CLIMATIC IMPLICATIONS OF THE KYOTO PROTOCOL: THE CONTRIBUTION OF INTERNATIONAL SPILLOVER *

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Abstract. We explore the long-run impact of the Kyoto Protocol commitments to limit greenhouse gas emissions under various assumptions about the international spillover arising from actions led by the industrialised countries. International spillover comprises many complex processes including substitution due to price effects, diffusion of technology innovations, and policy and political spillovers. We represent these in terms of their aggregate impact on emission intensities over the next century. Limiting industrialised country emissions alone has limited environmental benefit if there is no international spillover; in our base case atmospheric concentrations by the end of the century rise to 730 ppm. However, this implies a large divergence of emission intensities, contrary to both empirical long term aggregate trends, and to identifiable influences towards convergence associated with economic globalisation. In contrast, if spillover leads to convergence of emission intensities by 2100, atmospheric concentrations are kept to below 560 ppm and are close to stabilising. We argue that zero or negative international spillover, as assumed in many analyses, is not credible; we estimate the most likely range for the international spillover parameter in our model to be 0.5–1.0. For our base scenario this would imply a mean global average temperature change from pre-industrial levels by 2100 of 2.7–3.4 °C instead of 4.2 °C, and rising at only 0.15–0.29 °C/decade instead of 0.45 °C/decade. Long-run sea-level rise is greatly curtailed. The regional benefits to the industrialised countries are also magnified because of the spillover to developing county emissions. Although the aggregate degree of spillover is uncertain, the available evidence suggests that it will be important and environmentally beneficial in aggregate. Spillover will help to spread the global effectiveness of the Kyoto first period and subsequent commitments, and deserves much further scrutiny.

1. Introduction

The Kyoto Protocol on climate change sets a framework and initial commitments for quantified limits on greenhouse gas emissions. First period commitments, for 2008–2012, require a 5% reduction in collective industrialised country emissions from 1990 levels. This has been widely criticised in the scientific community for being too weak to have much impact upon future climate change; and in the economics community, for being too strong in its obligations upon industrialised

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countries. The then chairman of the IPCC criticised the relative weakness of the targets established (Bolin, 1998). Wigley (1998) published a quantitative analysis showing that the Kyoto commitments on their own would have limited impact on global trajectories of concentration, temperature or sea-level rise even with various scenarios of follow-up in industrialised countries. Economists such as Nordhaus (1999) claim the costs to the U.S. would greatly exceed the benefits. These arguments rest heavily on the claim that the lack of quantified commitments for developing countries makes the Protocol ineffective, and that action by the industrialised countries would be offset by 'leakage' of emissions as industries migrate from industrialised countries to developing countries to escape emission controls.

Developing countries are an intrinsic part of the Protocol and broader negotiations on climate change, but are excluded from quantified commitments for several reasons. Their historical contribution to the problem is minimal; their emissions per person are still a small fraction of those from industrialised countries; their institutional and technological capabilities are still far from those of the industrialised countries and their priority has to be basic development and poverty alleviation. The original Rio Convention agreed that industrialised countries must establish leadership in emissions control and show that they could return emissions to former levels. That has not yet been achieved and this strongly influenced developing country attitudes at Kyoto. Nevertheless, the claim remains that excluding developing countries from quantified commitments in the Protocol renders it ineffective. Developing countries accounted for about 4/5 of the world's population and about 30% of global CO_2 emissions in 1990. Their rapid growth means that global emissions could grow substantially even if industrialised countries meet their commitments, which in turn are puny compared with the deep emission cuts that would be required to stabilise the atmosphere.

However, quantitative studies to date have paid little attention to how action in the industrialised world is itself likely to affect technological and policy choices globally, and the implications of this for global emission trends. Detailed analysis of technological trends and possibilities highlight the extent to which energy technologies have developed and are continuing to do so, with the potential to lead to steady ongoing declines in carbon emission intensities (Grubler et al., 1999), but conventional analyses neglect the fact that both technology and institutional structures (including policy reforms) diffuse internationally. Modern economies are linked by vast and continually expanding flows of trade, investment, people and ideas. The technologies and choices of one region will inevitably be affected by developments in other regions.

This paper explores sensitivities to alternate viewpoints that address the scope for innovation in response to emission constraints and the global diffusion of better technologies and policies. These aspects are all interrelated by a common theme of how initial developments in technologies, systems and policies in the industrialised world may affect developments elsewhere, an issue we generalise with the term *international spillover*. Using recent data and scenarios, we build upon the methodology in Grubb (2000) to present a new analysis which highlights these features, clarifies the different components of international spillover, and examines the potential climatic impact of the Kyoto Protocol for plausible ranges of international spillover.

2. Components of International Spillover

There are many components to international spillover. The most familiar component in economic analysis is the *substitution* of inputs in response to policies: increasing the price of carbon in one region will lead to a substitution of carbon-based inputs by other inputs. If only part of the world is doing this, carbon-intensive industries may migrate to or otherwise prosper in non-controlled regions, and reducing energy consumption may lead to lower international prices that may stimulate greater use outside the controlled zone.

