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Uncertainty and International Climate Change Negotiations

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Abstract

This paper explores the failure of countries to coordinate climate policies as an equilibrium outcome of a game where countries optimize in the face of both unprecedented economic and environmental uncertainty. Because issues associated with climate change are historically unprecedented and thus policymakers do not have a prior distribution over possible outcomes, the usual theoretical framework based on governments maximizing expected utility may not be suitable for analyzing climate policy choice. Under an alternative plausible assumption that policymakers act strategically but choose the policy that incurs the highest possible gain in the worst-case scenario, this paper shows how coordination can be inferior to unilateralism in both carbon mitigation and economic loss minimization. In order to make progress in reaching a global agreement in this situation, additional restrictions that help to reduce uncertainty can lead to a coordinated outcome that benefits the environment and minimizes economic cost.

Keywords

climate change, policy game, coordination, robust control

JEL Classification

C71, C72, Q52, Q54

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Uncertainty and International Climate Change Negotiations[1]

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[1] This paper draws on Chapter 4 of Yiyong Cai (2012).

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ABSTRACT

This paper explores the failure of countries to coordinate climate policies as an equilibrium outcome of a game where countries optimize in the face of both unprecedented economic and environmental uncertainty. Because issues associated with climate change are historically unprecedented and thus policymakers do not have a prior distribution over possible outcomes, the usual theoretical framework based on governments maximizing expected utility may not be suitable for analyzing climate policy choice. Under an alternative plausible assumption that policymakers act strategically but choose the policy that incurs the highest possible gain in the worst-case scenario, this paper shows how coordination can be inferior to unilateralism in both carbon mitigation and economic loss minimization. In order to make progress in reaching a global agreement in this situation, additional restrictions that help to reduce uncertainty can lead to a coordinated outcome that benefits the environment and minimizes economic cost.

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1 Introduction

The rapidly increasing concentration of greenhouse gases in the atmosphere due to human activity is believed by many to be a key contributing factor in climate change. The emission of greenhouse gases is generally considered as a market failure where emission reduction requires multilateral policy cooperation between countries (Hoel, 1991; Uzawa, 2003; Stoft, 2010). Governments are well aware of the fact that if emissions of greenhouse gases continue to follow recent trends, the world may be at risk of catastrophic disasters in the decades to come. Nevertheless, global efforts towards greenhouse gas mitigation keep running into delay as is seen at the numerous meetings of the UNFCCC[2] Conferences of Parties.

The key feature of the policy debate on climate change is uncertainty. The consequences of global warming and the socioeconomic impacts of attempting to address climate change are scientifically unclear, historically unprecedented and highly uncertain. However, policymakers know that if the consequences predicted by many scientists are to be avoided, decisions need to be made now to reduce greenhouse gas emissions because climate change is due to the cumulative nature of carbon concentration (Ulph and Ulph, 1997; Weitzman, 2010). This is exemplified in the 2010 BBC Radio 4 interview of Tony Blair[3] : *It doesn't need to be certain for us to act...if you find out 2030 or 2040 'that was a real problem, we should have dealt with that', you're going to pay a pretty heavy price in history.* Under this uncertainty, policymakers are faced with making decisions while knowing that the consequences of their policy choices under the worst case scenario if realized may be dire. However the problem facing policymakers is actually even more complex than this quote suggests. Apart from climate uncertainty, policymakers are also faced with economic uncertainty surrounding the costs of carbon mitigation. This form of uncertainty is reflected by John

[2]UNFCCC stands for the United Nations Framework Convention on Climate Change.

[3]Tony Blair was the British Prime Minister from 1997 to 2007. He used the United Kingdom's G8 presidency in 2005 to address the issue of climate change.

Howard's[4] 2006 speech to the Business Council of Australia where he stated: *[Ratifying Kyoto] could have damaged the comparative advantage this country enjoyed...I do not intend to preside over policy changes in this area that are going to rob Australia of her competitive advantage...*

This paper aims to formalize and explore the consequences of these two types of uncertainty (environmental and economic) and the effects of each on policymaker behavior and the equilbrium outcome of negotiatioons between countries.

Many of the issues surrounding climate change are historically unprecedented. This makes formulating national policy extremely difficult. It also creates problems for analyzing the international policy coordination problem in the usual context of a game being played between countries. The standard approach to policy choice is based on maximizing expected utility. However this approach is not suitable for analyzing climate policy choice when policymakers do not have a well defined prior distribution over possible outcomes. Consequently, the conventional wisdom that uncertainty facilitates coordination (e.g. Ulph and Ulph, 1996)[5], which is based on the theory of expected utility, may not hold . This paper takes an alternative approach to much of the existing literature. We propose a non-probabilistic approach to the analysis of international climate policies, which we argue is more in line with the observed behavior of many political leaders. This is exmplified in the statements of the British and Australian political leaders quoted above.

Our approach is to apply the theory of minimax robust control (Basar and Olsder, 2008; Basar and Bernhard, 2008; Hansen and Sargent, 2008). We assume that policymakers formulate policies that secure the highest payoff in the least-

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[4]John Howard was the Australian Prime Minister from 1996 to 2007. He refused to ratify the Kyoto Protocol.

