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Premium for heightened uncertainty: Explaining pre-announcement market returns[☆]

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ABSTRACT

We find large overnight returns with no abnormal variance before nonfarm payrolls, ISM, and GDP announcements, similar to the pre-FOMC returns. To explain this common pattern, we propose a two-risk model with the uncertainty about the magnitude of the impending news' market impact as an additional risk, and link the pre-announcement return directly to the accumulation of heightened uncertainty and its later resolution prior to the announcement. We empirically test and verify the model's distinct predictions on the joint intertemporal behavior of return, variance, and particularly VIX – a gauge of impact uncertainty by our model, surrounding macroeconomic announcements.

1. Introduction

Macroeconomic announcements are among the most important news events for the stock market. To the extent that these announcements bring aggregate risk to the market, they should be associated with a higher expected return, independent of their directional impact. Indeed, Savor and Wilson (2013) document significant positive stock market returns on days of well-known macroeconomic announcements, including the consumer price index, producer price index, employment figures, and the Federal Open Market Committee (FOMC) decisions. Lucca and Moench (2015) further show that these returns in fact arise mainly from the FOMC announcements. More importantly, they find that such returns are realized before the actual announcement, with no significant increase in the conventional risk measures such as return variance. Interestingly, post announcement market returns are on

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average small and insignificant, despite the high variances the announcement causes.

Against this backdrop, we document in this paper the presence of large pre-announcement returns ahead of a number of other important macroeconomic announcements, including nonfarm payrolls (NFP), the Institute for Supply Management's manufacturing index (ISM), and gross domestic product (GDP). From September 1994 to May 2018, the pre-announcement returns for NFP, ISM, and GDP are on average 10.1 bps, 9.1 bps, and 7.5 bps, respectively, and all statistically significant. Using S&P 500 index futures, these pre-announcement returns are calculated from the close of the previous trading day at 4 pm to 5 min before the respective announcements, which are pre-scheduled at 8:30 am for NFP and GDP and 10 am for ISM. Effectively, the pre-announcement returns documented in our paper are realized mostly overnight – a key reason why this empirical fact has been missed by early studies including Lucca and Moench (2015). Benchmarked against the average overnight return of 0.69 bps for non-announcement days, the pre-announcement returns documented in our paper are large economically, and comparable to that of the pre-FOMC drift.[1] The average post announcement returns for NFP, ISM, and GDP are on average small and insignificant, while exhibiting large variances, similar to the post-announcement patterns for FOMC.

Emerging from these findings is the rather intriguing realization that, common to the market-moving announcements such as NFP, ISM, GDP, and FOMC, there exists a unique risk-and-return pattern – large pre-announcement returns with small variances, followed by small post-announcement returns with large variances. Using the return-to-variance ratio as a measure of market price of risk, which is insensitive to time scale, we can infer that more than one aggregate risk is driving the stock market return in the pre- and post-announcement windows. In particular, since the same risk carries the same risk premium, a single risk cannot generate the significantly different return-to-variance ratios before and after the announcement, even allowing for pre-announcement news leakage.[2]

Motivated by these observations, we develop a parsimonious two-risk model to capture the different risks surrounding a macroeconomic announcement and the resulting risk-and-return pattern. In our model, the news is given by a random shock ε, which is directional in nature and has zero mean ($\mathrm{E}[\varepsilon] = 0$). The magnitude of the news' impact on the market is given by σ, which is non-directional (hence always positive). The total market impact of the news is then given by the product of these two components, $\sigma\varepsilon$. In general, σ is uncertain, which gives rise to the second risk concerning the announcement, the "impact uncertainty." While the news risk itself is fully resolved at the announcement, its "impact uncertainty" is resolved before the announcement.[3] Central to our model is the presence of this second risk concerning σ, whose variability is determined by its own volatility, given by a parameter λ. Intuitively, depending on the realization of σ, the same news ε could have substantially different market impact, with parameter λ capturing the level of this uncertainty – when λ is large, the impact uncertainty is large, giving rise to heightened uncertainty in anticipation of a major macroeconomic announcement.

Each of these two risks, news risk vs impact uncertainty, carries its own premium and impacts the price dynamics differently. In our model, we show that when λ is sufficiently high, the impact uncertainty carries a higher risk premium in equilibrium than the news risk. Moreover, the premiums for the two risks are realized over different time windows owing to the timing difference of their respective rise and resolution. Throughout of the paper, in both model development and empirical test, we focus on three distinct time windows surrounding an announcement: 1) the accumulation period is when, in anticipation of a scheduled announcement, the impact uncertainty builds up; 2) the pre-announcement period is when the impact uncertainty resolves prior to the announcement and the premium for impact uncertainty is realized; and 3) the post-announcement period is when the news risk is fully resolved. To directly connect to data, our model further provides distinctive empirical measures for the two risks – the magnitude of the news risk is properly captured by return variance, while the magnitude of the impact risk λ is found to be linked directly to the market price of a variance swap (i.e., VIX^2).

Depending on the magnitude of impact uncertainty λ, the model leads to the following predictions on the joint intertemporal dynamics of return, variance, and VIX. First, in the absence of impact uncertainty ($\lambda = 0$), the return-to-variance ratio should be the same for both the pre- and post-announcement periods, regardless of whether or not there is partial resolution of the news risk before the actual announcement. This is simply because the same risk carries the same risk premium. Second, in the presence of heightened impact uncertainty (λ large), both the pre-announcement return and return-to-variance ratio will be higher than their post-announcement counterparts. In addition, the high pre-announcement return will be accompanied by a large drop in VIX, reflecting the resolution of impact uncertainty. Third, a large increase in VIX during

[1] The pre-FOMC return, also calculated from the previous day's close to 5 min before the announcement, is on average 27.1 bps during our sample period. This is lower than the 49 bps reported in Lucca and Moench (2015) for two reasons. First, our pre-announcement window starts from 4 pm on the previous day, shorter than their 24-hours window. Second, we update their sample period to include the post-2011 period, when the pre-FOMC drift turned weaker. As we show later, while the pre-announcement returns for NFP, ISM and GDP are smaller than that for FOMC on event basis, they are actually larger on annual basis since there are more of them within a year.

[2] Theoretically speaking, a single risk factor can lead to different return-to-variance ratios for different time periods if its resolution is nonlinear overtime and return variance fails to properly measure risk. Such a nonlinearity can arise from various causes ranging from risk dynamics itself to market imperfections including information asymmetry. Given the short horizons for the pre- and post-announcement periods and the public nature of the information, it is unlikely that the issue of nonlinearity is substantial to explain the empirical magnitudes shown later in the paper.

[3] Our model also allows part of the news risk ε to be resolved prior to the announcement to accommodate the possibility of news leakage prior to the announcement. The use of "uncertainty" here for the σ risk is only in an intuitive sense, to differentiate from the news risk itself.

the accumulation period will be accompanied by a drop in price, and then followed by a large pre-announcement return, a large return-to-variance ratio, and a large decrease in VIX. This signature pattern – a gradual built-up of heightened uncertainty followed by its rapid resolution prior to the announcement – is uniquely linked to the key underlying mechanism of our model.

Taking the model to the data, we examine the model's predictions on the joint behavior of return, variance, and VIX over the three time periods, defined empirically as follows. The post-announcement period begins 5 min before the announcement and ends 55 min after the announcement, covering a one-hour window. The pre-announcement period begins at the previous day's close and ends at the beginning of the post-announcement window. The accumulation period begins six days before the announcement and ends at the beginning of the pre-announcement window.[4] Our empirical results can be summarized as follows.

Pre-announcement returns: According to the model, the pre-announcement period is when the premium for heightened uncertainty is realized. Consistent with this prediction, we find large pre-announcement returns for the four major macroeconomic announcements, NFP, ISM, GDP and FOMC. Pooling the four announcements together, the average pre-announcement return is 5.66% annually, realized over the pre-announcement windows of a mere 44 announcements per year.[5] Excluding FOMC, whose pre-announcement return has been previously documented by Lucca and Moench (2015), the average pre-announcement return remains important and significant at 3.41% per year, realized over the pre-announcement windows, mostly overnight, of 36 announcements per year. By comparison, the average annual return over the same sample period is 9.10%, realized over 252 days per year. These results, measured across four different types of macroeconomic announcements, provide a compelling evidence that the presence of heightened uncertainty is common to important macroeconomic announcements. Compared with NFP, ISM, and GDP, the single-day impact of FOMC announcement might be larger, but the essence of its pre-announcement return is the same and not unique. Cumulatively, NFP, ISM and GDP actually yield larger pre-announcement returns than FOMC, 3.41% vs. 2.25% per year respectively, as they have more announcements per year.

Our examination of the pre-announcement returns across a broad spectrum of macroeconomic indicators also reveals a substantial heterogeneity across these indicators. In the context of our model, the varying levels of pre-announcement return reflect the varying magnitudes of impact uncertainty. Some macroeconomic indicators, such as NFP, ISM, GDP and FOMC, exhibit significant pre-announcement returns on average, indicating strong heightened uncertainty brought upon by these announcements to the market, while some indicators are found to have insignificant pre-announcement returns, indicating weak impact uncertainty. Indeed, lining up macroeconomic indicators by their pre-announcement returns, the ranking is consistent with their relative importance, both intuitively perceived by market participants and empirically documented by prior literature.

Return-to-risk ratios: We find the return-to-variance ratio to be markedly different between the post- and pre-announcement periods, a clear challenge to the single-risk model. The return-to-variance ratio, which is invariant to the scaling of time, is 35.53 and strongly significant during the pre-announcement period, and 10.29 and insignificant during the post-announcement period.[6] This result, robust with and without FOMC as part of the macroeconomic announcements as well as over different subperiods, also contradicts the explanation that information leakage with only the news risk might be behind the large pre-announcement return. In the context of our setting, having only one news risk, regardless of leakage, cannot explain the differing return-to-variance ratios across the two time periods.

Resolution of impact uncertainty: One important implication of our model is that the pre-announcement return arises out of the resolution of heightened uncertainty, which can be captured by the reduction in VIX during the pre-announcement period. Exploring this connection, we use the pre-announcement reduction in VIX to sort announcement days into groups of high and low resolution of uncertainty. As predicted by the model, we find significantly larger pre-announcement returns for the high group and insignificant and negative pre-announcement returns for the low group.

Given the well-known negative correlation between market returns and changes in variance, we further double-sort announcement days using pre-announcement reductions in VIX as well as variance, and find the result to be driven by VIX. Specifically, using the macroeconomic announcements of NFP, ISM, GDP, and FOMC, we find that days of high reduction in VIX are associated with large pre-announcement returns, averaged at 102.71 bps and 79.54 bps, respectively, for groups of high and low reduction in variance. By contrast, days of low reduction in VIX yield pre-announcement returns of −7.72 bps and 1.14 bps, respectively, for groups of high and low reduction in variance. Given that VIX and variance contain different information in our model, with VIX uniquely linked to the magnitude of impact uncertainty, this result further strengthens the connection between the presence of impact uncertainty and the pre-announcement return.

Another implication of our model is that when impact uncertainty and news risk are resolved differently over time, the resulting return distributions will be different. In particular, when heightened uncertainty is mostly resolved during the pre-announcement period as captured by

[4] One empirical challenge in defining the accumulation window is that we do not know exactly when uncertainty starts to build up, which may vary substantially across announcements. Using any fixed window across all announcements inevitably introduces noises in our measurement and weakens our results. Moreover, the pre-scheduled nature of macroeconomic releases allows investors to trade well in advance, which in turn mask the real market impact over a relatively long time window.

[5] There are 12 pre-scheduled announcement days per year for NFP, ISM and GDP, respectively, and 8 announcement days per year for FOMC.

[6] With an average daily return of 4 bps and daily variance of 1 bp observed for the aggregate market, the return-to-variance ratio is benchmarked at 4 for an average day in the US stock market.

a large VIX drop, the resulting post-announcement return will be mostly driven by news risk, assumed to be normal. Indeed, we find that for days of high reduction in VIX (i.e., the high group), the post-announcement returns have an excess kurtosis of 0.92 and statistically insignificant. By contrast, for the low group, the post-announcement returns exhibit a statistically significant excess kurtosis of 4.09. In addition, using neighboring non-announcement days to form a control group that matches the high group in its average reduction in VIX (hence the magnitude of uncertainty resolution), we find that the control group still exhibits a significant excess kurtosis of 3.01. These results add further support to the notion that different risks are resolved differently during the pre- and post-announcement periods. Compared with the low group and the control group, where both the impact uncertainty and news risk are gradually resolved over time, the high group is unique in that its resolution of uncertainty occurs within the narrow pre-announcement window and is complete. As a result, its post-announcement returns are closer to normal.

Heightened uncertainty and its risk premium: The accumulation period is when heightened uncertainty arises in anticipation of the impending announcement. In the context of our model, the higher the impact uncertainty λ, the stronger the built-up during the accumulation period, which leads to lower returns in the same period and larger pre-announcement returns. Following this prediction, we use the increase in VIX during the accumulation period to sort announcements of the four major macroeconomic indicators (NFP, ISM, GDP, and FOMC) into high and low impact uncertainty groups. As predicted by the model, we find that the accumulation periods in the high group indeed exhibit low contemporaneous returns, which are further followed by significantly higher returns and steeper VIX reductions in the pre-announcement period. This predictive result, driven by the fact that one single quantity λ, as a measure of uncertainty, has implications for both time periods, offers rather compelling evidence that the pre-announcement return is indeed a premium for heightened uncertainty.

The fact that heightened uncertainty leads to large market return is an important and rather unique prediction of our model. To further strengthen this novel empirical fact, we use the change in VIX over the six-day accumulation window to predict the pre-announcement return for the four major macroeconomic indicators. Indeed, we find that changes in VIX during the accumulation period can positively predict pre-announcement returns with an adjusted R-squared of 3.13%. For such high-frequency predictive regressions of daily market return, this level of predictive power is rather large. Moreover, with the exception of FOMC, a large fraction of the pre-announcement returns are in fact realized overnight.

