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Uncertainty, investment, and managerial incentives

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ABSTRACT

This study provides evidence that managerial incentives, shaped by compensation contracts, help to explain the empirical relationship between uncertainty and investment. We develop a model in which the manager, compensated with an equity-based contract, makes investment decisions for a firm that faces time-varying volatility. The contract creates incentives that affect both the sign and magnitude of a manager's optimal response to volatility shocks. The model is calibrated using compensation data to quantify this predicted investment response for a large panel of firms. Our estimates help explain the variation in firm-level investment responses to volatility shocks observed in the data.

1. Introduction

An empirical literature in macroeconomics and finance has found a strong connection between uncertainty shocks and capital investment policies.[1] Theoretical explanations for the response of investment to changes in idiosyncratic volatility have traditionally focused on the real option feature of investment. With costly reversibility, an increase in volatility changes the optimal timing of investment.[2] In addition, following the financial crisis of 2007–2009, imperfections in financial markets have been explored as a potential mechanism that generates the observed link between uncertainty and investment.[3]

In this paper we investigate the role of an agency conflict between a firm's manager and shareholders in explaining the relationship between uncertainty and investment. Increasingly, compensation contracts for executives of US public firms consist largely of own-company stock and options. These contracts expose a manager to firm-specific risk, which is not borne by diversified shareholders. This drives a wedge between the pricing kernels, and therefore optimal investment policies, of a firm's manager and diversified shareholders. If shareholders are unable to perfectly monitor managers, firm investment policies observed in the data are likely to reflect the manager incentives induced by the compensation contract. Importantly, the manager's optimal response to an uncertainty shock will depend on the structure of their incentive-based compensation contract.

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[1] See, for example, Leahy and Whited (1996), Guiso and Parigi (1999), Bloom et al. (2007), Panousi and Papanikolaou (2012), Bachmann et al. (2013), and Gilchrist et al. (2013).

[2] See, for example, Brennan and Schwartz (1985), McDonald and Siegel (1986), and Dixit and Pindyck (1994).

[3] Gilchrist et al. (2013) explore this effect in a model that also features capital irreversibility and investigate the quantitative impact of each mechanism.

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We show that this agency conflict is important in understanding the response of investment to volatility shocks. To quantify the investment incentives of the manager, we develop a neoclassical model of firm investment that embeds an agency conflict between the manager and outside shareholders. Firms are operated by managers who are compensated with their own company's stock and options, in addition to a fixed salary. Thus, the model explicitly links manager compensation contracts to optimal firm investment policies and provides predictions for the relationship between idiosyncratic volatility shocks, the compensation contract, and a manager's optimal investment policy.

The model predicts a conditional relationship between firm-specific uncertainty and investment that can vary across firms and over time. We show that an increase in firm-specific uncertainty can incentivize a manager to either increase or decrease firm investment, where the sign and magnitude of the response depend on the structure of the compensation contract.

We use firm-level data on production and compensation contracts for a sample of US public companies over the period 1956–2012 to calibrate the model to match firm-year-level variation. From the calibrated model, we compute the optimal investment response to a volatility shock for a manager with the observed compensation contract. We do this for each firm-year in our sample and compare this panel of estimated manager investment incentives to the investment policies that would be optimal for a diversified shareholder.

The panel of predicted manager investment responses to volatility shocks, which are estimated from the model, exhibit significant cross-sectional and time series variation. Moreover, we show that the predicted manager responses have strong predictive power for firms' observed investment responses to volatility shocks in the data. In particular, we find that the documented negative relationship between volatility and investment is only present for those firms that provide compensation contracts that predict this negative response. Taken together, our results suggest that understanding the structure of executive compensation contracts is important for understanding the link between uncertainty and investment observed in the data.

A significant strand of the investment literature has theoretically characterized the effect of uncertainty on optimal investment policies under different conditions for the firm's production technology, capital adjustment costs, the market structure, and risk aversion. One set of results finds that greater uncertainty can generate an increase in firm investment. If a firm's profits are convex in costs or demand, and the firm is able to easily scale up or down, then greater uncertainty increases the marginal value of an additional unit of capital and, consequently, investment.[4] A second set of results has predicted a negative relation between uncertainty and investment. These papers show that with costly reversibility of capital, an increase in uncertainty can increase the value of the option to delay investment and result in a drop in investment. This real options effect generally predicts that the investment response to an increase in uncertainty will be negative as a firm's optimal inaction region expands.[5] Thus, the response of investment to uncertainty predicted by economic theory can be ambiguous and depends critically on the assumptions of the model environment.[6]

The empirical literature on the relationship between uncertainty and investment has, in most cases, found a negative relationship, whereby an increase in uncertainty predicts a reduction in investment. Leahy and Whited (1996) study the empirical relationship between uncertainty, measured using the volatility of firm equity returns, and investment for a panel of US manufacturing firms. They find that uncertainty has a strong negative impact on investment and that this is driven by idiosyncratic, firm-level uncertainty, not a priced source of systematic risk. Bloom et al. (2007) take a similar approach, using data for UK manufacturing firms for the period 1972–1991. They find evidence that the investment behavior of large manufacturing firms is consistent with a real options effect generated by costly reversibility.

Bachmann et al. (2013) use business survey data for the US and Germany in a structural VAR framework and find that innovations in uncertainty have a negative impact on economic activity. They find these effects to be prolonged, however, and argue that the observed responses are not consistent with the delay and fast rebound that would be predicted by a real options effect. Guiso and Parigi (1999) study a sample of Italian manufacturing firms and measure uncertainty using the subjective probability distribution of demand reported by the entrepreneurs in their sample. They find that this measure of uncertainty displays a negative relation with the responsiveness of investment, consistent with a real options effect.

Panousi and Papanikolaou (2012) investigate the uncertainty-investment relationship by estimating panel regressions for US public firms, using idiosyncratic equity return volatility as their measure of uncertainty. They find a negative relationship between investment and uncertainty and show that the magnitude of this effect is increasing in the fraction of insider ownership. They attribute these results to the impact of undiversified idiosyncratic risk borne by managers that have incentive-based compensation packages.

The empirical results of this paper are complementary to those of Panousi and Papanikolaou (2012) in that we also find an important role for executive compensation contracts in shaping firms' investment response to uncertainty shocks. Additionally, our structural model allows us to compute a manager's predicted response to an uncertainty shock for each firm and year in our sample. We show that there is significant variation, both in the cross-section and time series, in our estimates of a manager's optimal response to an uncertainty shock. Specifically, we find that some managers receive compensation contracts that incentivize them to increase investment following an uncertainty shock.

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[4] See Oi (1961), Hartman (1972), and Abel (1983).

[5] See, e.g., Bernanke (1983), Brennan and Schwartz (1985), McDonald and Siegel (1986), Pindyck (1988), and Dixit and Pindyck (1994).

[6] For more on this, see Caballero (1991), Abel et al. (1994), Abel et al. (1996), Abel and Eberly (1996), and Abel and Eberly (1999).

An additional proposed explanation for the investment-uncertainty relationship comes from costly external financing. The basic intuition is that higher idiosyncratic volatility increases the probability of distress and consequently increases the cost of external financing. Gilchrist et al. (2013) investigate the costly reversibility and costly external financing mechanisms in a general equilibrium model of firm investment and financing. They conclude that the costly external financing channel has a greater ability to explain the empirical patterns they find in the data.

Our focus in this paper, the role of executive compensation contracts, represents a third, complementary mechanism to the existing literature. While these proposed mechanisms need not be mutually exclusive, they each carry different implications and predictions for the relationship between uncertainty and investment. An important distinction of the agency conflict we study in this paper is that it predicts that the relationship between investment and uncertainty will be conditional, varying both across firms and over time. In panel regressions of firm investment, we find support for this prediction.

This paper also relates to a growing literature that studies the quantitative impacts of agency conflicts on firm investment and financing policies. While the agency conflicts that arise between management and outside investors have long been studied, the literature that seeks to quantify these effects is more recent.[7] Additionally, previous work has considered the impact of undiversified, firm-specific risk on optimal firm policies in the setting of entrepreneurial finance.[8]

The remainder of the paper is organized as follows. Section 2 presents the model framework and introduces the measurement of the manager's investment distortion. Section 3 discusses the data sources used in the model calibration. In Section 4 we present our calibration approach that gives us a panel of manager investment incentives. We also present model comparative statics and impulse responses to illustrate how features of the compensation contract shape a manager's optimal investment policy and response to volatility shocks. In Section 5 we use firm-level investment data and a panel of manager investment incentives computed from the model to test the model's empirical predictions for the investment-uncertainty relationship. Section 6 concludes.