[5]In the theory of monetary economics, inter-governmental cooperation has been shown to improve welfare in most standard settings, as it internalizes the spillover effect of policies. See Hamada (1976), Oudiz and Sachs (1984), Ghosh (1986), Canzoneri and Henderson (Chapter 2, 1991), McKibbin and Sachs (Chapter 7 and 8, 1991), Ghosh and Ghosh (1991), and Masson (1992), Ghosh and Masson (1994), or Bryant (1995).

favorable situation. This approach means that there will not be any regrets of policymakers under the worst-case scenario. This idea is modelled by introducing an additional strategic player called "*nature*" into the game between countries[6]. This additonal player confounds the policy response of countries in the climate policy game and thus captures a policymaker's concern about worst-case outcomes. With a simple model that features the interaction between economic output, greenhouse emissions and climate policies, this paper shows that in the context of the assumed goals of policymakers, coordination is not generally optimal. Indeed, there are cases when unilateralism is superior for both carbon mitigation and economic loss minimization.

This paper draws on the empirical literature on macroeconomic policy coordination such as Frankel and Rockett (1988) and Holtham and Hughes-Hallett (1987) which is based on model correctness and the desirability of policy coordination. However rather than macroeconomic policy, this paper applied these ideas to the coordination of climate change policy. It provides a solid analytical framework that can be easily applied to numerical simulations. In addition, our introduction of an additional strategic player (temptation) in the international climate policy game is functionally similar to the existence of a self-interested private sector or a bystander country in undermining the desirability of inter-governmental monetary cooperation (Oudiz and Sachs, 1985; Rogoff, 1985; Kehoe, 1989; Tabellini, 1990; Canzoneri and Henderson, Chapter 3, 1991; Persson and Tabellini, Chapter 18, 2000). In a policy **game** with three or more players, the welfare contribution of a subgroup coalition generally cannot be determined a priori, and it is often the case that policy coordination worsens welfare as in the papers cited above.

The rest of this chapter is structured as follows. Section 2 sets out the basic model for analysis. Section 3 formulates a game scenario in which governments act to secure the highest payoffs given the least-favorable market and climate shocks. Section 4 investigates features of the model that undermine the desirability of

[6] Cai (2012) names this player "policymakers' lament". Others in the literature of robust control (e.g. Basar and Bernhard, 2008; Hansen and Sargent, 2008), a similar player generating least favorable shocks is introduced as "*Evil Nature*".

policy coordination. Section 5 provides a numerical example that potentially explains the current climate deadlock. Section 6 concludes by summarizing the policy implications. Appendix A presents a benchmark model for comparison in which statistical expectations of the shocks are available for the governments, and policy coordination is consequently welfare-improving.

2 The Model

Let us begin with some preliminary notation. Denote $R=(-\infty,\infty)$ and $R_+=[0,\infty)$. We assume that R, R_+ are endowed with the Euclidean metric and ordered by the binary relation $\leq$. For any two real functions f, g defined on the same domain X, we shall compactly denote the sum of f, g such that $(f+g)(x)=f(x)+g(x)$.

Background

We consider a static general equilibrium model with two producers, home h and foreign f. Each of them produces one differentiated good, the process of which generates emissions. Both home and foreign products are exported to the world market, and supply is demand-driven. Emissions are public bads (negative public goods). A carbon tax is the only policy instrument of governments, although the framework can also be extended to any other carbon policy that has equivalent effects; for example, the emission permit price in a cap-and-trade system. Idiosyncratic uncertainties exist in relation to the market and catastrophic climate change.

To avoid the effect of size and its effect on relative gains, the home and foreign economies are constructed to be symmetric, both having identical technology and preferences. Subjective beliefs about uncertainties are also assumed to be symmetric. In most of what follows, only the structural equations of the home country will be specified, with the understanding that comparable equations hold in the foreign country. Lower case variables represent the logarithms of their upper-case counterparts, unless otherwise specified.

This paper uses a stylized model with two symmetric countries only in order to address the effects of uncertainty in extreme scenarios on decision making. Such a theoretical abstraction enables us to focus on the policy problem of particular interest. However, we recognize that countries are asymmetric in the real world. They differ in market structure, climate vulnerability, carbon footprints and economic status. These are all important factors contributing to the deadlock of global carbon mitigation. For integrated assessment of international climate policy coordination, it is therefore desirable to incorporate the methodology this is proposed in this paper into multi-country empirical economic models.

Output and Emissions

Both home and foreign goods are produced at cost 1, and marked up by gross tax rates of $R_h, R_f \in R_+$, respectively. The world demand for home product is

$$D(R_h, R_f, w_h) := R_f \cdot R_h^{-(1+w_h)} \quad (1)$$

where $w_h \in R_+$ is the home government's concern about unmodeled effects of tax[7]. The realization of w_h can be arbitrarily small or large. If $w_h = 0$, demand is increasing in the exchange rate R_f / R_h, which is consistent with the Mundell-Fleming-Dornbusch model.

Because supply is demand-driven, the home output is

$$Q_h = D(R_h, R_f, w_h) = R_f \cdot R_h^{-(1+w_h)} \quad (2)$$

The logarithm of (2) is

$$q_h = d(r_h, r_f, w_h) = r_f - (1 + w_h) r_h$$

Symmetrically, the foreign output is

$$q_f = d(r_f, r_h, w_f) = r_h - (1 + w_f) r_f$$

Remark 2.1 *It is implicitly assumed here that the home export loss as a consequence of carbon tax does not necessarily accrue to the foreign export gain, and vice versa. This could be a more realistic assumption about the US and*

[7]See Brainard (1967) for a discussion on uncertainties surrounding the multiplier effect of a policy instrument.

