Expecting the Unexpected:

Macroeconomic Volatility and Climate Policy*

Warwick J. McKibbin**
Australian National University,
The Brookings Institution and
The Lowy Institute for International Policy

Adele Morris
The Brookings Institution

Peter J. Wilcoxen
The Maxwell School, Syracuse University and
The Brookings Institution

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** Send correspondence to Professor Warwick J McKibbin, Centre for Applied Macroeconomic Analysis, ANU College of Business and Economics, Australian National University, ACT 0200, Australia. Tel: 61-2-61250301, Fax: 61-2-61253700, Email: warwick.mckibbin@anu.edu.au.

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ABSTRACT

To estimate the emissions reductions and costs of a climate policy, analysts usually compare a policy scenario with a baseline scenario of future economic conditions without the policy. Both scenarios require assumptions about the future course of numerous factors such as population growth, technical change, and non-climate policies like taxes. The results are only reliable to the extent that the future turns out to be reasonably close to the assumptions that went into the model. This paper examines two kinds of unanticipated macroeconomic shocks under two global climate policy architectures. We explore potential unanticipated interactions between climate policy and macroeconomic events on emissions and economic activity, paying special attention to outcomes that could undermine individual countries' incentives to remain party to the global agreement.

The first shock we examine is high economic growth in developing countries, not unlike the rapid economic expansion in China and India over the last decade. The second shock is a global financial crisis with significant downturns in the housing sectors of developed countries. Using the G-Cubed model, we examine the effect of the shocks on economic activity, carbon emissions, and marginal carbon abatement costs under two canonical climate policy regimes: a global cap and trade system (which fixes emissions quantities) and a policy that equalizes global marginal costs of carbon abatement (which fixes carbon prices). Our results for the pricing approach could be consistent with a global carbon tax or a cap and trade program with full

optimal banking and borrowing. For each policy, we compare the outcome after the shocks with a reference scenario in which the quantity and price approaches are calibrated to produce the same emissions abatement and the same marginal costs.

We find that both a regime of fixed emissions levels strongly propagates growth shocks between regions while price-based systems do not. We also find that in a global downturn, a price-based system exacerbates the economic decline. Overall, quantity-based policies perform badly during unexpected economic booms and price-based policies perform badly during downturns. Indeed, we find that under a quantity-based policy, the rise in the global price of permits in a growth shock is so large that GDP in some economies actually contracts, creating an incentive for such countries to withdraw from the arrangement.

Finally, we argue that a hybrid policy could avoid the problems of both pure price and pure quantity approaches and would therefore be more stable over long periods of time.

1. Introduction

The global financial crisis, a deepening global recession, and continued turmoil in credit markets drive home the importance of developing a global climate architecture that can withstand major economic disruptions. A well-designed global climate regime and the attendant domestic policies in participating countries need to be resilient to large and unexpected changes in economic growth, technology, energy prices, demographic trends, and other factors that drive costs of abatement and emissions. Ideally, the climate regime would not exacerbate macroeconomic shocks, and would possibly buffer them instead, while withstanding defaults by individual members. Because climate policy must endure indefinitely in order to stabilize atmospheric concentrations of greenhouse gases, all sorts of shocks will occur at some stage in the policy's existence. Anticipating such shocks may mean rejecting policies that might reduce emissions reliably in stable economic conditions but would be vulnerable to collapse—with consequent deterioration in environmental outcomes—in volatile conditions.

Macroeconomic volatility is the practical manifestation of an issue that has received considerable attention in the theoretical literature on the design of environmental policies: uncertainty about the costs and benefits of reducing emissions.[1] In particular, macroeconomic shocks can cause the cost of regulation to be much higher or lower than anticipated. Unexpectedly stringent and costly regulations may become political lightning rods. Recent world events, for example, highlight the fact that economic surprises can subject governments to enormous pressures to relax or repeal taxes or other policies perceived to impede economic growth. For a climate policy to survive future shocks, therefore, it must not violate time

[1] See, for example, Weitzman (1974), Roberts and Spence (1976), Pizer (1997), McKibbin and Wilcoxen (1997), Pezzey (2003), von Below and Persson (2008), Hoel and Karp (2002) and Quirion (2004).

consistency: it must be optimal for each government to continue to enforce the policy even when confronted with sharp departures from the conditions expected when the governments undertook the commitments. All else equal, a climate regime that exacerbates downward macroeconomic shocks or depresses the benefits of positive macroeconomic shocks would be more costly and less stable than a system that better handles global business cycles and other volatility.

The stability of the policy has important environmental implications for two reasons. First, collapse of the policy could set back progress on emissions reductions for years. Second, decisions of economic actors depend on their expectations of future policy, and this dependency affects the performance of the policy itself.[2] In the case of climate change, a system that is more robust to shocks, and is thus more likely to persist, would increase the expected payoffs of investments in new technologies and emissions reductions relative to a system that is less robust. In particular, a system of rigid and ambitious targets may seem the most environmentally rigorous approach, but if the rigidity decreases the probability the agreement would be ratified, or reduces compliance, or limits long term participation, households and firms will take that into account in their investment decisions. They will invest too little in abatement and alternative energy technologies, causing the system to be less effective in practice that one with more flexibility. If governments try to compensate for low credibility by imposing more a stringent target, they could inadvertently worsen the incentives for investment by further reducing the program's credibility. This all points to the central importance of establishing a regime that is credibly robust to changing economic conditions.

This paper uses the G-Cubed model to explore how shocks in the global economy propagate differently depending on the design of the climate policy regime. G-Cubed divides the

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[2] Kydland and Prescott (1977) make this point more broadly.

world economy into ten regions: the US, the EU, Japan, Australia, the rest of the OECD, Eastern Europe and the Former Soviet Union, China, India, other developing countries, and oil exporting developing countries.[3] Using the model, we construct two reference case scenarios for policies for addressing climate change: a quantity-based approach similar to an international cap and trade system and a price-based approach similar to a harmonized carbon tax.[4] The scenarios are calibrated so that they produce identical emissions levels and marginal abatement costs in the absence of unexpected shocks. We then subject each of the policies to two kinds of shocks relevant to recent experience: (1) a positive shock to economic growth in China, India, and other developing countries, and (2) a sharp decline in housing markets and a rise in global equity risk premiums, causing severe financial distress in the global economy. We analyze the effects of each shock on key economic indicators for the first decade after the shock occurs. We compare the results from the two policy regimes and draw inferences about the strengths and weaknesses of each regime in the context of these economic disruptions. We then compare the two regimes against a hybrid policy, such as of the form described in McKibbin and Wilcoxen (2002a).

A number of authors have explored the properties of different climate policies under uncertainty. Much of the work has focused on the relative advantages of intensity-based approaches in which national emissions targets are indexed to GDP. For example, Ellerman and Sue Wing (2003) and Sue Wing et al (2006) compare the performance of an intensity-based policy to a traditional system of fixed absolute emissions limits when future GDP growth is uncertain. They find that the intensity-based system leads to abatement that is more predictable

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[3] The model is summarized in Appendix A and described more fully in McKibbin and Wilcoxen (1998).