Set against this are various sources of positive spillover. Technologies will respond to emissions control, and globalisation is increasingly linking economies by flows of trade, investment, technology and ideas. Pressures to improve efficient and low carbon technologies in the industrialised world will have an impact on global product lines, and developing countries increasingly strive to acquire the better, cleaner, more efficient technologies developed in the industrialised countries, as they grapple with their own resource and pollution problems.

In addition, policy and political developments diffuse. The idea that large subsidies for fossil fuel production are economically undesirable has now gained widespread recognition: reductions of such subsidies in China help to account for the remarkable decline in Chinese CO_2 emissions during the 1990s. The experiment of electricity liberalisation in Latin America and the U.K., generally leading to considerable improvements in efficiency and greater use of natural gas and co-generation, is spreading globally. Institutional developments would also include the spread of commitments. Most global environmental treaties (and many other global regimes) differentiate commitments between industrialised and developing countries. The Kyoto Protocol's core structure of rolling commitment periods provides a natural base for the evolution of commitments, building on the first-period commitments of industrialised countries. Some developing countries have already started to discuss their possible involvement in CO_2 emissions trading systems that are beginning to emerge in some OECD countries under the Kyoto Protocol. Appropriate action by industrialised countries under Kyoto will increase the willingness of developing countries to adopt commitments over time; and industrialised countries are likely increasingly to insist that more countries adopt commitments over time if their own commitments are to be strengthened in subsequent periods.

These are all components of what we term ‘international spillover’. Unfortunately, no global models yet exist that could credibly quantify directly the process of global diffusion of technologies and policies. Important improvements in the modeling of technical change have illustrated the potential for low emission intensity futures globally at modest cost (Gritsevskyi and Nakicenovic, 2000). Such studies highlight the potential for global diffusion of low emissions technologies. But the complexity of such modeling has precluded geographical disaggregation with such induced technical change; and, as noted, there are other components to spillover including institutional and policy reforms led by good examples. Consequently, in this paper we use a proxy index and explore the sensitivity of results to this generalised index of spillover. Thus we explore the implications of different assumptions about how actions by the industrialised countries diffuse and extend globally.

3. Methodology

The IPCC has recently produced a revised set of long-term emission scenarios (Nakicenovic and Swart, 2000). These use improved scenario techniques and take into account, far more fully than before, improved understanding of technology dynamics, and ongoing and possible structural changes in global energy systems. In this analysis we start with the 'marker' A2 scenario, that most closely reflects traditional thinking about emission prospects, which lies slightly above the IPCC's previous standard 'IS92a' scenario, that was the basis for the analysis of Kyoto commitments by Wigley (1998).

Building upon the approach in Grubb (2000), we represent international spillover in terms of its impact on the relative *emissions intensity*, defined as the ratio of CO_2 emissions to GDP, in different parts of the world. We consider emissions intensity the most relevant indicator because it factors out the effects of differential economic growth rates and in part reflects technology choices. To the extent that emissions intensity is a function of deployed technology, global technology diffusion would tend to lead to convergence in emission intensities, and evidence for this is discussed below.

Thus we represent international spillover in terms of the impact that accelerating the trend of decarbonisation (declining emissions intensity) in the industrialised world is likely to have on the rest of the world. We define aggregate emissions intensity separately for the Annex I countries that have quantified commitments under the Kyoto Protocol, and the developing countries that do not:

$e_r(t)$ is the emissions intensity (i.e., the ratio of emissions to GDP) at time t in the Annex I ($r = 1$) and developing ($r = 2$) regions respectively.

$e_r^*(t)$ represents the corresponding trajectories in the SRES A2 marker scenario in the absence of any abatement in *either* region.

Where $T = 110$ years goes from 1990 to 2100; we start from 1990 since some action to address CO_2 emissions has already begun and there is already discernible change in developing country technologies and policies. Note that the geographical division also reflects wider economic, legal and political divisions, and the dominant direction of international technological flows (with advanced technologies and institutions mostly generated in the OECD and diffusing globally). Also, with the industrialised countries forming such a large share of the global technological economy, it is clear that action taken in the industrialised world will exert huge influence on technology development and choice.

Spillover is then represented in terms of relative convergence of emissions intensity over the 21st century to a degree specified by the aggregate spillover parameter σ.

$$e_2(t) = \left(1 - \sigma\frac{t}{T}\right) e_2^*(t) + \sigma\frac{t}{T}e_1(t)\,.$$

Thus $\sigma = 0$ represents the simplified case (e.g., Wigley, 1998) in which intensities in one region are completely independent of those in another (there is no spillover or other effect), whilst $\sigma = 1$ represents a case in which aggregate emission intensity in the developing world converges to the same level as in the Annex I countries by the end of the century.

Following the discussion set out above, we note that the spillover parameter comprises three broad components:

$$\sigma = \sigma_s + \sigma_t + \sigma_p\,,$$

where σ_s is the spillover due to economic *substitution* effects, σ_t is the spillover due to the diffusion of *technological* improvements, and σ_p is the spillover due to *policy and political* influence of industrialised country action upon developing country actions.