China. Both are key but not the only players in the world market, so the threat of substitutes from the rest of the world always exists. In addition, the income effect of industry restructuring due to carbon reduction may result in an immense market depression.

With unit carbon intensity, home emissions are

$$E_h = G(Q_h, R_h) := Q_h \cdot R_h^{-\tau}$$

where the parameter $\tau > 0$ measures the effectiveness of taxation in facilitating the substitution from high to low-carbon technologies. Taking (2) into consideration, we have

$$E_h = G(D((R_h, R_f, w_h)), R_h) = R_f \cdot R_h^{-(1+w_h)} \cdot R_h^{-\tau} \quad (3)$$

When no countries impose the carbon tax ($R_h = R_f = 1$), the business-as-usual (BAU) level of emissions is 1. The logarithm of (3) is

$$e_h = g(r_h, r_f, w_h) = r_f - (\mu + w_h) r_h$$

where $\mu = 1 + \tau$.

Catastrophic Climate Change

Greenhouse gases accumulated in the atmosphere disturb the climate system, and thus lead to more frequent extreme climate events. As a result, a proportion of the home output is forgone to compensate for these climate-related damages, giving the home welfare

$$y_h = U_h(Q_h, E_h, E_f, \varepsilon_h, \varepsilon_f) := \ln \frac{Q_h}{\left[1 + \frac{\phi}{2n}\left(\ln \frac{E_h}{\overline{E}} + \varepsilon_h\right)^2 + \eta \frac{\phi}{2n}\left(\ln \frac{E_f}{\overline{E}} + \varepsilon_f\right)^2\right]^n} \quad (4)$$

where $\overline{E} < 1$ is the reference level of emissions for climate stability, $\varepsilon_h, \varepsilon_f \in R$ are the uncertainties surrounding the consequence of global warming, and ϕ, η, n are the damage parameters with positive values.

Our functional form of (4) is similar to that of Nordhaus and Yang (1997). The parameter n can be understood as the complexity of the economy that accumulates negligible individual effects to immense aggregate outcomes, and η

is a measure of the global impacts of local emissions. For simplicity and tractability, it is assumed that $n = \infty$, and $\eta = 0$.

Remark 2.2 *Admittedly, climate externalities are trans-boundary, but in this special case with the home and foreign countries being symmetric, the equilibrium results satisfy* $E_h = E_f$ *and* $\varepsilon_h = \varepsilon_f$ *as to be shown shortly, and hence the simplification that* $\eta = 0$ *is not likely to be a problem.*

Taking (2) and (3) into consideration, we can approximate (4) as follows:

$$y_h \approx u_h(r_h, r_f, w_h, x_h) = r_f - (1 + w_h)r_h - \frac{\phi}{2}(r_f - r_h + x_h - \bar{e})^2 \quad (5)$$

where $x_h = -w_h r_h + \varepsilon_h$ can be considered as an aggregate climate shock which has also accounted for policy-induced adaptation ($-w_h r_h$).

Rmark 2.3 *It is worth noting that even if* r_h *is known and* w_h *is fixed, as long as* ε_h *is unknown,* x_h *still remains unknown.*

Strategic Interactions with Concern about Robustness

Denote the pair of carbon taxes $\Upsilon = \{r_h, r_f\} \in R^2$. As is clear from Equation (5) and its foreign counterpart, when choosing taxes the governments must trade off the climate damages avoided and the abatement costs incurred, while at the same time being concerned about the robustness of their policies. There are likely to be two types of carbon leakages. When the foreign carbon tax is low, the home government will find it difficult to deliver ambitious emission reduction without losing export advantage to the foreign country. When the foreign carbon tax is high, the home government will again find it hard to do so without being exposed to amplified market shocks. Coordination could be potentially profitable, but this is not necessarily the case.

Remark 2.3 *By construction, there is no conflicting domestic interest between the government and private sectors and no problem of time inconsistency of policy, either, as the setup is static.*

With the consequences of their policy choices not being clear, policymakers fear that the worst-case scenario, if realized, may be dire. To model such beliefs, the existence of a fictitious player (*nature*) is assumed, who chooses the realization of $\xi = \{[w_h, x_h], [w_f, x_f]\} \in R^4$ to make both the home and foreign countries worse off.

Although not having a probability distribution of uncertain events, the home government has confidence in the stability of policy, that is,

$$\max_{\|[w_h, x_h]\| \le 1} \{-u_h(r_h, r_f, w_h, x_h)\} \le \lambda, \quad \text{given} \quad (6)$$

where $\|\cdot\|_2$ is the euclidean norm on R^2, and $\lambda > 0$ is the measure of policy stability. That is, the home government knows that a carbon tax incurs bounded loss in the presence of bounded uncertainties ($\|[w_h, x_h]\| \le 1$). The foreign government also considers these factors.

Remark 2.5 *It may appear at a first glance that the home government worries more about the market shock as* w_h *also intervenes* x_h. *This is not the case. As has been discussed in Remark 2.3,* $x_h = w_h r_h + \varepsilon_h$ *is jointly unknown. Through reparametrization, (6) can be made equivalent to*

$$\max_{\|[w_h, \varepsilon_h]\| \le 1} \{-u_h(r_h, r_f, w_h, x_h)\} \le \lambda', \quad \text{given} \, \Upsilon$$

This paper uses (6) because it simplifies the algebraic presentation.

