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Climate variability, economic adaptation, and investment timing

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Abstract: Recent models of adaptation to climate change have allowed economic agents perfect foresight about future climatic conditions. We argue that it is time to move beyond assumptions of perfect foresight to consider the impacts of changing climate predictability on adaptation dynamics. An option value investment model is used to illustrate the impact of one significant determinant of predictability – climate variability – on the timing of adaptation. Decreased predictability leads to postponed adaptation and increased pre-adaptation damage costs, indicating that estimates of the damage reductions to be gained through adaptation based on perfect foresight have been excessively optimistic.

Keywords: climate change; economic adaptation; investment uncertainty; option value.

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1 Introduction

Recent work in greenhouse gas policy analysis has broadened the focus from a sole concentration on the costs and timing of emissions mitigation to include consideration of adaptation to post-mitigation economic damages. Adaptation measures, typically defined as economic investments made to avoid or limit economic damages due to climate change, offer several advantages. They avoid the free rider problem that plagues mitigation policy, and may be relatively inexpensive compared to stringent emissions controls [1]. The inclusion of discounting in climate-economy models further favours future adaptation over current mitigation.

In posing a trade-off between mitigation and adaptation, several researchers have suggested that appropriate investments in adapting to climate change would allow society to postpone or even avoid significant investments in greenhouse gas (GHG) mitigation [2]. Implicit in this view is the assumption that adaptation can be carried out so successfully as to eliminate much of the foreseen damages from anthropogenic climate change, or even take advantage of new environmental conditions such as a CO_2 fertilisation effect on vegetation. Nordhaus [3] offers an opinion representative of this optimism: “Thanks to modern technology, humans live and thrive in virtually every climate on earth.” The implication is apparently that the capacity to adapt to climate is an inherent human attribute that should not be underestimated.

What is less clear is the length of time required for successful adaptation to a changing climate. Diverse societies in equally diverse regions of the globe have had hundreds of years to learn about and adjust to their particular climate niches. The ability to adapt and the timing of investments in new infrastructure, technologies, or general patterns of living depend critically on a society’s ability to form expectations about future conditions. Economic damages due to climate change (and their reduction through adaptation) will therefore be a function of investment timing. Qualitative changes in climate that act to speed up or slow down adaptation may have a significant impact on economic damages.

The view that adaptation will allow many segments of industrial society to adjust to climate change with small or negative net costs depends on a particular representation of climate change. The integrated assessment cost-benefit (IACB) studies that have been used to analyse optimal policy have modelled the climate-economy interaction based largely on smooth, continuous, well-behaved functions. Global mean temperature has been modelled as a monotonic, gradually increasing function of atmospheric GHG concentrations. Economic damages have then been represented as a monotonic, gradually increasing function of mean temperature. Such a characterisation allows economic adaptation by ‘clairvoyant’ economic actors with perfect foresight about future climatic conditions [4]. Under this gradualist paradigm, effective adaptation appears trivial.

However, as Working Group II's contribution to the Intergovernmental Panel on Climate Change's recent Third Assessment Report emphasises, the key features of climate change for both damage estimation and opportunities for adaptation are climate variability and extremes, not changes in mean values [5]. Extensive study of the palaeoclimate record suggests that we should not expect climate change to be smooth, gradual, and perfectly predictable. Past climate change has in general been characterised by 'climate surprises' in the form of sudden, unexpected shifts between alternative patterns of atmosphere and ocean circulation, leading to rapid changes in regional and global climates [6]. A large body of literature has concluded that the complex nature of the climate system makes transitions between such quasi-stable states inherently unpredictable [7]. Economic analyses of abstract 'catastrophes' have sometimes included references to this literature, but most have used *ad hoc* and highly abstracted descriptions of the damages from such events [8]. Further progress in assessing the potential damages from such events and implications for climate policy will require systematic study of specific geophysical, economic, and social impacts that might result.

This paper focuses on one potential outcome of a change in global-scale climate patterns: changes in climate variability. The palaeoclimate record suggests that increased climate variability is a likely consequence of shifts in atmosphere and ocean circulation modes. For example, electrical conductivity analysis of dust in Greenland ice cores has indicated that past instances of rapid, globally synchronous climate change have been accompanied by century-scale periods in which the climate changed rapidly (over years to decades) between very different states [9]. Entering such a variable regime would greatly compromise climate predictability and the ability to form reliable investment expectations.