2. Model

We employ a neoclassical model of investment that embeds an agency friction to study the impact of incentive-based executive compensation contracts on firm investment behavior. To study how uncertainty interacts with compensation-induced investment incentives, we extend the model of Glover and Levine (2014) to allow for stochastic volatility of the firm's productivity process.[9]

2.1. Firm production, volatility and financing

Firm i at time t generates pre-tax cash flows according to

$$\pi_{i,t} = e^{z_{i,t}} k_{i,t}^{\alpha} \tag{1}$$

where $z_{i,t}$ is firm-specific productivity, and $k_{i,t}$, is the stock of capital. We assume that the log of a firm's idiosyncratic productivity evolves according to

$$z_{i,t+1} = \rho z_{i,t} - \frac{\sigma_t^2}{2} + \sigma_t \epsilon_{i,t+1} \tag{2}$$

where $\epsilon_{i,t+1} \sim \mathcal{N}(0,1)$. The volatility of innovations to log productivity, $\sigma_t \in \{\sigma^L, \sigma^H\}$, is stochastic and follows a two-state Markov chain with a transition matrix parameterized by p_{LL} and p_{HH}:

$$P_\sigma = \begin{bmatrix} p_{LL} & 1-p_{LL} \\ 1-p_{HH} & p_{HH} \end{bmatrix}. \tag{3}$$

Volatility σ_t is common across firms and represents the average level of idiosyncratic volatility in the economy. Note that the process for log productivity, $z_{i,t}$, is constructed such that the conditional mean of productivity, $\mathbb{E}[e^{z_{i,t+1}} | z_{i,t}, \sigma_t]$, does not depend on σ_t. This is convenient in that shocks to idiosyncratic volatility do not represent shocks to expected aggregate productivity even though they are common across firms.

Henceforth, firm and time subscripts are suppressed, and we adopt recursive notation throughout where the $'$ superscripts denote next period values.

Each period the firm makes an investment decision i and capital accumulates according to

$$k' = (1-\delta)k + i \tag{4}$$

[7] See, for example, Nikolov and Schmid (2012), Morellec et al. (2012), Nikolov and Whited (2014), Li and Whited (2013), and Glover and Levine (2014).
[8] See, for example, Bitler et al. (2005) and Chen et al. (2010).
[9] See Gourio and Michaux (2013) and Gilchrist et al. (2013) for examples of models with time-varying volatility of the productivity process.

where $\delta \in (0,1)$ represents the depreciation rate of capital. Investment is subject to convex adjustment costs given by

$$\Phi(i,k) = b\left(\frac{i}{k} - \delta\right)^2 k. \tag{5}$$

If internal cash flows are insufficient to pay for current-period investment, the firm may finance investment externally. External financing entails a proportional cost on the size of the issuance e:

$$\Lambda(e) = \lambda e \tag{6}$$

where $\lambda \geq 0$.

The firm pays corporate income tax on earnings, after deducting depreciation, at a rate τ_c and equity payouts are taxed at a personal rate of τ_d. The firm's net cash flows are

$$D(i,k,z) = (1-\tau_c)\pi(k,z) + \tau_c \delta k - i - \Phi(i,k) \tag{7}$$

which correspond to external financing when D is negative. Finally, after accounting for any equity issuance costs, the after-tax value of the dividend is

$$d(i,k,z) = (1 + \mathbb{1}_{[D<0]}\lambda - \mathbb{1}_{[D>0]}\tau_d)D(i,k,z), \tag{8}$$

where negative $d(i,k,z)$ represents external financing.

2.2. Benchmark value of the firm

In the frictionless benchmark case, investment is chosen to maximize the expected present value of future cash flows, $V^*(k,z,\sigma)$. In this case the value of the firm satisfies the following Bellman equation:

$$V^*(k,z,\sigma) = \max\left\{0, \max_i [d(i,k,z) + \beta \mathbb{E}[V^*(k',z',\sigma')|z,\sigma]]\right\}, \tag{9}$$

where $k' = (1-\delta)k + i$. Denote as $i^*(k,z,\sigma)$ the investment policy function that satisfies this maximization. The outer max represents the shareholders' limited liability protection. This specification will serve as the frictionless benchmark to understand how incentive-based compensation contracts impact a manager's optimal investment policy.

2.3. The manager

In the model, the manager derives value from the firm distinct from the shareholder. Specifically, the manager derives utility from the compensation she is awarded. We define the compensation contract by $\Theta \equiv \{\theta_s, \theta_o, F\}$, where θ_s is stock compensation, θ_o is option compensation, and F is fixed salary, as these three terms comprise, in practice, the vast majority of compensation for executives. Furthermore, we assume that the manager has constant relative risk aversion (CRRA) preferences:

$$U(c) = \frac{c^{1-\gamma}}{1-\gamma}. \tag{10}$$

The manager lives for one period, making a single investment decision before retiring and receiving payment from the fixed and incentive-based compensation contract. Therefore, the manager chooses investment to maximize her expected utility over next-period compensation:

$$\max_{k'} \ \mathbb{E}[U(C(k',z',\sigma',k,z,\sigma))|z,\sigma] \tag{11}$$

where tomorrow's value of compensation is

$$C(k',z',\sigma',k,z,\sigma) = (1+r_f)\theta_s d(i,k,z) + F + \theta_s V(k',z',\sigma'|\Theta) + \theta_o \max(V(k',z',\sigma'|\Theta) - S(i,k,z,\sigma), 0), i = k' - (1-\delta)k, \tag{12}$$

$V(k,z,\sigma \mid \Theta)$ is the market value of the manager-run firm, and $S(i,k,z,\sigma)$ is the strike price on the manager's option compensation.[10] In practice, most options are issued at a strike price equal to the current market price (at the money), and we therefore make the assumption that the strike price is the ex-dividend equity value:

$$S(i,k,z,\sigma) = V(k,z,\sigma \mid \Theta) - d(i,k,z). \tag{13}$$

[10] For simplicity, we assume that the manager does not have any additional sources of wealth and has utility only over her next period compensation. While alternative sources of wealth could shape a manager's preference for risk and optimal policy choices, we do not have data that would allow us to implement this in a calibrated version of the model. Obviously a manager with alternative preferences, such as reputation concerns or a desire for empire building, would select different optimal investment policies. We leave the theoretical exploration of these implications for future work.

The first term in the manager's compensation, $(1+r_f)\theta_s d(i,k,z)$, is the dividend payment the manager receives in the current period that will depend on her investment decision. This dividend, which may be negative in the case of equity issuance, is held in a risk-free account until the next period.[11] Given the utility maximization problem in (11), we define $i(k,z,\sigma \mid \Theta)$ as the manager's investment policy which maximizes her utility.

The market value of the manager-run firm, $V(k,z,\sigma \mid \Theta)$, which is the expected present value of all future cash flows paid by the firm when management controls investment decisions, is defined as

$$V(k,z,\sigma \mid \Theta) = \max\{0,\ d(i(k,z,\sigma \mid \Theta),k,z) + \beta \mathbb{E}[V(k',z',\sigma' \mid \Theta) \mid z,\sigma]\}, \tag{14}$$

where

$$k' = (1-\delta)k + i(k,z,\sigma \mid \Theta).$$

We assume that the managers' compensation contracts remain constant across generations, and that shareholders and managers are aware of the terms of these contracts. Also note that even though the manager chooses investment and financing policies for the firm, the shareholders maintain their limited liability protection.[12]

2.4. Manager investment response to volatility

We have now defined the frictionless benchmark investment rate, $i^*(k,z,\sigma)/k$, and the investment rate chosen by the manager, $i(k,z,\sigma \mid \Theta)/k$. We now define the state-dependent over-investment incentive of the manager as the difference in these investment rates:

$$\omega_0(k,z,\sigma \mid \Theta) = \frac{i(k,z,\sigma \mid \Theta) - i^*(k,z,\sigma)}{k}. \tag{15}$$

For the current state (k,z,σ), positive values for ω_0 indicate that the manager has an incentive to invest more, and take on more risk, than is first-best optimal. Similarly, negative values for ω_0 indicate that the manager has an incentive to take on less risk and invest less.

We are interested in the manager's investment response to volatility shocks. To this end, we construct the difference between the manager's investment incentive in the high and low states as a measure of the investment-volatility sensitivity:

$$\phi_0(k,z,\sigma \mid \Theta) \equiv \omega_0(k,z,\sigma \mid \Theta, \sigma = \sigma^H) - \omega_0(k,z,\sigma \mid \Theta, \sigma = \sigma^L). \tag{16}$$

We define ϕ_0 to be the investment-volatility response that is driven by the manager's compensation contract. Details of the empirical estimation of this variable are discussed in Section 4.3.

3. Data

3.1. Data description

We collect data on executive compensation, firm financial statements, and equity returns for a sample of US public companies for the period 1956–2012. Firms' accounting data is taken from the Compustat annual database and equity returns and values come from CRSP. We gather data on salary, and equity and option ownership stakes for firm CEOs from two data sources. The first is the ExecuComp database, which lists compensation information for top officers of companies included in the S&P 1500 index. This database provides compensation data for a subset of executives of US public companies at an annual frequency for the period 1992–2012. We supplement the ExecuComp data with the hand-collected database constructed in Frydman and Saks (2010).[13]

Frydman and Saks (2010) construct a database on executive compensation for top officers of large firms that goes back to 1936. They hand collect executive compensation information for top officers from 10-K and proxy statements for the period of 1936-1991. Their sample consists of all companies that were among the 50 largest companies in the US in the year 1940, 1960, or 1990. We use the compensation data they report for the company CEO and merge this with accounting data from Compustat and equity return data from CRSP. After merging the data from all three sources, we have an unbalanced panel of 85 unique firms for the period 1956–1991. We extend the sample for these firms using ExecuComp data for the period 1992–2012. This unbalanced panel of 85 unique firms spanning the period 1956–2012 we refer to as the “Frydman–Saks” sample.

Additionally, we construct what we refer to as the “ExecuComp Sample,” which consists of all firms in the ExecuComp database in the period 1992–2012. We merge these data for CEO compensation from ExecuComp with firm accounting and

[11] This might appear to induce myopia on the part of the manager given that the entire payoff is received by the manager only one year hence. However, this is not the case: the manager's payoff is a function of the market value of the firm, which incorporates her investment decision, as well as all future investment decisions of future managers, all of whom have identical incentives. Thus, a one-period manager problem maintains parsimony by eliminating the modeling of a full consumption-savings problem without inducing managerial myopia.