Based on the theoretical framework of (6), it is a common practice in the literature of minimax robust control to approximate the governments' confidence in policy stability by the following **minimization** problem

$$\min_{\xi \in R^4} \{u_g(\Upsilon, \xi) + \xi' \Lambda \xi\}, \quad \text{given} \quad (7)$$

where

$$u_g(\Upsilon, \xi) = (u_h + u_f)(r_h, r_f, w_h, w_f, x_h, x_f) \qquad (8)$$

is the global welfare. The matrix

$$\Lambda = 2\, diag(\lambda_1, \lambda_2, \lambda_3, \lambda_4) \qquad (9)$$

contains a set of parameters so calibrated that the objective function of (7) is convex in ξ. As per Hansen and Sargent (Chapter 6, 2008), the entries of Λ can be understood as the Lagrangian multipliers when u_g is maximized under the constraints $\|[w_h, x_h]\| = \|[w_f, x_f]\| = C$, for some constant C. The larger the entries of Λ are, the less concerned the governments are about policy robustness. Therefore, (7) is a suboptimal approximation of (6). Interested readers could also consult Basar and Bernhard (Chapter 3, 2008), Zhou et al. (Chapter 16, 1996) for further details. In this paper, we follow the common practice and assume that PML's problem is represented by (7).

3 A Compounded Climate Policy Game

Given the socio-economic system described in the last section, a three-player two-stage game of international climate policy choice can be formulated. This game includes the home and foreign governments, and the fictitious player *nature*. In the first stage, the governments decide whether or not to coordinate carbon taxes in the second stage. However, no action is taken until the second stage when carbon taxes are implemented in the midst of worst-case uncertainties (i.e., all the three players move simultaneously). Then, if the home and foreign governments are pre-committed to coordinate, they jointly solve the following problem

$$\max_{\Upsilon \in R^2} \{u_g(r, \xi)\} \tag{10}$$

while taking ξ as given. Otherwise, they choose the carbon taxes to maximize their individual welfare while taking each other's action and ξ as given. In other words, neither government takes account of the spill-overs of its carbon policy onto the other country and the consequent policy reactions.

We consider the (pure strategy) *sub-game perfect equilibria* such that

- given the least-favorable market and climate shocks, the governments' choice of coordination (or not) and the carbon taxes maximize the home and foreign welfare, respectively;
- given the governments' choice of coordination and the least-favorable market and climate shocks, the carbon taxes maximize the home and foreign welfare, respectively.

It is clear that the sub-game perfect equilibrium could be solved by *backward induction*[8]. By further assuming that governments prefer not to coordinate when the two regimes result in the same level of welfare, it follows that the equilibrium is unique.

Remark 3.1 Given the structure of this game (the symmetry of home and foreign, and the timing of actions), the sub-game perfect equilibrium is adopted as it coincides with the global optimum. In all cases, whether the carbon taxes are coordinated or not, the equilibrium outcomes are also justified by collective rationality.

4 Non-Convexity in International Policy Coordination

In the game theory literature, the term *non-convexity* is commonly used to mean the feature of a game such that two disjoint groups of players are not necessarily better off by acting together than by acting separately (e.g. Topkis, Chapter 5, 1998). In what follows, we shall proceed by backward induction, and investigate the system of first order conditions that characterizes the Nash equilibrium of the period-2 sub-game, which gives rise to non-convexity and makes policy coordination possibly undesirable[9].

Nash Equilibrium of the Period-2 Sub-Game

Non-Coordination

Suppose that the governments do not coordinate in the second stage of the game. At the equilibrium the home and foreign taxes satisfy the following first order conditions

$$-(1+w_h)+\mu\phi(r_f-\mu r_h+x_h-\bar{e})=0 \qquad (11)$$

$$-(1+w_f)+\mu\phi(r_h-\mu r_f+x_f-\bar{e})=0 \qquad (12)$$

[8]The existence and uniqueness of equilibria in the second stage game follows from MorÃ© (1974) and Facchinei et al. (2007). Subsequently, by comparing welfare levels of the uncoordinated and coordinated regimes at the second stage, the governments' choice of participation at the first stage and hence the equilibrium solution(s) of the whole game can be attained. By definition, an equilibrium derived in this way is a sub-game perfect equilibrium.

[9]See Stiglitz (2010) on how non-convexity undermines the desirability of financial integration.

and the set of worst-case shocks satisfy

$$w_h = ar_h \tag{13}$$

$$w_f = ar_f \tag{14}$$

$$x_h = \hat{b}(r_f - \mu r_h - \bar{e}) \tag{15}$$

$$x_f = \hat{b}(r_h - \mu r_f - \bar{e}) \tag{16}$$

where $a = 1/\lambda_1 = 1/\lambda_2$ and $\hat{b} = \phi/(\lambda_3 - \phi) = \phi/(\lambda_4 - \phi)$. Substitution of (13) through (16) gives the following conditions that characterize the Stage-2 sub-game in the uncoordinated regime

$$-(1 + ar_h) + \mu\phi b(r_f - \mu r_h - \bar{e}) = 0 \tag{17}$$

$$-(1 + ar_f) + \mu\phi b(r_h - \mu r_f - \bar{e}) = 0 \tag{18}$$

where $b = 1 + \hat{b}$.