However, changes in climate variability are not an issue only for distant catastrophic events. Gradual anthropogenic climate change within current atmosphere and ocean circulation patterns is also expected to yield changes in climate variability [1]. For example, an accelerated hydrological cycle in warmed regions is expected to lead to a shift in precipitation patterns characterised by a greater proportion of rainfall in heavy precipitation events and the occurrence of frequent droughts, yielding significantly increased precipitation variability [10]. Such changes have the potential to affect the timing of adaptation in the near- to medium-term.

The paper begins with a review of the consideration of climate variability in economic models to date. Several approaches to the study of adaptation in the climate economics literature are then discussed. This body of work has tended to study either variability or adaptation, but not both. Our interest is in the intersection of the two, specifically on how climate variability could influence the success of adaptation. To investigate this influence, we next build upon an option value framework to explore the effect of climate variability on investment timing. A stylised model examines the decision of an individual investor to adapt to a changing climate when temperature is characterised by a random walk with drift. The effects of changes in variability, as represented by changes in the spread of the random walk, on the timing of the adaptation decision and resulting climate-related damages are explored and discussed.

2 Climate variability and economic adaptation

In a pure economic sense, successful adaptation to climate change would occur where the marginal benefit of adaptation (reduced damages from climate change plus avoided costs of mitigation) is *exactly* equal to its marginal cost (the explicit costs of exercising an adaptation strategy plus the pre-adaptation costs of committed climate change damages). To be successful at striking this balance between costs and benefits requires a certain degree of predictability over what the future climate may be together with an expectation of both avoidable (when adaptation is effective) and unavoidable (when adaptation is too late) damages.

In general, there are two discernible economic impacts of anthropogenic climate change on climate predictability: a learning effect and a variability effect. First, economic agents must learn about the changed or changing climates to which they wish to adapt. Expectations about future climate system behaviour are based on an accumulated stock of observations of past behaviour. When climate changes, past observations are no longer a reliable guide to future expectations, and predictability will be impaired until a sufficient set of new observations can be accumulated. For instance, Kelly and Kolstad [11] used a simple Bayesian learning framework embedded within an IACB policy model to find that several decades of observations would be needed simply to determine the rate at which mean temperature was changing in response to changing atmospheric GHG concentrations.

A second impact on predictability, and the focus of this paper, arises from the possibility of increased climate variability. As noted above, anthropogenic climate change is strongly expected to increase rainfall variability. Near-term effects on temperature variability are uncertain. However, extensive climate change may lead to the reorganisation of global weather patterns, accompanied by significant regional changes in variability [12]. An increase in the spread of climate distribution about its mean value implies greater uncertainty about the actual realisations of weather behaviour to be expected. As less of the probability density becomes concentrated directly around the mean, best guesses are less likely to be correct, and events far from the mean are more likely to occur.

Several studies have examined sector-specific impacts of climate variability, particularly on the agriculture sector. In a regression over economic, physical, and climate variables, Mendelsohn et al. [13] found that increasing inter-annual variability in temperature and precipitation negatively impacted crop revenues and the acreage devoted to cropland. Negative effects occurred for both temperature and precipitation in every season, except for spring temperature and winter precipitation, presumably because farmers can still adjust planting dates and other variables at this stage in the crop cycle. The effects of inter-annual variation in temperatures were large, with an increased variability of 25% in every month producing a decrease of about 35% in average farm values. Using a crop simulation model and a stochastic weather generator, Mearns et al. [14] also found that increased climate variability has a primarily negative effect on yields.

Changes in climate variability are likely to have effects beyond the agricultural sector. For instance, Fisher and Rubio [15] examined the possibility of increased variability in an analysis of water storage capacity. The supply of water resources is expected to become more variable due to increased variability of precipitation and changes in the amount and timing of snowpack melting. They found that increased variability led to an increase in the optimal water storage capacity in the region, implying that efficient adaptation required an increase in capital expenditures so that capital would be suitable for a wider range of outcomes. This need to increase capacity to cope with an increased potential for negative 'surprises' could likely be generalised to many sectors, including energy markets, hazard insurance, and climate-sensitive infrastructure.

