Using Prediction Markets to Guide Global Warming Policy*

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Abstract

There is currently great uncertainty about both the likely severity of global warming, and the most cost effective policies for dealing with the problem. We argue that suitably designed prediction markets can reduce some of the uncertainties surrounding this difficult issue, and thus assist in the policymaking process. Because *future* policymakers will be better placed to see the scale of the problem and feasibility of proposed solutions, policymakers today could benefit from current market forecasts of future global temperatures and atmospheric greenhouse gas levels. This would better allow policymakers to direct resources more effectively in the near term *and* the long term to address the global warming problem.

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1. Introduction

In recent years a growing consensus has developed among climate experts in favor of the twin propositions that global warming is occurring and that man-made greenhouse gas emissions are the primary culprit. This has led to policy initiatives such as the Kyoto Treaty, which places mandatory caps on carbon dioxide emissions. Unfortunately, it appears that Kyoto will make only a small dent in the problem, partly because some of the biggest and fastest growing energy consumers are not even signatories to the treaty, but also because even a substantial reduction in emissions growth would have only a small impact on global temperatures during the 21st century.[1] Some are skeptical as to whether a problem even exists, while others argue that proposed policy solutions are just too costly, particularly in light of rapid growth in developing countries. In this paper we show how the creation of artificial climate prediction markets could provide valuable assistance to policymakers.

There is already a fairly large literature on prediction markets, and widespread agreement that, for some forecasting problems, they can be a relatively efficient method of aggregating information. We believe that economists have overlooked the advantages of utilizing prediction markets in climate forecasting for three reasons:

1. A widespread belief that only climate experts would be able to contribute useful information to such markets.

2. A misunderstanding of the nature of the *circularity problem* (where prediction market traders respond to policymakers, and policymakers respond to prediction market forecasts).

3. An assumption that the current lack of a long term climate prediction market suggests that there would be little interest in artificial long term prediction markets.

A key goal of this paper is to show that all three of these widely held views are incorrect. First, we will show that climate experts are only a tiny fraction of the population of individuals who are likely to bring useful information to climate prediction markets. In addition, there is good reason to believe that a simple poll of climate experts is likely to elicit highly biased forecasts. Second, that the circularity problem can easily be circumvented by setting up

[1] See Nordhaus and Boyer (2000, p. 152.)

prediction markets in such a way as to elicit conditional forecasts. And finally, we will show how an artificial prediction market created for any measurable stochastic variable can be made highly liquid, and that the current lack of such markets for long term climate variables is actually an *advantage*, not a disadvantage, if one seeks an unbiased forecast.

In section two we discuss some of the uncertainties surrounding the global warming issue. We then argue that suitably designed prediction markets may be able to reduce some of these uncertainties, and thus assist in the policymaking process. In section three we discuss some of the previous literature on how prediction markets can be used to assist policymakers, and conclude that there are no insurmountable barriers to the construction of effective prediction markets. We also discuss some literature that suggests prediction markets may be a more effective prediction tool than committees composed of experts. In section four we spell out a specific proposal for the creation of a set of 10 or more prediction markets. These markets would be designed to predict future levels of greenhouse gases (GHG) and future average global temperatures. In section five we discuss how policymakers could derive useful information from looking at the market equilibria in these prediction markets. Section 6 presents some concluding remarks.

2. Why is Global Warming Such a Difficult Problem?

Many scientists believe that in order to prevent a steady increase in global temperatures, the emissions of GHGs such as carbon dioxide, methane, and chlorofluorocarbons must be severely restricted. Barrett (2006, p. 22) argued that "An effective climate change treaty must promote the joint supply of two global public goods: climate change mitigation and knowledge of new technologies that can lower mitigation costs." But there is currently much debate about exactly which strategy should receive priority. Because carbon dioxide remains in the atmosphere for centuries, in the long run there is little difference between GHGs emitted today and a few decades from now. And because technology is likely to improve dramatically over time, it may be less costly to wait until new techniques are available before making a major attempt to reduce greenhouse gas emissions. On the other hand, many environmentalists believe that we are on the verge of catastrophic climate change, and favor radical changes in our current energy use patterns.

Although awareness of climate change has grown recently in the scientific and public arenas, there is little reason to be optimistic that the world community will take effective steps to slow the increase in atmospheric GHG concentrations. The Europeans have been at the forefront of this issue, but even they are falling short of meeting the goals laid out in the Kyoto treaty. Where reductions have occurred (as in Britain and Russia), they have typically represented structural shifts (away from coal) that were motivated by economic factors, not concern over global warming. Even if the U.S. becomes more involved in the issue, it will not be enough if GHG emissions in the developing world continue growing at a rapid rate.

Some scientists have become so pessimistic about the prospects for effective limits on carbon emissions that they have suggested the world may have to rely on the fallback strategy of *geoengineering*. Schelling (2006) defines geoengineering as policies aimed at global climate change that are both intentional and unnatural. For instance, Crutzen (2006) suggested that injecting about 5 million tons of sulfate aerosols into the stratosphere to block sunlight would offset a doubling of CO_2, which is expected to occur during the 21st century. This sort of proposal is estimated to cost roughly $100 billion per year. Crutzen does not view this as an ideal solution—CO_2 levels will still eventually need to be capped in order to prevent acidification of the oceans—but he is so pessimistic about current efforts to address global warming that he argues it may be necessary as a fallback solution until society is willing and able to address the fundamental problem. Alternatively, one could view geoengineering as a stopgap measure until new technologies were available. The plan would involve some environmental damage, but Crutzen sees the side effects as being relatively small in comparison to the potential damage from global warming.[2]

Here are just a few of the uncertainties surrounding the global warming problem:

1. How much will atmospheric GHG levels rise over the next century?
2. For any given increase in atmospheric GHG levels, how much will average global temperatures increase?

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[2] Acid rain would increase, but by less than 10%. The healing of the ozone layer would slow, but not reverse. See Crutzen (2006) and Wigley (2006).

3. For any given increase in global temperatures, how much will sea levels rise? And, more importantly, when?
4. Will global warming cause mass extinctions of animals and plants?
5. How much will global warming impact global agricultural output? Regional agricultural productivity? Will it increase the severity of storms?
6. Will global warming acidify the oceans, killing organisms at the bottom of the food chain?
7. What technologies for reducing GHG emissions are most promising?
8. What policies for reducing GHG emissions are most effective? Quantitative controls (such as tradable CO_2 emission permits), or price-type regulations (e.g. carbon taxes)?
9. How urgent is the problem? How costly are the proposed solutions?
10. If the world is not willing and able to reduce GHG emissions, can alternative policies such as geoengineering prevent global warming?

A recent paper by Lawrence (2006) noted that many in the climate science community are strongly opposed to public discussion of "shortcuts" such as geoengineering. The fear is that the possibility that there might be an easy way out of the global warming crisis could lull the public into a false sense of security, and slow the adoption of painful but necessary policy reforms. Because climate scientists clearly believe that the public has not yet woken up to the severity of the climate threat, and because some have publicly stated that information should be withheld if it will lead the public to underestimate the threat, it seems clear that any poll of climate experts regarding future temperatures would be biased upward, especially if the experts knew that the results would be used for policy purposes.[3]

Even if climate expert forecasts are unbiased, there is every reason to believe that they would not be optimal, as all sorts of information outside the realm of climate science are highly relevant to this problem. A recent set of articles in the *New York Review of Books*, by Freeman Dyson, William Nordhaus, and others, discussed a wide range of unconventional technologies that might be able to address global warming. These involved ideas such as genetically engineered trees, grasses, or phytoplankton which could absorb carbon, i.e. ideas that are

[3] A related problem noted by Barker and Peters (1993) is that governments often survey experts merely to validate choices that they have already decided upon for political reasons.

somewhat outside the realm of climate science. And we have already seen that geoengineering is another possible solution coming from "outside the box" thinking.