Remark 4.1 *The parameters* $a \in R_+$ *and* $b \in [1, \infty)$ *indicate the scale of market and climate uncertainties, respectively. They have significant numerical implications for the desirability of international policy coordination, as is shown in the next section.*

Coordination

Alternatively, suppose that the governments coordinate in the second stage of the game. Then at the equilibrium the home and foreign taxes satisfy the following first order conditions

$$1 - \phi(r_h - \mu r_f + x_f - \bar{e}) = (1 + w_h) - \mu\phi(r_f - \mu r_h + x_h - \bar{e}) \tag{19}$$

$$1 - \phi(r_f - \mu r_h + x_h - \bar{e}) = (1 + w_f) - \mu\phi(r_h - \mu r_f + x_f - \bar{e}) \tag{20}$$

and the set of worst-case shocks satisfy the same first order conditions as in the uncoordinated regime. Again, substitution of (13) through (16) gives the following conditions that characterize the Stage-2 sub-game in the coordinated regime

$$1 - \phi b(r_h - \mu r_f - \bar{e}) = (1 + ar_h) - \mu\phi b(r_f - \mu r_h - \bar{e}) \tag{21}$$

$$1 - \phi b(r_f - \mu r_h - \bar{e}) = (1 + ar_f) - \mu\phi b(r_h - \mu r_f - \bar{e}) \tag{22}$$

Nature and Non-Convexity

It follows from (13) through (16) that, ex post, the worst-case welfare given the carbon taxes $\{r_h, r_f\}$ chosen are

$$u_h(r_h, r_f) = r_f - r_h - ar_h^2 - \frac{\phi}{2}b^2(r_f - \mu r_h - \bar{e})^2 \qquad (23)$$

$$u_f(r_f, r_h) = r_h - r_f - ar_f^2 - \frac{\phi}{2}b^2(r_h - \mu r_f - \bar{e})^2 \qquad (24)$$

However, as is implied by (17), (18), (21) and (22), due to the *ex ante* concern about policy robustness the governments behave and make the policy calculation as they do in an otherwise identical game[10] where no uncertainty exists and the home and foreign welfare are

$$\tilde{u}_h(r_h, r_f) = r_f - r_h - \frac{a}{2}r_h^2 - \frac{\phi}{2}b(r_f - \mu r_h - \bar{e})^2 \qquad (25)$$

$$\tilde{u}_f(r_f, r_h) = r_h - r_f - \frac{a}{2}r_f^2 - \frac{\phi}{2}b(r_h - \mu r_f - \bar{e})^2 \qquad (26)$$

As a matter of reference, we shall call this the game of observational equivalence.

Remark 4.2 *The discrepancy between the original and the observational equivalence is clear from the different coefficients of the quadratic terms of (23) and (24) as compared with (25) and (26). In other words, a gap exists between the governments' policy calculations and their realized outcomes.*

In the game of observational equivalence, the home and foreign governments are the only two players, and thus coordination is welfare-improving as it eliminates the policy spill-overs. In our original game, however, the presence of a third player *nature* complicates the strategic interactions: The worst case shocks ξ are dependent on the governments' choice of taxes Υ, and policy coordination provides a possible channel to amplify the transmission of shocks.

When climate and market uncertainties are negligible ($a \to 0$, and $b \to 1$), the game of observational equivalence is a good approximation of our original game. Therefore, the same result could be expected regarding the superiority of

[10]The conditions (17), (18), (21) and (22) also characterize the uncoordinated and coordinated equilibria of this game.

coordination[11]. Nevertheless, when climate and market uncertainties are immense, the game of observational equivalence deviates substantially from our original game. Intuitively, the governments would behave in a profoundly different way to what would be otherwise expected, as is implied by the conventional wisdom on the desirability of policy coordination that is based on the theory of expected utility. Coordination is generally not optimal. We shall confirm this by a numerical example in the next section.

5 Numerical Illustration

In this section, we report the numerical results of a calibrated game of international climate policy. In this exercise, the parameter τ in the emission generating function is set equal to 1 (or equivalently $\mu = 2$), which implies that if the carbon tax is doubled, emissions will be halved. Currently, road fuel economy is roughly $8L/100km$ in the Europe and $12L/100km$ in the US (Schipper, 2008) given that the price of automotive diesel oil is generally 50% higher in the Europe than in the US (International Energy Agency, 2010), which supports our parametric assumption. The climate damage parameter ϕ is set equal to 0.4, which implies that a doubling of the atmospheric carbon accumulation from the reference level increases global temperature by 2-4 Celsius degree, which leads to an annual GDP loss of no more than 10%. This is consistent with the estimation of Stern (2006). The reference level of emissions $\overline{E}$ is set equal to 5% of the BAU (i.e., $\overline{e} = -3$). The US government has committed to an 83% carbon mitigation in 2050 from the 2005 level, and our parametric assumption thus implies that the 2050 US emissions under the BAU scenario would triple from the 2005 level.

Case 1

In the special case when the economies are only subject to climate uncertainty, i.e., $a = 0, b \geq 1$, it is generally true that coordination is the dominant strategy because the governments can hedge against climate risks by imposing carbon taxes to the global optimal level and reap the highest welfare (see table 1). This is

[11] This follows by Berge's Maximum Theorem (see Aliprantis and Border, Theorem 17.31, 2006).

consistent with results of the benchmark game in Appendix A, where governments have statistical expectations of both the market and climate shocks.