Far fewer cross-sectoral studies have explicitly incorporated the impacts of climate variability. In one such study, Conrad [16] used an optimal stopping model to analyse the timing of the decision by a social planner to enact GHG mitigation policies that would decrease the rate of climate change. Conrad modelled mean temperature change as a random walk with drift, where temperature variability is represented as the standard deviation of the random walk. He found that a policy that could eliminate variability would have nearly as high an option value as a policy to eliminate temperature drift.

Although not the focus of this paper, the level of variability will also have impacts on the potential rate of learning. Greater variability masks trends, making them more difficult to discern. Schneider et al. [4] suggest that it may take decades for individual economic agents to discern climate change trends sufficiently well to make adaptation decisions within today's level of climate variability. Along with Lempert et al. [17], they add that variability is as likely to mislead agents into adapting too soon as it is to lull them into inefficiently postponing adaptation. Any increases in climate variability would only exacerbate these problems.

Unfortunately, studies with adaptation as their focus have not considered climate variability, and vice versa. Conrad [16] comes close, but focuses only on the mitigation question. As a result, adaptation in most models has been rather deterministic and predictable. For instance, early work by Kaiser et al. [18] modelled adaptation to climate change at the individual farm level. Despite the inclusion of a stochastic weather generator, all weather and weather-dependent agricultural variables are simulated before the representative farmer makes their optimal planting decision. The model farmer is given perfect information about any new weather distributions from climate change scenarios and is able to perfectly adapt.

Other agricultural studies have allowed their farmers similar foresight in making adaptation decisions. In the MINK study [19], records of the Dust Bowl climate of the 1930s were used to construct an analogue to anthropogenic climate change in the MINK region (Missouri, Iowa, Nebraska, and Kansas). Agricultural experts from the region were consulted to develop a package of farm-level adjustments tuned to this analogue climate. The benefits of adaptation (~35% reduction in damages) were gauged by comparing the results of the model when run with the adjustment package over a no-adaptation scenario run without it.

In the most recent cross-sectoral US climate damage assessment by Mendelsohn and Neumann [20], studies of the potential for adaptation were extended beyond the agricultural sector. 'Natural climate experiments' were used to measure the potential for adaptation by comparing the values of economic variables between two climates in different geographical regions during the same time period. These comparisons were then used to draw inferences about the economic impact of a change in climate between two different times in the same place. Mendelsohn and Neumann [20] describe the method in an example:

> …by observing the energy expenditures, leisure activities, and farming values of town A (which experiences 25°C temperatures) and comparing them to a similar town B (which experiences 30°C temperatures), one can learn how a 5°C temperature increase may affect town A. These cross-sectional comparisons reveal long run changes in which firms and people adapt to their new environment.

They argue that this method allows the assessment of real adaptation as actually carried out by people in response to real climates, as opposed to the hypothetical adaptation measures employed in the agricultural adaptation studies discussed above. However, like these studies, this method assumes undiminished predictability. The current firms and people of town B are adapted to a climate that has been relatively fixed in the long run, whereas the future residents of town A will be expected to adapt to a climate that is changing. Here again, the effects of the need for learning about the new climate and the importance of timing in new investments are ignored. In addition, this method cannot capture the challenges posed by adaptation to any climate in which variability exceeds that of any of the current climates in the geographic sample. By ignoring the impacts of compromised predictability on adaptation dynamics, both the agricultural and the natural climate experiment studies potentially overstate the damage reductions to be gained by adaptation.

3 Investment timing in an optimal stopping problem

The approach to investment in climate change economics has drawn predominantly from the tradition of cost-benefit analysis (CBA), where an investment (disinvestment) is signalled if the discounted expected benefits of the project exceed (fall below) its discounted expected costs. To account for risk, well-defined probability distributions are incorporated within an expected value framework.

However, when the investment is irreversible, future costs and benefits are uncertain, and timing is flexible, then there is frequently a pre-investment value to wait for further information. When an irreversible investment is made, the opportunity to wait for more information is lost. In order to model the investment decision correctly, the value of this lost opportunity must be included on the cost side of the cost-benefit calculations. This approach is often called the 'real options' or 'quasi-option value' approach to investment under uncertainty [21].