Furthermore, history shows that useful environmental predictions can be made by people completely outside the physical sciences. For instance, in the 1970s the famous "Club of Rome" made some highly pessimistic predictions about future trends in the earth's natural resources. These predictions were widely disputed by economists, who argued that they underestimated the potential of markets to respond to economic incentives. We now know that the forecasts of many scientists were overly pessimistic, or at least premature. There may well be useful information about future climate trends in the climate science community, the biology or biotech communities, among mechanical engineers (working on non-carbon energy sources like wind solar and nuclear), in the energy production industries (i.e. how much natural gas is likely to be found), among economists, demographers, sociologists, and numerous other professions.

Given the enormous uncertainty surrounding this issue, the difficulty in getting unbiased forecasts from experts, and even the difficulty of knowing who is an "expert," it may be useful to consider alternative ways of forecasting the impact of various policy options. One alternative would be to develop a mechanism capable of eliciting truthful revelation of the rational expectation forecast of future trends in GHG levels and global temperatures.

In recent years there has been increasing interest in artificial prediction markets. Wolfers and Zitzewitz (2004) showed that prediction markets can often outperform experts in predicting a wide range of variables, including everything from corporate revenue growth to the outcome of political elections. Hanson (2008a) advocates using such prediction markets for a wide range of policy applications, and addresses several dozen criticisms and technical details commonly cited as barriers to prediction market efficacy.

Some economists have advocated using prediction markets to guide monetary policy as a way of circumventing the problems associated with policy lags. Bernanke and Woodford (1997), however, warned that a monetary policy responding to forward-looking market data was subject to a "circularity problem" unless the market forecasts were conditional on specified policy instrument settings. That is, a futures market for inflation could not help the central bank determine the appropriate money supply, unless policymakers also knew the monetary policy stance implicit in the market forecast of inflation. In this paper we show that creating two separate futures markets, one for average global temperatures, and the other for atmospheric

GHG levels can help policymakers avoid the circularity problem. The market prices of these two climate futures contracts would provide useful information for policymakers trying to devise an optimal climate change strategy.

A key assumption is that policymakers in future decades will be better placed to see the scale of the problem, and the feasibility of various proposed solutions. If so, then today's policymakers could benefit from current forecasts of future climate levels *combined* with forecasts of future atmospheric GHG levels (a proxy for future carbon emission policies). This would avoid the circularity problem, and could allow policymakers to discriminate between four baseline scenarios likely to be of special interest to experts and policymakers: no action and no climate change; no action and further global warming; policies limiting GHG emissions and climate change mitigation; and geoengineering.

3.a The Logic of Prediction Markets

In a recent book entitled *The Wisdom of Crowds*, Surowiecki (2004) discusses a wide variety of examples where aggregating the views of a large collection of relatively uninformed individuals led to surprisingly accurate forecasts. For our purposes, one of the most relevant examples cited by Surowiecki was a study by Maloney and Mulherin (2003) analyzing the aftermath of the Challenger disaster of 1986. On the day of the accident the price of stock in Morton Thiokol fell much more sharply than stock in other subcontractors, as investors anticipated that the company might be held liable for the accident. This was well before there was any investigation into the cause, and also during a period when the *New York Times* was still reporting that "There are no clues to the cause of the accident". In this case the market turned out to be right–six months later Morton Thiokol was found liable for the faulty O-rings that led to the explosion. In addition, the study found that the stock decline was apparently not based on insider trading.

Some of the most interesting examples in Surowiecki's book involve the use of prediction markets as a guide to policymaking. Perhaps the most controversial example involved a proposal by a unit with the U.S. defense department to create a "Policy Analysis Market"

(PAM), which was widely viewed in the media as a betting market for future terrorist attacks and assassinations.[4] In fact, PAM was never intended to thwart specific terrorist attacks, but rather provide general information on aggregate measures of geopolitical risk in the Middle East as a supplement to existing intelligence and policy operations. Because of the perception that market participants would be 'profiting from terrorism,' the plan met fierce political opposition and was dropped. But there are numerous other examples of artificially created betting markets that allow betters to gamble on future political and financial events. These include tradesports.com, the Iowa Electronic Markets, and the Hollywood Stock Exchange.[5]

Smith (2003, p. 477) noted that the implicit forecast of political election outcomes in the Iowa Electronic Markets tended to show a smaller forecasting error than the average exit poll. Wolfers and Zitzewitz (2004) discussed how more and more firms are constructing internal prediction markets as a way of eliciting forecasts of useful variables such as sales revenue.[6] They argued (p. 121) that the "power of prediction markets derives from the fact that they provide incentives for truthful revelation, they provide incentives for research and information discovery, and the market provides an algorithm for aggregating opinions." Their research suggests that these markets are often quite effective, *despite a relatively low volume of trading*.

Recent price volatility in tech stocks and real estate has created renewed interest in market "bubbles." There is now a fairly widespread perception that markets often overshoot their fundamental values, and this has led to a great deal of skepticism about whether markets aggregate information efficiently. Of course we really don't know much about what might cause a market bubble, or even how to go about identifying this type of phenomenon. But let's assume that bubbles do exist. Would this weaken the argument for basing policy on prediction markets? Here we will offer a contrarian view, that market bubbles may actually provide one of the strongest arguments in favor of using the market to guide policy.

Surowiecki (pp. 23-65) argued that bubbles are caused by "groupthink," or "herding" behavior. The key to avoiding this phenomenon is to insure that decisions are made by diverse groups featuring a wide range of independent analysis. In fact, he argues that decentralized decision making will often be superior even if the average intelligence of the group is lower than

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[4] See Hanson (2006a) for a detailed description of PAM.
[5] See also the essays in *Information Markets: A New Way of Making Decisions* for more examples and applications of prediction markets.
[6] Wolfers and Zitzewitz (2004) noted that internal prediction markets in companies such as Siemens and HP, have proven to be very accurate.

that of "expert" opinion. Surowiecki doesn't deny that markets may also be susceptible to groupthink–he even cites the overly-optimistic forecasts on internet traffic growth that echoed around Wall Street during the late 1990s. But he seems even more concerned by the groupthink arising out of small insular committees, citing examples such as the (unanimous) committee decision to approve the Bay of Pigs invasion of 1961.

We obviously don't know whether Surowiecki's groupthink hypothesis explains some or all bubble-like phenomena, although it's not clear we have a better explanation. More importantly, however, we have become so conditioned to looking for bubbles in markets, that we may have overlooked the fact that essentially the same phenomenon is much more common in decision making by small, homogeneous policy committees. If so, then large and diverse prediction markets may actually reduce the chances that policy decisions become distorted by this sort of "market inefficiency."

There are currently no prediction markets that extend more than a few years into the future. But as Hahn and Tetlock (2005, p. 243) have argued, there is no reason why a suitably subsidized artificial prediction market could not extend many decades into the future:

> "Long latencies present no problem in principle for the information market mechanism . . . There are liquid financial markets for 30-year U.S. Treasury bonds and for 30-year residential mortgage-backed securities. Traditional equities have a potentially infinite maturity."

3.b Prediction Markets, Monetary Policy, and the Circularity Problem

A set of papers by Sumner (1989, 1995) and Dowd (1994) discussed the possibility of using CPI or GDP futures markets as a guide to monetary policy. Soon after, Bernanke and Woodford (1997) published an important critique of all monetary policies that "targeted the forecast," specifically citing proposals by Sumner and Dowd. For instance, consider a policy regime where the central bank tightened monetary policy whenever CPI futures with a 12 month maturity rose more than 2% above the current CPI, and vice versa. Bernanke and Woodford showed that if the private sector anticipated these preemptive moves, and if the policy were completely credible, then the price of CPI futures contracts would never rise above its target value, and hence there would have been no market signal for the central bank to have responded to in the first place. This dilemma, variously termed the *circularity problem* or the *simultaneity* *problem,* would seem to preclude the development of monetary regimes where central bank policy was based solely on private sector forecasts.