We emphasise the uncertainty in σ. Economic models generally focus upon substitution effects and exclude the induced development and diffusion of technologies, and policy and political spillovers. The resulting $\sigma = \sigma_s$ is generally negative due to ‘leakage’ of emissions as polluting activities migrate outside the control zone, and as world oil prices decline in response to emission controls. Conversely, some strands of the technological literature argue the case for ‘super-spillover’ in which developing countries might ‘leapfrog’ industrialised countries and become *more* carbon efficient (less carbon intensive) than established industrialised countries, because they would not be held back by existing infrastructure and vested interests, and could move more promptly to adopt more efficient and low-carbon technologies. This would imply $\sigma > 1$. Our initial focus is upon the *sensitivity* of results to these different perspectives, we then consider more likely ranges for the parameter and the climatic implications.

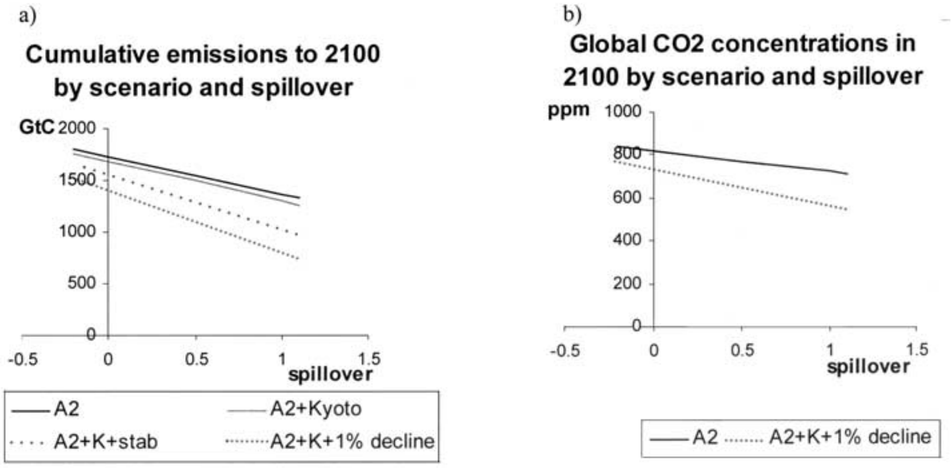

Figure 1. Cumulative emissions and concentrations under different scenarios of control and spillover.

4. Impact of International Diffusion/Spillover on Global Emissions and Concentration

We take as our reference case the SRES A2 scenario, as indicated, modified by the Kyoto targets for industrialised country emissions. The analysis of Wigley (1998) explored cases in which these targets were followed by post-Kyoto scenarios in which emissions from industrialised countries either shadow their 'business-as-usual' increase again after 2010 (no further action), are capped at Kyoto levels, or decline by 1%/yr thereafter. Emissions from developing countries were unaffected in any of these cases.

Figure 1a shows how cumulative emissions to 2100 for these cases vary as a function of spillover. Note that spillover reduces emissions even in the base case: in the A2 scenario for industrialised country emissions with no abatement action, unitary spillover ($\sigma = 1$: intensity convergence by 2100) reduces cumulative emissions by c.350 GtC compared to zero spillover. The effect of spillover in this case is to bring the cumulative emissions much closer to those of the A1 scenario developed by IIASA, which has cumulative emissions by 2100 of around 1500 GtC, and which is explicitly described as representing a more integrated global economy.

In the strongest of Wigley's control cases (Kyoto + 1%/yr decline), however, unitary aggregate spillover (intensity convergence) reduces emissions by almost 700 GtC, from 1480 (zero spillover) to 800 GtC. This of course is because tight controls imply a far more rapid technological improvement and decline in carbon intensities in the industrialised world, which therefore has far more impact when these technologies and policies diffuse globally.

The corresponding changes in atmospheric concentration by 2100 are illustrated in Figure 1b. With zero spillover, CO_2 concentration in the Kyoto + 1%/yr decline case is about 90 ppm lower (11%, or 17% of pre-industrial concentrations) in 2100 than in SRES Scenario A2. This compares with a reduction of about 80 ppm found with the Kyoto + 1%/yr decline case of Wigley (1998), based on IPCC scenario IS92A (Leggett et al., 1992). All these and subsequent climatic results assume that deforestation emissions follow the Scenario A2 path in all cases, rising from about 1 GtC in 1990 to nearly 2 GtC by 2030, and falling back to just over 1 GtC by 2100. Unitary spillover brings a reduction of about 100 ppm (12%, or 18% of pre-industrial levels) in 2100 in SRES Scenario A2, and about 170 ppm (23%, or 37% of pre-industrial levels) in the Kyoto + 1%/yr decline case. The drops in cumulative emissions are about 21% and 43% respectively.

Conversely, negative spillover (net leakage: $\sigma < 0$) results in industrialised-country-only action having less impact, shown in Figures 1a,b for values of σ down to –0.2; whilst super spillover, or ‘leapfrogging’ ($\sigma > 1$) could result in the atmosphere being stabilised before the end of the century at below a doubling of pre-industrial CO_2 concentrations.

Figure 2 illustrates emission trends and shows why results are so sensitive to spillover, particularly for the strongest control case. With abatement being led by the industrialised countries, if there is zero spillover their emissions are soon swamped by the growth in developing country emissions. Since in this case, the emissions intensity in the developing world grows to five times that of industrialised countries, any convergence of intensities due to spillover exerts huge leverage on global emissions. With unitary spillover (intensity convergence by 2100), developing country emissions are stabilised around mid century and start to decline slowly thereafter.