[4] The quantity and price approaches we model are polar policy cases that produce the most extreme potential interactions of climate policy and macroeconomic shocks. Other policy proposals, such as a cap and trade system that allows banking, lie between these poles so our results reflect the bounds of likely climate policy on the effects of interest.

and less volatile. Jotzo and Pezzey (2005) examine GDP-indexed intensity targets in an international context and show that by reducing uncertainty, indexing can encourage countries to adopt more stringent emissions targets than would be optimal under a traditional permit system. Fischer and Springborn (2007) add to the literature by examining the performance of intensity targets under uncertainty using a real business cycle model. They point out that although intensity-based policies provide greater stability of abatement than ordinary permit systems, it comes at the cost of increasing the variability of emissions. They also emphasize that conventional permit systems act as a form of automatic stabilizer, with permit prices (and therefore the effective stringency of the policy) increasing in booms and decreasing during downturns.

In this study we extend the literature in two respects: we explore how the global climate regime can affect the propagation of shocks between economies, and we use that information to evaluate the merits of a hybrid policy. We find that although quantity-based and price-based climate regimes are similar in their ability to reduce carbon emissions efficiently in the absence of shocks, they differ importantly in how they affect the transmission of economic disturbances between economies. In particular, a quantity target with an annual cap on global emissions can cause unexpectedly high growth in one country to reduce growth in other economies or even force their growth to be negative. The rise in the global carbon price caused by higher growth can have a larger negative impact on other economies than the positive spillover of growth through trade. This effect is absent in the price-based regime. However, in the case of the global financial crisis we find that the quantity-based approach works well because it is globally counter-cyclical: carbon prices fall as the world economy slows, which acts to dampen the economic slowdown. A hybrid policy, however, could achieve the best of both policies: it could provide the counter-cyclical advantages of a permit system in a downturn but also provide the flexibility of a price-based mechanism in a boom.

We discuss each climate policy system in more detail in Section 2. Section 3 reviews key sources of uncertainty in the design of climate policy and describes the particular shocks we introduce into the model. Section 4 reviews the results, and Section 5 concludes, with particular emphasis on the policy relevant insights from the study.

2. Alternative Climate Policy Regimes

Analysts have offered a wide range of alternative frameworks for international climate policy upon the expiry of the Kyoto Protocol in 2012.[5] Each of these approaches has advantages and disadvantages with respect to stability in the face of shocks. Some propose an agreement similar to the Kyoto Protocol with targets and broader participation. Frankel (2007) explains that targets could be indexed to economic growth so that parties do not face unanticipated stringency with strong economic growth or benefit from international allowance sales when their reductions are a result of downturns and rather than explicit actions on climate. Bodansky (2007) argues that targets and timetables have proven to be politically untenable for those who sat out the Kyoto Protocol and that the successor agreement should be more flexible. For example, the agreement could include an explicit range of domestic actions that parties could take including taxes, efficiency standards, and indexed targets, with the mix chosen at the discretion of each party. Some combination of targets and timetables for industrialized countries and more flexible provisions for developing countries could emerge as parties seek to expand participation and China and India resist hard national targets.

An agreement that is tailored at least to some extent to different countries' national circumstances is likely. Nonetheless, analysis of more analytically tractable policies is useful.

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[5] See for example Aldy and Stavins (2007).

Analysts have paid particular attention to an international system of binding emissions caps, like the Kyoto Protocol, that reaches a specified target with certainty (at least in principle) and a system of agreed price signals on greenhouse gas emissions, such as a harmonized carbon tax, which promises a certain level of effort but leaves emissions levels uncertain. For example, Nordhaus (2006) and others find that a price signal approach reduces the risk of inadvertent stringency and is likely to be more efficient than a system of hard caps in the context of uncertainty over both the costs and benefits of abatement.

In addition to conventional price or quantity approaches, hybrid policies have been proposed that would combine features of cap and trade and a tax in a way that seeks to capture the advantages of each. The hybrid system proposed in McKibbin and Wilcoxen (2002a and 2002b) would create and distribute a set of long-term permits, each entitling the owner to emit a specified amount of carbon every year for the life of the permit. Once distributed, the long-term permits could be traded among firms, or bought and retired by environmental groups. In addition, the government would agree to sell annual permits for a pre-set but increasing fee (possibly harmonized within an international agreement). There would be no restriction on the number of annual permits sold, but each permit would be good only in the year it is issued.

Under the McKibbin-Wilcoxen hybrid, robust economic growth leads to more demand for emissions permits than can be satisfied by the long-term permits alone. The government would supply the difference via annual permits and the policy would essentially function as a tax at the margin. However, during a severe downturn, the demand for permits could drop enough that it could be supplied entirely by long-term permits. In that case, the rental price of a permit would drop below the government's annual permit price and the policy would behave like an ordinary permit system. As we discuss below, the fact that the hybrid can perform like a tax in a boom and like a permit system in a downturn is an important strength.

A key attribute of any climate policy is its ability to build a constituency that would oppose its repeal.[6] Any significant climate policy will have important distributional implications within the country adopting it. Large transfers of income that involve organized sub-groups are particularly likely to affect the political dynamics of the program. Such transfers could become increasingly important as the stringency of the climate policy increases, particularly if marginal abatement costs do not fall over time. For example, a carbon tax contributing to general government revenue could generate increasingly strong political pressure for its repeal or relaxation as the tax rate rises. This could be true even if the tax is fully revenue neutral because as the effect on energy prices becomes increasingly salient, energy-intensive stakeholders would organize against it. A carbon tax in which the revenues are earmarked for particular purposes may develop the same sort of constituency that other special interest tax provisions do, and the political contention would then be between recipients of the revenue and those on whom the tax falls.

A hybrid system or a conventional cap and trade policy in which all the allowances are in the hands of private actors, such as electric utilities, produces a constituency with a strong financial stake in perpetuation of the policy, which may help counteract objections from those who bear the costs of abatement, such as electricity consumers. However, a cap and trade policy with annual allowance auctions and revenue recycling would run some of the same political risks as a carbon tax that funds the general treasury, with the exception that holders of banked allowances and private futures and options contracts on emissions allowances would have an incentive to preserve their asset values.

[6] For a discussion of this topic, see McKibbin and Wilcoxen (2002a, 2002b).

3. Sources of Uncertainty and Shocks

Many uncertainties affect the optimal climate policy and the willingness of individual countries to undertake binding international commitments. A key uncertainty is the cost of complying with any given commitment, making it risky for a country to agree to a hard target that may later prove to be infeasible. Uncertainty in economic growth, energy prices, and the development and cost of abatement technologies all contribute to uncertainty in costs.[7] Because these factors are not necessarily correlated, together they could amplify or attenuate the overall stringency of the program. For example, higher than expected macroeconomic growth would increase the stringency of a given cap, but if accompanied by the development of technologies with lower than expected abatement costs, the net effect of these dual shocks could be modest. But at its core, the targets and timetables approach requires each participant to achieve its national emissions target regardless of the cost of doing so. Even if the targets are indexed to factors correlated with the feasibility of the target, the basic approach does not bound costs.

The history of the Kyoto Protocol shows that ambitious targets do not guarantee significant reductions. Countries facing potentially high costs either refused to ratify the protocol, such as the United States, or have so far failed to achieve an emissions level consistent with their 2008 to 2012 targets. The latter group is not necessarily out of compliance with the protocol since it may be possible for those countries to acquire allowances from other protocol participants before the end of the commitment period. However, countries that are on track to reduce emissions to match their assigned amounts have been aided by historical events largely unrelated to climate policy, such as German reunification, the Thatcher government's reform of

[7] For a range of estimates of the costs of complying with the Kyoto Protocol, see Weyant (1999). Other studies include Bohringer (2001), Kemfert (2001), Buchner et al. (2002), Loschel and Zhang (2002), International Monetary Fund (2008). Literature surveys appear in the Intergovernmental Panel on Climate Change (2001, 2007).

coal mining in Britain, or the collapse of the Soviet economy in the early 1990's. This suggests that despite sincere intentions of those countries that ratified the Kyoto Protocol, the targets negotiated in 1997 did not fully anticipate the economic expansion of the ensuing years.