Unanticipated heightened uncertainty: Besides scheduled announcements, heightened uncertainty can also be triggered unexpectedly. In the context of our model, a large spike in VIX on a single day can be viewed as a condensed, sped-up version of the slow accumulation of VIX in anticipation of a scheduled announcement. Just as a large accumulation in VIX triggered by an anticipated announcement leads to a higher subsequent return, so should a sudden spike in VIX be followed by a large subsequent return. This is indeed what we find in the data. Focusing on non-announcement days, we identify days of unanticipated heightened uncertainty using sudden and large increases in VIX. Consistent with our model's prediction, we find that such heightened VIX days are followed by large next-day market returns, with magnitudes comparable to the pre-announcement returns.

In parallel to the scheduled announcements, we repeat the same predictive regression for non-announcement days, also using changes in VIX over a six-day window to predict the next-day market returns. Interestingly, we find predictability only for those non-announcement days with heightened VIX and the magnitude of predictability is comparable to that for the scheduled announcements. For all other "normal" days (i.e., excluding days of scheduled announcement and heightened VIX), changes in VIX do not predict the next-day return, indicating that the predictability of VIX buildup is uniquely linked to the presence of heightened uncertainty, either anticipated as in the case of macroeconomic announcements or unanticipated as in the case of VIX hikes. This finding that unanticipated heightened uncertainty also leads to large market returns serves as an out-of-the-sample test of our model, further strengthening its empirical support. After all, regardless of its origin, heightened uncertainty, anticipated as well as unanticipated, brings risk as well as risk premium to the market, and this is the essence of our model.

Literature and discussion

Our paper is most closely related to the empirical literature studying the stock impact of macroeconomic announcements. Savor and Wilson (2013) provide some of the earliest evidence linking the risk from macroeconomic announcements to stock-market risk premium. Lucca and Moench (2015) are the first to identify the large market returns prior to FOMC announcements.[7] Following this literature, we are the first to uncover the significant overnight return prior to the release of a number of other macroeconomic indicators including NFP, ISM and GDP. Proper inclusion of the overnight window in the pre-announcement period sets our empirical findings apart from those of Lucca and Moench (2015), which, excluding the overnight window, report small and insignificant pre-announcement returns for non-FOMC macroeconomic indicators.[8] Moreover, instead of focusing exclusively on the

[7] See also Gilbert et al. (2018) and Lucca and Moench (2018). Brusa et al. (2020) and Guo et al. (2019) have examined pre-announcement returns for other major central banks' monetary policy decisions and found mixed results. For a set of non-FOMC macroeconomic announcements, Ai and Bansal (2018) also report positive announcement-day returns when pooling together the pre- and post-announcement returns, without separating them. Ernst et al. (2019) have also studied the announcement-day returns for a range of other macroeconomic indicators and their potential connection with sample selection.

[8] Ai and Bansal (2018) also report insignificant pre-announcement returns on a set of non-FOMC macroeconomic indicators, excluding the overnight window from the pre-announcement period.

pre-announcement period, we also examine the risk-and-return patterns surrounding the announcements. In particular, it is important to show that there is no abnormal return after the announcement, from 5 min before the announcement to the day's closing, despite a high return variance over the same period.

Our paper also contributes to the theoretical modeling of the asset pricing implications of the market-moving macroeconomic announcements. Combining the results for FOMC from Lucca and Moench (2015) and for NFP, ISM and GDP from our paper, there is compelling evidence that the macroeconomic "announcement-day" returns in the U.S. stock market are predominantly pre-announcement returns. Motivated by this observation, our model departs in an important way from other models in the literature that study conditions under which macroeconomic announcement generates a positive stock return, such as Ai and Bansal (2018) and Wachter and Zhu (2019). While these studies do not distinguish pre-announcement and post-announcement returns, our evidence reveals the importance of this distinction: the pre-announcement part dominates in average return and has a much higher return-to-variance ratio than the post-announcement counterpart. Therefore, a key contribution of ours is the explicit modeling of the pre-announcement period through the lens of impact uncertainty and the empirical characterization of the joint dynamics of returns and VIX during the accumulation and pre-announcement periods.

By extending our empirical analysis beyond FOMC and establishing a theoretical foundation common to all important macroeconomic announcements, we add discipline as well as richness to the literature that focuses exclusively on the pre-FOMC drift. For example, Cieslak et al. (2019) suggest that the large pre-FOMC drift is the result of news leakage prior to the announcement of unexpectedly accommodating monetary policy. To study the pricing implications of news leakage, our model allows part of the news risk to be resolved prior to the announcement and shows that gradual resolution of the news risk alone cannot explain the sharp difference in return and variance behavior between the pre- and post-announcement periods.[9] Because the pre-announcement revelation of impact uncertainty may be broadly interpreted as a form of "leakage" or learning, our model is not inconsistent with a general notion of learning or leakage. However, whatever is revealed pre-announcement must be distinct from the announced news itself to generate a much larger return-risk ratio as seen in the data. From this perspective, the leakage of the actual announcement itself as the only relevant information cannot be the full explanation of the pre-announcement drift.

Several recent papers focus on explaining the pre-FOMC drift. In a paper subsequent to ours, Laarits (2020) proposes an additional state variable for the economy (good or bad), whose revelation before the announcement yields the pre-FOMC return. Like in our model, this state variable introduces a second source of risk. However, unlike ours, his model does not fully explore its implications for the joint intertemporal behavior of return and risk around the announcements. Extending Ai and Bansal (2018), Ai et al. (2021) further include information acquisition and investor heterogeneity. In their model, the pre-FOMC drift is a result of ambiguity-averse investors' learning, but pre-announcement volatility can be muted because informed investors already incorporate some of the information in the price. Both papers focus on FOMC alone, whereas our analysis addresses the pre-announcement return common to all major macroeconomic announcements and does not rely on private information.

The fact that VIX emerges as a measure for impact uncertainty in our model connects our paper to the rich literature on the dynamic relationship between return, variance, and VIX. Generally, in the presence of multiple risks, VIX can merge as an instrument for risks in addition to the directional payoff risk, which can be captured by return variance.[10] The most salient empirical fact in this literature is the contemporaneous negative correlation between returns and changes in volatility as studied by Black (1976), Christie (1982), French et al. (1987), Campbell and Hentschel (1992), Bekaert and Wu (2000) and Wu (2001). Given the volatility information embedded in option prices as well as VIX, evidence of this negative correlation has also been documented by Bakshi et al. (1997) and Pan (2002) using option prices, and by Dennis et al. (2006) and Carr and Wu (2006) using VIX. Relating to this literature, we provide evidence that the magnitude of impact uncertainty surrounding the macroeconomic announcements is uniquely linked to VIX, not variance. In particular, we show that resolution of impact uncertainty during the pre-announcement window is captured by the reduction in VIX not variance. Another important empirical fact in this literature, as documented by Bollerslev et al. (2009), Carr and Wu (2009), Todorov (2010), and Bollerslev and Todorov (2011), is that variance premium – the difference between VIX^2 and realized variance, can predict stock market returns at the intermediate quarterly horizon. We contribute to this literature by showing that changes in VIX can positively predict the next-day stock returns under scenarios of heightened uncertainty, either triggered un-

[9] In standard rational expectations settings, He and Wang (1995) and Jiang et al. (2019) show that informed trading can lead to pre-announcement realization of the risk premium as private information gets incorporated into the price. However, as shown in Bernile et al. (2016) and Kurov et al. (2019), evidence on informed trading, if any, is only detected 30 min before macroeconomic announcements. In addition, informed trading tend to bring more variance to the price due to the risk of adverse selection, lowering the return-to-variance ratio.

[10] In the option pricing literature, Pan (2002) shows that option prices contain information not only about the underlying return variance but also the risk premium for crash as well as variance risk. In a model of dynamic information acquisition, Han (2019) shows that VIX squared can emerge as an endogenous measure of asset's payoff uncertainty when noise trading brings another source risk. In the context of macroeconomic announcements, one can also try to construct other empirical measures of uncertainty. For example, for FOMC, Bauer et al. (2019) use the standard deviation of LIBOR as a proxy for monetary policy uncertainty, and find this measure of uncertainty declines substantially on the day of FOMC announcements. Fisher et al. (2018) find a positive correlation between VIX and their "macroeconomic attention index" based on news articles at the daily frequency.

expectedly or in anticipation of an impending macroeconomic announcement.

More broadly, our paper is also related to the asset pricing literature concerning stochastic state variables such as volatility or tail risk as additional risk factors (see, for example, Merton (1973), Merton (1976) and follow up empirical studies including Pan (2002)). For example, Bansal and Yaron (2004) and Campbell et al. (2018), among others, explore how long-run stochastic volatility in macro-economy/market return can help to explain the overall behavior of asset prices, with horizons from quarterly to beyond. Our model also introduces impact uncertainty as an additional risk, which carries its own premium and varies over time according to its own dynamics. However, our horizon, daily or intraday, is much shorter. From this perspective, our paper is more related to Dew-Becker et al. (2017), who examine the term structure of variance swap prices over monthly horizons. They find that the risk premium contained in swap prices is significant at one month horizon but diminishes to zero for horizons beyond two months. This is consistent with our finding that time variation in risk at short horizons may demand an additional risk premium.

Our model is silent on what drives the heightening of impact uncertainty for certain announcements, its resolution and their timing. They may be linked to the exogenous flow of information to the economy and/or endogenous acquisition of information by investors. There is a an emerging literature that studies investor behavior prior to macroeconomic announcements, adding granular evidence for the resolution of uncertainty pre-announcement.[11] We return to the discussion of these issues in the concluding section.

The rest of our paper is organized as follows. Section 2 develops the two-risk model of macroeconomic announcements with impact uncertainty. Section 3 details the data used in this paper. Section 4 presents the main empirical results on macroeconomic announcements and Section 5 adds to the empirical results using unanticipated heightened uncertainty as an out-of-the-sample test of the key mechanism of our paper. Section 6 concludes the paper. Proofs for the theoretical results are provided in the appendices. An Online Appendix of the paper contains additional empirical results in support of the paper's main conclusions.

2. A Model of risks and returns around announcements

In this section, we develop a simple asset pricing model, which captures two types of risks concerning a macroeconomic announcement. One risk is about a directional news on the economy; the other risk, also referred to as uncertainty for distinction, is about the magnitude of the news' impact on asset payoffs. In general, these two risks generate different risk premiums and return variability. When the resolution of these two risks occur at different times, it will lead to rich intertemporal return patterns. We demonstrate that the resolution of heightened uncertainty brought by a news, followed by the resolution of the news itself can generate the return and risk patterns similar to those around macroeconomic announcements.

2.1. Setup

For simplicity, we consider an economy with three dates, $t = 0, 1, 2$.

Securities market

There is frictionless securities market, which include two primitive securities, a bond and a stock. Each unit of the bond yields a terminal sure payoff of 1 at $t = 2$. Each share of the stock pays a terminal risky payoff D at $t = 2$. D is given by:

$$D = \bar{D} + \sigma\, \varepsilon = \bar{D} + \sigma\, (\varepsilon_1 + \varepsilon_2), \tag{1}$$

where $\bar{D}$ is a positive constant, and σ, ε_1, and ε_2 are independent random variables. We assume that σ has a positive mean while ε_1 and ε_2 have zero means. Without loss of generality, the variances of ε_1 and ε_2 are assumed to sum to 1 (i.e., ε has a variance of 1). Thus, $\bar{D}$ gives the expected dividend and σ^2 gives the variance of dividend.

In the context of this paper, ε_1 and ε_2 are two components of a market-moving news ε, and σ^2 captures the size of its impact on asset payoffs. All three variables are unknown to the market ex ante but revealed over time gradually. In particular, heightened uncertainty prior to the news is represented by a high ex ante variance of σ^2.

Both the bond and the stock are traded in the market at dates 0, 1 and 2. We will use the bond as the numeraire and denote the price of the stock at date t as P_t, $t = 0, 1, 2$. Since the bond is the numeraire, its price will remain at one and its return is always zero.

For tractability, we further assume that σ^2 follows an exponential distribution with location parameter $\lambda_0 \geq 0$ and scale parameter $\lambda \geq 0$, where λ_0 and λ are known constants. That is, σ^2 has the support $[\lambda_0, \infty)$, and $\sigma^2 - \lambda_0$ follows an exponential distribution with variance λ^2. In addition, ε_1 and ε_2 follow normal distributions with mean zero and variances δ and $1 - \delta$, respectively, where $\delta \in [0, 1]$ is also a known constant.

Let $\mathrm{E}_t[\cdot]$ and $\mathrm{V}_t[\cdot]$ denote the conditional mean/expectation and variance of a random variable at time t, $t = 0, 1$, respectively. The conditional mean and variance at $t = 0$ also give the unconditional mean and variance, respectively, for which we drop the time subscript for convenience. We then have:

$$\mathrm{E}[\sigma^2] = \lambda_0 + \lambda, \qquad \mathrm{V}[\sigma^2] = \lambda^2. \tag{2}$$

Thus, a larger value of λ corresponds to a higher unconditional mean and variance of σ^2. For comparative statics, we can hold the mean of σ^2 constant and increase its

[11] For example, Savaser (2011) finds that investors in the GBP/USD foreign exchange market submit significantly more stop-loss orders and take-profit orders between 3:30 am and 6:30 am on days with an impending 8:30 am U.S. macroeconomic announcement (including NFP and GDP) than non-announcement days. These orders are limit orders with given prices, so investors seem to have formed their views on the impact of the upcoming announcements during the overnight period, coinciding with the high overnight stock return. Benamar et al. (2021) find that clicks on news articles related to NFP increases significantly from 4 am to the announcement time of 8:30 am, indicating that learning intensifies approaching the announcement.

variance by increasing λ and decreasing λ_0 by the same amount. Thus, increasing λ corresponds to increasing the variance of σ^2 or uncertainty.

Investors

There is a unit mass of identical, infinitesimal, and competitive investors, who are endowed with zero unit of the bond and one share of the stock. In addition, we assume that all investors have CARA utility over their terminal wealth:

$$-\exp\{-\alpha W_2\}, \tag{3}$$

where $\alpha > 0$ is the risk aversion coefficient and W_2 is the wealth at $t = 2$.