[12] Calibration of the production parameters will be the key determinant of the exit rate. The calibration in Section 4 results in an exit probability very close to zero.

[13] We thank Carola Frydman for making these data available on her website.

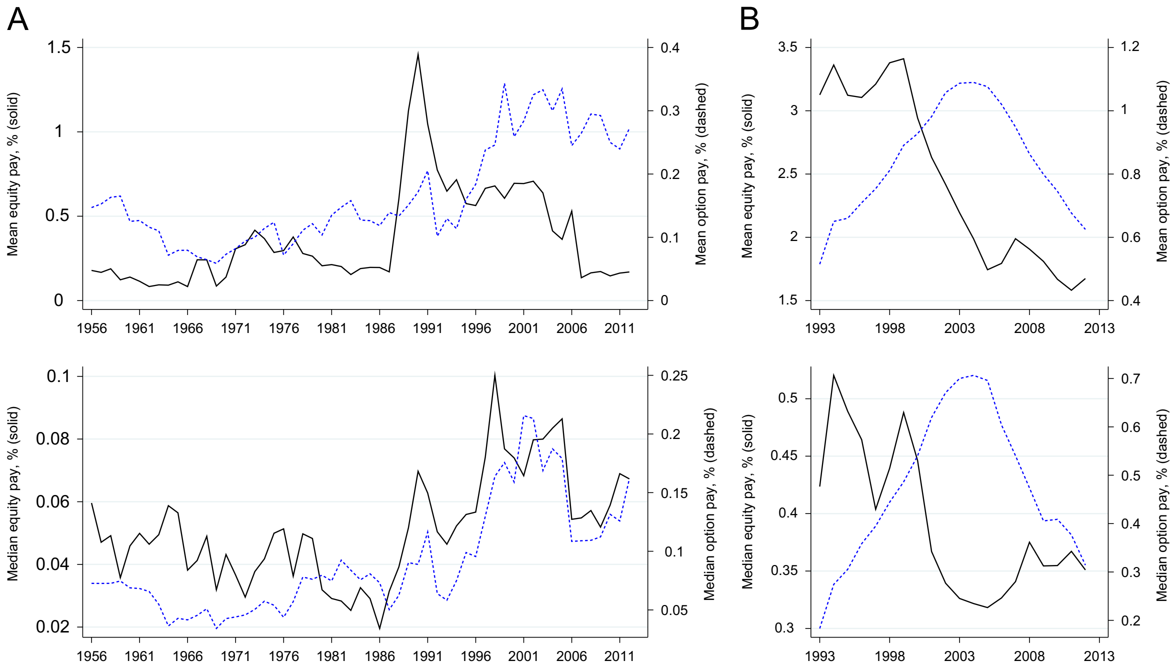

Fig. 1. Equity and option compensation. Shows the cross-sectional mean (top row) and median (bottom row) equity (dashed line) and option (solid line) compensation. Equity and option compensation are expressed as a fraction of total shares outstanding. Panel A shows the Frydman–Saks sample spanning 1956–2012, and Panel B shows the ExecuComp sample spanning 1993–2012.

return data as before and arrive at a sample of 24,624 firm-year observations, consisting of 2435 unique firms over the period 1992–2012. In all cases, we apply a standard set of filters used in the empirical finance literature.[14]

We define the manager's equity compensation to be the fraction of the firm owned by the manager. Option holdings is defined as the number of unexercised options held by the manager divided by the total shares outstanding. The equity and option holdings include both vested and unvested shares. While some of the manager's options are not exercisable, these holdings still affect manager incentives and are therefore included. Finally, fixed salary is defined following Dittmann and Maug (2007) as the sum of five non-equity-based components of compensation. We normalize fixed pay by capital stock to ease calibration.

We define investment to be capital expenditures divided by the lagged replacement value of capital. The replacement value of capital is calculated using the approach of Eberly et al. (2008). Our results are qualitatively similar if investment is defined as capital expenditures divided by lagged net property, plant, and equipment.

3.2. Compensation contracts

Before estimating the investment incentives derived from the model, we first explore the time variation in the mean and median compensation contract over our two samples. Fig. 1 plots the mean and median equity and option compensation for the Frydman–Saks sample in Panel A and for the ExecuComp sample in Panel B. Equity compensation is indicated with a solid line on the left axis, and option pay is indicated with a dashed line on the right axis.

For the Frydman–Saks sample, there is significant time variation in both the mean and median, with a significant and temporary rise in equity pay in the late eighties. The median level of incentive pay, both for stock and option, rises dramatically throughout the nineties, and then falls somewhat in the last seven years of the sample.

For the ExecuComp sample, which includes a much broader cross section of firms, we see a dramatic rise and fall of option compensation between 1993 and 2012, starting at a mean of 0.5%, more than doubling to 1.1% in 2004, and then falling again to 0.6% in 2012. During the same period, we see a dramatic fall in equity compensation, from a mean of over 3.1% in 1993 to 1.7% in 2012. Medians follow similar patterns. These patterns suggests that the convexity of the manager's compensation increased significantly in the 1993–2004 period, as compensation shifted away from equity and toward option pay, before falling again after 2005. This dramatic decline in option compensation, coupled with a decline in stock pay, suggests that the manager's incentives to invest in risky capital may have declined during this period, something we will explore quantitatively in the model.

[14] For example we remove firms with negative book assets, negative sales, negative gross property, plant, and equipment.

Throughout the paper, we do not take a stance on the underlying sources of the observed variation in executive compensation contracts. From the perspective of the model, we take the observed compensation contracts as given. Prior empirical work has argued that accounting and regulatory changes can explain a significant portion of the change in mean option compensation during the ExecuComp period of our sample. In 2006, the Financial Accounting Standards Board adopted FAS 123R, which required firms to expense option compensation at fair value. Hayes et al. (2012) document a significant reduction in the use of stock options for all firms following the adoption of FAS 123R.

Similarly, Carter et al. (2007) find evidence that financial reporting costs shape the structure of executive compensation contracts. They conclude that the favorable accounting treatment led to higher option use prior to the adoption of FAS 123R. Shue and Townsend (2014) document that executive stock and option grants are rigid in the number of shares granted and that this nominal rigidity can help to explain features related to both the trend and dispersion of executive compensation in US firms. They also find evidence that the adoption of FAS 123R helps to explain the observed changes in compensation contracts after 2006.

4. Calibration and model evaluation

In this section, we first discuss the choice and construction of parameter values used to calibrate the model and describe the numerical evaluation of the model. As we are interested in estimating the manager's investment-volatility sensitivity for the entire panel of firms, we set compensation Θ to its empirical counterpart, denoted Θ_{it}, for each firm i and year t in our empirical sample. This firm-year calibration follows the approach of Glover and Levine (2014). Next, we gain intuition for the investment incentive estimates that come out of the model and their relationship to volatility shocks by exploring comparative statics in the compensation contracts and impulse responses to volatility shocks.

4.1. Parameter choice

Calibrating the model involves selecting parameter values which are either common across all firms, specific to a firm across all years, or specific to a firm for a given year. Common parameters include the production parameters: returns to scale α, depreciation rate δ, persistence in productivity ρ, and capital adjustment costs b. The discount rate β, external financing costs λ, and corporate income and dividend tax rates τ_c and τ_d are also common across firms. We use the parameter values given by Glover and Levine (2014), who directly estimate the production parameters using data on earnings, labor, and capital. The external financing cost parameter λ is set to 0.02, consistent with Gomes (2001). The manager's risk aversion γ is also common across firms, and is set to 3 in the calibration. Alternative parameter choices for risk aversion change the distribution of estimated ω_{it}, however the rank ordering of these estimates across firm-year observations remain similar. The complete set of parameter values which are common across all firms are given in Panel A of Table 1.

The manager's compensation contract, Θ, is defined by her stock holdings θ_s, option holdings θ_o, and fixed salary F. We denote by Θ_{it} the empirical values taken directly from ExecuComp and Frydman and Saks (2010) used to calibrate the manager's compensation contract for firm i in year t. The distributional properties of Θ_{it} are shown for the ExecuComp and Frydman–Saks samples in Panel B of Table 1.

For a given calibration there are two volatility parameters, σ^L and σ^H. As explained in the model description, shocks to idiosyncratic volatility are common across firms such that all firms are in either the high or low volatility state. However, because volatility varies widely in the cross-section, we assume each firm's volatility is proportional to the common component of volatility, such that $\sigma_i^H = \zeta_i \sigma^H$ and $\sigma_i^L = \zeta_i \sigma^L$. Thus while σ^L and σ^H are system-wide, ζ_i is firm-specific. We directly estimate ζ_i for each firm in our empirical sample. The final two rows of Panel B of Table 1 report the distribution of the firm-specific parameters for idiosyncratic volatility in the high and low volatility states, σ_i^L and σ_i^H. The following section gives details on the construction of the volatility parameter values.