The uncertainty each country faces around its own growth matters, but in a global economy—and particularly with international allowance trading—other countries' growth matters, too. For example, even if a country perfectly predicts its own economic performance, higher than expected growth in another major economy could induce inadvertent stringency by increasing the global demand for permits. To quantify this effect and others, in Section 4 we explore what happens if China, India, and other developing countries experience unexpectedly high levels of growth during the tenure of a climate policy. We compare and contrast the impacts of this shock in a regime of harmonized global price on carbon and a global cap and trade system.

The experiment is highly pertinent to recent growth trends in Asia. As an example of how difficult it is to project the future even over short periods, Figure 1 (from McKibbin Wilcoxen and Woo [2008]) shows projections for Chinese energy consumption from the *2002 International Energy Outlook* and the *2007 International Energy Outlook*.[8] The surprising fact is that for the future years that were overlapping in both reports, in every case China's projected energy consumption in the *low*-growth scenario in the 2007 report was above the projected energy consumption in the *high*-growth scenario in the 2002 report. For example, the 2002 high-growth forecast for 2020 was 103 quadrillion BTU and the 2007 low-growth forecast for 2020 was 107 quadrillion BTU: that is, the updated low-growth forecast was 4 quadrillion BTU *above* the original high-growth forecast.

The change in the *International Energy Outlook*'s reference case forecast emphasizes

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[8] Energy Information Administration (2002, 2007)

how much expectations changed between the two editions: the 2002 reference case forecast was 84 quadrillion BTU in 2020, and the 2007 reference case forecast was 113 quadrillion BTU in 2020 – an upward revision of 34 percent. Even more important, carbon dioxide emissions in 2005 were 50 percent higher than the forecast for 2005 made in 2002. The surge in energy use since 2002 is obvious from the figure, and it resulted from a number of factors including rising growth in gross domestic product (GDP) since 1998 as well as a rise in the energy intensity of GDP. The shift in the energy intensity of the Chinese economy was due to a number of factors driving structural change including: increased electrification; greater energy demand from manufacturing; greater energy demand by households; and greater use of cement and steel as infrastructure spending has risen. The unexpected growth shock we present in Section 4 is similar to that experienced by China over this period.

For comparison, we also examine a second unexpected event: a financial crisis of roughly the magnitude of one unfolding in the fall of 2008. As discussed in Section 4, we impose an unexpected fall in the return to housing in each economy, with the largest drop occurring in the United States. We add to this an exogenous rise in the equity risk premium in all sectors in all economies. Together, the shocks causes a substantial financial crisis including a sharp fall in equity markets, declines in household wealth, a sharp contraction in consumption, a jump in the required rate of return on investment, and a sharp decline in investment. These adjustments lead to a global recession.

4. Methodology and Results

In this section we use a global economic model called G-Cubed to explore the uncertainties in costs and carbon abatement under a pair of alternative climate policies. G-Cubed is a widely-used intertemporal general equilibrium model of the world economy. It divides the world into the ten regions listed in Table 1: the United States, Japan, Australia, Europe, a region representing the rest of the OECD (often abbreviated ROECD in the remainder of the paper), China, India, oil exporting developing countries (OPEC), Eastern Europe and the former Soviet Union (abbreviated EEFSU), and a final region representing all other developing countries (LDC). Each region is subdivided into the 13 industries listed in Table 2. The model produces annual results for trajectories running decades into the future. Appendix A provides additional details.[9]

We begin by generating a baseline projection as set out in detail in McKibbin and Wilcoxen (2008).[10] In the baseline, we assume that one of two canonical market-based climate policies (discussed further below) will be implemented to constrain greenhouse gas emissions relative to business-as-usual. Under either policy, emissions in each country, and for the world as a whole, are initially allowed to rise along a business-as-usual path until 2028. In effect, we assume that through 2028, the baseline climate policy grants each country exactly the number of emissions permits it would need for its business-as-usual emissions. After 2028, however, both policies require that emissions begin to fall. By 2050, global emissions are 10 percent below 2002 levels, and by 2100 they are 60 percent below. This trajectory is consistent with the World Economic Outlook (International Monetary Fund [2008]) and provides a useful starting point for evaluating the effects of unexpected shocks that might occur after the policy was adopted.

The two climate policies we consider are a global cap and trade system for carbon dioxide emissions, which we will refer to a quantity-based approach, and a price-based approach calibrated to induce an identical emissions trajectory. The price-based approach harmonizes the

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[9] See McKibbin and Wilcoxen (1998) for a complete description. The version of G-Cubed used in this paper is 80J.

[10] See McKibbin, Pearce and Stegman (2007) for a discussion of the importance of structural change in undertaking long term projections.

marginal cost of carbon abatement globally; possible implementations include a harmonized carbon tax, a cap and trade system with full banking and borrowing, or a hybrid policy along the lines of McKibbin and Wilcoxen (2002a).[11] The two regimes are normalized so that they produce identical trajectories for carbon prices and emissions absent any unforeseen shocks.

We then subject each regime to a pair of unexpected shocks: a productivity boom in developing countries and a global financial crisis. All told, there are four policy simulations: the two shocks run against two climate policies. In each case, we assume that the applicable climate regime is in place when the shock arrives.[12] Comparing the results for each shock under the two policies illustrates the strengths and weaknesses of each approach.

In each scenario, we hold climate and broader economic policy rules constant. The fiscal deficit of each economy is held at its baseline level, as are tax rates, so changes in tax revenues will result in corresponding changes in government spending.[13] The behavior of each region's central bank follows a region-specific Henderson-McKibbin-Taylor rule with a weight on output growth relative to trend, a weight on inflation relative to trend and a weight on exchange rate volatility.[14] The weights vary across countries with industrialized economies focusing on controlling inflation and output volatility, and developing countries placing a large weight on

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[11] The carbon tax and the hybrid policy would not be equivalent under a more severe shock to the world economy. If the shock were sufficiently damaging, the demand for emissions permits in one or more countries might drop low enough that no annual permits would be sold in that country. In that case, carbon prices would vary across countries and the Hybrid would have some of the counter-cyclical properties of a pure permit system. In the results presented here, however, the demand for permits is large enough that at least a few annual permits are sold under all circumstances.

[12] This approach was chosen to illustrate how each shock affects the global economy under each regime. Clearly this is not a reflection of current state of global climate policy.

[13] The assumption that fiscal deficits remain fixed is clearly at odds with current economic situation. We hold them constant in this paper in order to isolate the effect of the shock itself. Future research could assess the impacts of fiscal policy used for stabilization on emissions and abatement costs.

[14] See Henderson and McKibbin (1993) and Taylor (1993).

pegging the exchange rate to the US dollar.

4.1 Developing country growth shock

The first scenario we consider is an unexpected rise in growth rates in China, India and LDC region. The particular shock we analyze is an unexpected increase in labor productivity growth of three percent per year for sixteen years, after which each country's productivity growth returns to its baseline rate. The rise in productivity expands the effective supply of labor to each economy, rapidly increasing output in each sector and raising GDP. At the same time, it also increases the marginal product of capital, which causes a large rise in private investment in all three countries. The higher investment is financed partly from capital inflows, which cause each of the three currencies to appreciate and the countries' trade balances to worsen, and partly from higher domestic savings. Household consumption, as a result, rises more slowly than GDP. After the growth rates return to their baseline levels, the three economies are permanently larger. After 10 years, China's GDP is about 15 percent larger than it would have been in the baseline; India's GDP is 18 percent larger; and the GDP of the LDC region is almost 20 percent higher.