A stochastic dynamic programming approach in an option value framework can be used to explore the impact of climate variability on the timing of the adaptation decision. In this section, the Conrad [16] model of mitigation timing is modified to address the investment decision of an individual investor who cannot affect the rate of climate change, but who can invest in adaptation strategies to reduce damages. Two versions of an option value model of the adaptation decision are presented below. In the first, adaptation costs are time-independent, and in the second, they explicitly depend on time.

The underlying variable of temperature is modelled as a stochastic process. For an investor adapting to climate change, the relevant variable could just as easily be sea level, precipitation, snowfall, frequency of storm occurrence, or any combination of these. Using stochastic calculus and Itô's lemma, the differentials that are necessary to solve for the optimal investment decision can be derived [22].

Specifically, temperature $T(t)$ is modelled as a random walk with drift, which evolves according to $dT = m dt + s dz$, where m is the mean drift in temperature, s is the standard deviation about the mean drift, and dz is the increment of a Wiener process [23]. Based on a statistical analysis of historical global temperature deviations, Conrad [16] assumes m to be 0.025°C per year and the current value of s to be 0.1°C per year.

An individual investor suffers climate-related damages $f(T)$ which evolves according to temperature stochasticity specified by dT. The damage function is taken to be $f(T) = b \exp[c(T-T_0)]$, where $b > 0$, $c > 0$, and T_0 is the pre-climate change average temperature [24]. The parameter c is interpreted as the sensitivity of the investor's capital to temperature deviations, and b is the amount of weather-related damages the investor would incur from droughts, storms, etc. in the absence of temperature deviations.

In adapting to climate change, the investor may purchase a decreased sensitivity to weather (b), a decreased sensitivity to temperature change (c), or an increased base temperature (T_0). All three cases amount to a post-adaptation damage function of $g(T) = hf(T)$, where $0 \leq h < 1$. The case where $h = 0$ implies perfect capital insulation from the weather.

According to Itô's lemma, $f(T)$ evolves as $df = cf\,dT + (1/2)c^2 f(dT)^2$, or $\alpha f\,dt + \sigma f\,dz$, where $\alpha = cm + (cs)^2/2$ and $\sigma = cs$. Thus, α captures the average drift rate of damages, and σ is the standard deviation of damages.

At any instant, the investor may choose to incur a one-time adaptation cost $\bar{K}$ in order to reduce future damages to $g(T)$. In effect, the investor is purchasing a new damage function through investment in new capital or technology better suited to a new climate regime. The problem is to find the critical temperature T^* at which the investor will choose to incur $\bar{K}$. The problem may be divided into a 'continuation region', where it is optimal for an investor to do nothing, and a 'stopping region', where it is optimal for the investor to adapt.

Using dynamic programming on the continuation region, the value function $V(f)$ must satisfy the Bellman [25] equation, $rV = f(T) + (1/dt)\,E[dV]$, where r is the discount rate. Again using Itô's lemma, $dV = \alpha f V' dt + (1/2)\sigma^2 f^2 V'' dt + \sigma f V' dz$, where primes (') denote derivation with respect to f. Since $E[dz] = 0$ by the definition of the Wiener process, the Bellman equation becomes $rV = f(T) + \alpha f V' + (1/2)\sigma^2 f^2 V''$. Solving for V and simplifying yields the value function $V = f/(r-\alpha) + Af^q$, where q is given by $q = 1/2 - (\alpha/\sigma^2) + \sqrt{[(\alpha/\sigma^2) - 1/2]^2 + (2r/\sigma^2)}$, and A is an unknown constant to be determined by the boundary conditions. This solution is valid for all parameter values where $\alpha < r$ [26].

Continuity in V and its first derivative are required at the boundary between the continuation and stopping regions. The first of these conditions yields $V(T^*) = \bar{K} + NPV[g(T)] = \bar{K} + [hf/(r-\alpha)]$, the one-time adaptation cost plus the net present value (NPV) of post-adaptation damages. Continuity of the first derivatives across the boundary further requires $V'(T^*) = h/(r-\alpha)$.