For the model to be well-defined, the following parameter condition is needed:

$$\lambda < \frac{2}{\alpha^2}. \tag{4}$$

Since the mean of σ^2 will be held constant, condition (4) imposes upper bounds on its variance, i.e., uncertainty. From now on, we assume (4) always holds without repeating it.

Time line

The time line for the economy is summarized as follows:

- $t = 0$: Investors know about the underlying parameters of the economy, $\bar{D}$, λ_0, λ and δ, but observes none of σ^2, ε_1, and ε_2. Based on their probability distributions, investors trade the stock (against the bond) by submitting competitive demand functions, and the market clears at the equilibrium price P_0.
- $t = 1$: Investors observe σ^2 and ε_1, but not ε_2. We refer to the revelation of σ^2 as the resolution of uncertainty. In addition, in terms of the news itself, a fraction δ of its content also becomes known to the market before it is officially announced. Investors trade in the market again, yielding the equilibrium stock price P_1.
- $t = 2$: The second component of the news ε_2 is realized, dividend D is paid on the stock, and investors consume their terminal wealth.

The time line above describes how the two risks, one about the news itself and the other about its impact, arise and resolve over time. In particular, at $t = 0$, the size of the news risk and impact risk, or uncertainty, are determined by λ_0 and λ. During the first period, i.e., by $t = 1$, the magnitude of the news' impact, σ^2, is learned. In addition, part of the news' content, ε_1, is also leaked to the market. The amount of leakage is captured by δ. For example, $\delta = 0$ corresponds to the case of no leakage, and $\delta = 1$ corresponds to the case of full leakage. By the end of second period, i.e., at $t = 2$, the remaining part of the news, ε_2, is revealed to the market.

Discussion

Several comments are in order before we move on. First, our model is intentionally simple, aimed at capturing the two important risks concerning a macroeconomic news, the risk about the news realization itself and the uncertainty about its impact, and their intertemporal resolution. Our main goal is to show qualitatively how such a model can lead to the possible return and volatility dynamics observed in the data. The model can be extended to a full intertemporal setting and to allow richer dynamics for the two risks.

Second, since we mainly care about the price implications of the model, we have abstracted away from potential heterogeneity among investors and the actual trading between them. The model can allow different types of heterogeneity, such as heterogeneous endowment shocks, signals on σ^2 and ε, and their interpretations, while yielding similar pricing implications.

In addition, the timing for the resolution of the two risks is given exogenously in the model. It is possible that this resolution process is driven, at least partially, by the investors' information production process. Our model can be extended to endogenize the timing of the risk resolution by explicitly modeling investors' information production decisions. But this is beyond the scope of this paper.

Finally, assumptions on probability distributions and investor preferences are made for tractability. Thus, our results are not meant to be restrictive but mainly illustrative.

2.2. Equilibrium

We solve the model backwards. Because investors are identical, we can solve the problem of a generic investor, without loss of generality. We denote by W_t the wealth of a generic investor at the end of date t, and denote by θ_t the investor's demand of the risky asset at date t.

Solution for date 1 An investor's consumption at date 2 is:

$$W_2 = W_1 + \theta_1(D - P_1). \tag{5}$$

At date 1, after σ and ε_1 are known, the final dividend D is normally distributed with mean $\bar{D} + \sigma\varepsilon_1$ and a known variance $(1-\delta)\sigma^2$. So the investor's optimization problem is:

$$\begin{aligned} J_1 &= \max_{\theta_1}\ \mathrm{E}_1[-\exp\{-\alpha[W_1 + \theta_1(D - P_1)]\}] \\ &= \max_{\theta_1} -\exp\Big\{-\alpha\Big[W_1 + \theta_1(\bar{D} + \sigma\varepsilon_1 - P_1) \\ &\quad -\frac{1}{2}\alpha(1-\delta)\sigma^2\theta_1^2\Big]\Big\}. \end{aligned} \tag{6}$$

The investor's demand function is then given by:

$$\theta_1 = \frac{\mathrm{E}_1[D - P_1]}{\alpha \mathrm{V}_2[D - P_1]} = \frac{\bar{D} + \sigma\varepsilon_1 - P_1}{\alpha(1-\delta)\sigma^2}. \tag{7}$$

The demand function is easy to understand. It is proportional to the expected net payoff from the stock, given by the numerator, and inversely proportional to the risk aversion α and the variance of the stock's payoff $(1-\delta)\sigma^2$, which measures the its remaining risk over the second period, as shown in the denominator.

From the market clearing condition $\theta_1 = 1$, the equilibrium stock price at $t = 1$ is:

$$P_1 = (\bar{D} + \sigma\varepsilon_1) - \alpha(1-\delta)\sigma^2. \tag{8}$$

The stock price has a simple interpretation. The first two terms, $\bar{D}+\sigma\varepsilon_1$, is the stock's expected payoff, given σ and ε_1, which are known at $t=1$. The second term, $-\alpha(1-\delta)\sigma^2$, gives the risk discount on the price. It is proportional to α, the risk aversion, and, more importantly, the remaining risk about the news, ε_2, which is $(1-\delta)\sigma^2$.

Solution for date 0 Substituting the equilibrium strategy at $t=1$ into J_1, we get:

$$J_1 = -\exp\left\{-\alpha\left[W_0+\theta_0(\bar{D}+\sigma\varepsilon_1-\alpha(1-\delta)\sigma^2-P_0)+\frac{1}{2}\alpha(1-\delta)\sigma^2\right]\right\}, \tag{9}$$

where we have also used $W_1 = W_0+\theta_0(P_1-P_0)$.

Recall that at $t=0$, investors have an exponential distribution for σ^2 with λ_0 and λ and a normal distribution for ε_1 with mean 0 and variance δ. To calculate $\mathrm{E}[J_1]$, we take iterated expectations, first by conditioning on σ:

$$\mathrm{E}[J_1|\sigma] = -\exp\left\{-\alpha\left[W_0+\theta_0(\bar{D}-P_0)\right]+\alpha^2\left[\frac{1}{2}(1-\delta)-(1-\delta)\theta_0-\frac{1}{2}\delta\theta_0^2\right]\sigma^2\right\} \tag{10a}$$

$$\equiv -\exp\left\{-\alpha\left[W_0+\theta_0(\bar{D}-P_0)\right]+\alpha^2 Q(\theta_0,\delta)\sigma^2\right\}, \tag{10b}$$

where

$$Q(\theta_0,\delta) \equiv \frac{1}{2}(1-\delta)-(1-\delta)\theta_0-\frac{1}{2}\delta\theta_0^2, \tag{11}$$

is a quadratic function of θ_0 as the coefficient in front of σ^2 in the exponent. Taking expectations over σ^2 gives:

$$\begin{aligned}\mathrm{E}[J_1] &= \mathrm{E}[\mathrm{E}[J_1|\sigma]]\\ &= -e^{-\alpha[W_0+\theta_0(\bar{D}-P_0)]}\int_{\lambda_0}^{\infty} e^{-\alpha^2 Q(\theta_0,\delta)x}\frac{1}{\lambda}e^{-\frac{x-\lambda_0}{\lambda}}dx\\ &= -e^{-\alpha[W_0+\theta_0(\bar{D}-P_0)]-\alpha^2 Q(\theta_0,\delta)\lambda_0}\frac{1}{1+\alpha^2\lambda Q(\theta_0,\delta)},\end{aligned} \tag{12}$$

subject to the condition that

$$1+\alpha^2 Q(\theta_0,\delta) = 1+\alpha^2\lambda\left[\frac{1}{2}(1-\delta)-(1-\delta)\theta_0-\frac{1}{2}\delta\theta_0^2\right] > 0. \tag{13}$$

In equilibrium, $\theta_0=1$, so this condition becomes $\alpha^2\lambda<2$, which is simply (4).

To solve the equilibrium price, we first solve for the investors' stock demand. The corresponding first order condition is:

$$\frac{d\mathrm{E}[J_1]}{d\theta_0} = 0, \tag{14}$$

which gives the optimal θ_0, as shown in the appendix. Substituting in $\theta_0=1$, the market clearing condition, we obtain the equilibrium stock price at date 0:

$$P_0 = \bar{D}-\alpha(\lambda_0+\lambda)-\frac{\frac{1}{2}\alpha^3\lambda^2}{1-\frac{1}{2}\alpha^2\lambda}. \tag{15}$$

The stock price P_0 given in (15) has a simple interpretation. Its first term is simply the stock's expected payoff at $t=0$. The next two terms then represent two separate discounts, for the two risks in the stock's payoff, ε and σ^2, respectively. The first discount, $\alpha(\lambda_0+\lambda)$, is associated with the news risk. It is proportional to $\lambda_0+\lambda$, which is the expected variance of D, $\mathrm{E}[\sigma^2]$, arising from the news itself and its expected impact. The proportionality coefficient is simple α, the risk aversion. It is important to note that this discount only depends on the mean of σ^2, which is $\lambda_0+\lambda$. Holding $\lambda_0+\lambda$ constant, this discount will not change even if $\lambda=0$ and there is no uncertainty.

The second discount, given by the third term in (15), is associated with impact uncertainty, which is captured by the variance of σ^2, λ^2. Indeed, this discount is independent of λ_0, but proportional to λ^2, as the numerator indicates. When there is no uncertainty, that is, when $\lambda=0$, this discount becomes zero. Holding $\mathrm{E}[\sigma^2]=\lambda_0+\lambda$ constant, this discount increases with λ. Furthermore, when λ becomes sufficiently large, for example, when it is close to its upper limit $2/\alpha^2$, this discount can be very large. This implies that a heightened uncertainty, as given by a large enough value of λ, will lead to a large discount on the current stock price. Moreover, the resolution of this uncertainty, when it occurs later, will lead to a large return, reflecting the corresponding risk premium for the uncertainty in σ^2.

The following proposition summarizes the equilibrium stock prices.

Proposition 1. The equilibrium stock price at dates 0 and 1 are given by (15) and (8), respectively. Moreover, the stock price at date 0 is decreasing in λ_0 and in λ.

2.3. Uncertainty and VIX

In order to test the model's implications, it is desirable to have measures that will allow us to capture the two separate risks in the model, $\mathrm{E}[\sigma^2]=\lambda_0+\lambda$ and $\mathrm{V}[\sigma^2]=\lambda^2$. $\mathrm{E}[\sigma^2]$ is easy to estimate empirically, since it is the expected variance of dividend (or return). What we hope to do is to find an observable variable that can capture the uncertainty about σ^2.

For this purpose, we consider a forward-looking variance swap, which pays $(D-P_1)^2$ at $t=2$. Its price, denoted by v_t, is given by:

$$v_t = \frac{\mathrm{E}_t\,[J'_{t+1}v_{t+1}]}{\mathrm{E}_t\,[J'_{t+1}]}, \quad t=0,1, \tag{16}$$

where J'_{t+1} is a shorthand for $J'_{t+1}(W_{t+1})$, $J_2=-\exp\{-\alpha W_2\}$, and $v_2=(D-P_1)^2$. We then have the following result:

Proposition 2. The equilibrium price of variance swap at dates 0 and 1 are given by:

$$v_0 = (1-\delta)(\lambda_0+\lambda)+(1-\delta)\frac{\frac{1}{2}\alpha^2\lambda^2}{1-\frac{1}{2}\alpha^2\lambda},$$

$$v_1 = (1-\delta)\sigma^2, \tag{17a}$$

$$\mathrm{E}\,[v_1-v_0] = -(1-\delta)\frac{\frac{1}{2}\alpha^2\lambda^2}{1-\frac{1}{2}\alpha^2\lambda} < 0. \tag{17b}$$

Thus, from (17b), the change in the price of variance swap provides a measure of $\mathrm{V}[\sigma^2]=\lambda^2$. Since the price of the variance swap can be viewed as equivalent to VIX squared, this proposition then predicts that VIX increases when uncertainty rises ahead of an announcement, and it decreases when the uncertainty is resolved. In what follows, we will use changes in VIX to gauge changes in uncertainty.

2.4. Return and variance

We now examine the returns on the stock over the two periods, from 0 to 1 and 1 to 2. Define the stock returns as follows:

$$R_t = P_t - P_{t-1}, \quad t = 1, 2. \tag{18}$$

From the stock prices given in Proposition 1, we have the following results for the mean and variance of returns on the stock over the two periods:

$$\mathrm{E}\,[R_1] = \alpha\delta(\lambda_0+\lambda) + \frac{\frac{1}{2}\alpha^3\lambda^2}{1-\frac{1}{2}\alpha^2\lambda} > 0, \tag{19a}$$

$$\mathrm{V}\,[R_1] = \delta(\lambda_0+\lambda) + \alpha^2(1-\delta)^2\lambda^2. \tag{19b}$$

and

$$\mathrm{E}\,[R_2] = \alpha(1-\delta)(\lambda_0+\lambda) > 0, \tag{20a}$$

$$\mathrm{V}\,[R_2] = (1-\delta)(\lambda_0+\lambda) + \alpha^2(1-\delta)^2\lambda^2. \tag{20b}$$

First, we observe that the expected return over both periods are positive, compensating the risks over each period. But, they are compensating for different risks. For the second period, the expected return, $\mathrm{E}[R_1]$ in (20), is proportional to $(1-\delta)(\lambda_0+\lambda)$, which is the risk associated with the remaining part of the news revealed at the announcement (i.e., ε_2). It has nothing to do with the uncertainty about σ^2, which is measured by λ^2. For the first period, however, the expected return, $\mathrm{E}[R_1]$ given in (19), compensates for both the news risk and the uncertainty. In particular, the first term reflects the risk premium for the news risk, which is proportional to the fraction of news revealed in this period δ, times its expected impact $(\lambda_0+\lambda)$. The second term, however, reflects the risk premium for uncertainty.

Using return variance as a measure of risk, we also see that the variances of R_1 and R_2 capture different combinations of the two risks. The first term in both $\mathrm{V}[R_1]$ and $\mathrm{V}[R_2]$ arises from the news risk, both proportional to $\lambda_0+\lambda$, one with a weight of δ while the other with a weight of $1-\delta$. The second term, however, comes from the impact risk or uncertainty – its resolution attributes to the variability in the stock price at $t=1$, P_1.