Strong growth in the developing countries is transmitted positively to other countries. Direct transmission occurs through increased trade flows between developed and developing countries. In addition, indirect transmission occurs through higher global wealth and increased trade flows more generally. The benefits of productivity growth in one country are also transmitted through international capital flows responding to the return to capital. Capital achieves a higher rate of return in rapidly growing economies and the resulting capital flows raise incomes globally.

The effect of the growth shock on the GDP of other regions is shown in Figure 2 for the price-based climate policy. The shock eventually leads to higher GDP in every country, although the timing and magnitude of the increase varies considerably. The United States, for example, experiences a slight decline in GDP at the onset of the shock, but quickly moves above the baseline. By the 10th year, US GDP is nearly 0.5 percent larger than it would have been otherwise. Japan experiences an immediate increase in GDP of 0.6 percent and by year 10 it is more than one percent higher than its baseline. The outcome for Australia is similar in timing to that of the US but larger in magnitude: its initial decline is -0.2 percent, about twice the US value, and by year 10 its GDP is 0.7 percent above the baseline. Three regions, however, experience a significant short-run reduction in GDP: ROECD, EEFSU, and OPEC. By year 10, however, GDP in ROECD has returned to baseline and GDP in EEFSU and OPEC is substantially above baseline.

The acceleration in GDP growth raises energy consumption and increases carbon emissions. China's and India's emissions grow faster than their GDPs: after ten years, China's emissions are 17 percent above baseline even though its GDP has only rise by 15 percent, and India's emissions are 23 percent above baseline while its GDP has increased by 18 percent. For the LDC region, emissions rise roughly in proportion to GDP: after ten years both are about 20 percent above their baseline values. The effect of the shock on emissions from other regions is shown in Figure 3. In all cases, the percentage change is much smaller than it was for the countries directly subject to the shock. The largest percentage change occurs in Japan, which sees its carbon emissions rise by about two percent after ten years. Emissions in the US rise by a little more than one percent—a considerable amount in absolute terms—and by less in most other countries. After a decade, emissions are at least slightly higher in all regions other than the rest of the OECD, which essentially remains at its baseline value.

In contrast, under a quantity-based climate policy the effect of the growth shock on GDP is less positive (or more negative) for every country in every year. The shock raises the demand for energy worldwide, which pushes up the price of emissions permits and effectively tightens the global emissions constraint. The permit price rises gradually and is $11 per ton of carbon higher after 10 years. The increase in productivity, which would otherwise tend to raise GDP, is thus partially offset by the tighter constraint. The overall effect varies across countries. China's GDP after 10 years is about 14 percent larger than the reference case rather than 15 percent. The effect on India and the LDC region is similar: year 10 GDP in both is about 1 percent smaller under the quantity policy than under the price-based policy. Although the form of the climate policy affects GDP in these countries, the impact is relatively small compared to the improvement due to higher productivity growth.

The effects on the remaining countries are shown in Figure 4. For the US, the amplitude of the GDP effect is considerably smaller in every year relative to the price-based policy, and the shock no longer has much effect at all. For Japan and Europe, the GDP effects are also smaller but are all still positive and significant in magnitude. For Australia, in contrast, the shock is no longer bad in the short run and good in the long run: under the quantity-based policy, Australian GDP is lower in every year. For ROECD, EEFSU and OPEC, under a quantity-based policy the growth shock is bad in the short run and even worse in the long run: the effect on GDP is negative and increases over time. For these three regions and Australia, a growth shock occurring under a climate system with a hard emissions cap raises abatement costs so much that the added costs outweigh the benefit from trade and financial spillovers.

The difference in GDP outcomes under the two policies is illustrated by Figure 5, which shows the GDP effect in year 5 under the price-based policy less the GDP effect under the quantity-based policy. In terms of GDP in year 5, the US and Japan would be better off by 0.2 percent under the price-based policy; Europe would be better off by 0.3 percent; Australia, ROECD and LDC by 0.5 percent; OPEC, China and India by 0.7 percent; and EEFSU would be better off by more than 1.5 percent.

The effects of the growth shock on emissions under a quantity policy differ considerably from the results under a price policy. By year 10, China's emissions are only 0.5 percent above baseline. China's emissions are sharply lower under the quantity policy because China's marginal abatement cost curve is relatively elastic: it is cheaper for the Chinese economy to keep emissions from growing than to buy additional permits on the world market. Emissions for India and the LDCs rise considerably more—by 12 and 13 percent relative to the baseline—but the increases are much smaller than under the price policy. Emissions from most of the other regions fall, as shown in Figure 6. The effect of the constraint on emissions is clear: in order for emissions from India and the LDCs to rise, emissions from the US, Australia, the rest of the OECD and Eastern Europe and the Former Soviet Union fall considerably. US emissions drop by 6 percent relative to the baseline, as do emissions from ROECD. Australian emissions drop by a little less, 4 percent, while emissions from EEFSU drop by much more: nearly 14 percent. Table 3 summarizes each region's changes in emissions in year 10 under both policies.

In summary, unexpectedly strong economic growth in one part of the world has sharply different effects under price-based and quantity-based climate policies. As would be expected from economic theory, a price-based policy accommodates the shock by allowing emissions to rise, and a quantity-based policy restrains emissions by allowing the price of permits to rise. What our results emphasize, however, is the magnitude of the effect. Under a quantity-based policy, the rise in the price of permits does more than slow GDP growth marginally: for several economies, GDP actually contracts. For those regions, the rise is more than enough to completely offset positive spillovers from the productivity shock. In contrast, under a price-based policy all regions eventually share in the gains, although emissions rise as a consequence. Roughly speaking, a quantity-based policy adds a strong zero-sum element to an event that would otherwise produce gains for everyone.

4.2 Rise in global risk: a financial crisis

The second shock we consider is a global financial crisis. We chose it because it differs from the growth shock in two respects: it affects every region directly (as opposed to being concentrated in a few regions with only indirect effects on the remaining regions) and it is an adverse shock for all regions. We represent the crisis as a rise in the equity risk premium in all sectors in all countries. The premium increases by ten percent in the first year and then declines by one percent per year until year six. From year six on, it remains five percent above baseline. In addition we introduce a permanent fall in the productivity of housing in developed countries. The reduction is five percent in all developed countries other than the US and ten percent in the US. This is intended to capture a housing bubble bursting.[15]

The shock to the equity premium causes the risk-adjusted required return on capital to rise. Combined with the fall in developed-country housing productivity, it leads to a portfolio reallocation in all countries away from equities and housing and into government bonds. This drives up bond prices and drives down bond yields, as well as sharply lowering the prices of housing and equities. At the initial set of capital stocks, the actual return to capital is too low after the shock and investment thus collapses. As the capital stock shrinks, the marginal product of capital (and hence the rate of return) gradually rises toward its new equilibrium level. Consumption falls because of the sharp decline in real wealth and that, combined with lower investment, reduces GDP.