5. Estimating International Spillover

Quantifying international spillover is intrinsically complex, but evidence can be adduced from both aggregate observed trends and component heuristic analysis.

5.1. AGGREGATE OBSERVED TRENDS

Both energy and carbon intensities can vary widely between countries, and in the short term are sensitive to exchange rate fluctuations. Energy intensities, particularly in developing countries, are also dependent upon whether they relate to commercial energy (in which intensities initially rise with development) or total energy (which decline).

Nevertheless, Mielnik and Goldemberg (2000) examine *aggregate* intensity data (commercial energy consumption per unit GDP) between industrialised and developing countries over recent decades, and conclude that energy intensities are converging. They attribute this in part to economic globalisation increasing the linkage between different economies. They estimate that the *aggregate* energy

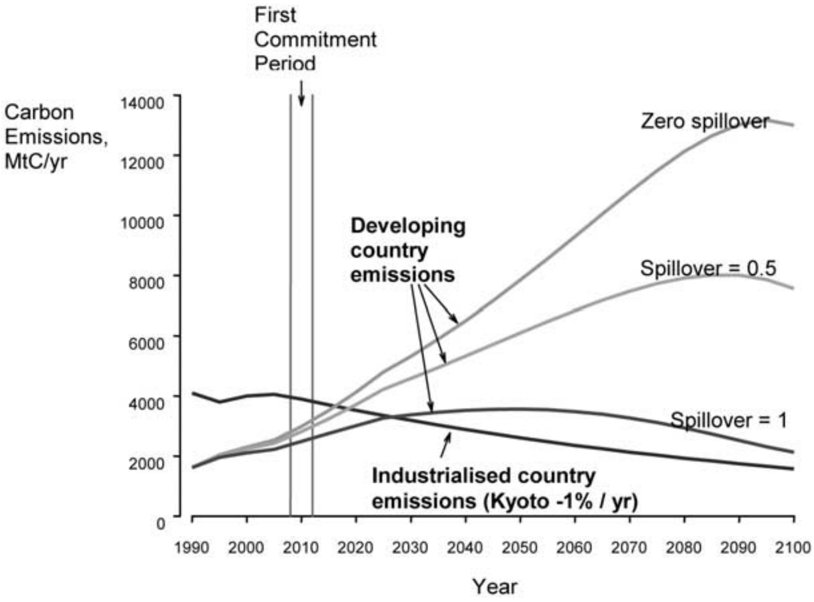

Figure 2. Emission trajectories for different spillover assumptions.

intensity in the developing world in the late 1990s is no more than 50% higher than in developed economies. This is similar to the data presented in Grubb (2000) for aggregate north-south carbon intensity differences. The Economies in Transition have had particularly complex trends, with significant short-term intensity increases associated with economic transition as economic collapse has outpaced energy savings.

Partly to factor out these short-term and EIT-specific effects, Figure 3 shows data collected by the authors on very long term trends in *national carbon intensity* for seven of the world's highest emitting countries (four developed, three developing). This appears to show a clear tendency for national carbon intensities (here, CO_2 emissions/GDP) also to converge. Divergence between these individual countries remains considerable – recently between 0.1 and 0.25 tonnes of carbon dioxide per $1,000 – but the general pattern is one of convergence as countries become more entwined in their choice of energy technologies, systems and policies. The U.S. and China are the two least carbon-efficient countries on these data, and Japan and Indonesia the most carbon-efficient: the aggregate north-south difference is clearly much smaller than the maximum inter-country difference.

The complexity involved and the range of processes has so far precluded regional economy-wide modeling of diffusion and spillover. However, it is most plausible that the apparent tendency to intensity convergence reflects increasing international economic linkages: trends include "worldwide liberalisation of national economies to trade and investments; privatisation; regional economic integration; the emergence of new generic or core technologies … and rapid technological

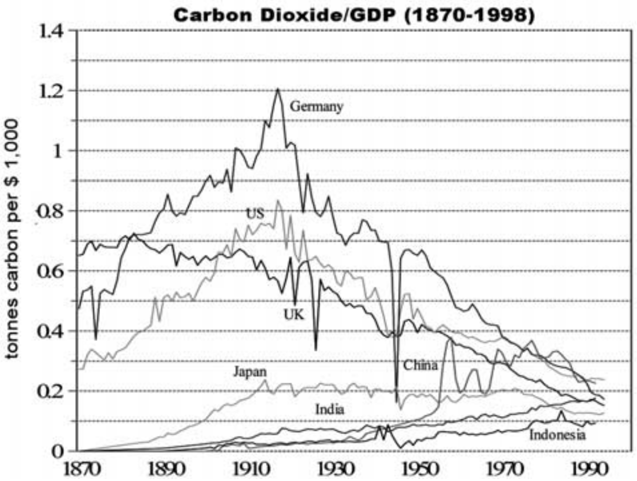

Figure 3. Convergence in Carbon Dioxide/GDP (1870–1998) (Source: CDIAC, 2001; Maddison, 1995; Pearson and Fouquet, 2001).

learning and industrialisation in the east Asian countries, among others" (Kumar, 1998).