The circularity problem applies to any policy based on a forecast that is unconditional, that is, not linked to a specified setting of the policy instrument. Bernanke and Woodford suggested that the circularity problem might be avoided if the central bank relied on forecasts of the policy instrument, instead of (or in addition to) the policy target. Later we will see that this insight has important implications for the optimal structure of global warming futures markets.

Previous proposals for a market-oriented monetary policy have focused on issues such as the information lag. Sumner (1989) used an island economy model to show that in a highly decentralized economy the market may have superior information about the current state of aggregate demand. Jackson and Sumner (2006) argued that model uncertainty was a more important issue, and used a meta-analysis by Stix and Knell (2004) to support their argument. Stix and Knell showed that in 503 previous money demand studies the mean estimate of the income elasticity of demand was 0.99 and the median estimate was 1.00, which is essentially equal to the predicted value in many conventional models of money demand. But because these studies varied in terms of time period, location, and definition of the monetary aggregate, the standard deviation of these income elasticity estimates was a surprisingly large 0.46. Unfortunately, we do not know the true income elasticity of money demand (nor if there is a "true" elasticity that is stable across time and region). Nevertheless, assume for the moment that the true income elasticity is close to unity. In that case it would be easy to envision a scenario where forecasts of this key parameter by central bank economic research departments were, on average, superior to most individual private forecasts, and yet far inferior to the market estimate (here proxied by the median value in the Stix and Knell study).

Of course the preceding example doesn't prove that markets are necessarily superior to centralized decision-making, but it suggests that if markets are capable of efficiently aggregating private information, then even a relatively high level of noise in individual forecasts might well be associated with highly accurate market forecasts. In a study of policy advice from multiple experts, Battaglini (2004, p. 1) found that "the inefficiency in communication converges to zero as the number of experts increases, even if the residual noise in experts' signals is large [and] all the experts have significant and similar (but not necessarily identical) biases."

The preceding research has several important implications for global warming policy. First, that prediction markets may be the optimal way of forecasting long run trends in key variables such as global temperature and GHG levels. Second, that if policy relies solely on the forecasts derived from a futures market in temperature levels, then there may be a circularity problem. That is, with a single market one doesn't know *why* climate change is or is not expected to occur. For instance, would the lack of an expected increase in future global temperatures reflect the perception that global warming is a "myth"? Or would it indicate that traders believe that governments will take effective steps to prevent that occurrence? What we need are parallel markets in both the policy instrument (GHG levels), and the policy goals (global temperatures).

Sumner (1997) identified another solution to the circularity problem: conditional prediction markets. He suggested that the government could create parallel prediction markets for each of the most likely future policy settings. At the maturity date of these contracts, only the prediction contract closest to the actual policy setting would become operational. This would elicit forecasts of the policy goal conditional on actual future policy settings. Thus one might have a set of futures contracts for next years CPI, conditional on various settings of the fed funds rate, or monetary base. In the field of climate science, future levels of GHGs are one obvious policy-related indicator of interest. In that case, several parallel future global temperature markets could be created, each conditional on a specified range of future GHG levels.[7] This would give policymakers an unbiased estimate of the likely impact of GHG reduction of future climate levels.

Berg and Rietz (2003) discuss conditional markets for the presidential nomination process. They find that in the 1996 presidential election, conditional markets on the Iowa Electronic Market indicated that Colin Powell would have been a much stronger Republican candidate against the incumbent Bill Clinton than Bob Dole, who although was well liked by the party, lost the presidential bid by a wide margin. In 2004 some supporters of John Edwards pointed to the fact that conditional markets showed him to be the strongest Democratic candidate in the general election. Thus conditional presidential markets could assist political parties that simply wished to put the strongest candidate forward.

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[7] Thus contracts might exist for global temperatures, given GHG levels of 400-420ppm, 420-440ppm, 440-460ppm, etc.)

In some existing conditional markets, such as those on tradesports.com, contract positions are "unwound" if certain contract conditions are not met, which means that bettors get their money back. In that case, bettors may be less likely to take a position on a conditional contract, especially if market participants must incur costs to gather appropriate information. Because conditional markets can be rather esoteric, their trading volume may be relatively low. On tradesports.com, trading volumes are several orders of magnitude higher in markets that represent direct bets on who will be elected president of the U.S., as compared to markets where the implementation of the bet is conditional on another market's outcome (as in bets on future policy outcomes conditional on a particular party taking power).[8]

Hanson (2008b) also noted that creating conditional contracts with many possible combinations can lead to market thinness. If so, then the market might fail to give accurate price signals. In our proposal, trading will be subsidized by the government, thus we do not need to worry about the lack of liquidity that has plagued some of the private sector conditional prediction markets. If there is not enough liquidity, the government can simply increase the trading subsidies (which might be an above market rate of interest on margin accounts).[9] Any subsidy costs are likely to be tiny compared to the social costs of global warming, or indeed of the cost of even modest policy errors in addressing global warming.

The motivation for our proposed global warming prediction market is closely related to the rationale behind the proposed Policy Analysis Market. PAM was to forecast several geopolitical risk indicators (such as military activity, political instability, U.S. military involvement, U.S. military casualties and western terrorist casualties) across various Middle Eastern countries each quarter.

In discussing the prospects for PAM, Hanson (2006a) indicated that "…By forecasting important outcomes conditional on different particular choices, such markets can directly inform crucial decisions." For instance, by looking at the forecasts for the total number of terrorist caused deaths in the West, in conjunction with the forecasts for the number of troops stationed in Iraq, the PAM could provide an estimate of whether invading Iraq deters terrorism (by

[8] For instance, one can purchase a contract on tradesports.com with a payoff linked to troop levels in Iraq in June 2010, conditional on a specific party winning the presidency in 2008.
[9] An additional option could be to employ an automated market maker mechanism as described in Hanson (2006c). Automated market makers are already in use on a limited basis for some contracts traded on intrade.com.

eliminating terrorists and sources of instability), or increases terrorism (by emboldening terrorists).

This 'instrumental variables' approach to the circularity problem is similar to Wolfers and Zitzewitz (forthcoming) who use the spot price of oil and other financial indicators, along with the price of contracts on whether Saddam Hussein will be removed as leader of Iraq to determine the ex-ante impacts of an Iraq war policy. Snowberg, Wolfers, and Zitzewitz (2007) similarly use an instrumental variables approach to determine the market's consensus view on economic and financial performance contingent on the Democratic and Republican candidates winning the 2004 presidential election.

In the context of global warming, using an instrumental variable approach would be seemingly unnecessary and cumbersome. First, the two main indicators – CO_2 emissions and global temperature change – are relatively well defined, easily measurable, and essentially define the issue. And, given the long timeframes involved, it's not obvious that there are better proxies to elicit the true relationship between the two.

Our proposal solves the circularity problem by allowing policymakers to distinguish between situations where global temperatures are expected to remain low because effective policy steps are anticipated, and the case where investors view global warming as a myth. And our proposal is unlikely to run into the sort of ethical objections and fears of "moral hazard" that quickly torpedoed the proposed PAM.

In section 5 we will consider how policymakers can use the information from the parallel prediction markets of CO_2 and global temperature change to overcome the circularity problem and guide global warming policy. But first we need to consider how such markets can be created, and how the government can assure that global warming prediction market equilibria do not sharply diverge from the optimal forecast.