Figure 7 shows the effect of the risk shock on each region's GDP under the price-based policy. GDP drops below its baseline in all countries and all years. Initially, the largest effects

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[15] See McKibbin and Stoeckel (2006).

are felt by China, the US, ROECD and Japan, which experience immediate GDP declines of 6 percent, 4.5 percent, 3.2 percent and 2.5 percent, respectively. However, these four regions also rebound from the shock most quickly: China's GDP starts to recover in year 2 and the US, ROECD and Japan begin to recover in year 4. By year 10, the four regions are the closest to being back to their baseline GDPs. At the opposite end of the spectrum, OPEC is affected least in the first year but its GDP eventually falls furthest: to 7.8 percent below baseline in year 7. After that it begins to recover gradually but by year 10, its GDP is still 6.9 percent below baseline. The remaining regions—Europe, Australia, LDCs, India and EEFSU—lie in between: they experience short term declines of 1-2 percent, begin to recover in years 5 and 6, and are 3-5 percent below baseline in year 10.

Under the price-based policy, the carbon price is not affected by the shock and remains at its baseline level. As a result, it induces more abatement than planned when the economy grows more slowly than expected. As shown in Figure 8, emissions fall relative to the baseline in both the short and long run. For the regions other than OPEC and China, emissions drop by 1-3 percent at the onset of the shock and are down by 3-8 percent by year 10. China's immediate drop in emissions is larger, a decline of 6 percent, and OPEC's emissions actually increase very slightly in the first year. Both are consistent with the GDP effects for the corresponding countries: China's initial drop in GDP was largest and OPEC's was smallest. Over time, the largest change in emissions occurs in Eastern Europe and the Former Soviet Union: by year 6, EEFSU emissions have fallen by more than 10 percent and they remain nearly 8 percent below baseline in year 10.

Under the quantity-based policy, in contrast, emissions do not change but carbon prices fall. In the short run, the risk shock would cause permit prices to be $4 per ton of carbon lower than they would be in the baseline. The drop would gradually increase to $8 per ton by years 5 and 6 when the effects of the shock are at their peak. By year 10, permit prices would recover somewhat and would be $5 per ton below baseline.

Lower carbon abatement costs under a quantity-based policy help to moderate the decline in GDP caused by the risk shock. Figure 9 shows the difference in the effects of the two policies on GDP. The values plotted are the effect of the shock under the quantity policy less the effect of the shock under the price policy; a value of 1 percent, for example, indicates that GDP would be 1 percent higher under the quantity-based policy than it would under the price-based policy. Among the ten regions, EEFSU stands out: in the short run, its GDP under the quantity-based policy is 0.5 percent higher than it would be under the price-based policy; by year 6 the difference has widened to 1.75 percent; and by year 10, its GDP is still 1.2 percent higher under the quantity policy than it would be under the price policy. At the opposite pole are Japan, the US and Europe: all three are slightly better off under the quantity policy but the difference is at most 0.25 percent.

Under the quantity-based policy, the risk shock does not change the total amount of emissions but it shifts the geographic distribution substantially. Figure 10 shows the change in emissions by region for years 2, 5 and 10. In all three years, emissions shift significantly toward China. The effect is largest during the peak of the shock around year 5, when Chinese emissions are more than 8 percent higher than under the baseline. As noted in the discussion of the growth shock, China's abatement is very elastic with respect to the price of emissions permits.

To summarize the risk shock, we find that a price-based climate policy would tend to exacerbate the economic downturn caused by the shock. A quantity-based policy, on the other hand, tends to be countercyclical. Under a quantity-based policy, the drop in permit prices during a downturn prevents GDP in most countries from falling as sharply as it otherwise would. However, a quantity-based policy does produce significant changes in the geographic distribution of emissions and hence involves international transfers of wealth.

4.3 Summary

Our results show that neither of the main market-based policies performs well in all circumstances. A pure quantity-based approach behaves poorly when confronted with good economic news: in this case, an unexpected boom somewhere in the world economy. It causes permit prices to rise by enough that GDP in some regions would actually contract. Governments in those regions would be under severe pressure to abandon the policy. A pure price-based policy would allow emissions to rise somewhat, but it would be more likely to survive the episode intact. A price-based policy, on the other hand, has a significant disadvantage when economic events are worse than expected. It tends to exacerbate downturns by keeping the marginal cost of emissions high even in difficult economic conditions.

These results clearly demonstrate that unexpected future events may make sustaining an international climate agreement very difficult. However, a hybrid policy such as McKibbin and Wilcoxen (2002a) could avoid these problems.[16] Like a price-based policy, the provision for sales of annual permits would allow emissions to increase somewhat in order to accommodate an unexpected boom somewhere in the world economy. Unlike a pure quantity-based policy, it would not cause strong growth in one country to drive down growth among other participants in the agreement. At the same time, like a quantity-based policy, it would provide countercyclical stabilization during downturns. A sustained drop in economic growth would cause the rental price of a long-term permit to fall below the price of an annual permit. Sales of annual permits would cease until the economy recovered.

[16] Other hybrid approaches such as a cap and trade system with a safety valve would also avoid these problems.

5. Summary and Conclusions for Policy

The growth boom in China and the global financial crisis of 2008 have starkly emphasized a number of important lessons for the design of global and national climate policy. These lessons need to be considered explicitly during international negotiations on a new treaty to succeed the Kyoto Protocol after its 2008-2012 commitment period.

The first lesson is that a wide variety of macroeconomic shocks will undoubtedly occur over the coming decades, and a successful global climate framework would need to endure in spite of them. Thus there must be a mechanism built into the framework that directly addresses the issue of uncertainty and avoids imposing unsustainable economic costs during either an unexpected boom or bust. Otherwise, it will be much harder to negotiate a broad agreement, and the agreement may be vulnerable to collapse under adverse future shocks.

The second lesson is that it is critical to get the global and national governance structures right. There must be a clear regulatory regime in each country and a transparent way to smooth out excessive short-term volatility in prices. A system that enables or even encourages short term financial speculation in climate markets may collapse at huge expense to national economies. A hybrid system provides many of the advantages of a permit system while limiting opportunities for speculation through the annual permit mechanism. It provides a strong mix of market incentives and predictable government intervention.

The third lesson is that since shocks in one part of the world will certainly occur, the global system needs to have adequate firewalls between national climate systems to prevent destructive contagion from propagating local problems into a system-wide failure. A global cap and trade system, or alternative systems such as Stern (2006) or the Garnaut Review (2008), would be extremely vulnerable to shocks in any single economy. A system based on national hybrid policies, on the other hand, would be explicitly designed to partition national climate markets and limit the effects of a collapse in climate policy in one part of the world on climate markets elsewhere.[17]

This paper has explored these issues by examining the effects of shocks that have actually occurred in the past decade: a surprising surge of economic growth in developing countries and a global financial crisis. Quantity-based approaches such as a global permit trading regime tend to buffer some kinds of macroeconomic shocks: carbon prices rise and fall with the business cycle. However, price-based approaches such as a global carbon tax (levied at the national level) perform better during unexpected booms. A hybrid policy would provide the best of both worlds, and would build stronger firewalls to prevent adverse events in one carbon market from causing a collapse of the global system.

[17] For further discussion of the advantages of this point see McKibbin and Wilcoxen (2002a 2004, 2008).

Appendix A: The G-Cubed Model

The G-Cubed model is an intertemporal general equilibrium model of the world economy. The theoretical structure is outlined in McKibbin and Wilcoxen (1998)[18]. A number of studies—summarized in McKibbin and Vines (2000)—show that the G-cubed modeling approach has been useful in assessing a range of issues across a number of countries since the mid-1980s.[19] 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[20]. In contrast to static CGE models, time and dynamics are of fundamental importance in the G-Cubed model. The MSG-Cubed model is known as a DSGE (Dynamic Stochastic General Equilibrium) model in the macroeconomics literature and a Dynamic Intertemporal General Equilibrium (DIGE) model in the computable general equilibrium literature.