4.2. Constructing the volatility parameters

We calibrate the Markov chain for idiosyncratic firm volatility as follows. For each firm in our sample and each year, we regress the firm's daily equity returns on the three factors of Fama and French (1992). We denote the volatility of the residuals from this regression of daily returns for firm i in year t as σ_{it}^E. Given a nonzero amount of debt, this corresponds to idiosyncratic, levered equity volatility. We construct an unlevered measure of firm i's idiosyncratic volatility for year t, denoted σ_{it}^A, as

$$\sigma_{it}^A = \frac{E}{D+E}\sigma_{it}^E. \tag{17}$$

We compute the mean idiosyncratic, unlevered volatility for year t, $\overline{\sigma}_t^A$, as the cross-sectional average of the σ_{it}^A measures. We fit a two-state Markov chain to this average idiosyncratic volatility series such that $\overline{\sigma}_t^A \in \{\sigma^{A,L}, \sigma^{A,H}\}$. We identify the high volatility state ($\sigma^{A,H}$) as years in which the process is above the 90th percentile of its unconditional distribution in our estimated sample. We set $\sigma^{A,L}$ and $\sigma^{A,H}$, the mean idiosyncratic volatility in the low and high states, to their conditional means in the sample. We then calibrate the transition probabilities, p_{LL} and p_{HH}, for the constructed Markov chain to match the observed frequencies in our sample. Finally, we allow each firm's idiosyncratic volatility to load differentially on the

Table 1
Model Parameters.

This table presents the calibrated and estimated parameters of the model. Where applicable, the parameter refers to an annual frequency. Panel A reports the production and financing parameters that are set to be common to all firms. Panel B displays statistics for the distribution of the contract parameters and firm-specific volatility, where θ_S and θ_O refer to the manager's shares in stock or options, respectively, as a fraction of the total shares outstanding. The manager's fixed pay normalized by capital is denoted F/k. A firm's idiosyncratic volatility in the low and high state are denoted by σ_i^L and σ_i^H. All compensation contract moments are displayed as percentages.

Panel A: Production parameters

Description	Parameter	Value
Returns to scale	α	0.863
Depreciation rate	δ	0.091
Productivity shock persistence	ρ	0.737
Discount factor	β	0.95
Capital adjustment cost	b	0.5
External financing cost	λ	0.02
Manager risk aversion	γ	3
Corporate tax rate	τ_c	0.35
Personal tax rate	τ_d	0.15

Panel B: Statistics for the distribution of compensation parameters

	Mean	S.D.	p5	p10	p25	p50	p75	p90	p95
ExecuComp firms									
θ_s	2.34	5.26	0.01	0.03	0.11	0.37	1.51	6.84	13.43
θ_o	0.83	1.06	0.00	0.00	0.13	0.47	1.10	2.07	3.02
F/k	0.60	1.19	0.01	0.02	0.07	0.20	0.57	1.35	2.44
σ_i^L	0.22	0.13	0.06	0.08	0.12	0.19	0.30	0.41	0.47
σ_i^H	0.36	0.18	0.14	0.16	0.22	0.33	0.47	0.62	0.71
Frydman–Saks firms									
θ_s	0.26	0.92	0.00	0.01	0.02	0.05	0.12	0.38	1.00
θ_o	0.16	0.21	0.00	0.01	0.03	0.08	0.18	0.42	0.67
F/k	0.04	0.07	0.00	0.00	0.01	0.02	0.04	0.10	0.16
σ_i^L	0.16	0.10	0.06	0.07	0.09	0.12	0.22	0.30	0.30
σ_i^H	0.24	0.10	0.13	0.14	0.16	0.20	0.33	0.38	0.38

Markov chain of average idiosyncratic volatilities. We restrict this loading to be common across states, so we have the relation:

$$\sigma_i^{A,L} = \zeta_i \sigma^{A,L}, \tag{18}$$

$$\sigma_i^{A,H} = \zeta_i \sigma^{A,H}. \tag{19}$$

Given the parameters of the Markov chain for average idiosyncratic volatility, we compute the ζ_i for each firm by matching the unconditional unlevered volatility of its residual equity return. This gives a firm-specific estimate for the idiosyncratic component of a firm's unlevered equity volatility.

For each firm we now have estimates of the firm's unlevered equity volatility, i.e. asset volatility, in the high and low volatility states: $\zeta_i\sigma^{A,H}$ and $\zeta_i\sigma^{A,L}$. However, in the model the parameter of interest is the volatility of shocks to the log productivity process z_{it}. Therefore, we must map the estimates of asset volatility, σ_{it}^A, to the volatility of innovations to the log productivity process, σ_{it}. We take this approach because estimating the volatility of productivity at the firm level requires many years of data, as accounting data is at a low frequency. This indirect approach allows us to exploit high frequency equity data to construct asset volatility which is then mapped to σ_i.

We estimate the relationship between asset volatility σ_i^A and volatility of productivity shocks σ_i^{TFP} by estimating the following cross-sectional regression:

$$\sigma_i^{TFP} = \alpha + \lambda \overline{\sigma}^A \zeta_i + \gamma_j + \epsilon_i \tag{20}$$

where γ_j are industry fixed effects, and $\overline{\sigma}^A$ is the unconditional expected asset volatility given by

$$\overline{\sigma}^A = [\mathbb{P}(k=L)\sigma^{A,L} + \mathbb{P}(k=H)\sigma^{A,H}]. \tag{21}$$

The dependent variable, σ_i^{TFP}, is estimated as the standard deviation of the firm's TFP residual using the approach of Olley and Pakes (1996). We require at least 5 observations of the TFP residual to be included in the sample.

Using the coefficient estimates, $\{\hat{\alpha}, \hat{\lambda}, \hat{\gamma}_j\}$, we construct predicted values for the firm's volatility of productivity in the high and low volatility states:

$$\begin{aligned} \sigma_i^L &= \hat{\alpha} + \hat{\lambda}\zeta_i\sigma^{A,L} + \hat{\gamma}_j \\ \sigma_i^H &= \hat{\alpha} + \hat{\lambda}\zeta_i\sigma^{A,H} + \hat{\gamma}_j. \end{aligned} \tag{22}$$

These predicted values, σ_i^L and σ_i^H, are used as the firms' parameters for high and low volatility in the model.[15] The distributions of these values are reported in Panel B of Table 1.

4.3. Evaluating the model and constructing incentive estimates

For each firm-year set of parameters the model is evaluated numerically. Given the optimal investment policy for the manager, $i(k,z,\sigma \mid \Theta)$, and for the frictionless benchmark, $i^*(k,z,\sigma)$, we construct a very long simulation of the firm. At each simulation period, we construct the state-dependent investment incentive $\omega_0(k,z,\sigma \mid \Theta)$, given in (15). We construct our estimates of the manager's over-investment incentives ω_{it}^H and ω_{it}^L for the set of parameter values for that given firm-year by taking the expectation of ω_0 conditional on a high or low volatility state:

$$\begin{aligned}\omega_{it}^H &\equiv \mathbb{E}[\omega_0(k,z,\sigma \mid \Theta_{it})|\sigma=\sigma_i^H]\\ \omega_{it}^L &\equiv \mathbb{E}[\omega_0(k,z,\sigma \mid \Theta_{it})|\sigma=\sigma_i^L].\end{aligned} \tag{23}$$

This gives the investment incentives for firm i in year t without state dependence on k and z. The expectation is simply taken as the mean within the simulated data. We define ω_{it} by selecting ω_{it}^L or ω_{it}^H when the volatility state in the data is low or high, respectively, in data year t.[16]

Finally, the estimate of interest for this paper is the manager's investment-volatility response:

$$\phi_{it} \equiv \omega_{it}^H - \omega_{it}^L. \tag{24}$$

We will use ϕ_{it} as a measure of the anticipated response in investment to volatility shocks, conditional on the manager's incentives. We will explore if this measure predicts the relationship between uncertainty and investment seen in the data.

Before exploring the panel of investment incentive estimates, we look at how the individual components of compensation impact investment incentives and the investment response to volatility changes by looking at comparative statics and impulse responses within the model.

4.4. Comparative statics

In this section we explore comparative statics with respect to the terms of the compensation contracts to gain insight into how these variables affect the investment incentives of the manager, and how these incentives interact with time-varying volatility.

The comparative statics with respect to fixed, equity, and option compensation are shown in Columns A, B and C, respectively, of Fig. 2. Each of the three columns follows a common structure. The top row shows the model-generated investment incentive for a range of values for the compensation parameter of interest, while the other two compensation parameters are held constant at their median values from the ExecuComp sample: $F/k=0.20\%$, $\theta_s=0.37\%$, and $\theta_o=0.47\%$. Given that the investment incentive is a function of the current volatility state, we show ω^H and ω^L as the investment incentive conditional on a high or low volatility state, defined in (23). The top rows of plots show ω^H as a solid line and ω^L as a dashed line. The bottom row of plots shows the difference between these high- and low-volatility conditional investment incentives, ϕ.

Column A of Fig. 2 plots investment incentives for a range of values for fixed salary compensation. Stock and option holdings are held constant at their ExecuComp sample medians. The manager is risk averse to the firm's equity value, as it composes a non-trivial portion of total compensation. However, the manager also receives option pay, which increases the convexity of the manager's payoff and induces risk taking. For these median values of equity and option pay we see that the manager chooses to over-invest relative to the level preferred by the shareholder. As fixed pay increases, the portion of the manager's pay which is risky declines, and the manager increases over-investment. This can be seen in the increasing lines in the top plot of Column A.

When fixed pay is low, a large portion of the manager's wealth is tied to the firm. The manager's risk aversion causes the manager to be willing to take on higher investment in the low-volatility states than the high-volatility states. This can be seen by ω^L (dashed line) exceeding ω^H (solid line) for low levels of fixed pay and by negative values for ϕ in the lower graph of Column A. However, as fixed pay increases, the convexity induced by the option compensation becomes stronger relative to the manager's risk aversion. For sufficiently high fixed pay, this drives ω^H to exceed ω^L, meaning that the manager actually prefers to invest more when volatility increases. This can also be seen by ϕ changing from negative to positive as fixed pay increases.