4. Creating Prediction Markets for Key Global Warming Variables

We have already seen a number of examples of prediction markets that have been set up to forecast economic variables. Here we will propose that the U.S. government, the European Union, or a consortium of governments may want to set up a series of prediction markets linked to future global temperatures and atmospheric GHG levels. For instance, they might decide to create 10 contracts, five for each climate variable. If the market began operating in the year 2010, then the initial contracts would mature in the years 2020, 2030, 2040, 2050, and 2060. In addition, we propose that they create an additional 10 conditional prediction markets for contracts maturing in the year 2060, reflecting 10 likely ranges for future GHG levels. The fifty year contract is especially suited to a conditional prediction market setup, as the longer the time period the more sensitive are global temperatures to future GHG levels.

A given quantity of methane (CH_4) and chlorofluorocarbons (CFCs) has a much greater impact on global temperature than an equal amount of carbon dioxide.[10] On the other hand CO_2 emissions are much greater than CH_4 and CFC emissions, and thus CO_2 is expected to be responsible for most of the additional global warming over the next 100 years. We will assume that a composite GHG index is constructed each year, based on a weighted average of Intergovernmental Panel on Climate Change (IPCC) estimates of the atmospheric concentrations of each greenhouse gas, with each weight representing the degree to which each gas traps sunlight, also known as *radiative forcing*. If an IPCC estimate for GHG levels does not exist on the maturity date of the contract, an estimate will be derived through linear interpolation between the two nearest IPCC estimates.

Although even small prediction markets have been shown to be highly effective forecasting tools, in order to make the market as efficient as possible it would be useful to have the government subsidize traders. And in order to avoid exposing the government to default risk, it will be useful to require traders to open a margin account. The latter goal could be achieved by having a margin requirement large enough to make it unlikely that traders would default on their contract. And a subsidy for climate futures trading could be provided by having the government pay interest on the margin accounts at a rate high enough to attract investor interest.

For example, consider a 30-year global temperature futures contract with a maturity value equal to the average global temperature in the year 2040, and a market value equal to $21. For simplicity, assume a 100% margin requirement, i.e. $21. If actual global temperatures in 2040 turn out to be 20 degrees Celsius, then those who took a long position will lose roughly 5%, and those who took a short position will gain 5%. In practice, it is highly unlikely that global temperatures would rise or fall by 21 degrees, and thus the government could set the margin requirement at a much lower level as a way of spurring interest in global temperature futures

[10] See Johansson, Persson and Azar (2006.)

trading. It is important to emphasize that liquidity will not be a problem, as there is always some interest rate on margin accounts that will be high enough to spur trading in climate futures. It is simply a matter of how serious are policymakers about creating and nurturing this sort of policy tool.

The logic behind prediction markets suggests that if the current average global temperature is 19 degrees, then a market price of 21 would indicate that traders anticipated an additional two degrees of global warming over the next 30 years. There are obviously two key assumptions required, however, in order to draw any useful inferences from prediction markets. First the market price of global temperature futures must be equal to the market expectation of future global temperatures. And second, that the market expectation of future global temperatures must be the optimal forecast. In other words, there must be little or no risk premium embedded in the price of temperature futures, and investors must have rational expectations.

While a defense of the rational expectations hypothesis is beyond the scope of this paper, the issue of risk does require some discussion. If investors treat global warming contracts as a hedge against market risk, then the market price of the contracts will exceed the expected future global temperature. In that case the temperature futures market would provide an overestimate of the likely extent of global warming. And while we don't think it likely that an economically significant risk premium would result from investors hedging against global climate risk, there is no way of definitively proving or disproving this conjecture. Currently, no such long term futures markets exists, so it seems unlikely that there would be much demand for long term temperature futures as a hedging device.[11] This is a point worth emphasizing, far from being an impediment to the development of climate prediction markets, *the lack of current interest in long term climate contracts is actually a huge advantage*. If most of the traders are people enticed into the market by government subsidies, rather than by a hedging motive, then the contracts should not incorporate a significant risk premium. This suggests that the market price of these

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[11] The Chicago Mercantile Exchange does offer near term climate futures contracts, which some energy and heating oil companies use as a hedge against day-to-day and week-to-week market volatility. The trade exchange intrade.com currently offers a few near-term contracts related to CO_2 (whether governments will sign CO_2 reduction treaties) and global temperature change (whether 2008 will be among the hottest on record), but these types of contracts do not have the capacity of addressing the cause and policy implications of global warming as our proposal does.

contracts will be a relatively unbiased indicator of the rational expectation of future climate levels.

There are some other potential problems with drawing inferences from this sort of prediction market. One obvious concern is that powerful special interests that have an economic exposure to climate policy might try to corner the market, by buying or selling massive quantities of global temperature futures, as a way of affecting the equilibrium price of these contracts. Evidence from the field, and from experiments by Hanson (2006b) and Hanson, Oprea, and Porter (2006), suggest manipulation in prediction markets is difficult at best. Even so, policymakers may still find it desirable to limit trading by companies with an obvious financial stake in global warming policy, and also limit the exposure of any individual trader.

In the next section we will construct a simple climate model that will be used to compare several policy scenarios. We then run Monte Carlo simulations for each of these policy options. Finally, we will discuss how climate futures prices could assist policymakers.

5.a A Model of a Global Warming Futures Market

To demonstrate the feasibility of a global warming futures market, we assume market participants use a simplified version of the RICE-99 model of global temperatures, which was developed by Nordhaus and Boyer (2000). The dynamics of climate modeling are extraordinarily complex,[12] and we make no claim that this represents the optimal model of the global climate. Indeed, in any real world climate futures market traders would presumably use more sophisticated modeling techniques.

We assume global temperatures are determined by the process

$$T_{t+1} = \lambda T_t + \beta GHG_{t+1} - \rho G_{t+1} + \varepsilon_{t+1}, \qquad (1)$$

where T represents the increase in average global temperatures since 1900, measured in degrees Celsius. Each time period is one year. Because there is substantial inertia in the evolution of global temperatures, T_{t+1} depends partially on T_t, with $0 < \lambda \leq 1$, but probably closer to 1.[13] Even

[12] See Kaufmann, Kauppi, and Stock (2006a).
[13] See Kaufmann, Kauppi, and Stock (2006b).

if GHG levels were to be stabilized at current levels, the IPCC (2007a) estimates that global temperatures would continue to increase by another 0.6 degrees over the remainder of the 21st century.

Radiative forcing is positively correlated with GHG concentrations, which we measure as (CO_2 equivalent) parts per million above what is generally considered the benchmark level of 280 ppm in 1900. Several studies suggest that the relationship is roughly linear, at least in the short run.[14] Because CO_2 is by far the most important contributor to global warming, the calibration of our model is primarily based on estimates of the impact of CO_2 on global temperatures. If global warming is a myth, then traders would implicitly set the GHG parameter β equal to zero.

If climate futures traders believe that GHG emissions contribute to global warming ($\beta > 0$), and doubt the political feasibility of policies limiting carbon emissions, they may anticipate the adoption of a non-traditional policy such as geoengineering. Most geoengineering proposals involve increasing earth's *albedo*, i.e. the fraction of sunlight that is reflected back into space. For simplicity, we will assume that the variable G represents the impact of geoengineering policies on the earth's albedo.

One geoengineering proposal suggests placing large numbers of small reflective devices into space to reflect sunlight.[15] A more plausible set of alternatives involve the injection of small particles into the atmosphere. For instance, one proposal calls for injecting water vapor to increase the cloud cover over the polar regions during the summer months, which would directly cool the earth by blocking sunlight, and indirectly by gradually increasing the coverage of the highly reflective polar ice caps.[16] Perhaps the most well developed proposals involve injecting light-reflecting particles such as sulfate aerosols into the stratosphere.