- In order to track the macro time series, 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 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

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[18] Full details of the model including a list of equations and parameters can be found online at: www.gcubed.com

[19] 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.

[20] See Blanchard and Fischer (1989) and Obstfeld and Rogoff (1996).

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.

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Table 1: Regions in the G-Cubed Model

Num	Name	Description
1	USA	United States
2	Japan	Japan
3	Australia	Australia
4	Europe	Europe
5	ROECD	Rest of the OECD
6	China	China
7	India	India
8	OPEC	Oil Exporting Developing Countries
9	EEFSU	Eastern Europe and the former Soviet Union
10	LDC	Other Developing Countries

Table 2: Sectors in Each Region

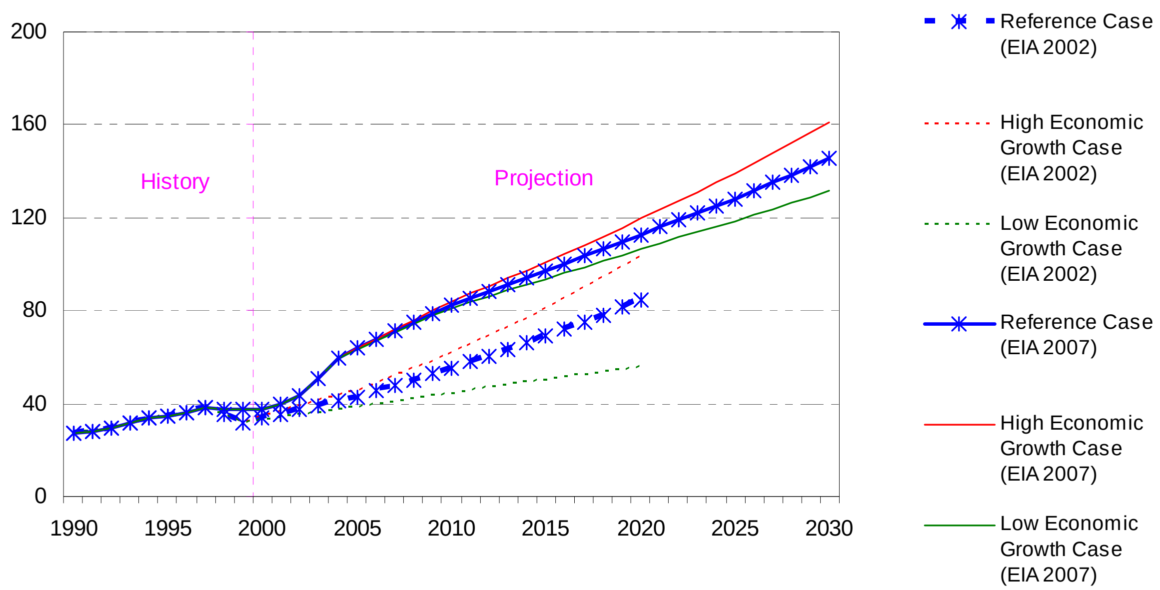
Num	Description
1	Electric Utilities
2	Gas Utilities
3	Petroleum Refining
4	Coal Mining
5	Crude Oil and Gas Extraction
6	Mining
7	Agriculture, Fishing and Hunting
8	Forestry/ Wood Products
9	Durable Manufacturing
10	Non-Durable Manufacturing
11	Transportation
12	Services
13	Capital Producing Sector

Table 3: Effect of a Growth Shock on Carbon Emissions in Year 10

Region	Price-Based Policy	Quantity-Based Policy
USA	1.4%	-6.2%
Japan	2.2%	0.1%
Australia	1.1%	-4.2%
Europe	0.8%	-1.2%
ROECD	-0.2%	-6.3%
EEFSU	0.5%	-13.3%
OPEC	0.3%	-0.7%
China	16.7%	0.5%
India	23.0%	11.9%
LDC	19.0%	13.4%

Figure 1: Comparison of projections of energy consumption for China

(Quadrillion Btu)



Note: The base years for projections reported in EIA 2002 and 2007 are 1999 and 2004, respectively.
Source: Energy Information Administration / International Energy Outlook 2002 and 2007

Source: Figure 1 in McKibbin Wilcoxen and Woo (2008)