Column B of Fig. 2 performs a similar exercise but varies equity holdings. Fixed pay and option holdings are held constant at their ExecuComp sample medians. As equity pay approaches zero, the manager's only wealth that is tied to the firm is in the form of option compensation. This means that the manager has a highly convex payoff, causing her expected payoff to be increasing in volatility. The manager balances this desire for taking additional risk against the value loss resulting from

[15] We construct these values for all firms in the sample, not just those that meet the data requirements to be included in the cross-sectional regression specified by equation (20).

[16] Note that t always refers to the year t of the empirical data used to parameterize the model, not the simulated data.

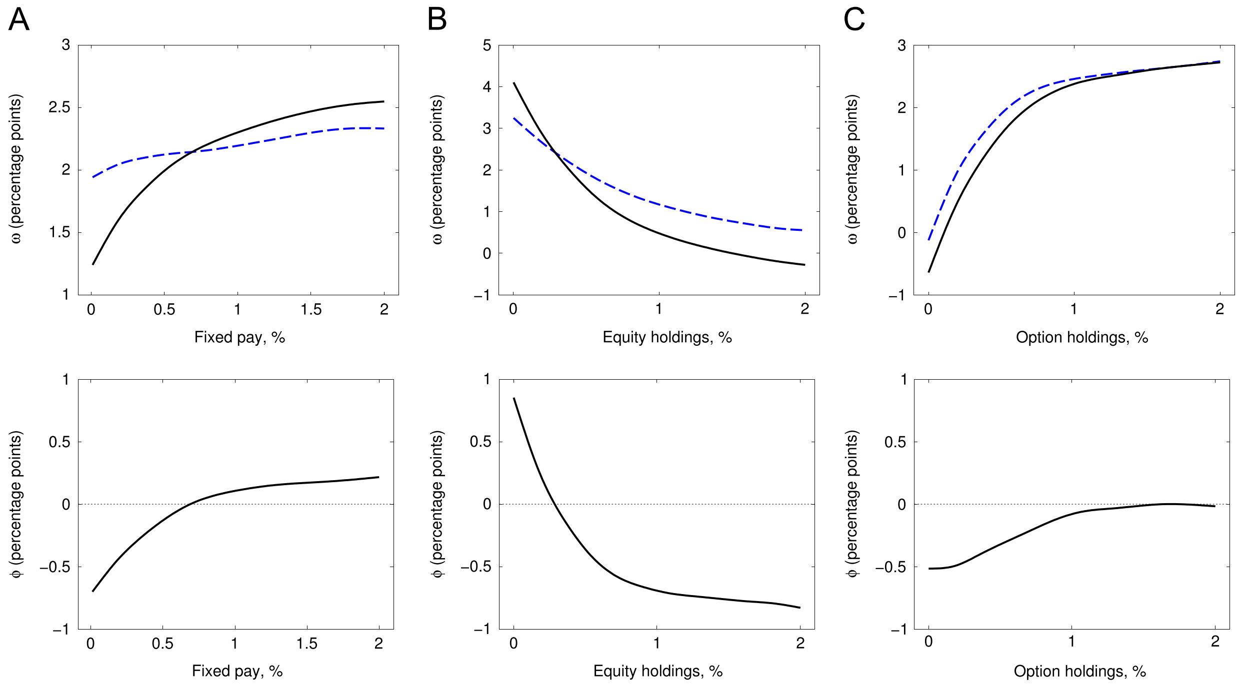

Fig. 2. Comparative statics. Shows comparative statics for the investment incentives, ω_H and ω_L, and their difference, ϕ, by varying fixed pay (F/k), shown in Column A, equity holdings (θ_s), shown in Column B, or option holdings (θ_o), shown in Column C. Each of the other respective compensation parameters are held fixed at their median values for the ExecuComp sample: $F/k = 0.20\%$, $\theta_s = 0.37\%$, and $\theta_o = 0.47\%$. The top row plots investment incentives conditional on volatility being high, ω_H, (solid line) and conditional on volatility being low, ω_L, (dashed line). The bottom row plots the difference in these values: $\phi \equiv \omega_H - \omega_L$.

inefficiently high investment. When equity holdings are low enough, the manager chooses to invest more when volatility is high than when volatility is low. This is reflected in positive values for ϕ in the bottom plot of Column B. As equity holdings become large enough, the value loss resulting from inefficiently high investment becomes more costly to the manager, and the incentive to over-invest declines. For sufficiently high equity holdings, the manager is more willing to invest when volatility is low, which is reflected in a negative value of ϕ.

Finally, Column C repeats the exercise by varying option holdings, where fixed pay and equity holdings are held constant. When option holdings are low, the manager's pay is closely tied to the firm's equity value. This results in investment rates close to that preferred by the shareholder, shown by ω^L and ω^H being close to zero in the top plot for low option holdings. At the same time, the manager is more risk avoidant than shareholders, causing the manager to invest less when volatility is high. This is seen by the negative values for ϕ in the bottom plot. As option pay increases, the convexity of the manager's payoff generates a strong over-investment incentive in both the high- and low-volatility states, generating a significant increase in both ω^L and ω^H. Simultaneously, this increase in option pay increases the manager's preference for risk as equity pay becomes a declining portion of total wealth. This is indicated by ϕ approaching zero in the bottom plot as option holdings increase.

4.5. Response to volatility shocks

The comparative statics showed that the manager's investment incentives depend on current volatility. To understand how volatility interacts with compensation contracts in driving investment decisions, in this section we explore the manager's investment response to shocks in volatility. We construct impulse responses to volatility shocks in the following way. For a given compensation contract, we run a simulation by allowing the firm to evolve naturally for many periods. Then, at event year 0, the firm is given a high shock to volatility such that $\sigma_{t=0} = \sigma^H$, after which the firm is allowed to evolve naturally. This exercise is repeated for 500,000 firms, and the mean investment rates at each event year are plotted in Fig. 3. The dashed lines indicate the mean investment response for the firm simulated under the frictionless benchmark, while the solid lines are for the manager-run firm. The benchmark and manager-run firm receive the same sequences of shocks to z and σ, but their capital stocks k evolve independently.

Panel A shows the response to a high volatility shock at year 0 for a firm with median-firm parameter values ($\theta_s = 0.37\%$, $\theta_o = 0.47\%$, and $F/k = 0.20\%$). We see that investment rates drop in both the benchmark and manager-run case, however, the manager reduces investment to a larger degree, and investment rates remain lower for several years following the shock. This is a result of the manager being risk averse to idiosyncratic volatility.

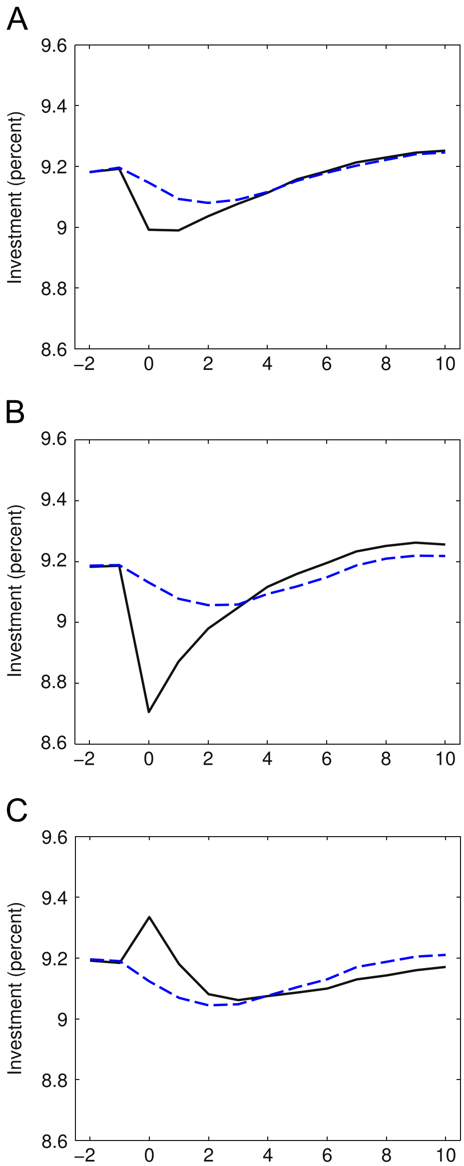

Fig. 3. Impact of a volatility shock: Shows the impulse response for a firm which receives a high volatility shock in year 0, and for which the volatility process is allowed to evolve naturally thereafter. The plots show average investment rate responses for the manager-run firm (solid line) and for the frictionless benchmark (dashed line). The results are shown for three different compensation contracts: Panel A shows the results for the median compensation contract in the ExecuComp sample ($\theta_s = 0.37\%$, $\theta_o = 0.47\%$, and $F/k = 0.20\%$); Panel B shows results for a high stock, no option contract ($\theta_s = 1.0\%$, $\theta_o = 0.0\%$, and $F/k = 0.20\%$); and Panel C shows results for a low stock, high option contract ($\theta_s = 0.01\%$, $\theta_o = 2.0\%$, and $F/k = 0.20\%$). Each plot is the average of 500,000 firm simulations where each firm has been allowed to evolve naturally over a long horizon prior to year 0.