These conditions fix A, the constant in the value function, and f^*, the critical level of damages at which the investor will choose to adapt to be $A=\bar{K}/(1-q)f^{*q}$ and $f^*=\bar{K}q(r-\alpha)/(1-h)(q-1)$. The critical temperature T^* which provokes adaptation is then $T^*=T_0+(1/c)\ln(f^*/b)$. Since T, on average, drifts upward at a rate of m, the expected time of adaptation is $\tau=(T^*-T_0)/m=\ln[\bar{K}q(r-\alpha)/(1-h)(q-1)b]/cm$.

Adaptation time (τ) is a near monotonically increasing function in s. Postponing adaptation due to increasing climate variability has the effect of increasing the pre-adaptation damage costs. The expected cumulative damage costs, Cum$f$, incurred before adaptation are given by Cum$f=E[\int_0^\tau f(t)\mathrm{d}t]=\int_0^\tau b\mathrm{e}^{at}\mathrm{d}t$ = $(b/a)\{[\bar{K}q(r-\alpha)/(1-h)(q-1)b]^{\alpha/cm}-1\}$ which is a convex function of s. In general, increasing temperature variability is shown to delay the optimal adaptation time and magnify cumulative damages.

In the more general case, the costs of adaptation may also include a time-dependent component. The fixed $\bar{K}$ only reflects the investment in new technologies or infrastructure appropriate to a changed climate. However, time-dependent adaptation costs may include those resulting from the premature retirement of undepreciated capital. To analyse the case in which one-time adaptation costs are dependent on time, let $K(t)$ take the form $K(t)=k\mathrm{e}^{-\delta t}$ to capture costs resulting from the retirement of undepreciated capital, where δ represents the rate of depreciation. This specification changes nothing in the dynamics of the adaptation decision; only $\bar{K}$ is replaced by $K(t)$, so that f^* and T^* become decreasing functions of time.

The expected adaptation time (τ) is now a function of the temperature expected to have been reached at time τ. That is, the problem is to find τ such that $T^*(\tau) = T_0 + m\tau$, or $m\tau=(1/c)\ln[\{kq(r-\alpha)/(1-h)(q-1)\}\mathrm{e}^{-\delta\tau}]$. This yields $\tau=\ln[\{kq(r-\alpha)/(1-h)(q-1)b\}/c(m-\delta)]$. This result is identical to the one above, except that the capital depreciation rate (δ) offsets the effect of the temperature drift rate (m), further postponing adaptation.

The interesting questions to ask of this stylised model relate to how the adaptation decision may respond to increasing variability and changes to other parameter values. Recall that adaptation has been considered in IACB models under an assumption of pure clairvoyance of the decision-maker. Nowhere does an investor, or social planner, take stock of the current stochasticity of the system and decide *when* to invest in climate adaptation technology, infrastructure, or entirely new means of production.

Table 1 summarises the effects that an increase in each model parameter has on the timing of adaptation. A higher cost of adaptation ($\bar{K}$ or k, regardless of time dependence) or a higher fraction of post-adaptation damages (h) would cause an investor to delay their adaptation decision, as would be expected with a positive rate of time preference. Similarly, a higher discount rate (r) or higher rate of capital depreciation (δ) pushes the adaptation decision further into the future. However, an investor experiencing either a higher scale of climate damages (b) or greater sensitivity to their impact (c) would be expected to adapt sooner. Thus, agricultural sectors feeling the direct impact of a new climate regime may indeed adapt relatively quickly, whereas sectors feeling most of the brunt of climate change through higher energy bills (for cooling and heating under a high climate variability scenario) may be slower to react.

Table 1 Effect of increasing parameter values on adaptation timing

Parameter	*Description*	*Adaptation timing*
$\bar{K}$	Constant one-time adaptation costs	Later
k	Scale of declining adaptation costs	Later
b	Scale of investor's climate damages	Earlier
c	Investor's sensitivity to climate	Earlier
h	Fraction of damages remaining after adaptation	Later
r	Discount rate	Later
δ	Rate of capital depreciation	Later
m	Mean drift rate of temperature	Earlier
S	Standard deviation of temperature	Later

Each of these parameters – K, k, h, r, δ, b, and c – is specific to some extent to investor characteristics such as industry, geography, market structure, and inter-industry linkages. The mean drift rate of temperature (m) has a more economy-wide influence on adaptation. Its increase would tend to lead to an early adaptation strategy. Most relevant to this analysis, an increase in temperature variability (s) leads to economy-wide postponement of adaptation and thus an increase in the pre-adaptation damage costs to society. Postponement occurs because there is an option value associated with waiting to see how quickly temperature will rise.