The returns over the two periods, as shown by their means and variances, can exhibit a rich set of patterns. In order to further explore their underlying structure, we now consider their ratio, the return-variance ratio (RVR), as a measure of risk premium or the price of risk:

$$RVR_t = \frac{\mathrm{E}[R_t]}{\mathrm{V}[R_t]}, \qquad t = 1, 2. \tag{21}$$

We use the return-variance ratio instead of the Sharpe ratio (the return-volatility ratio) to measure risk premium mainly because the former is scalable over time while the latter is not. Given that in the empirical analysis, the time window may vary when measuring returns, the return-variance ratio is a more appropriate measure to compare the risk premiums for different time windows and different risks.

Proposition 3. Let

$$\lambda^*(\lambda_0) = \frac{\sqrt{2}}{\alpha^2} + \frac{\left(2-\sqrt{2}\right)\lambda_0}{4+\alpha^2\lambda_0} \in \left[\sqrt{2}/\alpha^2, 2/\alpha^2\right). \tag{22}$$

When $\lambda > \lambda^*(\lambda_0)$, we have:

$$\mathrm{E}[R_1] > \mathrm{E}[R_2], \tag{23a}$$

$$\frac{\mathrm{E}[R_1]}{\mathrm{V}[R_1]} > \frac{\mathrm{E}[R_2]}{\mathrm{V}[R_2]}. \tag{23b}$$

An immediate implication of Proposition 3 is that if $\lambda > \lambda^*(\lambda_0)$, that is, if uncertainty is sufficiently high, then the expected return and return-to-variance ratio for the first period are both higher than their counterparts for the second period.

2.5. A special case with leakage of news but no uncertainty

To better illustrate our model's implications, it is instructive to consider the special case with leaks but no uncertainty. This corresponds to $\sigma^2=\lambda_0$, $\lambda=0$, and $0\le\delta\le 1$. From (19) and (20), we immediately have:

$$\mathrm{E}[R_1] = \alpha\delta\sigma^2, \quad \mathrm{V}[R_1] = \delta\sigma^2, \tag{24a}$$

$$\mathrm{E}[R_2] = \alpha(1-\delta)\sigma^2, \quad \mathrm{V}[R_2] = (1-\delta)\sigma^2. \tag{24b}$$

At this point, it is apparent that the return-to-variance ratio for the two periods are identical, both equal to α.

Corollary 1. If the variance σ^2 is known ex ante, i.e., $\lambda=0$, for any $0\le\delta\le 1$, the return-to-variance ratios in the two dates are identical:

$$\frac{\mathrm{E}[R_1]}{\mathrm{V}[R_1]} = \frac{\mathrm{E}[R_2]}{\mathrm{V}[R_2]} = \alpha. \tag{25}$$

Here, for δ equal to 0 or 1, the ratio is given by the limit as δ converges to 0 or 1, respectively.

The key takeaway from this special case is that if the leakage prior to its actual announcement is about the content of the announcement, then the return-to-variance ratios before and after the announcement have to be identical. Although we derive this result from a simple model, the intuition should be more general: the same source of risk should lead to the same return-to-variance ratios.

2.6. Empirical implications

Our model leads to clear predictions about the market behavior surrounding macroeconomic announcements. First, it identifies three relevant time periods.

- The first period is the "accumulation period", which corresponds to the time prior to date 0. Although this period is not explicitly specified in the model, it is clear that, if λ itself is a random variable, it would be realized during the time up to date 0. A large realization of λ by date 0 is what we refer to as heightened uncertainty.
- The second period is the "pre-announcement period", which is from date 0 to 1 in the model. During this period, the uncertainty about the news' impact σ is resolved. In addition, there can be partial leakage of the news itself, as measured by δ.
- The third period is the "post-announcement period", which is from date 1 to 2 in the model. During this period, the news is released and its impact on asset payoff is realized.

Next, the model yields the following predictions on the returns, return-to-variance ratios, return distributions, and changes in VIX over these three periods.

Prediction 1. Positive stock returns over the pre-announcement period occur whenever there is heightened uncertainty which is resolved prior to macroeconomic announcements.

In particular, pre-announcement return is not unique to FOMC and can also arise for other important macroeconomic announcements. Depending on the level of heightened uncertainty, the pre-announcement return can vary over different announcements, both cross different types of announcements and within each type of announcements.

Prediction 2. Prior to a pre-scheduled macroeconomic announcement (including FOMC), if there were only leakage about the content of announcement itself but no uncertainty concerning its impact, the return-to-variance ratios for the pre- and post-announcement periods should be identical, i.e., $\frac{\mathrm{E}[R_1]}{\mathrm{V}[R_1]} = \frac{\mathrm{E}[R_2]}{\mathrm{V}[R_2]}$.

A rejection of Prediction 2, i.e., evidence that the two return-to-variance ratios differ, would suggest that a second risk is present, separate from news leakage.

Prediction 3. The drop in VIX is a proxy of heightened uncertainty λ. A larger pre-announcement VIX drop leads to a higher return in the pre-announcement period.

We further observe that pre- and post-announcement periods may involve the resolution of *different risks*, namely, different composition of impact uncertainty and news risk. Consequently, their returns will have different distributions, especially when heightened impact uncertainty is resolved prior to the announcement. In particular, the news risk is assumed to be normal in our model. Hence, when impact uncertainty is (fully) resolved during the pre-announcement period, the post-announcement returns would be normally distributed conditioning on this information.

Prediction 4. When more heightened uncertainty is resolved during the pre-announcement period as reflected by a large VIX drop, the subsequent post-announcement returns will be closer to normally distributed and less fat-tailed.

The above observation also implies that for normal periods, when both the impact uncertainty and news risk are resolved simultaneously, the returns may exhibit fat tails even when the news risk has a normal distribution.

In addition, when uncertainty heightens substantially during the days prior the announcement, i.e., the accumulation period, it should lead to a rise in VIX accompanied by a price drop, followed by a higher return and variance before and after the announcement. We thus have the following prediction:

Prediction 5. A VIX build-up in the accumulation period captures an increase in uncertainty λ, which leads to a contemporaneous drop in price, a higher return and larger VIX drop in the pre-announcement period.

Finally, given that a rise in VIX is a proxy for heightened uncertainty before scheduled announcements, it is plausible that an unexpected increase in VIX reflects an unanticipated heightened uncertainty, with similar predictions about subsequent returns and VIX changes. We thus have the following prediction:

Prediction 6. Unanticipated spikes in VIX will be followed by VIX reversals and high returns.

In what follows, we will test these predictions using macroeconomic announcements, as well as VIX spikes, capturing both anticipated and unanticipated arrival of heightened uncertainty.

3. Data

We use several data sets in our analysis. For macroeconomic announcements, we consider the releases of major U.S. macroeconomic indicators. We include the top six macroeconomic indicators ranked by Bloomberg's "relevance score" (as of 2019): total Nonfarm Payroll employment (NFP), initial claims for unemployment insurance (INC), Gross Domestic Production (GDP), consumer price index (CPI), the Institute for Supply Management's manufacturing index (ISM), and the preliminary release of the Consumer Sentiment Index (CSI). We also include industrial production (IP), personal income (PI), housing starts (HST), and producer price index (PPI), partly because they have been used in previous studies. All of these macroeconomic indicators are released monthly (including GDP, which has one preliminary announcement and two revisions for each quarter). Data on these announcements are from the websites of their releasing entities.

The nature and timing of these announcements vary substantially. Except for ISM and CSI, all other economic indicators are public indices released by government agencies at either 8:30 am or 9:15 am (only for IP), Eastern Time. ISM an CSI are economic indicators released by private institutions. ISM is released at 10:00 am, while CSI's release time varies from 9:35 am to 10:00 am during our sample period. We exclude macroeconomic announcement days that coincide with FOMC announcement days to avoid potential confounding effect.

We also include the FOMC announcement, which occurs eight times a year. The timing of the FOMC announcements are based on the time-stamp of Bloomberg and Dow Jones news wires. We follow the same method of Lucca and Moench (2015) and Fleming and Piazzesi (2005), and extend the sample period to May 2018. We focus most of our analysis on the sample from September 1994 to May 2018. During this period, there are in total 190 scheduled releases of FOMC statements. From September 1994 to March 2011, 131 releases are consistently made within a few minutes around 2:15 pm, with only one exception, March 26, 1996, on which the release time was pre-announced to be in the morning because of the Chairman's other duties. From April 2011 to January 2013, seven releases are around 2:15 pm and eight releases are around 12:30 pm, one hour and forty five minutes earlier to accommodate the Chairman's press briefings at 2:15 pm. From February 2013 to May 2018, all of the 43 FOMC releases are around 2:00 pm. For the period before 1994, there is no official announcement and market participants need to inferred policy decisions through the Fed's open market operations, usually on the day after the FOMC meeting.

For all announcements, we define the pre-announcement period as the window from the close of the previous trading day (4 pm) to five minutes prior to the exact release time (ann - 5min). Using the market close as a natural starting point, our construction of the pre-announcement window is consistent with the one often used for FOMC and allows for a unified comparison of the pre-announcement drift across different releases. Similarly, we define the post-announcement period as the one-hour window from five minutes prior to the announcement to 55 min after the announcement. We believe that the one-hour window is wide enough to capture the market's reaction to the announcement while avoiding the potential influence of other factors such as market close.

We rely on the S&P 500 index futures, which are traded almost around the clock, to calculate market returns around announcements. We obtain the transaction-level data on E-mini S&P 500 index futures from September 1997 to May 2018 from the Chicago Mercantile Exchange (CME). Prior to September 1997, when the E-mini contract was not available, we use transaction-level data on the standard ("big") S&P 500 index futures from the CME.[12] To calculate market returns over a given time period $[t_1, t_2]$, we first pick the most active S&P 500 index futures contract as the one with the highest trading volume on the trading day of t_2, and then calculate the return as the percentage change of the last transaction price of this futures contract before time t_2, relative to the last transaction price of the same contract before time t_1.[13]

We use the intraday VIX tick data obtained from the Chicago Board Options Exchange (CBOE) to calculate the changes in VIX around macroeconomic announcements. The VIX intra-day tick data are available from January 1992, but the data for non-regular trading hours only began after April 2016. For this reason, the number of announcements for which we can calculate VIX changes around announcements are fewer for those macroeconomic news released outside the regular trading hours. As a robustness check, we also use the VIX futures data to calculate the VIX changes. The results remain similar.[14]

Since VIX has a one-month horizon, it also contains information about events beyond the announcement window. We further test the robustness of our results using the implied volatility from the prices of 10-day at-the-money S&P 500 index options provided by OptionMetrics. The changes of this implied vol is strongly correlated with changes in VIX, with a correlation of 0.94 and highly significant, and not surprisingly they yield similar results.[15] Overall, because we are primarily interested in the *change* rather than the level of variance swap prices, we use the VIX index, which is much more actively traded and liquid, as our main measure.

4. Empirical results: macroeconomic announcements

4.1. Pre-announcement returns

As outlined by Prediction 1 of our model, positive pre-announcement returns arise from the resolution of heightened impact uncertainty prior to the scheduled news announcement. As such, we should be able to find significant pre-announcement returns not only for FOMC, but also for other macro announcements, as long as they bring substantial heightened uncertainty. To test this prediction, we investigate the pre-announcement returns for a set of well known macroeconomic announcements. Given the extensive coverage on the pre-FOMC return in the existing literature, we focus our discussion on the positive pre-announcement returns for non-FOMC announcements, which have not been documented prior to our paper.

The pre-announcement returns are reported in Table 1, using data from September 1994 through May 2018. To achieve a consistent comparison across different announcements as well as to capture the price movement immediately before the announcement, we define the pre-announcement window as from the previous day's close at 4 pm to 5 min before the scheduled releases. Consistent with Prediction 1, we find that pre-announcement returns are significant for NFP, ISM, and GDP – three macro events

[12] Due to data limitations, prices of standard S&P 500 futures contracts are not available at non-regular trading hours. Therefore, the pre-announcement returns for macro-announcements that are released before market opens are only available after September 9, 1997, when E-mini S&P 500 index futures started trading. We have missing futures trading data on eight trading days in our sample period. One of these eight trading days, January 29, 2014, is a scheduled FOMC release day. For these eight trading days, we rely on the transaction level S&P 500 index data obtained from TAQ to construct the market return.

[13] We choose the most active futures contract as the one with the highest volume, which is usually the nearest-term contract and occasionally the next contract during rolling forward weeks.

[14] The VIX futures data starts to cover the non-regular trading hours after December 2010. The early VIX futures data, however, are very noisy due to thin trading.

[15] In examining pre-FOMC returns, Liu et al. (2021) use the prices of S&P 500 options that span the 24-hour window right before the announcement but mature within three days.

Table 1
Summary Statistics on Pre-Announcement and Post-Announcement Returns.