In Panel B we change the compensation contract to include a high degree of stock and no option pay ($\theta_s = 1.0\%$, $\theta_o = 0.0\%$). With no convexity in the payoff, and a high fraction of the manager's payoff tied to equity, the manager's over-reaction to the volatility shock is exacerbated, and investment rates are significantly lower than under the frictionless benchmark. However, given this initial over-reaction, the manager begins to increase investment rates rapidly, and by year 4 investment rates exceed the benchmark, although the capital stock remains lower.

Finally, Panel C shows the impulse response when option compensation is high and equity pay is low ($\theta_s = 0.01\%$, $\theta_o = 2.0\%$). Under this contract, the manager's payoff is highly convex, making an increase in volatility valuable. In this setting, the manager not only invests more relative to the benchmark, but invests at a level higher than she did prior to the high volatility shock. The convexity of the option compensation makes investment in risky capital more attractive when idiosyncratic volatility is higher.

The investment response of the manager to changes in volatility is a function of the manager's compensation contract. For example, a more convex payoff for the manager causes higher investment in response to high volatility shocks, and high equity exposure generates stronger underinvestment. The model allows us to measure the degree and direction of the manager's response to volatility shocks. We test this empirical prediction of the model in the following section.

4.6. Estimates of the investment incentive

After solving the model over the full sample of firms, we summarize the manager's investment incentives in Table 2, separately for the ExecuComp and Frydman–Saks samples. The first row shows the mean, standard deviation, and percentiles for ω_{it}, the over-investment incentive for the manager of firm i at date t conditional on the actual volatility state at date t. The second and third rows show these summary statistics for the estimated investment incentive were the firm in the high volatility state, ω_{it}^{H}, and the low volatility state, ω_{it}^{L}, respectively. Distributional information about the difference in

Table 2
Distributions of model-computed conditional investment incentives.

This table presents statistics for the distributions of conditional manager over-investment incentives, ω, computed in the calibrated model. The over-investment incentive for the manager of firm i at date t, conditional on the volatility state at date t, is denoted ω_{it}. The value ω_{it}^{H} denotes the over-investment incentive for the manager of firm i at date t if the economy were in a high volatility state. The analog for a low volatility state is given by ω_{it}^{L}. All values are reported in percentage points at an annual frequency.

	Mean	S.D.	p5	p10	p25	p50	p75	p90	p95
ExecuComp firms									
ω_{it}	0.83	1.80	−2.13	−1.48	−0.41	0.84	2.30	2.98	3.38
ω_{it}^{H}	0.64	2.17	−3.01	−2.14	−0.89	0.49	2.29	3.41	4.15
ω_{it}^{L}	0.95	1.52	−1.59	−1.04	−0.23	1.01	2.30	2.86	3.10
ϕ_{it}	−0.31	0.80	−1.48	−1.21	−0.82	−0.39	0.00	0.68	1.26
Frydman–Saks firms									
ω_{it}	1.62	1.25	−0.74	−0.26	0.81	1.92	2.61	2.97	3.15
ω_{it}^{H}	1.40	1.51	−1.35	−0.74	0.43	1.70	2.57	3.13	3.43
ω_{it}^{L}	1.64	1.23	−0.65	−0.24	0.90	1.94	2.62	2.96	3.14
ϕ_{it}	−0.24	0.35	−0.76	−0.63	−0.47	−0.26	−0.04	0.22	0.42

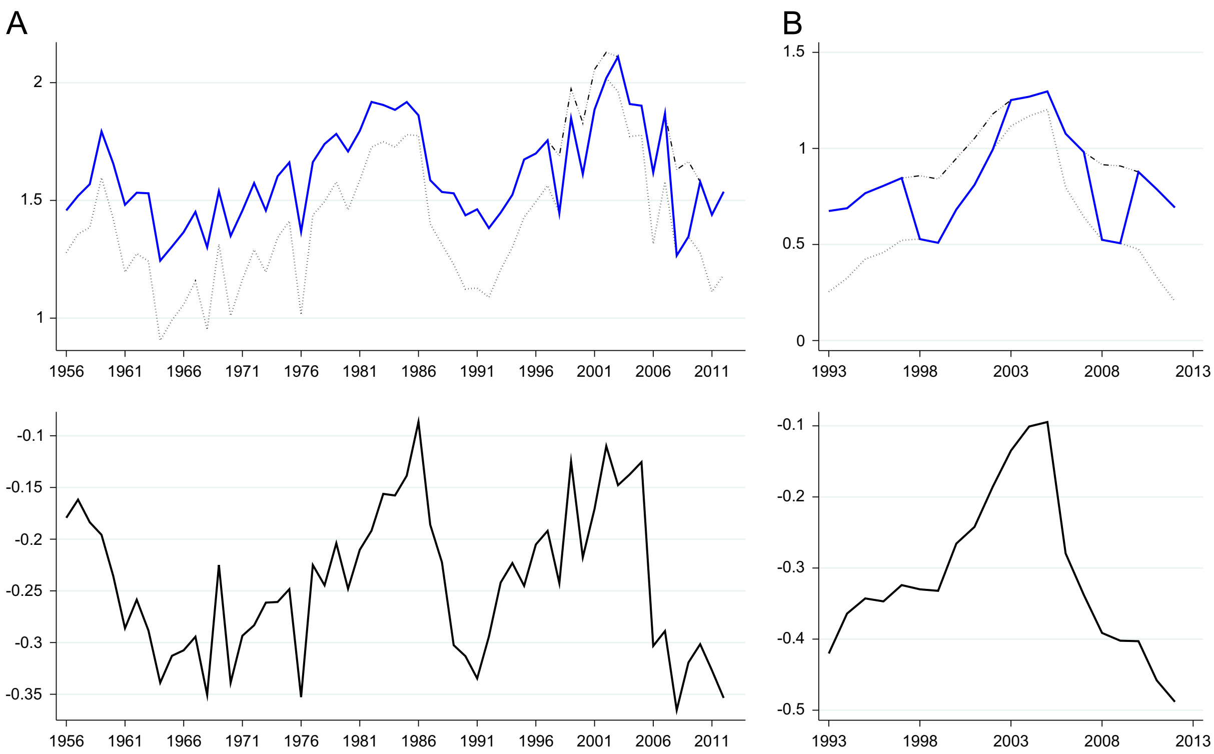

Fig. 4. Investment incentives. The top row shows the cross-sectional, equal-weighted mean investment incentive conditional on being in the low volatility state, ω_L (dash-dotted line), in the high volatility state, ω_H (dotted line), and the conditional investment incentive, ω_t (solid line). The bottom row shows the difference between the cross-sectional means of the high and low conditional investment incentives, $\phi \equiv \omega_H - \omega_L$. Panel A shows the Frydman–Saks sample spanning 1956–2012, and Panel B shows the ExecuComp sample spanning 1993–2012.

these estimates, ϕ_{it}, is given in the fourth row. This difference represents the change in the manager's investment incentives that would occur if the current volatility state switched from low to high. Specifically, for the ExecuComp sample, were the current volatility state switched from low to high, on average a manager would have the incentive to over-invest 0.31 percentage points less. There is significant heterogeneity in the manager's response to volatility changes: for the bottom 10th percentile of firms the model predicts a -1.21 percentage point decline in investment, compared to a 0.68 percentage point increase in investment for the 90th percentile.

We see that the conditional investment incentive, ω_{it}, is on average positive, at 0.83 percentage points. This means that on average the manager would like to invest at a rate 83 basis points higher than the investment rate that maximizes the present value of future cashflows given by the frictionless benchmark. In addition, 63% of the ExecuComp sample and 86% of Frydman–Saks sample have an incentive to over-invest relative to the benchmark.

In Fig. 4 we explore the time series dynamics of the mean over-investment incentives for the Frydman–Saks sample in Panel A and for the ExecuComp sample in Panel B. The top row plots the time series of cross-sectional, equal-weighted means of ω_{it}^H (dotted line), ω_{it}^L (dash-dotted line), and ω_{it} (solid line). For most of the Frydman–Saks sample, volatility is in the low state, and thus $\omega_{it} = \omega_{it}^L$. For the latter part of the sample, there are two high-volatility periods: 1998–2002, and 2008–2009. We see in the figure that the investment incentive dropped during those periods due to the increase in volatility. We see this more closely in the top plot in Panel B and the significant drop in investment incentives during these high-volatility periods.

The bottom row plots the mean difference between the manager's investment incentive between the high and low volatility states: $\phi_{it} \equiv \omega_{it}^H - \omega_{it}^L$. This shows that there is significant time variation in the degree to which the manager's incentives respond to changes in volatility. We see for the ExecuComp sample that the response of a shift from low to high volatility went from less -0.4% in 1993, rose to as high as -0.1% at its peak in 2004, and then fell to -0.5% in 2012. We will test this prediction of time variation, as well as cross-sectional variation, in investment responses to volatility shocks later in paper.

Glover and Levine (2014) show that managers' investment incentives, induced by their compensation contracts, have strong predictive power for Q, changes in investment rates, and acquisition activity. In contrast, in this paper we are interested in the investment response to changes in volatility and we therefore focus our empirical tests on that relationship.

5. Changes in volatility: empirical predictions

The model has direct predictions for the interaction between changes in volatility and the investment incentives of the manager. The comparative statics of the model, shown in Fig. 2, display a non-trivial relationship between the components of compensation and investment as a function of the current level of idiosyncratic volatility. In this section we investigate this empirical prediction of the model.