Most geoengineering proposals seem to involve fairly simple technologies that could be mass produced at roughly constant marginal cost. Thus we assume the level of geoengineering to increase albedo would be:

$$G_{t+1} = \omega G_t + \theta X_{t+1}, \qquad (2)$$

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[14] Hansen and Sato (2004) find a linear relationship using ancient air samples from Antarctic ice cores. Kaufmann, Kauppi, and Stock (2006a, p. 284) find a near-linear relationship in the short term.
[15] See *Space Daily*, November 6, 2006.
[16] See MacCracken (2006, p. 241.)

where ω is the technology specific depreciation rate (i.e. the rate at which sulfur particles fall out of the atmosphere), θ is the amount of albedo produced per billion dollars of expenditure on geoengineering, and *X* is real spending on geoengineering, in billions of dollars. Combining (2) into (1), we have

$$T_{t+1} = \lambda T_t + \beta GHG_{t+1} - \rho\,(\omega G_t + \theta X_{t+1}) + \varepsilon_{t+1}, \qquad (3)$$

where ε_{t+1} is the random component of global temperatures.

It is assumed that GHG's are determined by the process

$$GHG_{t+1} = \kappa GHG_t - \gamma Y_{t+1}^{1/2} + \delta S_{t+1} + \xi_{t+1.} \qquad (4)$$

The variable S_{t+1} is a state variable unknown at time t, but realized at time t + 1, representing contemporaneous exogenous influences on GHG emissions. For simplicity, we will assume that S_{t+1} is the growth rate of world real GDP (x100). The parameter κ represents the environment's ability to absorb GHG's from the atmosphere, where $0 < \kappa \leq 1$. In the absence of a major technological breakthrough, it would take many decades (or even centuries) for GHG levels to decline back to the 1900 benchmark through natural absorption. The error term ξ_{t+1} represents random fluctuations in GHG levels.

Policies aimed at reducing GHG emissions are captured through the policy variable Y_{t+1}, where Y_{t+1} is measured in billions of real dollars of resources devoted to emissions reductions. It is widely believed that there are sharply diminishing returns to expenditures aimed at reducing CO_2 emissions.[17] The parameter γ represents the effectiveness of policies aimed at reducing GHG emissions. As green technology becomes more efficient one would expect γ to get larger, which would reduce the cost of emissions abatement. Given the current state of technology, there are no cost effective means of *removing* large quantities of GHGs from the atmosphere,

[17] For instance, Johansson, Persson and Azar (2006, p. 296) argue that the marginal cost of reducing CO_2 emissions is a second degree polynomial.

once emitted, thus it is unlikely that policymakers will be able to reduce *net emissions* (i.e. – $\gamma Y_{t+1}^{1/2} + \delta S_{t+1}$) of GHGs below zero in the near future.[18]

5.b Prediction Market Outcomes Under Five Different Scenarios

In this section we will use plausible parameter values to calibrate the global climate model. We do not claim that traders would use exactly these values, indeed the parameter values are one of the sources of uncertainty that these markets can help address. Instead, these parameters are calibrated solely for demonstration purposes. In a real world climate futures market traders would develop consensus estimates based on all available information.

Calibrating Key Parameters

All parameters are calculated for a model where each time period is one year.

S_{t+1}: We assume for simplicity that global GDP will grow at 3% per year.

λ, β : We calibrate λ and β to match 2 standard emissions scenarios from IPCC (2007a, p. 14): holding emissions constant at 400 ppm, and one which presumes temperatures will rise to about 3.2 °C by 2100. This yields $\lambda = 0.9845$, corresponding to a temperature half-life of about 45 years, which is close to that of Hope (2003) of 50 years. The value of $\beta = 0.00017$ corresponds to about a 0.02 °C warming each year, at 400 ppm CO_2 equivalent.

ω, θ, ρ: Crutzen (2006) noted that the eruption of Mt. Pinatubo in June 1991 injected 10 gigatons of sulfate (10 Tg S) aerosols into the atmosphere, with about 6 Tg remaining in the atmosphere after 6 months. This implies $\omega = 0.36$. Crutzen also suggests that in 1992 it would have cost $25 billion for each Tg S injected into the atmosphere. In real (2007) terms, that is around $35 billion per Tg S, which implies $\theta = 0.0286$. (i.e., each billion dollars spent on geoengineering increases atmospheric aerosols by 0.0286 billion tons.) Crutzen suggests that a steady state level of 5.3 Tg

[18] However, it is possible that traders may anticipate future technology that can effectively remove GHG's from the atmosphere, allowing for the possibility that $\gamma Y_{t+1}^{1/2} > \delta S_{t+1}$ *The Economist* (June 2, 2007, pp. 87-88) recently discussed a proposal by Alfred Wong to use the Earth's magnetic field as a sort of conveyer belt to eject excess carbon dioxide into outer space.

S in the atmosphere would be needed to offset the effects of a doubling of CO_2 levels, implying that about 3.4 Tg S would need to be injected each year (assuming $\omega = 0.36$), which would cost around $118 billion per year. If Crutzen is right that a steady state level of 5.3 Tg S would offset a doubling of CO_2, then ρ would equal roughly 0.0125.

κ, γ, δ: There is considerable uncertainty about the half-life of CO_2. Some studies suggest the half-life of CO_2 is roughly 100 – 150 years (see Hope (2003)), while others, such as Kaufmann et al. (2006b) estimate this figure to be much lower. Given the uncertainty, we choose to use the low-end number reported by Hope (2003) of a half-life of 100 years, implying $\kappa = 0.993$. For the policy parameter γ, IPCC (2007b, p. 16) indicates that hitting a CO_2 target of about 560 ppm in the year 2100 would require a reduction in GDP of about 0.6% per year. If global GDP in 2007 is $70 trillion, this would imply about $420 billion per year of expenditures would be necessary to meet that target. Thus $\gamma = 0.15$ matches this scenario, offsetting about 3 ppm CO_2 equivalent per year. δ is chosen from the figure given in IPCC (2007b, p. 6) showing that for every 1% increase in world GDP, GHG emissions grow approximately ½ % . Assuming a starting point of 400 ppm, this translates to an increase of about 2, thus $\delta = 2$.

Given the above calibrations, we present Monte Carlo simulations for 5 representative global warming scenarios. We denote the forecasts (at time t) of the private-sector traders who participate in the GHG and temperature prediction markets with a superscript *f*.

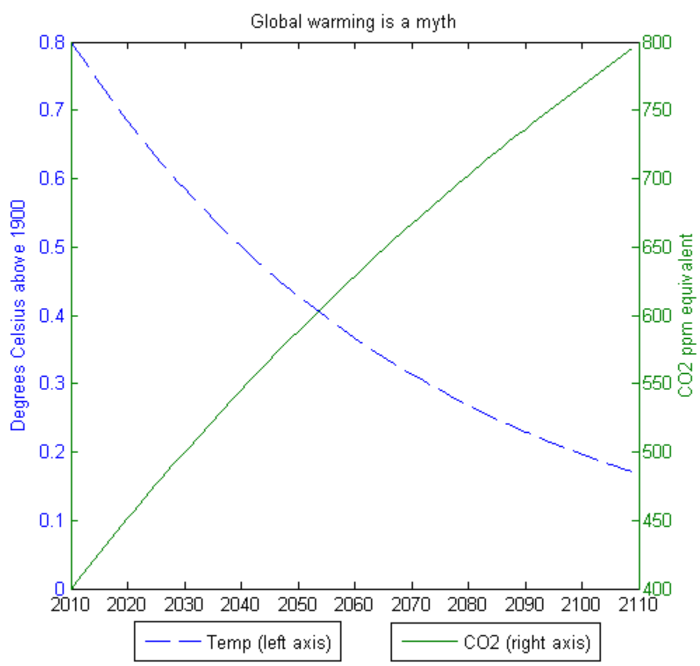
Case 1: Global Warming is a Myth

If market traders believe global warming is a myth, then any policies to tackle the problem will be unnecessary, hence $Y^f_{t+1} = G^f_{t+1} = X^f_{t+1} = 0$, and $\beta = 0$. In that case the prices of GHG and global temperature contracts might be as follows:

$$GHG^f_{t+1} = \kappa GHG_t + \delta S^f_{t+1},$$
$$T^f_{t+1} = \lambda T_t.$$

Here we assume that despite expectations that GHG levels will continue to rise, global temperatures are expected to remain stable, or even decline back to the average level of previous decades. Figure 1 shows the expectation that global temperatures return back to their long run average, despite the anticipated increase in GHG levels. Alternatively, global warming skeptics might view the global average temperature as a random walk ($\lambda = 1$). In that case, temperatures would be expected to show essentially no trend over the next 50 years.