	Pre-Announcement (4 pm to ann - 5min)							Post-Announcement (ann - 5min to ann + 55min)							
	Mean	TStat	Std	Skew	Kurt	Min	Max	Mean	TStat	Std	Skew	Kurt	Min	Max	Obs
FOMC	**27.14**	5.95	62.9	1.3	5.2	−164	336	6.19	1.28	66.9	0.2	2.1	−207	278	190
NFP	**10.10**	3.63	43.4	−0.2	3.0	−165	177	2.48	0.69	56.2	−0.2	1.5	−204	212	243
ISM	**9.14**	2.10	72.5	−1.1	7.0	−461	213	2.04	0.66	51.1	0.2	1.6	−150	205	276
GDP	**7.46**	2.08	54.7	0.9	10.4	−233	356	1.08	0.45	36.4	−0.7	7.8	−207	138	233
IP	5.23	1.19	68.0	−0.7	4.8	−339	291	**−6.24**	−2.33	41.4	−1.3	4.6	−195	115	240
PI	3.50	0.94	58.3	−1.0	3.8	−248	191	1.13	0.87	20.3	0.0	1.9	−80	75	244
HST	2.46	0.69	53.9	−0.2	4.2	−177	279	1.02	0.59	26.0	−0.1	3.0	−100	91	230
INC	1.56	0.95	53.8	−0.1	5.4	−259	356	−0.29	−0.34	27.7	−0.2	7.8	−207	169	1073
PPI	−0.58	−0.17	52.3	−2.4	14.3	−392	129	−3.47	−1.60	33.6	−0.6	3.3	−137	113	241
CPI	−2.14	−0.69	47.1	−0.8	2.8	−208	130	2.08	0.91	34.9	−0.7	6.3	−188	155	232
CSI	−4.03	−0.88	68.7	0.9	8.1	−232	439	−4.10	−1.55	39.7	−0.7	3.8	−211	128	226
	Close to Open (4 pm to 9:30 am)							**Open to Close** (9:30 am to 4 pm)							
	Mean	TStat	Std	Skew	Kurt	Min	Max	Mean	TStat	Std	Skew	Kurt	Min	Max	Obs
Non-Ann	0.69	0.78	62.1	−0.7	13.5	−668	547	0.09	0.07	97.7	0.0	10.3	−781	920	4976
All Days	1.99	2.45	62.60	−0.6	11.8	−668	547	1.20	0.94	98.6	0.0	8.8	−781	920	5965

This table reports summary statistics on the pre-announcement and post-announcement returns (in basis points) on macroeconomic index announcement days and other days. The macroeconomic announcements include: Federal Open Market Committee statement (FOMC), total nonfarm payroll employment (NFP), the Institute for Supply Management's manufacturing index (ISM), Gross Domestic Production (GDP), industrial production (IP), personal income (PI), housing starts (HST), initial claims for unemployment insurance (INC), producer price index (PPI), consumer price index (CPI), and the preliminary release of the Consumer Sentiment Index (CSI). Macroeconomic announcement days that coincide with FOMC days are excluded for all non-FOMC macroeconomic announcements. The pre-announcement window is from 4 pm on the pre-announcement day to five minutes before the release time and the post-announcement window is from five minutes before to fifty five minutes after the release time on the announcement day. The average returns that are significant at the 5% level are in bold. "Non-Ann" refers to all trading days that are not FOMC, NFP, ISM, or GDP announcements days; "All Days" refers to all trading days. For Non-Ann and All Days, the close to open window is from 4pm on the previous trading day to 9:30am, and the open to close window is from 9:30am to 4pm. The sample period is from September 1994 to May 2018.

that are known to be important and highly ranked by Bloomberg's relevance score. Specifically, the average pre-announcement return is 10.10 basis points for NFP with a t-stat of 3.63; 9.14 basis points for ISM with a t-stat of 2.10; 7.46 basis points for GDP with a t-stat of 2.08. These results are not driven by outliers. After removing the 1% top and bottom returns, the average pre-announcement drift remains important and significant: 9.80 basis points for NPF, 10.31 basis points for ISM, and 6.09 basis points for GDP.

Benchmarked against the average market return of 3.61 basis points per day for the same sample period, the economic magnitudes of these pre-announcement returns of 7 to 10 basis points are rather significant. Further excluding announcement days, the benchmark return shrinks to less than one basis points per non-announcement day, making the contrast even more stark. Moreover, these pre-announcement returns are not full-day returns – the pre-announcement returns for NFP and GDP are realized overnight, from the previous day's close at 4pm to 8:25 am, while those for ISM are from the previous day's close to 9:55 am. The comparable benchmark return should therefore be measured from close to open, which, as shown in Table 1, is 1.99 basis points when averaged across all trading days and 0.69 basis points averaged across non-announcement days.

One important observation emerging from the results in Table 1 is that there is a substantial heterogeneity across macroeconomic announcements. In the context of our model, the varying levels of pre-announcement return is a reflection of the varying magnitudes of impact uncertainty. Indeed, the variation in impact uncertainty and its asset-pricing implications can be examined not only across different macroeconomic indicators, as listed in Table 1, but also across different announcement days for the same macroeconomic indicator, which will be examined later in the section.

Focusing on the cross-indicator variation in Table 1, we see that, not surprisingly, the pre-announcement returns associated with FOMC, with an average value of 27.14 basis points per event, are found to be the largest, indicating strong heightened uncertainty brought upon by the impending FOMC announcements, consistent with the abundant anecdotes of investors anxiously awaiting the FOMC outcome.[16] On the other hand, some of the macroeconomic indicators are found to have insignificant pre-announcement returns, indicating their low impact uncertainty. Indeed, lining up the macroeconomic announcements by their pre-announcement returns, the ranking is consistent with the relative importance of the announcements, both intuitively perceived by market participants

[16] Our calculation of the pre-announcement returns for FOMC is lower than those reported in Lucca and Moench (2015) for two reasons. First, our pre-announcement window starts from 4 pm on the previous day, shorter than the 24-hours window used by Lucca and Moench (2015), excluding the small price run-up from 2 pm to 4 pm on the day prior to the announcement. Second, we updated the sample period of Lucca and Moench (2015) to include the post-2011 pre-FOMC returns, which are on average smaller because of the unusual monetary policy post 2008.

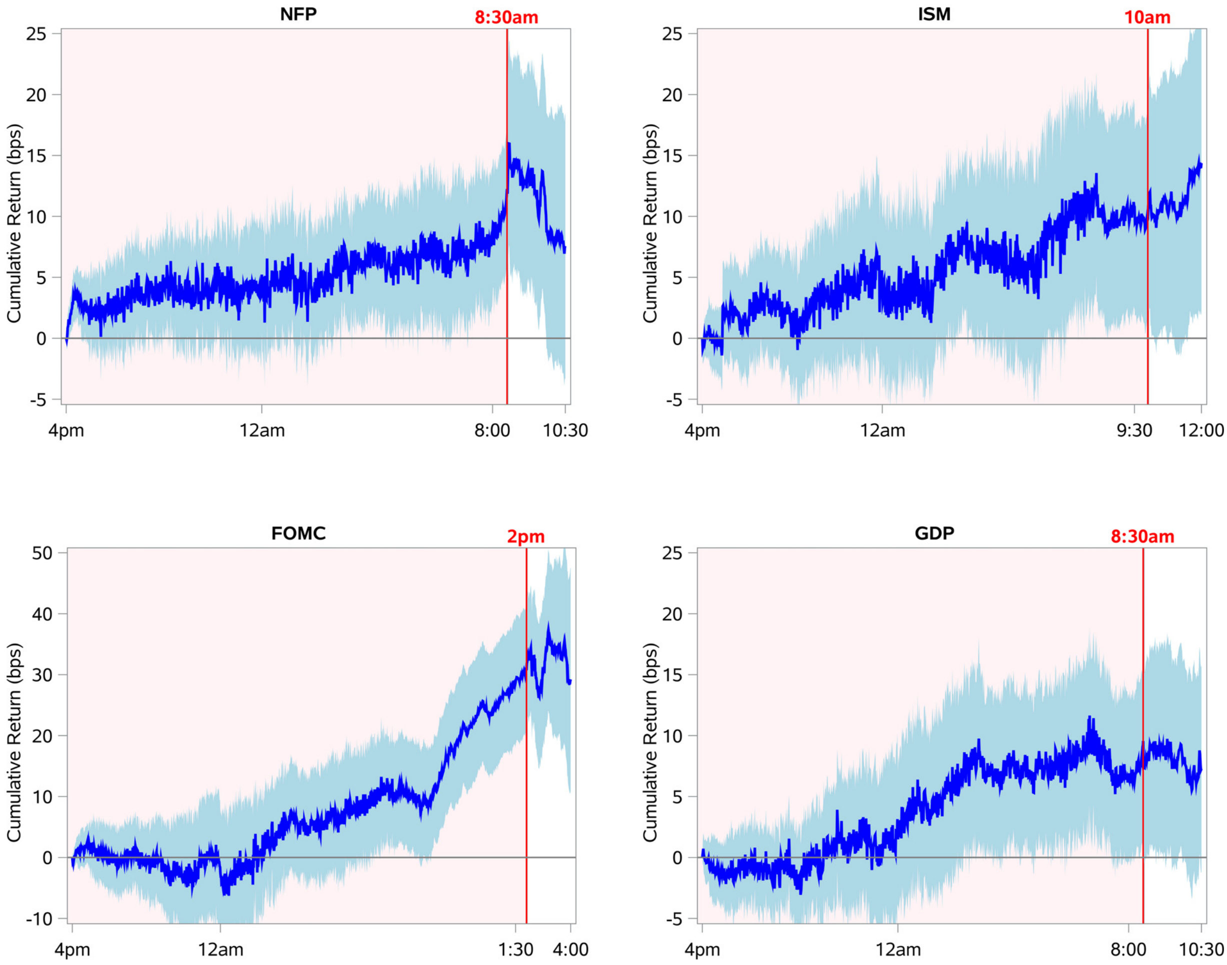

Fig. 1. Average Cumulative Returns on S&P 500 Futures around the Four Macroeconomic Announcements The thick lines show the average cumulative returns from 4pm of the previous trading day to approximately two hours after the releases of NFP, ISM, GDP and FOMC. The shaded areas denote the 95% confidence intervals. For NFP, ISM, and GDP, the announcement time is highlighted by the vertical line in red (8:30 am and 10 am). For FOMC, the announcement time varies around 2 pm in the sample, and 2 pm is highlighted by the verticle line.

and empirically documented by prior literature.[17] From this perspective, our results add discipline as well as richness to the literature that focuses mostly on the pre-FOMC drift. More importantly, we add a theoretical foundation to the unusual risk-and-return tradeoff surrounding the announcements that have puzzled the literature on pre-FOMC drift.

To further illustrate the return patterns before the releases of the non-FOMC macroeconomic indicators, Fig. 1 plots the average cumulative return of the E-mini S&P500 index futures, minute by minute, during the pre-announcement window.[18] For NFP, ISM, and GDP, there is a clear upward drift of the E-mini S&P500 index futures prices hours ahead of their releases. As the releases are made early in the morning, with NFP and GDP at 8:30 am and ISM at 10 am, most of the pre-announcement returns are in fact earned outside of the regular trading hours, making the overnight return uniquely important. Indeed, skipping the overnight window is the reason why earlier studies missed this important result. This is also the reason why the pre-FOMC return was captured first in the literature, since, as shown in Fig. 1, a significant portion of the pre-FOMC return is realized during the regular trading hours.

Examining the robustness of our pre-announcement results, Table 2 reports the pre-announcement returns over the three subperiods of 1994–2000, 2001–2011, and 2012–2018. Grouping all four macroeconomic announcement together, the average pre-announcement returns per event vary from 7 to 16 basis points over the three subperiods, and are all statistically significant. Separating the macroeconomic announcements into non-FOMC (NFP, ISM, and GDP) and FOMC, the sub-period performance for FOMC remains large and significant pre-2011 and becomes insignificant during 2012–2018. By contrast, the perfor-

[17] For example, among the 36 macroeconomic announcements analyzed by Gilbert et al. (2018), nonfarm payrolls has the largest explanatory power for U.S. Treasury yields, followed by ISM.

[18] We skip the 15-minute trading halt from 4:15pm to 4:30pm and the daily maintenance hour from 5:00pm to 6:00pm for E-mini S&P500 futures.

Table 2
Pre-Announcement Returns.

	Macro Announcements			All Days
	All 4	Ex FOMC	FOMC	(close-to-close)
Panel A: Pre-announcement return per event (in basis points)				
1994–2000	**16.00**	**9.60**	**35.81**	**6.95**
	[4.22]	[2.17]	[5.55]	[2.62]
2001–2011	**14.87**	**10.88**	**35.55**	**0.78**
	[4.58]	[3.16]	[4.27]	[0.30]
2012–2018	**7.02**	**6.98**	3.96	**5.14**
	[2.54]	[2.27]	[0.74]	[2.62]
1994–2018	**12.86**	**9.48**	**27.14**	**3.61**
	[6.49]	[4.40]	[5.95]	[2.39]
Panel B: Pre-announcement return per year (in percent)				
1994–2000	7.04	3.46	2.86	17.51
2001–2011	6.54	3.92	2.84	1.97
2012–2018	3.09	2.51	0.32	12.95
1994–2018	5.66	3.41	2.17	9.10
# events/yr	44	36	8	252

This table reports the average and the annualized pre-announcement returns on important macroeconomic releases, for the full sample as well as the three subperiods. “All 4” includes NFP, ISM, GDP and FOMC, and “Ex FOMC” excludes FOMC from the four. In Panel A, the average pre-announcement returns across events and the associated t-statistics (in square brackets) are reported. The average returns that are significant at the 5% level are in bold. In Panel B, the annualized pre-announcement returns are calculated by multiplying the average pre-announcement returns with the number of macroeconomic releases per year. “All Days” refers to all trading days in the sample period; and the daily close-to-close returns on S&P 500 index are used to calculate the respective average and annualized returns.

mance of the non-FOMC macroeconomic announcements remains stable and significant across all three subperiods. In particular, during the last subperiod of 2012–2018, the pre-announcement return is on average 6.98 basis point and statistically significant for the non-FOMC macroeconomic announcements, compared with the statistically insignificant 3.96 basis points for the FOMC announcements.

Another way to gauge and compare the magnitudes of the pre-announcement return is by measuring the returns annually – adding the pre-announcement returns across all events within a year. As shown in Panel B of Table 2, the pre-announcement returns, realized over 44 macroeconomic announcements per day, add up to 5.66% per year, a significant fraction of the total stock return of 9.10%. Separating the four macroeconomic announcements into FOMC and non-FOMC (i.e., NFP, IMS and GDP), the pre-announcement returns add up to an annual number of 3.41% for non-FOMC, and 2.17% for FOMC. From this yearly perspective, we see that, while FOMC is in general more intense than other macroeconomic announcements, its cumulative impact is in fact smaller when compared to the other three macroeconomic announcements combined. Their relative importance also varies across different subperiods along with the changing macroeconomic conditions. For example, post 2011, the relative contribution of FOMC diminishes to 0.32% per year while the contribution of the other three macro indicators remains stable at 2.51% per year. Also interesting is the fact that, while the market return performs poorly at 1.97% per year during the subperiod of 2000–2011, the pre-announcement returns remain large at 6.54% per year.[19]

The same message is conveyed, at a higher frequency, by Fig. 2, which plots the yearly pre-announcement returns for the four macroeconomic announcements combined (red squares), FOMC only (green crosses), and the three non-FOMC combined (blue circles). As a comparison, the annual market returns are also plotted in the background (gray diamonds). One striking feature of this plot is that, while the overall market experiences some rather negative returns throughout the sample period, rarely do the yearly pre-announcement returns dip significantly below zero. Another interesting feature is that pre-2010, there is quite a bit of similarity between FOMC and non-FOMC in terms of their time-series variation. Post-2010, however, the yearly pre-announcement returns of FOMC flatten out while those for non-FOMC remain relatively robust. This, of course, is likely related to the unconventional monetary policy after the 2008-09 financial crisis.