The empirical data of aggregate intensity trends does suggest increased economic interlinkage which underpins the spillover hypothesis. To consider the likely extent of spillover in the future, it is useful to consider in more depth the individual components. As noted, the aggregate spillover comprises three main components and we consider these in turn.

5.2. SUBSTITUTION-BASED LEAKAGE

Economic analysis to date has concentrated almost exclusively on the first, the leakage (negative spillover) arising from substitution effects given fixed assumptions about technologies, production functions and policies in different regions. Since manufacture of internationally tradeable goods only accounts for 30% of total industrialised country emissions, the scope for leakage from industrial migration is intrinsically limited. Wider price effects are limited by the modest role of international coal trade and relatively high elasticity of international oil and coal supply relative to the elasticity of demand. The review by the IPCC of economic modeling studies concludes that implementation of the first-period Kyoto commitments with uniform carbon taxes could involve emissions leakage through these processes totaling 5–20% (Watson et al., 2001, Chapter 8). The dominant source is industrial migration and in reality, governments take steps to minimise this (the mobile carbon-intensive sectors have generally been exempted from taxes or other controls to avoid it) reducing the size of σ_s further.

5.3. TECHNOLOGICAL SPILLOVER

The second component of spillover, σ_t, arises from the international diffusion of more efficient and lower carbon technologies that are developed in response to emission controls in the industrialised world. These processes have been little studied. Freeman (1998) notes “the contrast between the general consensus that technical change is the most important source of dynamism in capitalist economies and its relative neglect in most mainstream literature”, and Krugman (1995) concurs that “international economics has paid too much attention to resource endowments and too little to technological competence”. In fact, substantial north-south spillover of general productivity gains from R&D has been well established empirically (Helpman and Hoffmaister, 1997), and Hegazi and Safarian (1999) demonstrate that the rapid increase in foreign direct investment is leading to much greater spillovers than occurs through trade alone. These studies demonstrate significant international technological spillover, though none quantify it in a way that can be readily converted in terms of intensity linkages.

Recent studies (such as Grubler et al., 1999; Gritsevskyi and Nakicenovic, 2000; and others reviewed in Grubb and Koehler, 2000) have demonstrated the central importance of induced technical change in relation to climate change. The identified scope for technologies with lower emissions is vast, and it is evident that a world in which industrialised country emissions are ultimately reduced to a small fraction of ‘business as usual’ projections could involve a very different technological and industrial basis: on decadal timescales, innovation dominates over economic substitution in these studies. Technologies such as fuel cells and highly efficient transport technologies, radical developments in renewable energy for power generation and heat supply, and more efficient processes for industrial manufacturing, would become far more widespread.

Diffusion of lower carbon technologies could be further enhanced by direct measures: the Climate Change Convention and the Kyoto Protocol commit all countries to adopt policies and practices to encourage transfer of cleaner technologies, and the Clean Development Mechanism gives financial incentives for such international investments (Grubb et al., 1999).

Cost reductions and co-benefits will further influence the international diffusion of such technologies, according to sectoral characteristics. CO_2 emissions in OECD countries in aggregate are roughly equally divided between transport, manufacturing, and domestic and service (building sectors), with electricity supplying mainly the latter two. The great majority of motor vehicles are dominated by designs and innovations of only about half a dozen multinational corporations. Technologies for bulk power generation are similarly dominated by a few major global engineering companies. Increasingly, these companies seek to design and market new products for use worldwide. Technologies such as fuel cell vehicles are already being extensively pursued and could appeal to consumers in terms of power, style, and quietness, as well as having lower running costs. Their lower emissions of conventional pollutants can also help to address urban pollution problems that are endemic from Birmingham to Beijing. A high degree of international diffusion would be expected from such technologies. In manufacturing, too, technologies that raise resource efficiency and bring other co-benefits (such as reduced waste) could be expected to diffuse widely. Only in the building sector does international diffusion seem likely to be small, and even here, technologies such as greatly improved integrated solar designs or small scale combined heat and power systems could be expected to spread albeit perhaps quite slowly. The degree of international diffusion is perhaps hardest to judge for power generation, because although the industry is fairly globalised, the scope for substitution is high: local cheap coal for example could continue to dominate in some areas even if there are improvements in renewable energy technologies.

High diffusion of improved technologies in the manufacturing and vehicle sectors combined with lower diffusion in others would suggest an upper bound to σ_t, in the range 0.5–0.75 depending particularly upon the power sector. The lower bound depends upon the degree to which technical innovation does occur in response to emission constraints. If there is little innovation, emission controls will be relatively costly and large carbon price differentials will impede spillover to non-controlled regions. Extensive innovation would imply both lower costs and higher international spillover.

5.4. POLICY AND POLITICAL SPILLOVER

Even if innovation is modest, however, this would just bring to the fore the third, policy and political, component of spillover, σ_p. It is both a principle established in the Climate Convention, and an obvious political reality, that action in the industrialised countries will help to engender more widespread action over time ($\sigma_p > 0$). If innovation makes the cost of emission constraints low, the industrialised world may be prepared to strengthen their emission controls even with little controls in developing countries; developing countries would probably adopt many of the improved technologies and associated policies anyway.