Figure 1



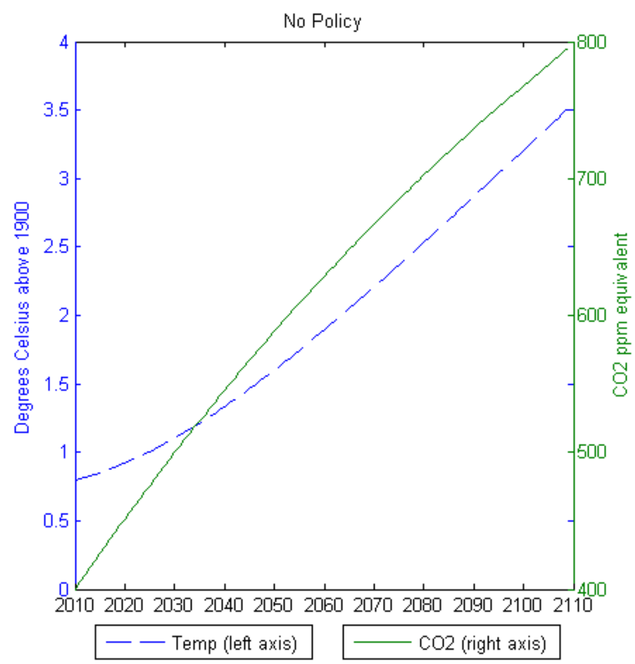
Case 2: Global Warming is Real, but Policy Fails to Address the Issue

Now assume that traders believe that global warming is real, but that markets do not expect either effective controls on carbon emissions (i.e. $Y = 0$) or geoengineering ($X = 0$.) In that case the prices of GHG and global temperature contracts would be

$$GHG^{f}_{t+1} = \kappa GHG_t + \delta S^{f}_{t+1},$$
$$T^{f}_{t+1} = \lambda T_t + \beta(\kappa GHG_t + \delta S^{f}_{t+1}).$$

Figure 2 shows that both GHG levels and global temperatures would be expected to rise in the absence of effective policy actions.

Figure 2



Most experts seem to agree that the global warming problem is real, and that rising GHG levels are a major cause of the problem. So it may be doubted as to whether the proposed futures market will actually provide much in the way of useful information. However the entire global warming problem is much more complicated than many of the press accounts suggest. In particular, we would emphasize two of the major uncertainties discussed in section two. First, how much warming is expected to occur over the next 50 years? Admittedly, this is partially dependent on future levels of GHGs, but Nordhaus and Boyer (2000) argue that any plausible changes in GHG emissions will have only a tiny impact on global temperatures in the short run, which in this case means over the next 50 years. The second uncertainty relates to whether global warming can be addressed more effectively through emissions abatement or geoengineering. Cases 3 and 4 consider two different scenarios for preventing global temperatures from rising by more than 2 degrees Celsius over the next century, a figure widely cited as the outer limit of acceptable climate change.

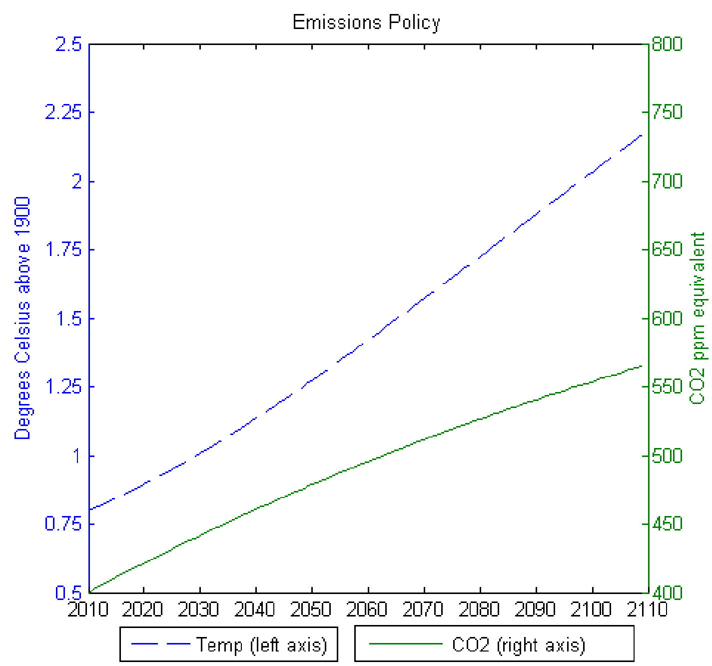
Case 3: Emissions Reduction Policy

If traders believe that a Kyoto-style policy solution will be implemented to curb global warming, then a geoengineering solution will not be necessary, hence $G = X = 0$, and $\beta > 0$. In this case, the price of GHG and global temperature futures contracts will be

$$GHG^{f}_{t+1} = \kappa GHG_t - \gamma Y^{f}_{t+1}{}^{1/2} + \delta S^{f}_{t+1},$$
$$T^{f}_{t+1} = \lambda T_t + \beta(\kappa GHG_t - \gamma Y^{f}_{t+1}{}^{1/2} + \delta S^{f}_{t+1}).$$

Figure 3 shows a scenario where the growth in GHG emissions slows enough to limit temperature increases to two degrees Celsius. Global average temperatures follow a similar pattern, albeit with a significant lag.

Figure 3



Case 4: The Geoengineering Solution

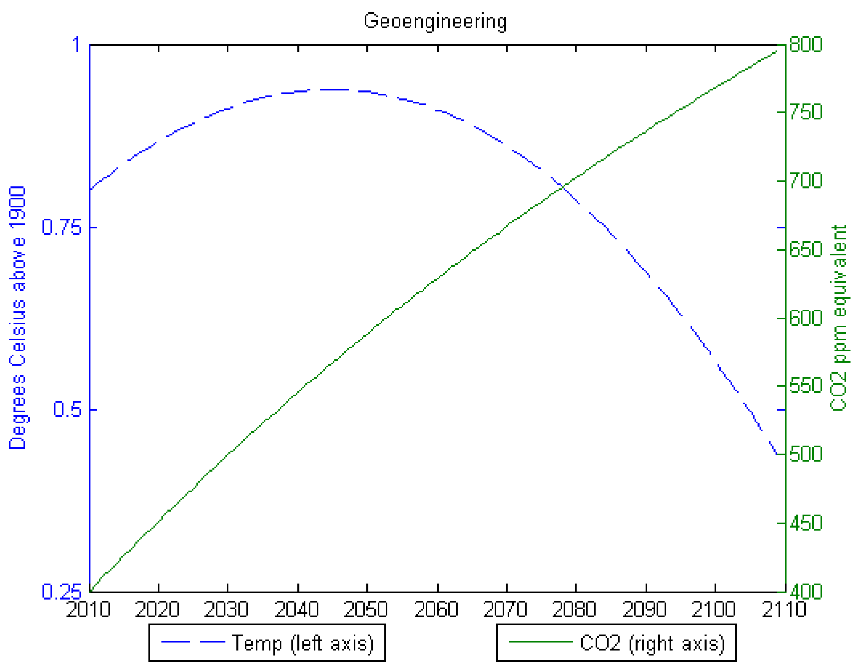
Under a pure geoengineering solution, it is assumed that policymakers are either unwilling or unable to reduce GHG emissions, thus $-\gamma Y_{t+1}{}^{1/2} = 0$. In that case, the price of GHG and temperature futures contracts would be:

$$GHG^{f}_{t+1} = \kappa GHG_t + \delta S^{f}_{t+1},$$

$$T^{f}_{t+1} = \lambda T_t + \beta(\kappa GHG_t + \delta S^{f}_{t+1}) - \rho[\omega G_t + \theta X^{f}_{t+1}].$$