Figure 2: Effect of a Growth Shock on GDP, Price Policy

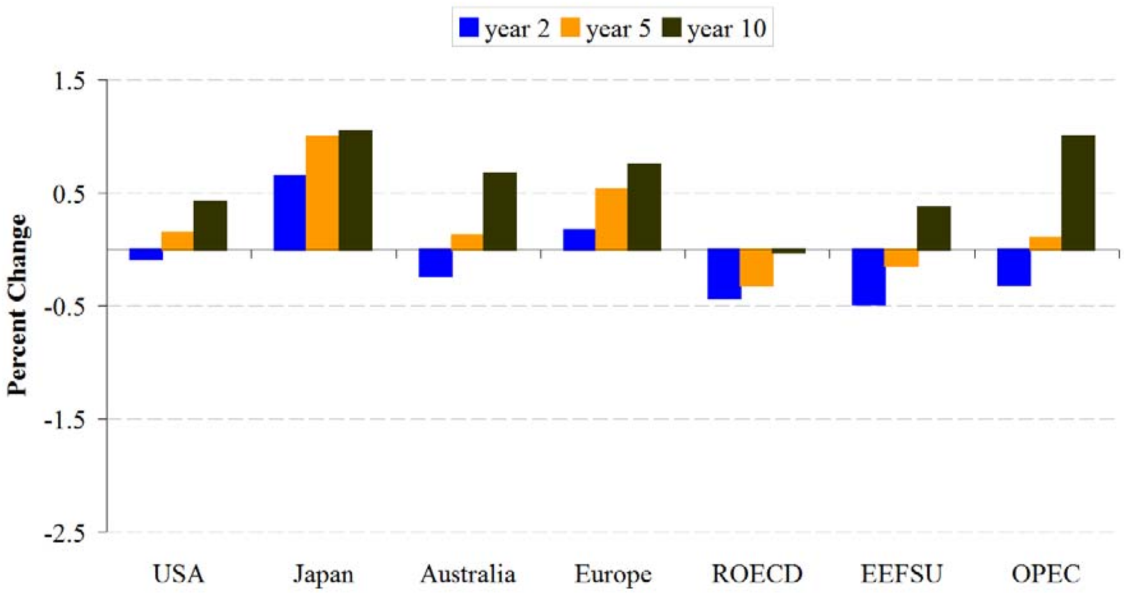


Figure 3: Effect of a Growth Shock on Emissions, Price Policy

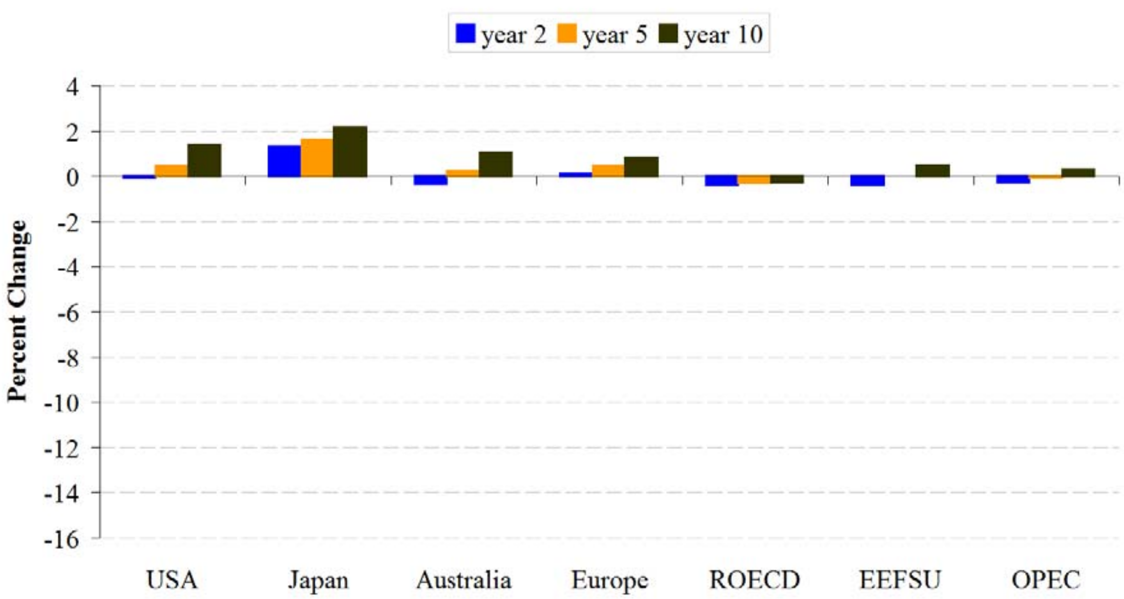


Figure 4: Effect of a Growth Shock on GDP, Quantity Policy

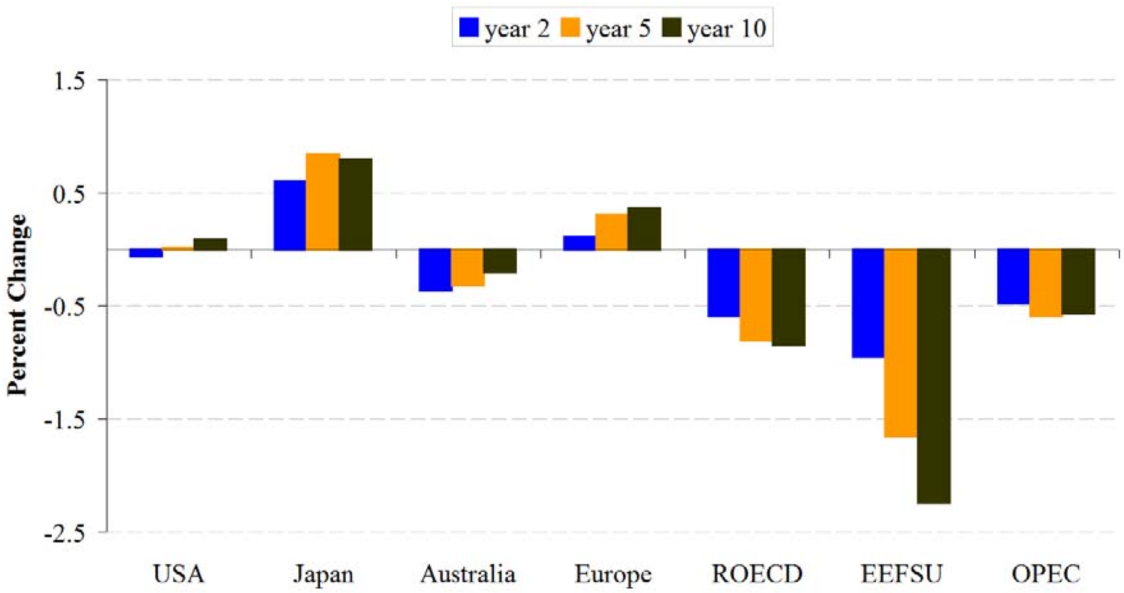


Figure 5: Year 5 Difference in GDP, Price less Quantity Result

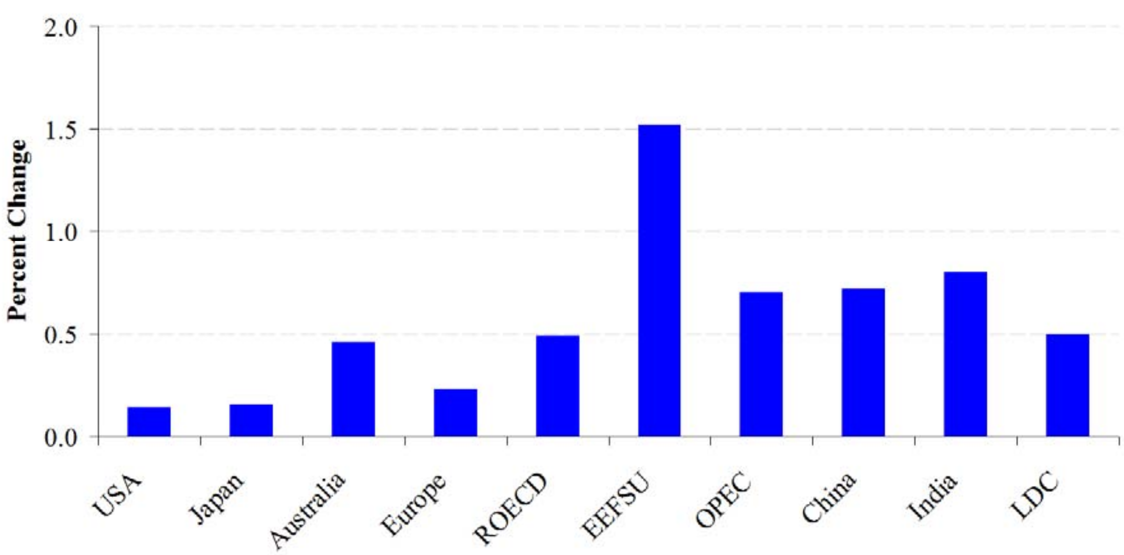