However, if innovation is less, such action would become both increasingly costly and less and less effective given growth in developing country emissions, and in these conditions industrialised countries clearly would refuse to continue increasing commitments without concomitant action by developing countries. Scenarios which combine strengthening control in industrialised countries with low innovation and a lack of action in developing countries are thus internally inconsistent. The policy and political spillover, σ_p, must be large to sustain action if technological innovation and diffusion is low (low σ_t).

5.5. ESTIMATING SPILLOVER: CONCLUSIONS

Quantifying all this is of course difficult but some estimation may be made. As indicated, the technological studies available suggest that extensive innovation is available to meet CO_2 constraints, and the economic studies suggest that international technological spillover is a substantial and growing feature of the world economy. The discussion indicates that this could lead to spillover values above 0.5, much greater than the negative substitution component; over a period of decades, therefore, the diffusion of technological change is likely substantially to outweigh the classical substitution-based leakage arising from σ_s even in the absence of *any* policy spillover to developing countries. Reality would more likely involve a mix of technological innovation and diffusion with an expanding geographical scope of policy developments and quantified commitments under successive Kyoto periods.

As discussed above, the aggregate difference in energy and carbon intensities between developed and industrialised countries appears to be already under 50% and is narrowing. For the SRES + control base scenario used here, any spillover parameter below 0.9 implies reversing this trend. A value of 0.5 means that by 2100 the developing countries emit more than three times as much carbon per unit real output compared to the industrialised countries. Given the considerations noted above we do not consider still lower spillover values – with even greater divergence – to be plausible.

This of course is in sharp contrast to the classical mode of analysis (as exemplified for example by the widely-cited study by Wigley (1998) and numerous economic studies which claim that action by industrialised countries would be swamped by the rise in developing country emissions), which implicitly assume a zero value for international spillover. All the analysis above suggests that this common assumption has no empirical foundation and is contrary to all the available evidence.

At the opposite extreme, although ‘technological leapfrogging’ may seem an appealing idea, there is little evidence that developing countries in aggregate will become *more* carbon-efficient than industrialised countries; lower energy efficiency, and with it somewhat higher aggregate carbon intensity, is generally an endemic feature of developing countries. Consequently we also reject $\sigma > 1$. These arguments imply a likely range of $0.5 < \sigma < 1$. This is is still a very wide range, and we emphasise the uncertainties, recognising for example that individual countries in special circumstances could differ more widely. In terms of aggregate difference between industrialised and developing countries, however, the logic set out above implies that values outside this range are economically and politically implausible.

6. Climatic Impacts of International Spillover

To explore quite *how* important spillover and associated uncertainties may be with regard to the climatic implications, we use the PAGE95 integrated assessment model of emissions and climate change. The model traces the effects of greenhouse gas emissions through the climate change that they cause to the impacts that result. It also performs all calculations under uncertainty and gives results both as mean values and as probability distributions (Plambeck et al., 1997). For example, the climate sensitivity to a doubling of CO_2 concentrations – which is widely acknowledged as still a major uncertainty in climatic modelling – is represented as a distribution of possible sensitivities from 1.5 to 6.0 °C, with a most likely value of 3.0 °C.

For this more detailed analysis we focus upon the scenario of Kyoto commitments followed by 1%/yr decline of industrialised country CO_2 emissions. We note that *collective* industrialised country emissions are in fact currently below their Kyoto target (due to the contraction in eastern Europe) and that in the three years 1997–1999 U.S. CO_2 emissions grew on average less than 1%/yr despite rapid economic growth and few significant control policies as yet. There are widely different views about the feasibility and costs of different degrees of continuing reductions, but long-run atmospheric stabilization will clearly require ongoing reductions from the high per-capita emitters of the industrialised world. Our scenario for industrialised country emissions is within the range of scenarios reviewed by the IPCC (Nakicenovic and Swart, 2000).

To model the climatic effect, we have had to make assumptions about the emissions of other greenhouse gases, such as methane, trace gases and N_2O, and about sulphates. In the runs with no spillover, these have been taken from the SRES scenario A2, with the exception of trace gases and N_2O, which were taken from the second assessment report of the IPCC (1995).

In the spillover runs, emissions of methane, and radiative forcing from industrial trace gases and N_2O have been scaled proportionally to global CO_2 emissions. Thus at time t:

$$Xs_t = 100 + (Cs_t - 100) * (X_t - 100)/(C_t - 100) ,$$

where $Cs_t, Xs_t =$ indexed global emissions of CO_2 and other greenhouse gases respectively with spillover (1990 = 100); $C_t, X_t =$ indexed global emissions of CO_2 and other greenhouse gases respectively with no spillover (1990 = 100).

A distinct regional approach is taken to the control of sulphates, given existing trends and legislation. In Annex I countries, sulphates were assumed to be at 80% of their 1990 levels by 2000, 75% by 2020 and 50% by 2100. In the no spillover runs, sulphates in non-Annex I countries were adjusted to make global emissions consistent with scenario A2. This implies sulphate emissions in non-Annex I countries rising to a peak of 410% of their 1990 levels by 2040, falling back to 185% of their 1990 levels by 2100.