Figure 4 shows the scenario where a geoengineering scheme is adopted. Note that global GHG levels would be expected to continue rising rapidly, even as global temperatures stabilize and then decline.

Figure 4



At first glance, the geoengineering scenario illustrated in Figure 4 seems similar to the "global warming is a myth" scenario: Both show global temperatures and GHG levels moving in opposite directions. In practice, however, there are likely to be some subtle but important differences. In particular, it seems exceedingly unlikely that there will be enough warming in the next few years, or even the next two decades, to trigger a plan as radical as geoengineering. If this supposition is correct, then investors who expect the geoengineering outcome would presumably anticipate *some* global warming to occur before the plan was actually implemented. Under the global warming is a myth scenario, there would be no expectation of rising global temperatures, even in the short run.

Case 5: A Hybrid Policy

Traders might also expect policymakers to pursue a mix of geoengineering and carbon abatement strategies. Because there are diminishing returns to controlling carbon emissions, policymakers who wish to minimize the costs to global warming mitigation will want to pursue reduction strategies up to the point where the marginal cost of temperature reduction through GHG reduction, $2(-\Delta T)/(\beta^2\gamma^2)$, is equal to the marginal cost of geoengineering, given by $1/(\rho\theta)$; see Figure 5. Any additional expenditure beyond this point should then be devoted exclusively to geoengineering. It might seem overly optimistic to assume that the marginal cost of carbon abatement starts at zero, but in fact that assumption might actually be too pessimistic. A recent study suggests that more than 5 gigatons of carbon reduction could be achieved at negative marginal cost—as better insulation, lighting, etc. would have a positive economic payoff even in the absence of any environmental benefits.[19]

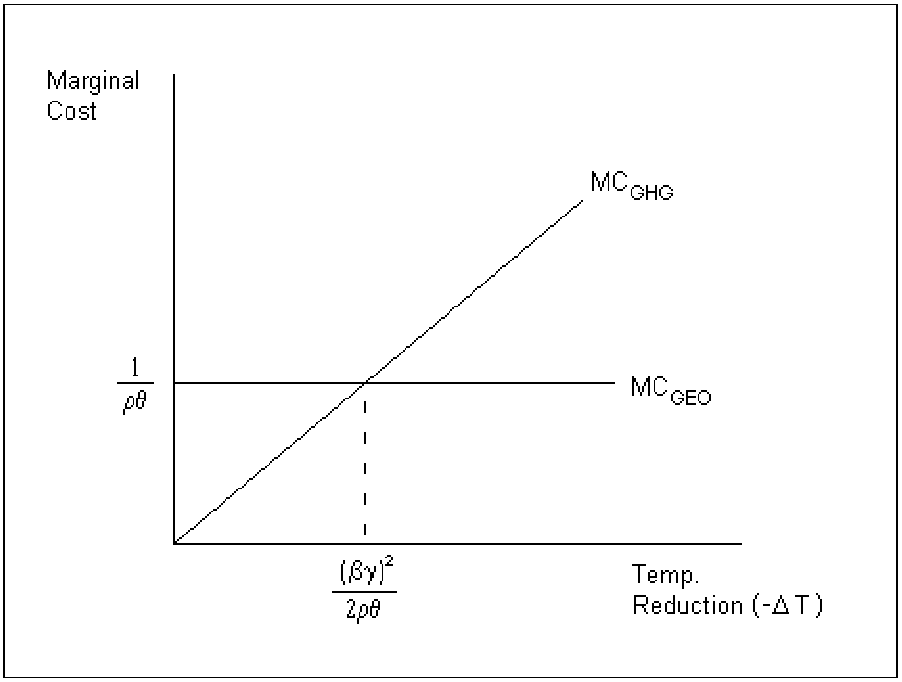
As noted earlier, it is likely that with technology improvements over time, ρ, θ, and γ will increase as technology improves, shifting both the geoengineering and GHG marginal cost schedules downward, thus altering the efficient mix of policies for global warming mitigation. Under a cost minimization strategy, it can be shown that policymakers should spend up to a maximum of $Y^* = [\beta\gamma/(2\rho\theta)]^2$ on GHG reduction, with any additional expenditures devoted to geoengineering.

Under this sort of hybrid policy the price of GHG and global temperature futures contracts would be

$$GHG^f_{t+1} = \kappa GHG_t - \gamma {Y^f_{t+1}}^{1/2} + \delta S^f_{t+1},$$
$$T^f_{t+1} = \lambda T_t + \beta[\kappa GHG_t - \gamma {Y^f_{t+1}}^{1/2} + \delta S^f_{t+1}] - \rho[\omega G_t + \theta X^f_{t+1}].$$

[19] This estimate is taken from a study by the Swedish power company Vattenfall, discussed in *The Economist*, June 2, 2007, Special Report, p. 9.

Figure 5



It is difficult to predict exactly how GHG levels and global temperatures would evolve under a hybrid policy regime. Nevertheless, a few general observations can be made. Because carbon emissions are very long lasting, the gains from reducing carbon emissions would be spread over a long period of time. In contrast, geoengineering schemes such as placing sulfate particles in the stratosphere tend to provide only short-lived relief from warming, as the particles wash out of the atmosphere in a year or two.[20] While geoengineering proposals tend to cost much less in the short run, they may prove much more costly as a long term solution to permanently high GHG levels. Indeed, Bengtsson (2006) criticizes geoengineering on the grounds that it would require society to commit to a policy that would have to be maintained for many centuries.

If traders and policymakers anticipate that technological breakthroughs will provide a long term solution to global warming, then the challenge may be to manage the transition to a post-carbon fuels economy. Given the slow rate at which carbon is re-absorbed into the

[20] Although acid rain would increase modestly, the effect would be less than what one might expect. Most ground-based pollution from coal-fired power plants stays in the troposphere and thus washes out in a week or two, making it a much greater source of acid rain.

environment, it would make sense to restrict the use of geoengineering to peak levels of global warming. This is analogous to the problem of minimizing the cost of electricity generation. The traditional argument is that high capital cost-low marginal cost technologies (hydro, nuclear, etc.) are best used around-the-clock, whereas low capital cost- high marginal cost technologies (oil, gas) are best restricted to peak demand periods.