4.2. Return-to-variance ratios

As outlined by Prediction 2 of our model, in presence of only one risk (i.e., the news risk), the return-to-variance ratio during the pre-announcement period should be identical to that of the post-announcement period, regardless of information leakage. As a direct test of the one-risk hypothesis, we compare the return-to-variance ratios, which are invariant over time scale, for the two periods immediately before and after the announcement. Again, the pre-announcement window is from 4 pm of the previous day to five minutes before the announcement, while the post-announcement window is from the end of the pre-announcement window to 55 min after the announcement time.

As reported in Table 3, the return-to-variance ratio is substantially higher pre- than post-announcement. With the four macroeconomic announcements combined, the pre-announcement returns have an average of 12.86 basis points and variance of 0.36 basis points, yielding a return-to-variance ratio of 35.53 with a highly significant t-stat of 5.27. The post-announcement returns, by comparison, are substantially smaller in magnitudes (2.89 basis points in one hour) and higher in variance (0.28 basis points for one-hour return), yielding a return-to-variance ratio of 10.29 and is statistically insignificantly from zero. The difference of the return-to-variance ratios is 25.23 and statistically significant at the 1% level, rejecting the hypothesis that the pre- and post-announcement returns have the same return-to-variance ratio. The patterns are similar for FOMC as well as for the three non-FOMC macroeconomic indicators. Table 3 further examines and documents the robustness of this result over the three subperiods of 1994–2000, 2001–2011, and 2012–2018.

[19] Institutional trading right before market close might affect our measurement of the pre-announcement returns. To check this, we shift the starting time of the pre-announcement window from the original 4:00 pm to 3:30 pm and re-calculate the pre-announcement returns for the four macroeconomic announcement days. Our result remains robust and is reported in Section A of the Online Appendix.

Table 3
Pre- and Post-Announcement Return-to-Variance Ratios.

	Pre-Ann. (4 pm to ann - 5min)			Post-Ann. (ann - 5min to ann + 55min)			Pre - Post
	Ret (bps)	Var (bps)	Ret/Var	Ret (bps)	Var (bps)	Ret/Var	Ret/Var
All 4 Macro	**12.86**	0.36	**35.53**	2.89	0.28	10.29	**25.23**
	[6.49]		[5.27]	[1.66]		[1.65]	[2.75]
Ex FOMC	**9.15**	0.35	**26.38**	2.03	0.24	8.56	17.82
	[4.20]		[3.49]	[1.13]		[1.12]	[1.66]
FOMC Only	**27.14**	0.40	**68.58**	6.19	0.45	13.82	**54.75**
	[5.95]		[5.41]	[1.28]		[1.28]	[3.28]
Subperiods for All 4 Macro							
1994–2000	**16.00**	0.28	**56.73**	4.48	0.38	11.84	**44.89**
	[4.22]		[3.71]	[1.02]		[1.00]	[2.33]
2001–2010	**15.22**	0.47	**32.27**	1.83	0.32	5.70	**26.57**
	[4.54]		[3.52]	[0.66]		[0.66]	[3.43]
2011–2018	**7.63**	0.26	**29.22**	3.32	0.16	6.52	20.21
	[2.62]		[2.46]	[1.44]		[1.40]	[1.61]

"All 4 Macro" includes NFP, ISM, GDP and FOMC. "Ex FOMC" excludes FOMC from the four. Post-announcement begins 5 min before the announcement and ends at the announcement day's close at 4 pm. Pre-announcement begins at the previous day's close and ends at the beginning of the post-announcement window. Numbers that are significant at the 5% level are in bold. The sample period is from September 1994 to May 2018.

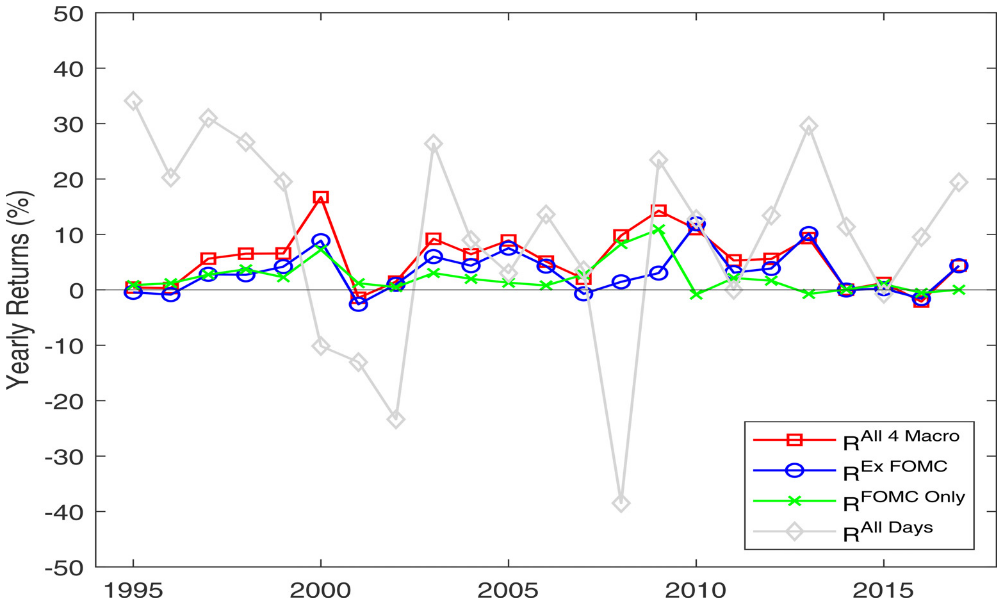

Fig. 2. Yearly S&P 500 Pre-Announcement Returns Realized on Event Days For macroeconomic index announcements, the pre-announcement returns realized within each calendar year are used to calculate the respective yearly return. "All 4 Macro" includes NFP, ISM, GDP and FOMC, and "Ex FOMC" excludes FOMC from the four. "All Days" refers to all trading days and the daily close-to-close returns on S&P 500 are used to calculate the respective yearly return.

Overall, the apparent discrepancy in return-to-variance ratio during the pre-and post-announcement periods strongly indicates the presence of at least one more risk surrounding the macroeconomic announcements and is counter to the hypothesis that the large pre-announcement return is driven only by information leakage about the news risk alone.

4.3. Resolution of impact uncertainty

According to Prediction 3 of the model, the pre-announcement reduction in VIX, reflecting the resolution of impact uncertainty, can be used as a proxy for the magnitude of impact uncertainty λ, which, in turn, has a positive impact on the pre-announcement returns.

Exploring the cross-announcement variation in the magnitude of impact uncertainty λ, we sort macroeconomic announcement days into a high-uncertainty group, defined as the top 20% of the announcements with the largest reduction in VIX during the pre-announcement period, and a low-uncertainty group, defined as the remaining announcements.[20] Panel A of Table 4 reports ΔVIX

[20] Sorting by ΔVIX is performed across all announcement days within the respective group of macro indicators. The reported results are based

Table 4
Measuring Resolution of Impact Uncertainty using Pre-Announcement Changes in VIX.

	All 4 Macro			Ex FOMC			FOMC Only		
	High	Low	H - L	High	Low	H - L	High	Low	H - L
Panel A: Returns and ΔVIX, Sorted by Pre-Announcement ΔVIX									
Pre-Announcement Period									
Ret	**85.97**	0.17	**85.80**	**81.22**	−8.70	**89.92**	**100.39**	**9.23**	**91.16**
	[12.05]	[0.05]	[11.69]	[10.35]	[−1.73]	[8.26]	[8.50]	[2.48]	[9.60]
ΔVIX (sorting var)	**−1.32**	**0.31**	**−1.63**	**−1.07**	**0.46**	**−1.53**	**−1.57**	**0.11**	**−1.68**
	[−16.98]	[6.27]	[−15.53]	[−9.77]	[5.86]	[−9.14]	[−14.05]	[1.96]	[−13.41]
Post-Announcement Period									
Ret	0.34	5.80	−5.46	11.15	1.35	9.80	−5.87	9.19	−15.06
	[0.05]	[1.89]	[−0.80]	[1.72]	[0.43]	[1.38]	[−0.56]	[1.67]	[−1.22]
ΔVIX	**−0.20**	**−0.22**	0.02	−0.11	−0.07	−0.04	−0.32	**−0.39**	0.07
	[−2.20]	[−5.76]	[0.22]	[−1.00]	[−1.53]	[−0.37]	[−1.89]	[−6.43]	[0.49]

	All 4 Macro			**Ex FOMC**			**FOMC Only**		
	High (ΔVIX)	Low (ΔVIX)	H - L (ΔVIX)	High (ΔVIX)	Low (ΔVIX)	H - L (ΔVIX)	High (ΔVIX)	Low (ΔVIX)	H - L (ΔVIX)
Panel B: Pre-Announcement Returns, Double-Sorted by Pre-Announcement ΔVIX and **ΔVol**									
High (ΔVol)	**102.71**	−7.72	**110.43**	**72.33**	−19.53	**91.86**	**126.71**	**28.14**	**98.57**
	[7.17]	[−0.58]	[5.53]	[6.18]	[−1.14]	[2.96]	[4.35]	[2.38]	[3.64]
Low (ΔVol)	**79.54**	1.14	**78.40**	**84.18**	−6.18	**90.36**	**89.45**	6.75	**82.70**
	[10.14]	[0.35]	[9.21]	[8.64]	[−1.30]	[8.18]	[7.48]	[1.49]	[7.14]
H-L (ΔVol)	23.16	−8.86		−11.86	−13.35		37.26	21.39	
	[1.53]	[−0.92]		[−0.65]	[−1.04]		[1.38]	[1.82]	

Announcement days are sorted by pre-announcement ΔVIX into “High” and “Low” in Panel A, and, in Panel B, by pre-announcement ΔVIX and ΔVol, where Vol is the realized volatility estimated using minute-by-minute returns. The double-sort is performed independently, with “High” containing announcement days ranked top 20% in VIX reduction and “Low” containing the rest; “High (ΔVol)” containing announcement days ranked top 20% in Vol reduction and “Low (ΔVol)” containing to the rest. “All 4 Macro” includes NFP, ISM, GDP and FOMC, and “Ex FOMC” excludes FOMC from the four. Numbers that are significant at the 5% level are in bold. The sample period is from September 1994 to May 2018.

and return for both the pre-announcement and post-announcement periods. As predicted by the model, the high uncertainty announcements (larger λ), on average, have much larger pre-announcement returns. Using all four macroeconomic indicators, we observe that for the high uncertainty group, the average pre-announcement return is positive at 85.97 basis points and highly statistically significant, whereas in the low uncertainty group, the average pre-announcement return is merely 0.17 basis points and not statistically different from zero. The average pre-announcement return difference between the high- and low-uncertainty group is 85.80 basis points and statistically significant at the 1% level. The same pattern obtains if we restrict attention to Macro excluding FOMC or FOMC only.

Given the well established contemporaneous relation between return and changes in return volatility, it is important for us to differentiate the return-VIX relation from that of return-volatility. For this, we further use intraday minute-by-minute returns on E-mini S&P 500 index futures to estimate the realized volatility. To capture the pre-announcement changes in realized volatility, we subtract the realized volatility of the pre-announcement window by its counterpart on the previous trading day, where the realized volatility is calculated as the square root of the sum of squared log returns on E-mini S&P 500 index futures sampled at 1-minute frequency. We then assign announcement days into four independently sorted groups, by change of VIX (ΔVIX) and change of realized volatility (ΔVol) during the pre-announcement period. High groups contain announcements with the largest 20% reduction in VIX or realized volatility, and low groups contain the rest of the announcements. As reported in Panel B of Table 4, the difference in pre-announcement return across the ΔVIX dimension remains rather robust, with magnitudes close to the findings in Panel A, for both the high and low ΔVol groups. By contrast, across the ΔVol dimension, we do not observe any significant difference in pre-announcement returns. This contrast between VIX and realized volatility confirms our model's prediction with respect to VIX and λ. In particular, as stated in Proposition 2, the reduction in the equilibrium price of the variance swap (i.e., VIX^2) during the pre-announcement period, reflecting the resolution of impact uncertainty, increases with the magnitude of impact uncertainty λ.

We now turn to the post-announcement period. Focusing first on the dynamics of VIX, we see that VIX continues to decline post-announcement for both high- and low-uncertainty groups. For high uncertainty groups, the magnitude of the decline is about 10% to 20% of their pre-announcement counterparts, indicating that uncertainty is resolved mostly before the announcements. For low uncertainty groups, VIX increases before the announcements and declines slightly afterward. The timing of uncertainty resolution, as captured by the dynamics of VIX,

on the 20% threshold for ΔVIX. We also used 30% as a threshold, and the results remain robust. The number of events for each type of announcements (NFP, ISM, GDP and FOMC) varies somewhat with the threshold, but they yield similar results.