In the runs with spillover, sulphates were treated identically to CO_2: intensity of sulphate emissions was assumed to converge by 2100 to the degree indicated by the spillover parameter. The effect of this is to restrict the sulphate peak in non-Annex I countries to 350% ($\sigma = 0.5$), or 290% ($\sigma = 1$) of their 1990 emissions in 2040. As sulphates act to oppose climate change, these assumptions decrease the difference in mean temperature between the spillover and no-spillover cases.

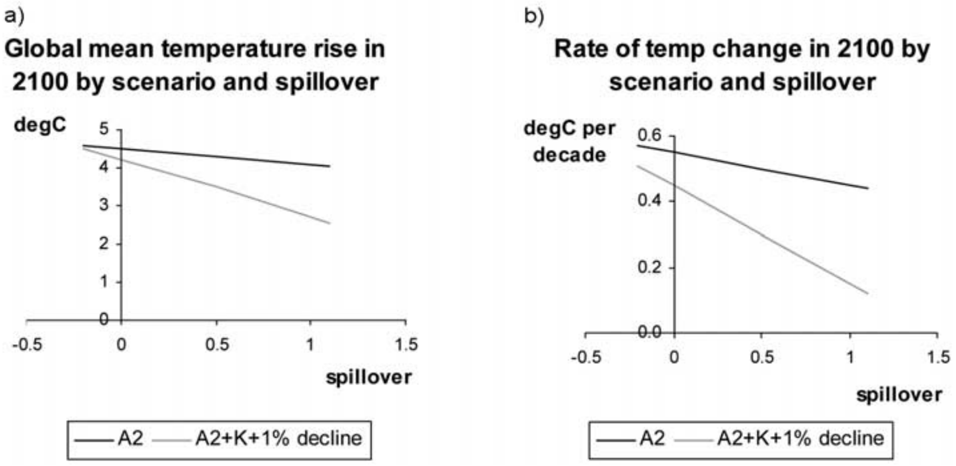

Figure 4. Global mean temperature implications by scenario and spillover.

Figure 4 shows the impact on (a) mean temperature rise by 2100 and (b) rate of temperature change in 2100, using other reference assumptions under uncertainty (Hope and Maul, 1996). The mean global temperature rise in the A2 scenario is larger than that found in Wigley (1998) due to higher emissions in this scenario, a higher mean climate sensitivity (2.5 °C in Wigley, compared to a <1.5, 3.0, 6.0> triangular distribution used here), and our presentation of temperature change since pre-industrial times rather than 1990. The 90% confidence interval for global mean temperature rise by 2100 is 2.45 to 6.42 °C.

The mean temperature results confirm that spillover is much more beneficial if Annex I countries are controlling their emissions. With the uncontrolled A2 scenario for industrialised country emissions, spillover of 0.5–1.0 reduces the global mean temperature in 2100 by 0.2–0.4 °C, but under the controlled scenario, the reduction is 0.8–1.5 °C, limiting the overall increase to 2.7–3.4 degrees above pre-industrial temperatures. The *rate* of global mean temperature change in 2100 is particularly sensitive to spillover in the controlled case, where spillover of 0.5–1.0 reduces the mean rate of change in 2100 from 0.45 to 0.15–0.29 °C per decade. In the uncontrolled scenario A2, the temperature is continuing to rise at 0.45 °C per decade in 2100, even with unitary spillover.

This shows that the relative importance of spillover uncertainties depend upon the climatic index studied and the time horizon. For the *mean* temperature rise, the climate sensitivity itself remains a dominant uncertainty. However, the *rate* of temperature rise by 2100 – and hence longer term impacts – is more sensitive to the spillover assumptions. With unitary spillover , the atmosphere is getting close to stabilisation by 2100, and the rate of temperature change is responding to this.

This has particular impact upon long term sea level rise. Using the conventional ratio of 25 cm sea level rise per °C rise in temperature implies that spillover would

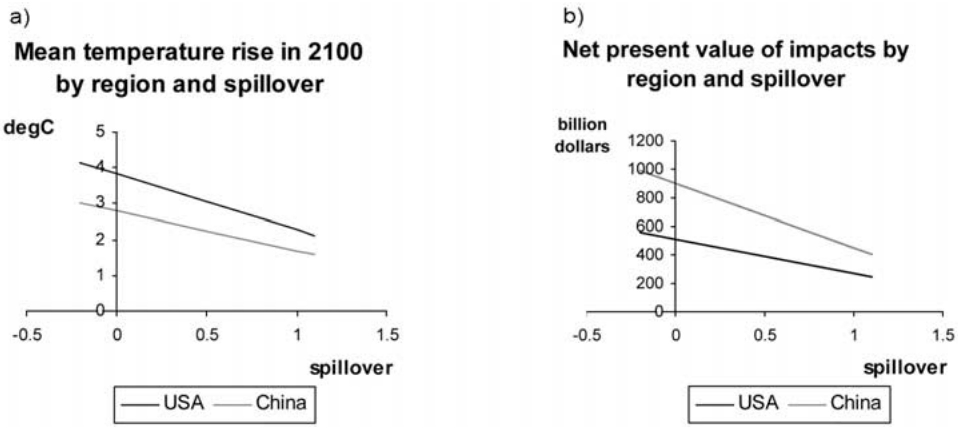

Figure 5. Regional results and economic impacts: Illustrations for the U.S. and China.

reduce mean sea level rise in 2100 by about 10 cm in the uncontrolled case, and by nearly 40 cm under the controlled scenario. As sea level continues to rise for many decades after concentrations have stabilised, the impact of spillover upon sea level rise in the 22nd century would be even greater.