Figure 6: Effect of a Growth Shock on Emissions, Quantity Policy

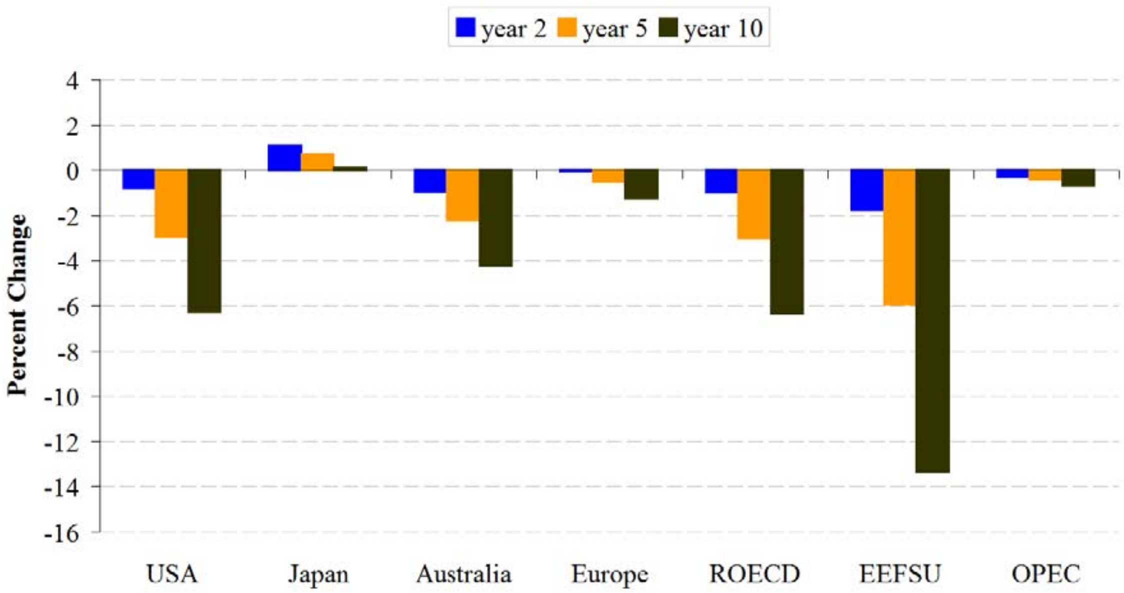


Figure 7: Effect of a Risk Shock on GDP, Price Policy

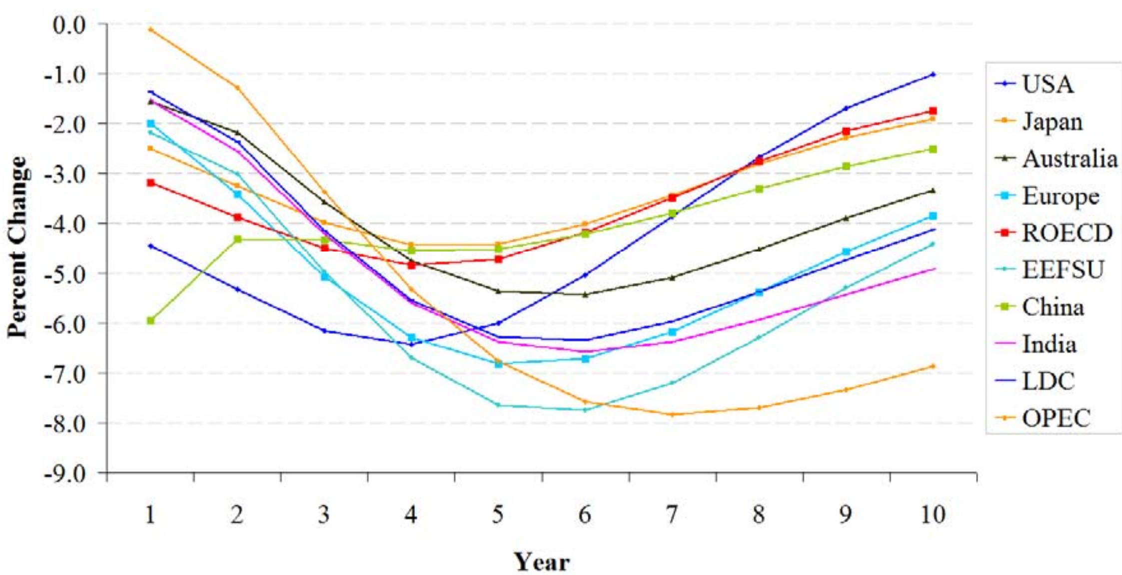


Figure 8: Effect of a Risk Shock on Emissions, Price Policy

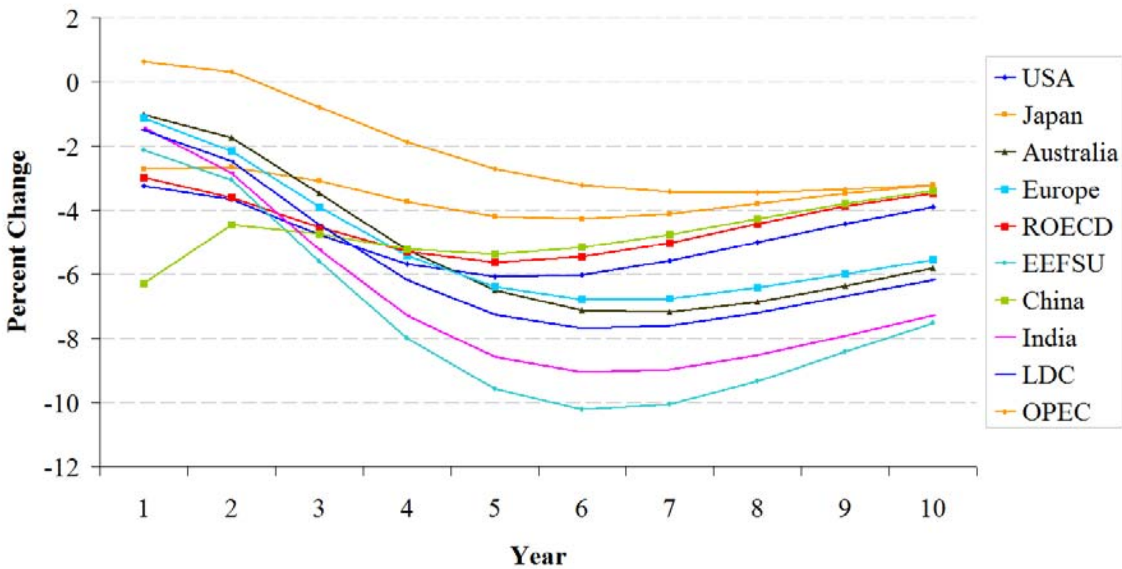


Figure 9: Difference in GDP, Quantity less Price Result

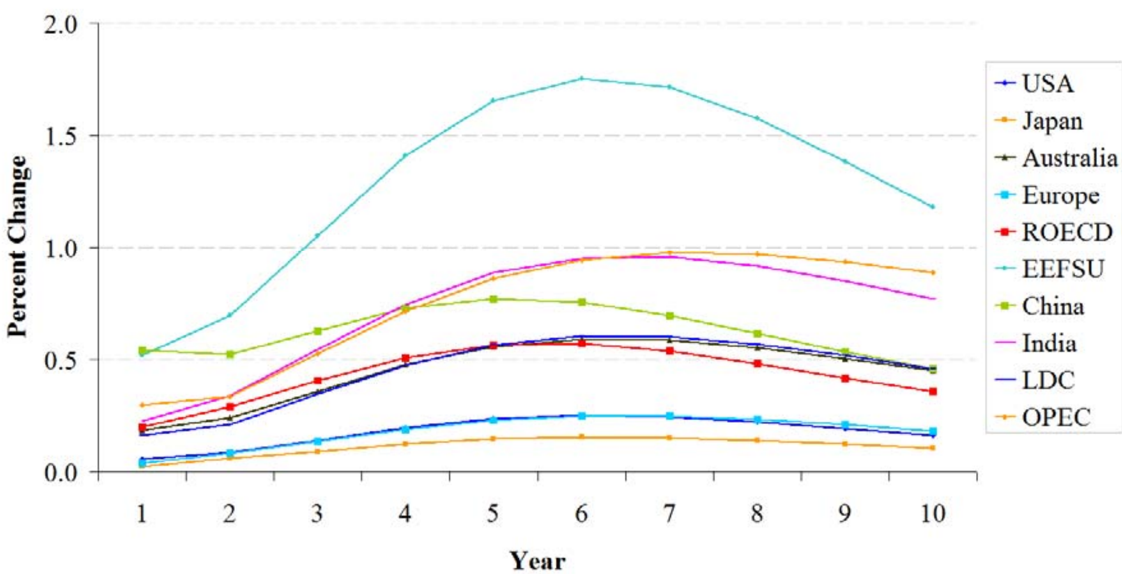


Figure 10: Effect of a Risk Shock on Emissions, Quantity Policy