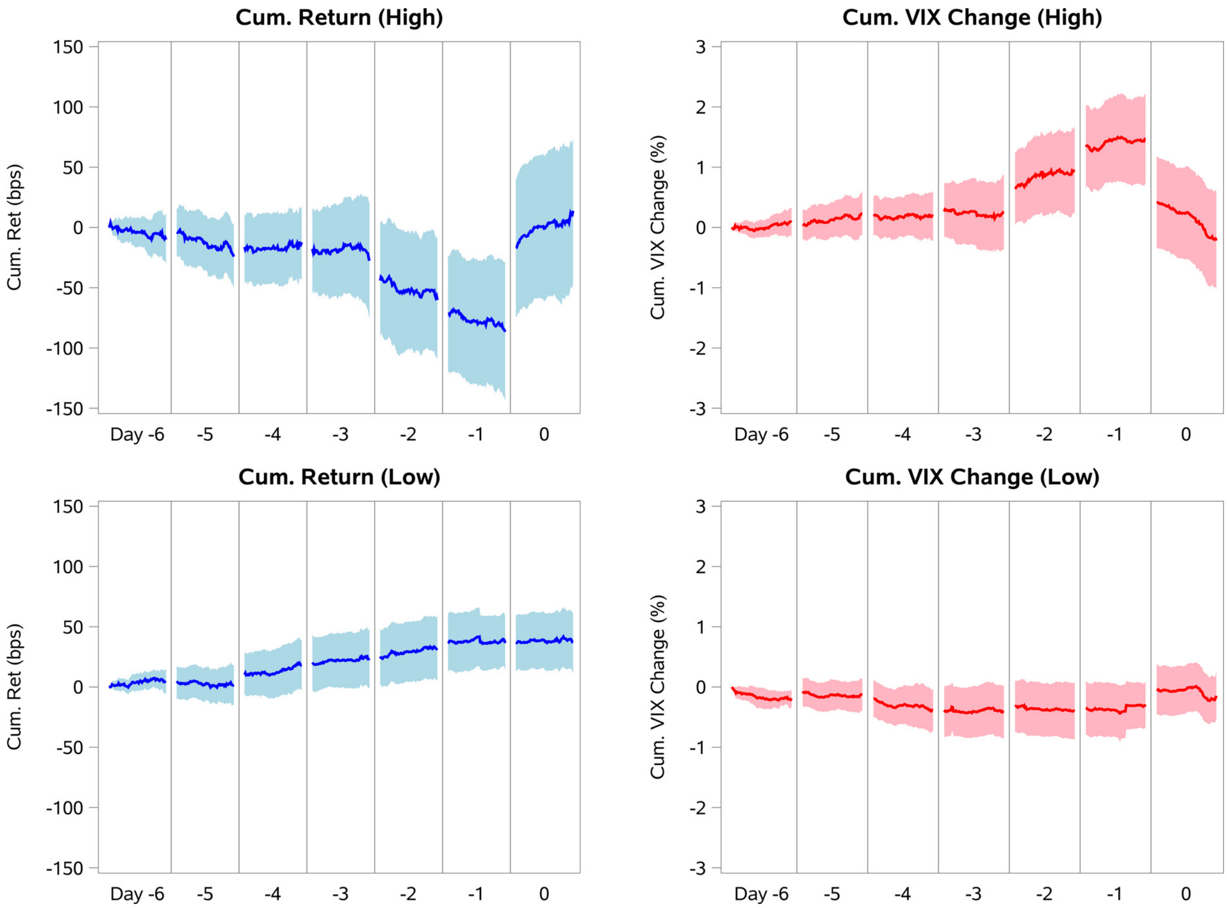

Fig. 3. Average Cumulative Returns and VIX Changes around High and Low Uncertainty Macroeconomic Announcement Days Macroeconomic (NFP, ISM, GDP, and FOMC) announcement days are sorted by pre-announcement ΔVIX into high and low uncertainty groups, with "High" containing announcement days ranked top 20% in VIX reduction and "Low" containing the rest. Day 0 is the announcement day. Regular hours from 9:30 am to 4 pm are plotted. The shaded area denotes the 95% confidence interval. The sample period is from September 1994 to May 2018.

is therefore different between high- and low-uncertainty groups.

The pattern of the post-announcement returns are much weaker. Panel A of Table 4 shows that post-announcement returns are generally statistically insignificant for the high uncertainty groups, and their magnitudes are substantially lower than the observed pre-announcement returns. For the three macroeconomic announcements not including FOMC (Macro ex FOMC), the post-announcement return is 11.15 basis points in the high-uncertainty group, which is only marginally significant with a t-stat of 1.72 and substantially lower than the 81.22 basis points pre-announcement return. For the four macroeconomic announcements (All Macro) and FOMC only, the post-announcement returns of the high-uncertainty groups are 0.34 and -5.87 basis points, respectively, and both are statistically insignificant.

Finally, Fig. 3 plots the pattern of return and ΔVIX surrounding the macroeconomic announcements for both the high and low uncertainty groups. Contrasting the patterns between the two group serves as a graphical illustration of the key mechanism of our model. With heightened uncertainty, the high-uncertainty group serves as a "turbo" version of the average results and paints a sharper picture of our model predictions. During the accumulation period, as a result of heightened uncertainty, we observe a gradual rise in VIX, accompanied with a gradual decline in stock price. Immediately before the announcement, mostly during the overnight period before the market open, we observe a sharp drop in VIX and a large rise of stock prices as a result the resolution of impact uncertainty. By contrast, the low-uncertainty group does not exhibit such patterns. In particular, the gradual decline in stock price and build-up in VIX are missing for the low-uncertainty group during the accumulation period.

4.4. Return distribution conditioning on the resolution of uncertainty

The resolution of impact uncertainty affects not only the mean and variance of the market return, but also its distribution. As stated in Prediction 4, the post-announcement returns are closer to conditionally normal if more of the heightened uncertainty is resolved in the pre-announcement period. Taking advantage of the pre-announcement information on the extent of uncertainty

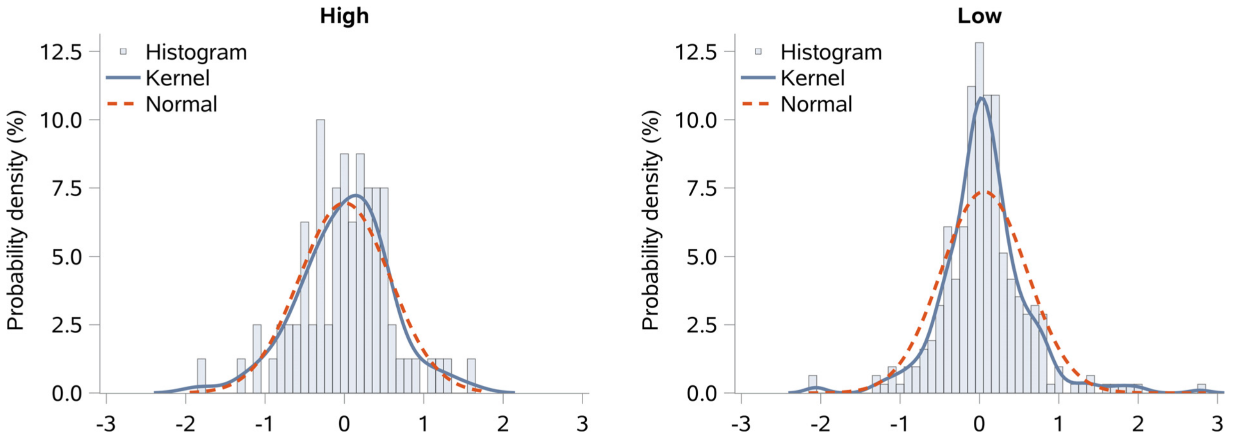

Fig. 4. Distribution of Post-Announcement Returns Conditioning on Resolution of Uncertainty Macroeconomic (NFP, ISM, GDP, and FOMC) announcement days are sorted by pre-announcement ΔVIX into high and low uncertainty groups, with "High" containing announcement days ranked top 20% in VIX reduction and "Low" containing the rest. The histograms (in bar charts), the fitted kernel distributions (in solid lines), and the fitted normal distributions (in dashed lines) of the post-announcement returns are plotted separately for the high and low uncertainty groups.

resolution, we can test this prediction of our model directly.

Following the same approach as in Section 4.3, we use the reduction in VIX during the pre-announcement period as a measure of uncertainty resolution and sort the announcements of all four macroeconomic indicators into high and low groups of uncertainty resolution. As reported in Table 4, the high group contains announcements with the 20% largest reduction in VIX, and their average reduction in VIX during the pre-announcement window is 1.32%, indicating a rather strong resolution of impact uncertainty. By contrast, the low group, containing the remaining announcements, actually experiences an average increase of 0.31% in VIX during the pre-announcement window. The timing of uncertainty resolution, as captured by the dynamics of VIX immediately before the announcements, is therefore substantially different for these two groups. For the purpose of testing how the resolution of uncertainty affects post-announcement return distribution, the case of the high group, along with the precise timing of the scheduled announcements, provides the most ideal setting.[21]

Conditioning on this information, Fig. 4 plots the empirical distributions for the high and low groups separately. The empirical distribution of the post-announcement returns are marked in shaded areas, along with the fitted kernel distributions in solid lines and the fitted normal distributions in dashed lines. Indeed, consistent with Prediction 4, the empirical distribution for the high group is close to normal, with the empirical kernel distribution closely matching the normal distribution. By contrast, the empirical distribution for the low group deviates from the normal curve, with visible fatter tails.

Table 5 further tests this prediction formally by reporting the first four moments of the post-announcement returns. Conditioning on large reductions in VIX during the pre-announcement period, the excess kurtosis for the high group is 0.92 and statistically insignificant. By contrast, the excess kurtosis for the low group is 4.09 with a t-stat of 3.64. Further testing the difference in excess kurtosis between the high and low group, Table 5 yields a difference of -3.17 with a t-stat of -2.53. This result indicates that the information contained in the resolution of uncertainty is indeed useful in separating the announcements, and the post-announcement returns are closer to conditionally normal for the group with stronger resolution of uncertainty immediately before the announcement.

As a comparison, we also report the unconditional distribution using all announcements. Consistent with our model's prediction, the unconditional excess kurtosis, 2.88 with a t-stat of 4.64, is significantly larger than the conditional excess kurtosis of 0.92 (t-stat=1.66) for the high group. In other words, conditioning information is useful here. Interestingly, the unconditional excess kurtosis is smaller than the 4.09 for the low group, which experiences an increase in VIX immediately before the announcement. As previously discussed, the high and low groups differ in their timing of uncertainty resolution. Immediately before the announcement, the resolution of uncertainty has been mostly completed for the high group, while, for the low group, it has just began. The fact that the post-announcement average return for the low group is a statistically significant, 5.94 basis points per hour, could also be an indication of this process. By contrast, the post-announcement average return for the high group is 0.34 basis points with a t-stat of 0.04.

As a further robustness test, we use non-announcement days to form a control group that matches the high group. For each announcement day in the high group, we select, from the one-year window centered around this announcement day, one non-announcement day that closest matches the announcement day in the "pre-announcement" change in VIX. Although these normal days do not have news releases, we use the release time of

[21] Testing return distributions and higher moments requires higher numbers of observations. For this reason, we perform the tests using the version of high and low groups with all four macroeconomic indicators.

Table 5
Moments of Post-Announcement Returns on Macroeconomic Days.

	High	Low	All	Control	Diff btw High and Low	All	Control
Mean	0.34	**5.94**	3.26	5.09	−5.60	−2.92	−4.75
	[0.04]	[2.09]	[1.87]	[1.46]	[−0.62]	[−0.33]	[−0.51]
Std. Dev	**57.06**	**54.35**	**52.83**	**36.38**	2.71	4.23	**20.68**
	[8.56]	[11.06]	[22.46]	[8.56]	[0.33]	[0.60]	[2.52]
Skewness	−0.22	0.50	0.11	−0.33	−0.72	−0.33	0.11
	[−0.19]	[0.76]	[0.30]	[−0.37]	[−0.55]	[−0.28]	[0.08]
Ex. Kurtosis	0.92	**4.09**	**2.88**	**3.01**	**−3.17**	**−1.96**	−2.09
	[1.66]	[3.64]	[4.64]	[2.78]	[−2.53]	[−2.36]	[−1.72]

"High" contains announcement days with the largest 20% drop of VIX (ΔVIX) during the pre-announcement period; "Low" contains the rest of announcement days; "All" contains all announcement days (including NFP, ISM, GDP, and FOMC. "Control" contains non-announcement days matched to the "High" group. For each announcement day in the high group, we match it with a nearby (within one year) normal day (excluding NFP, ISM, GDP, and FOMC) with similar drop of VIX during the pre-announcement period. We used the release time of the corresponding announcement day as the pseudo release time on the matched days. The sample period is from September 1994 to May 2018. The t-stats are reported in the square brackets.

the matched announcement day to define the corresponding pseudo "pre-announcement" and "post-announcement" windows. As a result, the control group matches the high group in both the number of observations and the time of day when the post-announcement returns are observed. More importantly, this control group contains non-announcement days experiencing similar magnitudes of reduction in VIX as the high group. In other words, they are matched in the magnitude of uncertainty resolution immediately before the "announcement" window. There is, however, a very important difference: the post-announcement window is real for the announcement days in the high group but artificial for the matching days in the control group. Moving from the pre-announcement window to the post-announcement window, the resolution of uncertainty is largely complete for the announcement days in the high group. As a result, the distribution is close to normal. By contrast, the resolution might not be complete for the control group and there might be continued resolution of uncertainty. As a result, the distribution might be far from normal.

Table 5 compares the moments of the high group against the control group. As expected, in the absence of real announcements, the pseudo "post-announcement" returns of the control group are less volatile than their high group counterparts. Important for our test, they exhibit a statistically significant excess kurtosis of 3.01 (t-stat=2.78), compared with the excess kurtosis of 0.92 with a t-stat of 1.66 for the high group. The difference in kurtosis between the high group and the control group is −2.09 with a t-stat of −1.72. Overall, while the control group experiences the same magnitude of reduction in VIX immediately before the pseudo "post-announcement" window, their resolution of uncertainty is not as complete as the high group. And the key missing ingredient is the pre-scheduled announcements, which can force the timely resolution of uncertainty.

In Section B of the Online Appendix, we also investigate other potential proxies for the resolution of the impact uncertainty before announcements. In particular, we report the return distributions conditioning on the realized volatility and post returns. The evidence suggests that these two proxies give qualitatively similar results as ΔVIX, but the statistical power is much stronger when conditional on ΔVIX. This is consistent with what is expected from the model. As shown in Proposition 2 of the model, ΔVIX is affected by λ only while realized volatility and realized pre-announcement returns are affected by both λ and λ_0. Since the level of uncertainty is captured by λ, ΔVIX provides the most precise empirical measure for it.