As well as calculating global impacts, PAGE95 calculates them for eight regions of the world. We present here results for the U.S.A. and China as representatives of Annex I and non-Annex I countries. In this, we include a valuation of the climate change impacts, as well as regional temperature changes, for the Kyoto plus 1% per year decline scenario considered above.

Figure 5a shows the mean estimates of temperature rise by 2100 in the U.S.A. and in China. The temperature rise is lower in China because the emissions of sulphates, which have mainly a regional effect, are higher there than in the U.S.A. With no spillover, the 90% confidence interval for the temperature rise by 2100 in the U.S.A. is 2.1 to 6.0 °C, and 1.3 to 4.8 °C in China. Comparing these uncertainties with the results in Figure 4 shows that the mean effect of the spillover from industrialised to developing countries (reducing global mean temperature rise in 2100 to 2.7–3.4 °C) is very similar to the cumulative effect of all the other more traditional uncertainties – about sensitivity to CO_2 doubling, the lifetime of CO_2 in the atmosphere, the effects of CO_2 fertilisation and so forth.

Figure 5b shows the mean net present impacts of climate change in the U.S.A. and China. Even though spillover only affects emissions in the developing countries, the lower CO_2 concentration brings benefits in all regions. In particular, international spillover multiplies the returns to emission controls in the industrialised world, halving the mean net present impact of climate change in the U.S. at unitary spillover.

The valuation of impacts is a controversial issue. The mean valuations given here are based upon the default valuations in the PAGE95 model (Hope and Maul, 1996; Plambeck and Hope, 1996). These assume aggressive adaptation measures are taken, which are highly effective at reducing the impacts in economic sectors in Annex I countries, but are less successful elsewhere. The net present valuation assumes a 3% rate of pure time preference, and a time horizon of 2200. Under these assumptions, spillover of 0.5–1.0 brings global mean net present benefits worth 0.7–1.4 trillion dollars in scenario A2, and 1.9–3.7 trillion dollars in the controlled scenario.

With no spillover, the 90% confidence intervals for mean net present impacts are $220 to $1200 billion for the U.S.A. and $810 to $4100 billion for China. For the world as a whole the net present impacts have a 90% confidence interval of 2.1 to 21.4 trillion dollars, with a mean value of 9.0 trillion dollars. There is a wider range of uncertainty about economic impacts than about temperature rise because the valuation of impacts brings additional uncertainties to those already present in the science of climate change.

We conclude also that despite considerable and continuing uncertainties, the issue of international spillover is crucial to any serious analysis of long-run climate change control. Projections cannot continue to assume that spillover is either zero, or is restricted to the negative, substitution-based leakage of most current economic models. The uncertainties, and opportunities, arising from the long term cumulation of positive spillovers are far too important to ignore.

7. Conclusions

Responses to the problem of climate change are clearly emerging. The rapid growth of renewable energy capacities in Europe with associated major cost reductions, and the heavy investment in fuel cell vehicle technologies by the major vehicle companies, indicate how technologies and companies are beginning to respond to both existing policies and the expectation of future policies in pursuit of the Kyoto targets.

Action taken by the industrialised countries will influence emissions in developing countries in varied ways. We have distinguished three main classes of international spillover. Economic substitution driven by price changes can result in ‘leakage’ generally estimated by economic models at 5–20%. However, as better low-carbon technologies and industries develop and become more efficient and established, these will tend to diffuse internationally, counteracting such leakage; this effect is not captured in the models but seems likely to dominate over time. In addition, industrialised country action is a necessary precursor for stronger action within developing countries. In previous environmental regimes, developing countries have become progressively more involved over time as industrialised country action leads the way; the rolling 5-year structure of the Kyoto commitments regime provides a natural structure for drawing more countries into quantified commitments over time, as appropriate to their level of development.

In modeling terms, casting the analysis in terms of lower carbon intensities reflects the view that energy technologies and systems will develop in response to carbon constraints given sufficient time, and that these adaptations and associated responses will diffuse internationally. In essence, adjustment costs borne by the leading group pave the way for lower trajectories in the rest of the world, and this will also yield multiplicative returns upon industrialised country actions and technology investments.

Overall, our analysis demonstrates that the spillover from industrialised country action can exert huge leverage on global emissions and hence climatic impacts are sensitive to the degree of spillover assumed. General economic processes of international investment and the dissemination of technologies and ideas – accelerated by specific provisions on technology transfer and other processes under the Convention and the Protocol – could contribute to global dissemination of cleaner technologies and practices. In addition, action by industrialised countries will pave the way for stronger action within the developing world.

We emphasise that the uncertainties and the varied components of spillover need more exploration. Nevertheless we conclude that international spillover, in all its forms, is extremely important. It highlights how initial implementation of industrialised country commitments could generate solutions that diffuse globally, and in so doing enable subsequent broader action in successive commitment periods, thus providing the foundation for global solutions to the world's most daunting environmental problem.

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