Specifically, for a given compensation contract, we use the model to estimate the investment incentive of the manager if volatility is high, ω^H, and if the volatility is low, ω^L. The difference in these investment incentives, $\phi \equiv \omega^H - \omega^L$, gives a prediction of the change in the investment rate that would result from switching from the low volatility state to the high volatility state. Our model predicts that the sensitivity of changes in investment rates to volatility changes should correlate with ϕ.

In what follows we test this empirical prediction using a panel regression approach, followed by an event study.

5.1. Panel regression: investment-volatility sensitivity

To test the predicted relationship between investment-volatility sensitivity and a manager's investment incentives we estimate a panel regression of changes in investment rates on changes in firm-specific volatility and various controls. Our prediction is that the coefficient on changes in volatility should be monotonically increasing in the model-estimated ϕ. The dependent variable in all regressions is constructed as the one-year change in a firm's investment rate, $I_{it}/K_{i,t-1}$. As discussed before, the model has predictions for how changes in volatility should affect changes in investment rates, which is the direct empirical test we perform. An advantage to this empirical approach is that differencing removes unobservable firm heterogeneity, mitigating the concern that the results are driven by correlation between our measure and an unrelated, but unobserved, firm characteristic.

A firm's idiosyncratic volatility, $\sigma_{i,t-1}$, is constructed as the standard deviation of the residual in a regression of the firm's daily equity returns on the three Fama-French factor portfolios. To test the model predictions, we compute innovations in firm idiosyncratic volatility as follows. We define $\eta_{i,t}$ as the innovation in firm i's log idiosyncratic volatility at date t. This innovation is estimated for the panel of firms in our sample via the regression:

$$\log(\sigma_{i,t}) = \mu_i + \xi \log(\sigma_{i,t-1}) + \eta_{i,t} \tag{25}$$

where μ_i represents a firm-specific intercept. Therefore, our innovations are computed as the fitted residuals, $\eta_{i,t}$.[17]

[17] For the results that follow, we have also implemented alternative specifications that use the difference in log idiosyncratic volatility, $\log(\sigma_{i,t}) - \log(\sigma_{i,t-1})$, in place of η_{it}. In all cases, the results are very similar. Alternative specifications for the regression (25) using additional lags of $\log(\sigma_{i,t})$ also produce very similar results. Additional lags included in (25) were generally statistically insignificant.

Table 3
Change in investment regressions: ExecuComp sample.

We perform panel regressions of the change in a firm's investment rate on lagged changes in the firm's log idiosyncratic volatility and changes in control variables. The dependent variable in all regressions is constructed as the one year change in a firm's investment rate, $I_{it}/(K_{i,t-1})$. A firm's idiosyncratic volatility, ($\sigma_{i,t-1}$), is constructed as the standard deviation of the residual in a regression of the firm's daily equity returns on the Fama-French 3 factor portfolios. Tobin's Q, ($Q_{i,t-1}$), is the sum of a firm's market equity and book debt normalized by net PPE. We construct cash flow, ($CF_{i,t-1}/K_{i,t-2}$), as operating income before depreciation normalized by lagged net PPE. A firm's leverage ratio, E_{it}/A_{it}, is measured as the ratio of the firm's book equity to book assets. The sample consists of the unbalanced panel of ExecuComp firms for the period 1992–2012 at an annual frequency. All regressions include firm and year fixed-effects. Standard errors are clustered at the firm-level and the reported R^2 measures the within-firm variation. Significance at the 5% and 1% levels are indicated by * and **, and t-statistics are reported in parentheses.

Variables	(1) $\Delta\left(\frac{I_{i,t}}{K_{i,t-1}}\right)$	(2) $\Delta\left(\frac{I_{i,t}}{K_{i,t-1}}\right)$	(3) $\Delta\left(\frac{I_{i,t}}{K_{i,t-1}}\right)$	(4) $\Delta\left(\frac{I_{i,t}}{K_{i,t-1}}\right)$
$\eta_{i,t-1}$	−0.0707**	−0.00646	−0.0185*	−0.0150
	(−7.00)	(−0.66)	(−2.00)	(−1.60)
$\Delta\log(Q_{i,t-1})$		0.247**	0.218**	0.219**
		(22.89)	(20.18)	(20.28)
$\Delta\left(\frac{CF_{i,t-1}}{K_{i,t-2}}\right)$			0.000797	0.000577
			(0.18)	(0.13)
$\Delta\ \log\left(\frac{E_{i,t-1}}{A_{i,t-1}}\right)$				0.125**
				(4.53)
Observations	18 055	17 937	15 702	15 625
Adjusted R^2	0.031	0.157	0.147	0.151

The regression is specified as follows:

$$\Delta\left(\frac{I_{i,t}}{K_{i,t-1}}\right) = \beta_0 + \beta_1\eta_{i,t-1} + \beta_2\Delta\log(Q_{i,t-1}) + \beta_3\Delta\left(\frac{CF_{i,t-1}}{K_{i,t-2}}\right) + \beta_4\Delta\ \log\left(\frac{E_{i,t-1}}{A_{i,t-1}}\right) + \upsilon_i + \gamma_t + \epsilon_{i,t.} \tag{26}$$

The independent variables, somewhat standard in investment regressions, are defined as follows. The innovation in a firm's idiosyncratic volatility, η_{it}, is constructed as described above. Controls include Tobin's Q, $Q_{i,t-1}$, defined as the sum of the firm's market equity and book debt normalized by net PP&E; cash flow, $CF_{i,t-1}/K_{i,t-2}$, defined as operating income before depreciation normalized by lagged net PP&E; and the leverage ratio, E_{it}/A_{it}, defined as the ratio of the firm's book equity to book assets. All independent variables are in one-year changes, denoted by the operator Δ, and all regressions include firm (υ_i) and year (γ_t) fixed-effects.[18] Standard errors are clustered at the firm-level.

Before exploring the relationship between the coefficient on volatility innovations and the investment incentive, Table 3 shows the unconditional results for this panel regression for the full ExecuComp sample. Column (1), which shows the univariate regressions, shows a strong negative relationship between changes in investment and lagged innovations in volatility, $\eta_{i,t-1}$. This coefficient becomes statistically insignificant in Column (2) with the inclusion of changes in Tobin's Q. In Columns (3) and (4) we add changes in cash flow and leverage as additional controls. The coefficient on $\eta_{i,t-1}$ is of similar signs for both specifications, but only statistically significant in Column (3). In total, Table 3 shows that for the full sample, an innovation in volatility seems to negatively relate to a change in a firm's investment rate, though this relationship is not always statistically significant.

We test whether the investment-volatility coefficient corresponds to the model-estimated ϕ in Table 4 by running the full specification of the panel regression conditioning on various levels of ϕ. The model predicts that lower values of ϕ predict lower values for the coefficient on volatility changes. We divide the sample into four groups using different subsamples on ϕ: strongly negative ($\phi_{i,t-1} < -0.5\%$), negative ($\phi_{i,t-1} < 0\%$), positive ($\phi_{i,t-1} > 0\%$), and strongly positive ($\phi_{i,t-1} > 0.5\%$). We find strong support for the predictions of the model: the coefficient estimates increase monotonically and significantly as ϕ increases. In addition, the coefficient is significantly negative for the negative ϕ bins and the coefficient is positive, although not statistically significant, for the two positive ϕ bins. These results provide evidence that the relationship between volatility and investment is driven at least in part by the manager's investment incentives induced by her compensation contract.[19]

To provide some context for the magnitude of these estimates, consider the effect of a change in $\eta_{i,t-1}$ for a firm in the lowest group ($\phi_{i,t-1} < -0.5\%$). For a firm of this group, a one standard deviation increase to $\eta_{i,t-1}$ corresponds to a predicted reduction in the investment rate of 1.1 percentage points. In contrast, the coefficient estimate of column 4 ($\phi_{i,t-1} > 0.5\%$) would imply an *increase* of 1.0 percentage points in investment, in response to a one standard deviation

[18] The results without firm fixed effects are similar.

[19] These results are robust to various regression specifications. In particular, the results are similar to a specification including lagged changes in investment rates as an independent variable, using the two-step GMM estimation proposed by Arellano and Bond (1991) to address the bias generated under OLS when the lagged dependent variable is included as a regressor.

Table 4
Change in Investment Regressions by ϕ: ExecuComp Sample.
The table reports regressions of changes in investment rates for four subsamples of firms. We perform regression specification (4) of Table 3 for subsamples of firm-year observations sorted according to the measure $\phi_{i,t-1} = \omega^H_{i,t-1} - \omega^L_{i,t-1}$ computed in the model. The controls are the same as described in Table 3. The sample consists of the unbalanced panel of ExecuComp firms for the period 1992–2012 at an annual frequency. All regressions include firm and year fixed-effects. Standard errors are clustered at the firm-level and the reported R^2 measures the within-firm variation. Significance at the 5% and 1% levels are indicated by * and **, and t-statistics are reported in parentheses.

