a variant of a convergence model. Here convergence is not in terms of GDP per capita or some exogenously specified income measure, but in terms of technical efficiency in input use. What happens to GDP per capita is an endogenous outcome, and may or may not involve convergence.
- In our default approach we specify convergence to the US, which is modeled as being on the frontier. We use real income differences (expressed in PPP terms) to define the initial gap between other countries and the US.
- To explore some implications of what has become known as the Castles and Henderson critique of the SRES, we have looked at the effect of using market exchange rate (MER) income comparisons rather than PPP comparisons to define the initial gap in the G-Cubed model. Using MER instead of PPP measures of initial GDP differences across countries results in total emissions 20% higher by 2050, and 40% higher 2100, than in the case of the PPP measure.
- The properties of the model are unaffected by whether base year of the model is in PPP or MER units, but the projections of productivity growth are very different if the rate of convergence is assumed to be the empirically measured

rate. The difference in emissions under the two approaches implies a significant overestimate of emissions in using MER measures of GDP.

- This PPP issue arises because we have chosen to construct our convergence model in a particular way. In this context, PPP is the appropriate base to use for real income comparisons between countries. While this is true in the context of G-Cubed, we cannot say how it applies to other models.
- A PPP issue does not inevitably arise in projecting emissions, however. First, it is possible to drive projections without using any form of convergence modelling. Convergence is, however, a powerful assumption. Indeed conditional convergence has strong empirical support for some countries. Second, using a convergence model at the sectoral level it is possible to avoid real income comparisons by focussing on productivity comparisons which can be defined in quantity terms using original country data. This approach is considerably more data intensive but also potentially very powerful.
- While in G-Cubed we find that lowering growth results in lower emissions, this result does not necessarily apply to other models and other scenarios. It is not difficult to construct a model in which emissions and GDP move in opposite directions, which appears to be the case for some of the SRES scenarios.
- While the PPP critique raises issues of good statistical practice, a far more fundamental issue for emissions projections is the underlying nature of the model used to project productivity changes. This is an area with enormous research potential.
- Finally, we note that in sharp contrast to the approach to uncertainty taken by the SRES, it is possible to get a very good grip on the uncertainties and sensitivities (arising from both parameter and scenario uncertainty) using Bayesian inspired simulation analysis. We think it is much better to give policy makers a considered

and transparent probability distribution than to rely on them to derive their own.

A key issue facing policy makers is how to interpret the projections of the SRES in the light of the various critiques that it has faced. On the basis of our methodological discussion in this paper, we offer the following observations.

First, it is crucial to understand the drivers of emissions projections and their sensitivity to changes in key assumptions. While this understanding cannot be gleaned from the SRES in its current form, there is no reason why the various SRES models could not be explored to further understand these sensitivities.

Second, as we have argued, a broad range of projections without any sense of likelihood is of limited use to policy makers. Indeed, it is potentially misleading as it can lead to researchers applying the upper bound as the most likely scenario. Currently there is no basis for such a choice and work is needed to further understand the likelihood of different projections.

It should be possible to increase understanding of both these issues even if the underlying SRES scenarios remain unchanged.

References

Bagnoli, P. McKibbin W. and P. Wilcoxen (1996), "Future Projections and Structural Change" in N, Nakicenovic, W. Nordhaus, R. Richels and F. Toth (ed) *Climate Change: Integrating Economics and Policy*, CP 96-1 , International Institute for Applied Systems Analysis (Austria), pp181-206.??

Bagnoli, P, W. McKibbin and P. Wilcoxen (1997), "Global Economic Prospects: Medium Term Projections and Structural Change," in *The Sustainable Future of the Global System*, Tokyo: The United National University.

Barro, R.J. and Sala-i-Martin (1991), "Convergence Across States and Regions", *Brookings Papers on Economic Activity*, Vol. 1991, No. 1, pp 107-182.

Barro, R.J. and Sala-i-Martin (1992), "Convergence", *The Journal of Political Economy*, Vol. 100, Issue 2, pp223-251.

Barro, Robert, and Xavier Sala-I-Martin, (1995), Economic Growth, McGraw-Hill.

Bernard, A.D. and Durlauf, S.N. (1995), "Convergence in International Output", *Journal of Applied Econometrics*, Vol. 10, Issue 2, pp 97-108.

Bernard, A.D. and Durlauf, S.N. (1996), "Interpreting Tests of the Convergence Hypothesis", *Journal of Econometrics*, 71, pp 161-173.

Bernard, A.D. and Jones, C.I. (1996a), "Comparing Apples to Oranges: Productivity Convergence and Measurement Across Industries and Countries", *The American Economic Review*, Vol.86, Issue 5, December, pp 1216-1238.

Bernard, A.D. and Jones, C.I. (1996b), "Technology and Convergence", The Economic Journal, Vol.106, Issue 437, July, pp 1037-1044.