Approaches that fail to take into account the dynamic effects of variability on adaptation timing will therefore tend to overstate the damage reductions to be gained through adaptation. If adaptation costs are a decreasing function of time, waiting until these costs decline may partially offset the cost-increasing effects of postponement. However, from the social planning perspective of most IACB models, significant pre-adaptation damage costs would have the effect of tipping today's policy decision more toward mitigation and away from tomorrow's hope of successful adaptation.

4 Concluding remarks

Palaeoclimate studies have suggested that climate change is unlikely to be a smooth, predictable process, and economic models of catastrophic change and climate variability point to an important role for predictability in the determination of damages. Here, we have investigated the link between variability, predictability, and adaptation dynamics and illustrated a general method for assessing the impact of changes in variability on adaptation timing. Our results indicate that increases in climate variability could significantly postpone adaptation by individual economic actors and lead to increased pre-adaptation damages not reflected in the social planner's problem considered in most integrated assessment cost-benefit (IACB) models.

This model is limited by the use of temperature as the sole damage-inducing weather parameter. Real adaptation decisions will involve weather parameters other than temperature and more general cost functions. Furthermore, weather processes, including temperature, may be better modelled using stochastic processes other than a random walk with drift. Modifying this model to examine the case of a particular investor profile would require a determination of the weather parameter or parameters of interest, the appropriate stochastic process, and the functional dependence of damages on this parameter.

Despite these modifications, the *qualitative* results obtained here are likely to apply to most adaptation decisions. In most cases, adaptation to climate change is likely to be characterised by flexibility of timing and uncertainty about costs and benefits. In these cases, variability will increase the option value of waiting, leading to delayed adaptation and increased pre-adaptation damage costs. Any climate change impacts that increase variability will thereby reduce the potential for damage reductions through adaptation.

This analysis did not consider sudden, discontinuous changes in climate or damages. Such changes are another potential aspect of the spectrum of catastrophic impacts that may result from anthropogenic climate change. Anticipation of a sudden increase in damages may alter the value placed on waiting. Resultant changes in adaptation timing would depend on the magnitude of the damage increase, the subjective probability placed on the increase, and the anticipated effectiveness of adaptation measures.

Furthermore, this analysis has not addressed an additional important source of impacts to climate predictability: the uncertainty arising from lack of knowledge about the underlying distributions characterising new climatic conditions. The model presented here assumes perfect knowledge of both the rate of temperature drift and its standard deviation, unrealistically shortcutting the need to learn about the changed climate. The interaction between the learning and variability effects on predictability will further complicate assessments of adaptation dynamics. However, the need to learn is likely to further delay adaptation and significantly decrease the gains from adaptation. These considerations indicate that recent suggestions that adaptation will significantly reduce the costs of climate change to industrial societies, or even yield net benefits, have been excessively optimistic.

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22 For further details, see Dixit and Pindyck, supra note 24, pp.70–82, 95–109.

23 $dz = \varepsilon(t)\sqrt{dt}$, where $\varepsilon(t)$ is a standard normal random variable, $\varepsilon(t) = N(0, 1)$. For a brief introduction to Wiener processes and Itô variables, see the appendix to Pindyck, R.S. (1991) 'Irreversibility, uncertainty, and investment', *Journal of Economic Literature*, Vol. 29, pp.1110–1152.

24 It is likely that investors in different sectors of the economy would be subject to climate change damage costs that would take various mathematical forms. An exponential damage cost is used here for analytical tractability.

25 Bellman, R. (1957) *Dynamic Programming*, Princeton University Press, Princeton.

26 When the drift rate of damages is greater than the social rate of time preference ($\alpha > r$), the effective discount rate becomes negative and the problem must be truncated at a finite horizon.