Variables	(1) $\phi_{i,t-1} < -0.5\%$	(2) $\phi_{i,t-1} < 0\%$	(3) $\phi_{i,t-1} > 0\%$	(4) $\phi_{i,t-1} > 0.5\%$
$\eta_{i,t-1}$	−0.0402**	−0.0240*	0.00290	0.0345
	(−2.81)	(−2.55)	(0.12)	(0.85)
$\Delta\log(Q_{i,t-1})$	0.226**	0.212**	0.245**	0.254**
	(13.79)	(16.97)	(9.27)	(7.32)
$\Delta\left(\frac{CF_{i,t-1}}{K_{i,t-2}}\right)$	−0.00353	0.00327	0.00392	−0.0137
	(−0.36)	(0.53)	(0.40)	(−1.01)
$\Delta\log\left(\frac{E_{i,t-1}}{A_{i,t-1}}\right)$	0.114**	0.106**	0.160*	0.197
	(3.59)	(4.31)	(2.26)	(1.53)
Observations	6199	11 220	3684	1754
Adjusted R^2	0.168	0.161	0.129	0.136

increase in $\eta_{i,t-1}$. In other words, the investment responses to a volatility shock for a firm in the first versus fourth column amounts to a 2.1% percentage point difference. This is a significant magnitude as it corresponds to 15% of the cross-sectional standard deviation in the change in investment rates for the firms in our sample for the year 2012. Thus, these differential effects seem to be economically significant in their ability to explain cross-sectional variation in the changes in investment rates, even after using other controls and fixed effects in the regression.

5.2. Volatility shocks of 1998 and 2008

The previous sections show that the model-implied manager investment incentive, specifically $\phi_{it} \equiv \omega^H_{it} - \omega^L_{it}$, predicts the response in investment to changes in volatility seen in the data. In this section, we explore the investment response of firms to two large increases in idiosyncratic volatility seen in the data: 1998 and 2008. In constructing the two-state Markov process for idiosyncratic volatility, detailed in Section 4.2, these two years are unique in that they represent an upward shock to volatility. Specifically, idiosyncratic volatility is in the low state in both 1997 and 2007, followed by the high state in 1998 and 2008. The upward volatility shocks in those years are a natural opportunity to explore the investment response for firms which differ in their manager's investment-volatility sensitivity, ϕ_{it}.[20]

Fig. 5 shows the investment patterns following these volatility shocks. In the year prior to the volatility increase, 1997 and 2007, firms are sorted in three bins based on their model-estimated ϕ_{it} for those years. The bin cutoffs are at the 20th and 80th percentiles for those years, representing low, medium, and high ϕ_{it}, and the assignments are maintained through the entire period shown. For each year shown, each firm's investment rate is scaled by its own initial investment rate in year 1997 or 2007, and the mean and median of these scaled investment rates are shown in Panels A and B. The solid line represents the firms in the low-ϕ bin, dashed for the middle bin, and dotted for the high bin. The investment rates are scaled by the initial pre-shock investment rates to control to heterogeneity in the investment rate levels across the different subsets. Thus, the mean and median rates shown represent percent changes in investment rates and do not reflect the levels. The sample of scaled investment rates is trimmed at the 2.5 and 97.5 percent levels to eliminate the effect of outliers. Firms are required to have data for all years shown to be included in the sample.

Panel A of Fig. 5 reveals investment response predicted by the model. For both the 1998 and 2008 shocks, firms with managers who have the highest ϕ (dotted line) invest at a rate higher than those with the lowest ϕ (solid line) in the years following the volatility increase. Furthermore, the investment response across the three subgroups is monotonic in ϕ. The economic magnitude of the differences is also significant. During the expansion in 1998, the highest group had investment rates which increased 11% while the lowest group's rates increased by only 2%, a gap which became even larger the following year. During the financial crisis, investment rates across the board declined significantly in 2009; however, the lowest-ϕ group's investment rates decreased, on average, by 33% from their 2007 levels, while the highest-ϕ group's

[20] The two-state Markov chain that we fit captures movements in idiosyncratic volatility that are common across all firms. We focus on 1998 and 2008 as years in which there was a significant increase in idiosyncratic volatility. However, it is worth noting that there are documented increases in measures of aggregate volatility around these events as well.

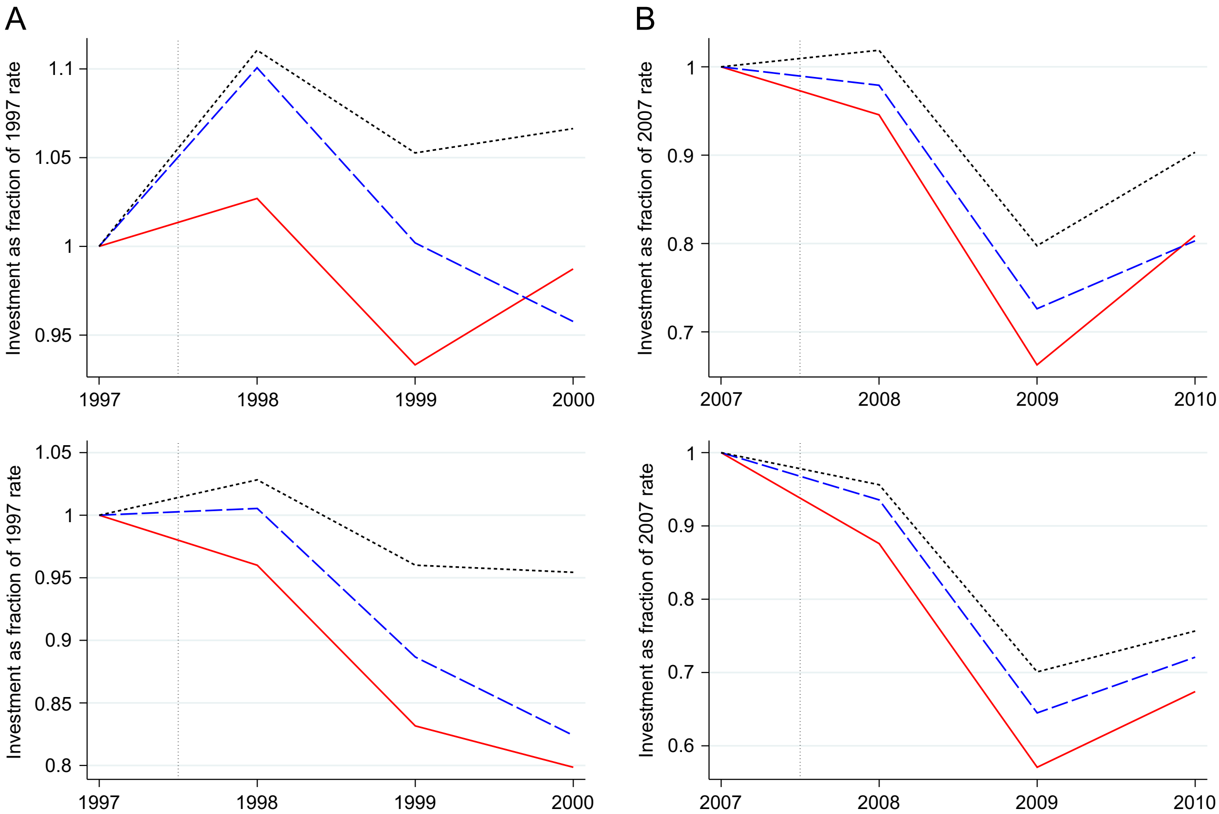

Fig. 5. Investment response to volatility increases of 1998 and 2008: Shows investment rates following the volatility shocks from σ^L to σ^H in 1998 and 2008. In the year prior to the volatility increase, 1997 and 2007, firms are sorted in three bins based on their model-estimated $\phi_{it} \equiv \omega_{it}^H - \omega_{it}^L$ for those years, and the assignments are maintained through the entire period shown. The bin cutoffs are at the 20th and 80th percentiles for those years, representing low, medium, and high ϕ_{it}. For each year shown, each firm's investment rate is scaled by its own initial investment rate in year 1997 or 2007, and the mean and median of these scaled investment rates are shown in Panels A and B. The solid line represents the firms in the low-ϕ bin, dashed for the middle bin, and dotted for the high bin. The investment rates are scaled by the initial pre-shock investment rates to control for heterogeneity in the investment rate levels across the different subsets. Thus, the mean and median rates shown represent percent changes in investment rates and do not reflect the levels. The sample of scaled investment rates is trimmed at the 2.5 and 97.5 percent levels to eliminate the effect of outliers. Firms are required to have data for all years shown to be included in the sample.

investment rates decreased by only 20%. The results using median values are shown in Panel B. The results are qualitatively similar, confirming that the results are not due to outliers or strong skewness in the distribution of investment rates.

The two periods, 1998 and 2008, represent very different periods in terms of aggregate conditions, the prior occurring during an expansion and the latter being driven by the financial crisis. A potential explanation for the pattern observed in Fig. 5 is that the model-constructed variable ϕ_{it} is correlated with the firm's optimal investment response to an aggregate productivity or demand shock. If so, the response to the 2008 shock was not driven by a differential response to volatility, but by heterogeneity in the firms' loadings on the aggregate productivity or demand shock. However, if this were the case we would expect that following the 1998 shock, which corresponds with a positive aggregate productivity or demand shock, that the lowest ϕ_{it} firms would have the strongest positive response to the shock. That the ordering of the investment responses across ϕ subgroups is preserved in both the expansion and contraction suggests that the model-estimated ϕ, and thus managers' incentives, play a role in the investment response to volatility shocks.

6. Conclusion

We find evidence that manager incentives are important for understanding a firm's investment response to changes in volatility. The previous literature has focused primarily on financial frictions and the "wait-and-see" real option effect in understanding the impact of uncertainty on investment. Using a large panel of model-predicted incentives of the manager's response to volatility shocks, we find that our measure predicts investment responses in both the cross section and time series. Further, we show that accounting for manager incentives helps to explain why some firms' investment rates declined so significantly. This suggests that future research should consider the impact of delegated control and agency conflicts when studying the relationship between uncertainty and investment.

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