Table 1: Equilibrium Outcomes with Climate Uncertainty Only

	Uncoordinated (uc)	Coordinated (co)	Comparison
Tax	$-\frac{1}{\mu(\mu-1)\phi b}-\frac{\bar{e}}{\mu-1}$	$-\frac{\bar{e}}{\mu-1}$	$uc < co$
Welfare	$-\frac{\phi}{2}\left(\frac{1}{\mu\phi}\right)^2$	0	$uc < co$

Case 2

In another special case when the economies are only subject to market uncertainty, i.e., $a \geq 0, b = 1$, we can use the symmetry of home and foreign, i.e., $r_h = r_f \equiv r$ and $w_h = w_f \equiv w$, to derive the governments' robust carbon tax as a function of the least-favorable market shock

$$r = B_{nc}(w) := -\frac{1}{\mu(\mu-1)\phi} - \frac{\bar{e}}{\mu-1} - \frac{w}{\mu(\mu-1)\phi} \qquad (27)$$

if uncoordinated, and

$$r = B_{co}(w) := -\frac{\bar{e}}{\mu-1} - \frac{w}{(\mu-1)^2\phi} \qquad (28)$$

the worst-case market shock as a function of the carbon tax

$$w = S(r) := ar \qquad (29)$$

and its inverse

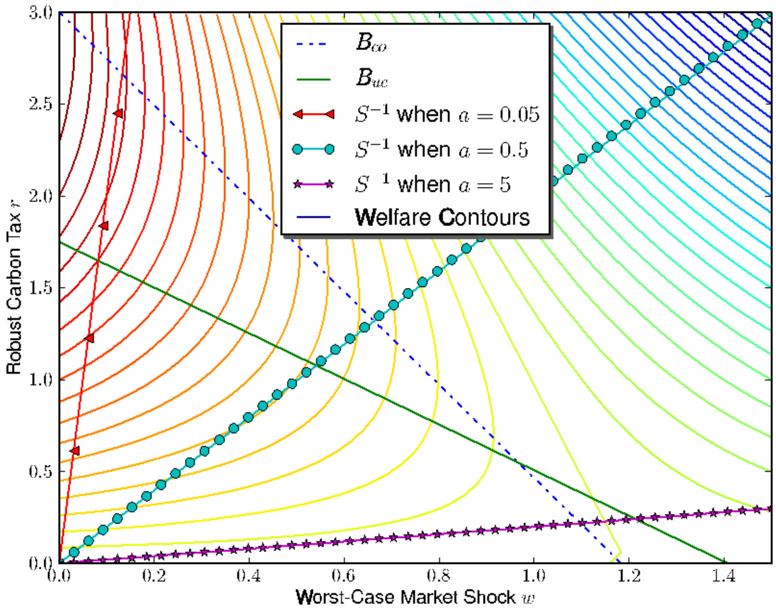
$$r = S^{-1}(w) := w/a \qquad (30)$$

where the subscripts nc, co denote the uncoordinated and coordinated regimes, respectively.

In figure 1, we plot the graph of B_{nc}, B_{co} and S^{-1} given different magnitudes of the market uncertainty of a. The intersection of graphs of B_{nc} and S^{-1} characterizes the Nash equilibrium of the period-2 sub-game if taxes are uncoordinated, and the intersection of B_{co} and S^{-1} characterizes that of the supplementary scenario. In addition, we also plot the welfare contours as per equation (4) given different combination of r and w. The rightmost isoquant represents the highest level of welfare.

As is clear from figure 1, when there is little market uncertainty (a=0.05), the benefit of internalizing policy spill-overs outweighs the risk of binding mitigation policies. This can be understood as the feasible set of "strong bargains" of Holtham and Hughes-Hallett (1987) which supports policy coordination. However, when market uncertainty is significantly foreseeable (a=0.5), a binding agreement is undesirable because it provides a channel for the transmission of shocks. When market uncertainty is substantial (a=5), the governments will find it necessary to collude and reach a silent consensus of passive actions. Subsequently, the under-achievement of carbon mitigation occurs.

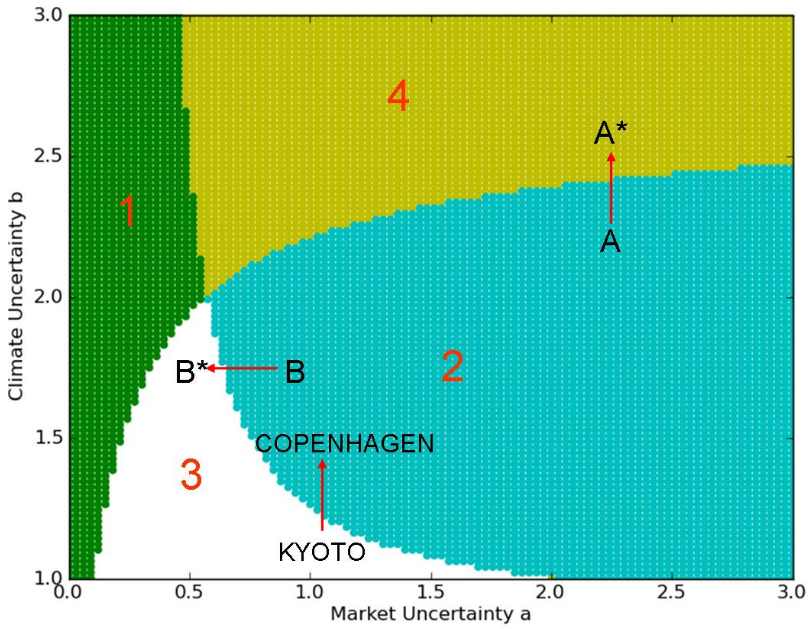
Figure 1: Equilibrium Welfare with Market Uncertainties Only