Blanchard O. and S. Fischer (1989), Lectures on Macroeconomics, MIT Press, Cambridge MA.

Denison, E.F. (1974), Accounting for United States Economic Growth 1929-1969, Washington: The Brookings Institution.

Castles, I and Henderson, D. (2003a) 'The IPCC Emission Scenarios: An Economic-Statistical Critique.' Energy & Environment, 14 (2&3): 159-185

Castles, I and Henderson, D. (2003b) 'Economics, Emissions Scenarios and the Work of the IPCC' Energy & Environment, 14 (4): 415-435.

Denison, E.F. (1979), Accounting for Slower Economic Growth: The United States in the 1970's, Washington: The Brookings Institution.

Denison, E.F. (1985), Trends in American Economic Growth, 1929-1982, Washington: The Brookings Institution.

Diewert, W.E. (1992), "The Measurement of Productivity", *Bulletin of Economic Research*, 44(3), July, pp. 163-98.

Dowrick, S (2001), "True International Income Comaprisons: correcting for bias in fixed price measures and exchange rate measures", paper presented at the Economic Group Measurement Workshop, March, UNSW.

Dowrick, S and Quiggin, J (1997), "True Measures of GDP and Convergence", *The American Economic Review*, Vol. 87, No. 1, March, pp 41-64.

Ehrlich, P. and Holdren, J. (1971), "Impact of Population Growth", *Science*, Vol.171, No. 3977, pp1212-1217.

Ehrlich, P. and Holdren, J. (1972), "Review of The Closing Circle", *Environment*, April, pp 24-39.

Gerschenkron, A. (1951), A Dollar Index of Soviet Machinery Output, 1927-28 to 1937, Rand Corporation, Santa Monica, CA.

Grubler, A. and Nakecenovic, N. (2001) 'Identifying dangers in an uncertain climate' *Nature*, Vol 412, July.

Grubler, A et al., 2004. 'Emissions Scenarios: A Final Response.' *Energy & Environment*, 15 (1): 11-24.

Hertel T. (1997) (ed) Global Trade Analysis: Modeling and Applications, Cambridge University Press

Heston, A and Aten, B (2002), "Linking Country Groups in International Real Product and Purchasing Power Comparisons", Paper presented at the Conference on the International Comparison Program, World Bank, March.

Hill, R (2000), "Measuring Substitution Bias in International Comparisons Based on Additive Purchasing Power Parity Methods", *European Economic Review*, 44, pp 145-162.

Hill, R (2002), "Measuring Price Differences Across Space and Time: The case of the European Union's Harmonized Index of Consumer Prices", University of New South Wales School of Economics Discussion Paper 2002/09.

Hill, R (2003), "Constructing Price Indexes Across Space and Time: The Case of the European Union", University of Groningen Growth and Development Centre Working Paper, No 200362.

Hogan, William W. and Dale W. Jorgenson (1991), "Productivity Trends and the Cost of Reducing CO_2 Emissions," *Energy Journal*, 12(1), pp. 67-86.

IPCC (2000), Emissions Scenarios, Special Report of the Intergovernmental Panel on Climate Change, Nebojsa Nakicenovic and Rob Swart (Eds.), Cambridge University Press, UK.

Jorgenson, D.W. (1988), "Productivity and Postwar U.S. Economic Growth," *Journal of Economic Perspectives*, 2(4), pp. 23-42.

Jorgenson, Dale W. and Peter J. Wilcoxen (1991), "Global Change, Energy Prices and U.S. Economic Growth," *Structural Change and Economic Dynamics*, 3(1), pp. 135-154.

Kravis, I.B., Heston, A. and Summers, R. (1982), World Product and Income: International Comparisons of Real Gross Product, Baltimore: The Johns Hopkins University Press.

Maddison, A. (1995), Monitoring the World Economy, l820-l992 , OECD Development Centre, Paris.

Maddison, A. (1987), "Growth and Slowdown in Advanced Capitalist Economics: Techniques of Quantitative Assessment", *Journal of Economic Literature*, vol. 25, June, pp. 649-98.

Maddison, A. (2001), The World Economy: A Millennial Perspective, OECD Development Centre, Paris.

Maddison, A. (2003), http://www.eco.rug.nl/~Maddison/Historical_Statistics/horizontal-file.xls

Malakoff, D (1999) 'Bayes offers a new way to make sense of numbers' *Science*, vol 286, 19 Nov.

Manne A. and R. Richels (1992) Buying Greenhouse Insurance: The Economic Costs of CO2 Mitigation. Cambridge MA, MIT Press.

Manne A. and R. Richels (2003) "Market Exchange Rates or Purchasing Power Parity: Do They Make a Difference to the Climate Debate? AEI-Brookings Joint Centre for Regulatory Studies Working Paper 03-11.