The preceding analysis may also have some policy implications for the optimal rate of carbon abatement. Let us assume that (without geoengineering) it is cheaper to allow temperature to rise by 2 degrees centigrade for 50 years as compared to an increase of one degree centigrade over 100 years. In that case, society may choose to allow a lot of global warming in the short run (i.e. 50 years), in the hope that new (non-carbon) technologies can allow for sharp reductions in carbon levels over the long run. But now let's also assume that environmental damage from higher temperatures is not linear, i.e. a two degree increase over 50 years does much more damage to the environment than a one degree increase over 100 years. In that case we might look for alternative technologies such as geoengineering, which could provide a cost-effective way of reducing peak temperatures over a moderate period of time. By supplementing emissions controls technologies with geoengineering, we may be able to come up with a much more cost effective climate policy, one that buys time for the sort of new technologies that could dramatically reduce the cost of carbon abatement. On the other hand, there is also a risk that this sort of delay in carbon abatement might reflect a time inconsistency problem—i.e. policymakers with a short time horizon may rely excessively on short term fixes like geoengineering.

5.c Interpreting Climate Futures Market Forecasts

In section 3 we saw that there is a potential circularity problem in interpreting global temperature futures, unless one is also able to simultaneously observe investor forecasts of the policy variable—in this case, atmospheric CO_2 levels. This would especially be true if markets indicated that global temperatures are not expected to rise significantly. We obviously would like to know if that were because policymakers were expected to address the problem before it became severe, or because global warming is a myth. Even most critics of the IPCC view of global warming now generally concede that some warming has occurred in recent decades, but argue that it merely reflects the normal variations in climate patterns that have been occurring over the millennia. If these fluctuations are random, then little further warming might be expected, even without steps to limit greenhouse gas emissions. By having parallel markets in both global temperature futures and GHG futures, it should be possible to tell whether an optimistic climate forecast reflects expectations that policymakers will effectively reduce GHG emissions, or whether global warming is not believed to be caused by increases in atmospheric GHG levels.

We believe that the most useful information from climate futures markets will not come from resolution of the "Is global warming for real?" question, but rather from what the markets tell policymakers about likely future policy choices. For instance, assume global temperatures are expected to rise for several decades, and then decline. Also assume that greenhouse gas levels are expected to continue rising sharply. In that case, the market would be forecasting that policymakers eventually adopt some sort of non-conventional option like geoengineering. In that case, policymakers might want to immediately put more funding into tests to examine the feasibility of that option.

In contrast, assume that global temperatures were expected to continue rising, even as the rate of increase in greenhouse gas levels slowed significantly. In that case policymakers could make several useful inferences. First, that global warming was real. And second, they would know that future policymakers are expected to have opted for policies that sharply reduce new emissions of greenhouse gases (the only policy that would sharply reduce growth in levels of GHGs). In contrast to the geoengineering case, markets would be telling today's policymakers that they could not rely on a simple fix, but needed to offer economic incentives and perhaps research funding to promote reduced-carbon technologies.

Even more useful information might be derived from conditional prediction markets. For example, suppose that the global temperatures futures contract conditional on year 2060 GHG levels of 420-440 ppm traded at a price of 23.0, and also suppose that the temperature contract conditional on 2060 GHG levels of 440-460 traded at a price of 23.6. In that case, we can infer that a net reduction in GHG levels over the next 50 years would be expected to result in a global temperature decrease of 6/10ths of one degree.

Climate futures markets might also be useful in other areas of global warming policymaking. Even if we knew how much global warming was likely to occur, there would remain great uncertainty about the economic impact of that warming. For instance, there is no obvious low cost solution for protecting the vast populations that would be submerged by a 7 to 14 meter increase in global sea levels, yet it is not at all clear how much melting is likely to occur over the next 50 years.[21]

If we had parallel markets in average global temperatures and average sea levels, it would be possible to get some kind of estimate of the expected economic damage that might result from global warming. For instance, if sea levels are expected to rise significantly within the next 50 years, then this would suggest that we cannot wait for technological breakthroughs, and instead need to either drastically reduce greenhouse gas emissions, or implement some sort of geoengineering scheme.

Suitably designed climate futures markets could also provide useful information which might help policymakers to design a more cost effective carbon abatement strategy. For instance, when comparing tradable carbon permits with carbon taxes, Nordhaus (2006, p. 33) noted that:

> "One key difference between price and quantity instruments concerns the structure of the uncertainties—and uncertainty is clearly a central feature of climate-change policy. As is well known, if the curvature of the benefit function is small relative to the curvature of the cost function, then price-type regulation is more efficient, and the converse holds true."

This insight suggests that it may also be possible to derive useful information from a climate options market. Such markets could help identify not just the expected temperature change or future atmospheric GHG levels, but also the level of uncertainties surrounding that forecast.

For any potential global warming policy, a suitably designed prediction market should be able to assist policymakers. For instance, some have advocated carbon capture and storage, but this technology would be very expensive if adopted on a large scale. A prediction market could be created to estimate the future quantities of carbon captured through this method. The market would essentially be estimating the direction of future policy; as such a technology would almost certainly require some sort of policy change. Of course there is no guarantee that the future policy decisions would reflect the optimal choice, but at the very least future policymakers will be making decisions on the basis of a much more complete information set than today's

[21] The oceans would rise by about 7 meters if the Greenland ice cap melted, and another 7 meters if the West Antarctic ice cap melted. Melting of ice in the Arctic Ocean would not raise ocean levels, and the massive East Antarctic ice cap is (fortunately) not expected to melt.

policymakers. Thus prediction markets could provide useful insights into promising areas where we should be focusing our research dollars today.

6. Concluding Remarks

One recurring theme in this paper has been the uncertainty surrounding the relative merits of carbon emissions controls and geoengineering. Lawrence (2006, p. 245) noted that "serious scientific research into geoengineering possibilities . . . is not at all condoned by the overall climate and atmospheric chemistry research communities." MacCracken (2006, p. 239) links this taboo to a widespread view that such research would create a moral hazard problem:

> "Geoengineering would really be, in essence, an enabler for undiminished addiction to fossil fuels, roughly equivalent to foregoing fire insurance based on an assurance that the fire department was right next door and could quickly put out any blaze."

We have a lot of sympathy for the view that reduction of carbon dioxide emissions should be the first priority of policymakers. Nevertheless, it is difficult to discount Schneider's (1996) warning:

> "Supposing, a currently envisioned low probability but high consequence outcome really started to unfold in the decades ahead (for example, 5° C warming in this century) which I would characterize as having potential catastrophic implications for ecosystems . . . Under such a scenario, we would simply have to practice geoengineering."

A wide variety of geoengineering proposals are now being discussed in the press; and now that this genie has left the bottle there is no putting it back—there is no longer any way to shield policymakers from an awareness of the possibility of these sorts of policies.

Schneider's warning also highlights the great importance of information. Policymakers are now forced to make highly costly and highly consequential decisions in a policy arena where there are great uncertainties. Climate futures markets are no panacea, but any additional information on likely climate outcomes could prove to be immensely valuable. Hanson (2006a) shares this view, noting that:

> "…Since the cost of creating a market is largely independent of the topic, the obvious place to look for high benefit-relative-to-cost applications is in advising our most important policy questions. Directly informing the highest-value decisions would seem to be the highest-value applications for prediction markets."

Given the stakes involved with the potentially catastrophic and irreversible consequences of global warming, such markets would be ideally suited to assist policymakers forced to choose between extremely expensive policy options.

For the most part, governments continue to rely on discretionary decisions made by experts, despite a worldwide shift toward market-oriented economic policies in recent decades. In the policy arena this trend has been most apparent in the widespread move toward privatization and deregulation. And in the academic world there has been increased respect shown to free market ideologies, even to policy views that would once have been regarded as impractical. Surprisingly, policy formation is one area that has been relatively unaffected by the neoliberal revolution. This policy transformation, as well as the revolutionary changes in information technology and financial market sophistication, all point in the same direction. It is likely that market-oriented policy techniques now considered quite fanciful will eventually become a routine part of the policymaking process. Although the world is not yet ready to completely turn the policy formation process over to prediction markets, it is time to begin experimenting with these markets as a way of providing useful information to assist policymakers.

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