Case 3

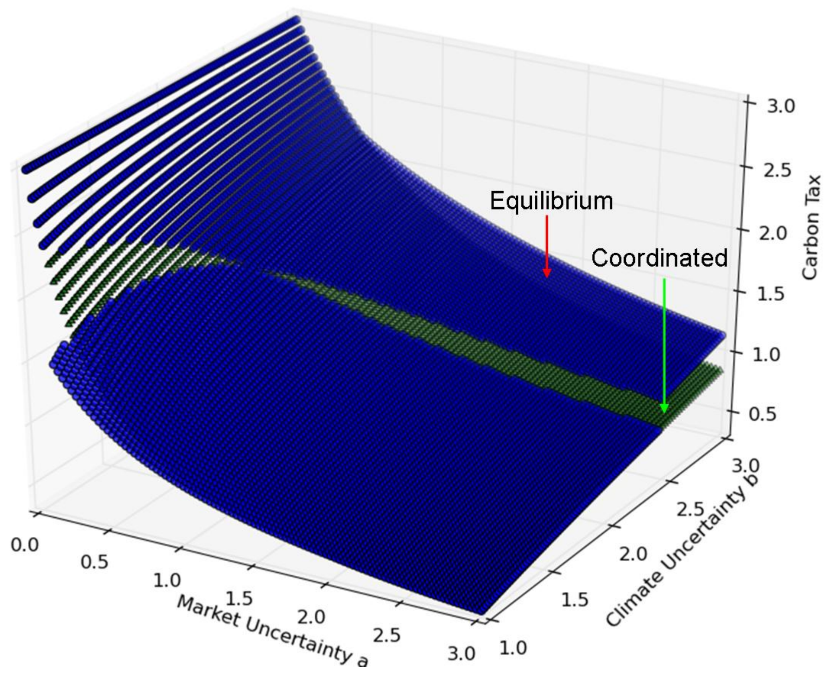
In the general case when governments are exposed to both market and climate uncertainties, four types of equilibria arise depending on values of market uncertainty *a* and climate uncertainty *b*. In figure 2, we categorize the range of *a* and *b* values into 4 regions. In region 1 where the fear of climate uncertainty dominates that of market uncertainty, there are incentives for the governments to coordinate and impose higher carbon taxes. In region 2, however, where the fear of market uncertainty dominates that of climate uncertainty, the governments only coordinate to impose lower carbon taxes. Collusion enables governments to collectively resist pressures from the environmental groups. More mitigation efforts would otherwise be necessary if they act alone, which worsens welfare. In region 3 where fears of both types of uncertainties are moderate, it is better for the governments not to coordinate, and this results in less ambitious carbon mitigation. In contrast, in region 4 where fears of the two sorts of uncertainties are immense, non-coordination is still the dominant strategy, but this in fact leads to more aggressive carbon mitigation (see figure 3).

Figure 2: Equilibrium Outcomes with Various Combinations of Uncertainties



Note: region 1 is the *a* and *b* values such that Coordination is welfare-improving and leading to higher carbon tax; region 2 is the *a* and *b* values such that Coordination is welfare-improving but leading to lower carbon tax; region 3 is the *a* and *b* values such that Noncoordination is welfare-improving and leading to lower carbon tax; region 4 is the *a* and *b* values such that Noncoordination is welfare-improving but leading to higher carbon tax.

Figure 3: Equilibrium Taxes with Various Combinations of Uncertainties



A Digression on the *Failure* of Coordination

It is important to stress that, as global welfare is maximized in each of the equilibria as represented by the four regions in figure 2, there is actually no failure of coordination. In other words, simply pushing governments into a binding agreement could worsen global welfare due to the contagion of market shocks. In particular, when governments are situated in region 4, collectivism could even lead to insufficient carbon reductions. Together, the results suggest the inappropriateness of measuring the success of an international climate agreement by its engagement of countries.

In addition, the existence of region 2 implies that no monotonicity of strategy is to be expected. In other words, there is no correlation between the scale of uncertainties and the desirability of policy coordination. To see this, suppose that governments are originally situated at point A. The increase of climate uncertainty (moving from A to A^*) breaks down the existing policy alliance, but it results in more aggressive mitigation. Alternatively, suppose that governments are originally at point B. The resolution of market uncertainty (moving from B to B^*) renders coordination undesirable until finally region 1 is reached. Indeed, many more results can be obtained by the same line of reasoning.

The numerical results above seem to provide a possible explanation to the climate deadlock currently seen at UNFCCC Conferences of Parties. In the 1990's when the risk of climate change was under-estimated, the fear of market uncertainty prevailed (region 3) and as a consequence the Kyoto Protocol was not able to engage all major fossil-fuel-burning countries at that time and thereby cover a sufficient proportion of the global carbon emissions. Entering the 21st century, as the worry of catastrophic climate change grows, the concern about economic costs of mitigation lingers because little policy experimentation has been carried out over in the last decade to test the responses of global consumers to carbon pricing of any form (region 2). Governments find it welfare-improving to coordinate but end up with minor mitigation commitments. As the Copenhagen Accord demonstrates, what governments have pledged internationally is no more than that which they have already committed to domestically.

6 Concluding Remarks

This paper argues that the theoretical framework which is based on maximizing expected utility is not well defined in the analysis of international climate policies when the issues associated with climate change are historically unprecedented, and when policymakers do not have a prior distribution over possible outcomes. Under the alternative assumption that policymakers act strategically but choose the policy that incurs the highest possible gain in the worst-case scenario, coordination is not generally optimal. Indeed, there are cases when unilateralism is superior for both carbon mitigation and economic loss minimization. Hence, it is not appropriate to judge the success of global climate talks by the extent of country engagement or each country's reduction commitments.