McKibbin W.J. and J. Sachs (1991) Global Linkages: Macroeconomic Interdependence and Co-operation in the World Economy, Brookings Institution, June.

McKibbin W.J. and D. Vines (2000) "Modelling Reality: The Need for Both Intertemporal Optimization and Stickiness in Models for Policymaking" *Oxford Review of Economic Policy* vol 16, no 4. (ISSN 0266903X)

McKibbin W. and P. Wilcoxen (1998) "The Theoretical and Empirical Structure of the G-Cubed Model" *Economic Modelling* , 16, 1, pp 123-148 (ISSN 0264-9993)

McKibbin, W. and P. Wilcoxen (2002a), Climate Change Policy After Kyoto: A Blueprint for a Realistic Approach, Washington: The Brookings Institution.

McKibbin, W. and P. Wilcoxen (2002b), "The Role of Economics in Climate Change Policy," *Journal of Economic Perspectives*, 16(2), pp.107-130.

Morgan. M. and Henrion, M (1990) *Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis,* New York, Cambridge University Press

Nakicenovic, N et al., 2003. ‘IPCC SRES Revisited: A Response.’ *Energy & Environment*, 14 (2&3): 187-214.

Nordhaus. W. (1994) *Managing the Global Commons* The MIT Press, Cambridge

Nuxoll, D.A. (1994), “Differences in Relative Prices and International Differences in Growth Rates”, *The American Economic Review*, Vol.84, No. 5, December, pp 1423-1436.

Obstfeld M. and K. Rogoff (1996*), Foundations of International Macroeconomics,* MIT Press, Cambridge MA.

OECD (1993), *Purchasing Power Parities and Real Expenditures*, Volumes I and II.

Overman, H.P. and Puga, D. (2002), “Unemployment Clusters Across Europe’s Regions and Countries”, Economic Policy, April.

Pittock, A., Jones, R. and Mitchell, C. (2001) ‘Probabilities will help us plan for climate change’ *Nature*, Vol 413, 20 September.

Quah, D.T. (1995a), “Empirics for Economic Growth and Convergence”, Centre for Economic Performance Discussion paper No. 253, July.

Quah, D.T. (1995b), “Convergence Empirics Across Economies with (Some) Capital Mobility”, Centre for Economic Performance Discussion paper No. 257, August.

Quah, D.T. (1996), “Convergence Endogenous Growth, and Productivity Disturbances”, Centre for Economic Performance Discussion paper No. 290, April.

Quah, D.T. (1997), “Empirics for Growth and Distribution: Stratification, Polarization, and Convergence Clubs”, Centre for Economic Performance Discussion paper No. 324, January.

Quah, D.T. (2000), “Cross-Country Growth Comparison: Theory to Empirics”, LSE Economics Department, January.

Ramsey, F (1928), “A Mathematical Theory of Saving”, *Economic Journal*, Vol. 38, December, pp 543-559.

Sala-i-Martin, X. (1996a), "The Classical Approach to Convergence Analysis", *The Economic Journal*, Vol. 106, No. 437, pp 1019-1036.

Sala-i-Martin, X. (1996b), "Regional Cohesion: Evidence and Theories of Regional Growth and Convergence", *European Economic Review*, Vol. 40, pp 1325-1352.

Sala-i-Martin, X. (2002), "15 Years of New Growth Economics: What Have We Learnt?",Columbia University Department of Economics Discussion Paper Series, No. 0102-47.

Schneider, S. (2001) 'What is dangerous climate change' *Nature*, vol 411, 3 May.

Solow, R. (1956), "A Contribution to the Theory of Economic Growth", *Quarterly Journal of Economics*, Vol. 70, pp 65-94.

Solow, Robert M., (1957), "Technical Change and the Aggregate Production Function," *Review of Economics and Statistics*, vol. 39(3), 1957, August, pp. 312-20.

Treadway, A. (1969) "On Rational Entrepreneurial Behavior and the Demand for Investment." *Review of Economic Studies* 36(106), pp.227-239.

UNFCC (1992) http://unfccc.int/resource/docs/convkp/conveng.pdf

Weyant, John (ed.) (1999), "The Costs of the Kyoto Protocol: A Multi-model Evaluation," *The Energy Journal*, Special Issue.

Webster, M., Forest, C., Reilly, J., Babiker, M., Kicklighter, D., Mayer, M., Prinn, R., Sarofim, M., Sokolov, A., Stone, P. and Wang, C. (2003) 'Uncertainty Analysis of Climate Change and Policy Response', *Climatic Change*, vol 61 pp 295-320, Kluwer Academic Publishers.

Wigley, T. and Raper, S (2001) 'Interpretation of High Projections for Global-Mean Warming' *Science*, Vol 293, 20 July.