The model presented here not only improves our understanding of the current deadlock in international climate change negotiations, it also allows us to highlight ways in which the development of global carbon mitigation agendas could move forward. One important implication of this study is that the approach of climate policy negotiation should be both gradual and experimental with different policy interventions to enable learning and should focus on mechanisms that reduce economic uncertainty. One such device might be a "safety valve" that could be made available in order to truncate the negative impact of unexpected market shocks[12]. In addition, the focus of talks on climate change should be on the resolution of uncertainties, especially those related to the economic cost of mitigation policies. In this respect, what have been achieved in the recent UNFCCC Conferences of the Parties (Copenhagen, Cancun and Durban) should be considered as successful. Although still limited, the concrete actions that have been promised by the participating countries allow experimentation and thus the generation of knowledge of the nature of this policy problem. This should reduce uncertainty around the economic costs of policies and facilitate more cooperative and ambitious mitigations in the future.

[12]See e.g. McKibbin and Wilcoxen (2002).

Appendix A The Benchmark Model

Let us consider a benchmark policy game where expectations of the shocks $Ew_h = Ew_f = M_w$ and $Ex_h = Ex_f = M_x$ are known by the governments. In this case, the classic framework of policy analysis based on maximizing expected welfare is well defined. Given carbon taxes $\{r_h, r_f\}$, we have the home and foreign welfare

$$\hat{u}_h(r_h, r_f) = E\left[(r_f - w_h r_h) - \frac{\phi}{2} b(r_f - \mu r_h + x_h - \bar{e})\right]$$

$$\hat{u}_f(r_f, r_h) = E\left[(r_h - w_f r_f) - \frac{\phi}{2} b(r_h - \mu r_f + x_f - \bar{e})\right]$$

We will proceed by backward induction and solve for the sub-game perfect equilibrium.

Non-Coordination

Suppose that the governments do not coordinate in the second stage of the game. At the equilibrium, the home and foreign taxes satisfy the following first order conditions

$$-(1+M_w) + \mu\phi(r_f - \mu r_h + M_x - \bar{e}) = 0 \qquad \text{(a. 1)}$$

$$-(1+M_w) + \mu\phi(r_h - \mu r_f + M_x - \bar{e}) = 0 \qquad \text{(a. 2)}$$

Jointly solving (1) and (2) gives the equilibrium carbon tax

$$\hat{r}_{h,nc} = \hat{r}_{f,nc} = \frac{M_x - \bar{e}}{\mu - 1} - \frac{M_x}{(\mu-1)\mu\phi} - \frac{1}{(\mu-1)\mu\phi}$$

and welfare

$$\hat{y}_{h,nc} = \hat{y}_{f,nc} = -M_w\left(\frac{M_x - \bar{e}}{\mu - 1} - \frac{M_x}{(\mu-1)\mu\phi}\right) - \frac{M_w^2}{2\mu^2\phi} + \frac{2M_w - \mu + 1}{2(\mu-1)\mu^2\phi}$$

Coordination

Alternatively, suppose that the governments coordinate in the second stage of the game. At the equilibrium, the home and foreign taxes satisfy the following first order conditions

$$1 - \phi(r_h - \mu r_f + M_x - \bar{e}) = -(1+M_w) + \mu\phi(r_f - \mu r_h + M_x - \bar{e}) \qquad (3)$$

$$1-\phi(r_f-\mu r_h+M_x-\bar{e})=-(1+M_w)+\mu\phi(r_h-\mu r_f+M_x-\bar{e}) \quad (4)$$

Again, jointly solving (3) and (4) gives the equilibrium carbon tax

$$\hat{r}_{h,co}=\hat{r}_{f,co}=\frac{M_x-\bar{e}}{\mu-1}-\frac{M_x}{(\mu-1)\mu\phi}-\frac{1}{(\mu-1)\mu\phi}\frac{M_x}{\mu-1}$$

and welfare

$$\hat{y}_{h,co}=\hat{y}_{f,co}=-M_w\left(\frac{M_x-\bar{e}}{\mu-1}-\frac{M_x}{(\mu-1)\mu\phi}\right)-\frac{M_w^2}{2\mu^2\phi}+\frac{M_w^2}{2(\mu-1)^2\mu^2\phi}$$

Superiority of Coordination

Although nothing can be said about the equilibrium policy without specifying the expectations of the shocks and other parameter, the superiority of coordination is clear from the observation that

$$M_w^2-2(\mu-1)M_w+(\mu-1)^2\geq 0$$

Indeed, as long as $M_w \neq \mu-1$, there will be gains from policy coordination. This is not surprising because the welfare spill-overs arising from the governments' choice of carbon policy is internalized and fully exploited.

In cases when the marginal benefit of tax dominates the expected risk of it, i.e., $M_w/(\mu-1)<1$, incentive exists for both governments to impose higher carbon taxes and achieve more ambitious mitigation. In particular, if there is no market uncertainty, i.e., $M_w=0$, the adverse effects of global warming will be totally eliminated, which leads to the highest global welfare attainable.

While consistent with the expectation of advocates of global cooperation, the equilibrium results of the benchmark game above is nevertheless contradicting the current failure of international climate policy negotiations. If policy coordination is meant to improve global welfare, why would governments refrain from signing an international agreement that enforces it? This paradox motivates our study of uncertainty as a source of the failure of international climate change negotiations.

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