4.5. Heightened uncertainty and its risk premium

Prediction 5 of our model proposes the build-up of VIX during the accumulation period as another alternative measure of the magnitude of impact uncertainty. Varying across different announcement days, the higher the impact uncertainty, the larger the build-up of VIX during the accumulation period. The empirical challenge, however, is that we do not know exactly when uncertainty starts to build up, which may vary substantially across announcements. Using any fixed window across all announcements inevitably introduces noises in our measurement and weakens our results. Moreover, the pre-scheduled nature of macroeconomic releases allows investors to trade well in advance, which in turn masks the real market impact over a relatively long time window.

In our empirical tests, we measure the VIX build-up over a six-day accumulation period. Specifically, the accumulation-period ΔVIX is measured by VIX$_{t-1}$-VIX$_{t-7}$, using information up to the day before the announcement day t. Using this accumulation-period ΔVIX, we sorting announcement days into high and low uncertainty groups, with the high group containing days with accumulation-period ΔVIX in the top 20 percentile of the sample, and the low group containing the rest. As reported in Table 6, our analysis is performed over three groups of macroeco-

Table 6
Measuring Heightened Uncertainty Using Accumulation-Period ΔVIX.

	All 4 Macro			Ex FOMC			FOMC Only		
	High	Low	H-L	High	Low	H-L	High	Low	H-L
Accumulation Period									
Ret	**−254.73**	**83.69**	**−338.42**	**−247.05**	**80.19**	**−327.24**	**−283.59**	**95.32**	**−378.91**
	[−15.41]	[12.13]	[−21.07]	[−13.29]	[10.56]	[−18.38]	[−7.31]	[5.82]	[−9.95]
ΔVIX (sorting var)	**4.29**	**−0.80**	**5.09**	**4.10**	**−0.85**	**4.95**	**5.15**	**−0.56**	**5.71**
	[20.21]	[−10.54]	[27.54]	[18.67]	[−9.86]	[24.19]	[8.51]	[−3.61]	[13.27]
Pre-Announcement Period									
Ret	**21.89**	**10.47**	**11.42**	**16.95**	**7.09**	9.86	**43.65**	**23.01**	20.64
	[4.05]	[5.11]	[2.35]	[2.89]	[3.12]	[1.84]	[3.33]	[4.96]	[1.82]
ΔVIX	**−0.32**	0.05	**−0.38**	−0.12	**0.23**	−0.34	**−0.60**	**−0.12**	**−0.48**
	[−2.10]	[1.00]	[−2.86]	[−0.62]	[2.63]	[−1.74]	[−2.53]	[−2.04]	[−2.82]
Post-Announcement Period									
Ret	−1.12	**3.95**	−5.07	−0.33	2.66	−2.99	−3.09	8.51	−11.60
	[−0.25]	[2.11]	[−1.18]	[−0.07]	[1.39]	[−0.67]	[−0.26]	[1.60]	[−0.96]
ΔVIX	−0.13	**−0.24**	0.11	0.09	**−0.12**	**0.21**	**−0.39**	**−0.37**	−0.02
	[−1.35]	[−6.55]	[1.26]	[0.65]	[−3.19]	[2.06]	[−2.68]	[−5.82]	[−0.13]

"High" refers to a subgroup of announcement days with the highest 20% increase of VIX (ΔVIX) during the accumulation period, "Low"refers to the rest of announcement days. "All 4 Macro" includes NFP, ISM, GDP, and FOMC, and "Ex FOMC" excludes FOMC from the four. The sample period is from September 1994 to May 2018.

nomic indicators, with the most comprehensive analysis including all four of the macroeconomic indicators (NFP, ISM, GDP and FOMC).[22]

Focusing first on the accumulation period, we see that, by construction, there is a large VIX build-up for the high uncertainty group during the accumulation period. Using all four macroeconomic indicators, the average ΔVIX is 4.29 percentage points for the high group, and associated with the VIX spikes are large negative returns of −255 basis points over the six-day accumulation period. For the low-uncertainty group of events, VIX declines by 0.80 percentage points and the associated market return is 84 bps. So far, we've constructed two groups of announcement days exhibiting distinctively different patterns in ΔVIX and return during the accumulation period. In particular, the announcement days in the high group are unique in their substantial build-up in VIX, accompanied by large negative return.

Following these two groups into the pre-announcement period, we find rather interesting empirical results that are consistent with Prediction 5 of our model. As shown in Table 6, the average pre-announcement return is 21.89 basis points for the high group, statistically significant and twice as large the 10.47 basis points for the low group. Consistent with Prediction 5 of our model, the high group, which contains announcement days of heightened uncertainty, yields higher pre-announcement returns. Also consistent with the prediction, we find significant decline of the pre-announcement of VIX, reflecting the resolution of impact uncertainty, only for the high group. As shown in Table 6, the average pre-announcement change in VIX is −0.32 percentage points and statistically significant for the high group, and 0.05 percentage points and statistically insignificant for the low group. Table 6 further tests the differences in pre-announcement returns as well ΔVIX between the high and low groups, and find the differences to be statistically significant.

For the post-announcement period, returns are in general statistically insignificant. The average post-announcement return is −1.12 basis points for the high-uncertainty group of events, and 3.95 basis points for the low-uncertainty group of events. The differences in returns, however, is not statistically significant. VIX continues to decline after announcements. There are no significant differences in the decline of VIX between the high- and low- uncertainty group of events.

In addition to the comprehensive test using all four macroeconomic indicators, Table 6 also reports the tests using the three macroeconomic indicators (NFP, ISM, and GDP) as well as using the FOMC only. Overall, the empirical results paint a rather consistent story, confirming Prediction 5 of the model. Since heightened uncertainty is measured during the accumulation period which takes place before the pre-announcement period, this result lends independent support to the two-risk explanations for the pre-announcement return premium.

To further strengthen this result, which is predictive in nature, we regress pre-announcement returns on ΔVIX measured in the accumulation period, and report the results in Table 7. Consistent with Prediction 5 of the model, across all three specifications, accumulation-period ΔVIX can positively predict the pre-announcement return. For example, for specification using all four macroeconomic indicators, a one percentage point increase of VIX in the accumulation period leads to a 3.40 basis points increase in pre-announcement return. The adjusted R-squared of the regression is 3.13%, which is rather large for predictive regressions of daily stock returns and a large fraction of the pre-announcement returns in this predictive regression are in fact realized overnight.

[22] Under this specification, the high uncertainty group contains a balanced set of announcement days from the four indicators, with 80 announcement days for NFP, 93 for ISM, 77 for GDP, and 51 for FOMC. In other words, our results are not dominated by any subset of the indicators and sorting within each indicator yields robust results.

Table 7
Predicting Pre-Annoucement Returns by Accumulation-Period ΔVIX.

	All 4 Macro		Ex FOMC		FOMC Only	
	Ret	ΔVIX	Ret	ΔVIX	Ret	ΔVIX
Constant	12.86***	−0.03	9.15***	0.14*	27.14***	−0.22***
	[6.59]	[−0.67]	[4.28]	[1.91]	[5.98]	[−3.25]
ΔVIX [−6, −1]	3.40***	−0.10***	3.51**	−0.12**	2.48*	−0.06
	[2.79]	[−2.79]	[2.34]	[−2.48]	[1.71]	[−1.51]
Adj R-Sqr (%)	3.13	7.82	3.38	10.57	1.16	4.17
Obs	922	392	732	204	190	188

Returns and changes in VIX during the pre-announcement period are regressed on lagged changes in VIX during the accumulation period. The regressands are demeaned so that the intercept reflects the average event day returns and ΔVIX. Returns are in basis points and ΔVIX are in percent. "All 4 Macro" includes NFP, ISM, GDP, and FOMC, and "Ex FOMC" excludes FOMC from the four. The sample period is from September 1994 to May 2018.

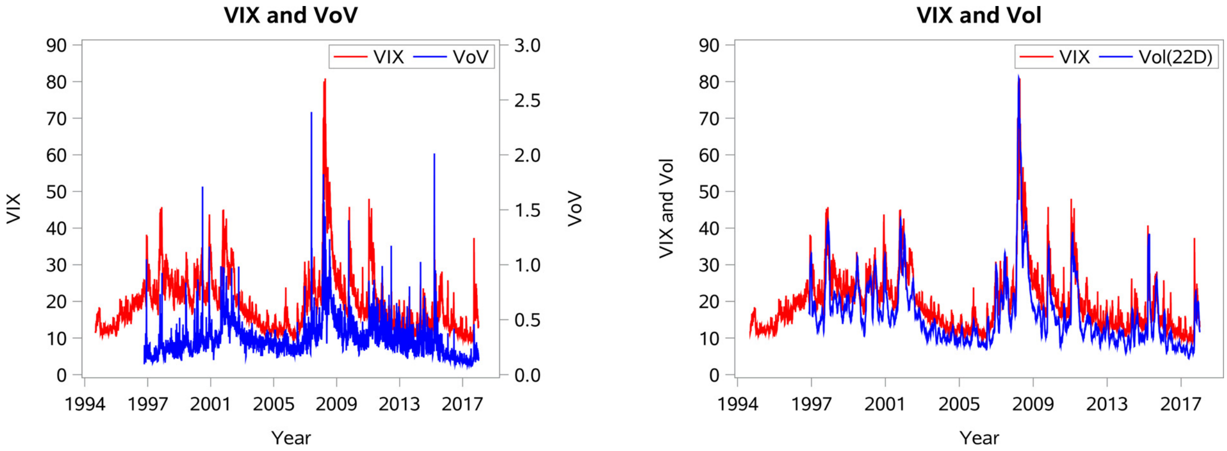

Fig. 5. VIX, Volatility of Volatility (VoV), and Realized Volatility (Vol) To calculate VoV, we first estimate the realized volatility for each 5-minute interval as the square root of the sum of squared returns, based on the trade-by-trade returns on the E-mini S&P 500 index futures. The 5-minute realized volatility is annualized by multiplying $\sqrt{252 \times 23 \times (60/5)}$. We then calculate VoV as the volatility of the estimated realized volatility from 4 pm of the previous trading day to 4 pm. The realized volatility (Vol) is calculated as the squared root of the realized variance, which is the summation of the five-minute squared returns on the E-mini S&P 500 index futures covering the normal trading hours from 9:30 am to 4:00 pm along with the close-to-open overnight returns (78 returns per day) in a rolling 22-day window. Vol is annualized and reported in percent. VIX is obtained from the CBOE website. The sample period is September 1997 to May 2018 for VoV and Vol, and September 1994 to May 2018 for VIX.

4.6. Alternative measures of impact uncertainty

Central to our empirical analysis is the usage of changes in VIX as a proxy for impact uncertainty. From the perspective of our model, this is indeed the right measure: the reduction in the equilibrium price of the variance swap (i.e., VIX^2) during the pre-announcement period, as shown in Proposition 2 of the paper, depends only on the magnitude of impact uncertainty λ. Empirically, however, this proxy deserves further exploration and we investigate this issue in three dimensions: 1) volatility of volatility; 2) variance risk premium; and 3) implied volatility of 10-day SPX options.

Volatility of volatility (VoV)

Following our model, changes in VIX best captures the heightening and resolution of uncertainty. Nonetheless, the model shows that the magnitude of impact uncertainty λ is also related to the variance of post-announcement return variance, holding the expected post-announcement return variance fixed. Thus, another potential proxy of λ is the volatility of volatility (VoV) for returns.

Unlike VIX, which is based on the prices of traded financial contracts, VoV is not directly observable. To estimate VoV, we first estimate the intra-day realized volatility for each 5-minute interval as the square root of the sum of squared E-mini S&P 500 index futures returns. The 5-minute realized volatility is annualized by multiplying $\sqrt{252 \times 23 \times (60/5)}$, where we use the fact that the E-mini futures contract trades about 23 h per day. We then calculate VoV for a given time window as the volatility of the estimated realized volatility during the period.[23] The left panel of Fig. 5 shows the estimated daily VoV (close-to-close) during our sample period, along with VIX. It is evident that the estimated VoV strongly comoves with VIX, but tends to be much choppier. The correlation between VIX and VoV is 0.69 for levels and 0.23 for daily changes,

[23] The CBOE E-mini S&P 500 index futures tick data starts from September 1997. Although we could use the "big" standard S&P 500 index futures data before 1997, the "big" futures were significantly less liquid and the estimated volatility of volatility is choppier than with that based on E-mini futures. For this reason, we report the volatility of volatility measures only for the period after September 1997.

Table 8
Measuring Resolution of Impact Uncertainty using Pre-Announcement Changes in VoV .

	All 4 Macro			Ex FOMC			FOMC Only		
	High	Low	H - L	High	Low	H - L	High	Low	H - L
Panel A: Returns and ΔVoV, Sorted by Pre-Announcement ΔVIX									
ΔVIX (sorting var)	**−1.32**	**0.31**	**−1.63**	**−1.07**	**0.46**	**−1.53**	**−1.57**	**0.11**	**−1.68**
	[−16.98]	[6.27]	[−15.53]	[−9.77]	[5.86]	[−9.14]	[−14.05]	[1.96]	[−13.41]
Ret	**85.97**	0.17	**85.80**	**81.22**	−8.70	**89.92**	**100.39**	**9.23**	**91.16**
	[12.05]	[0.05]	[11.69]	[10.35]	[−1.73]	[8.26]	[8.50]	[2.48]	[9.60]
ΔVoV	**−2.34**	−0.59	−1.75	3.39	0.03	3.36	**−5.11**	**−2.44**	**−2.67**
	[−2.60]	[−1.14]	[−1.57]	[1.50]	[0.04]	[1.85]	[−4.53]	[−5.89]	[−2.70]
Panel B: Returns and ΔVIX, Sorted by Pre-Announcement ΔVoV									
ΔVoV (sorting var)	**−8.66**	**1.69**	**−10.35**	**−7.90**	**2.27**	**−10.17**	**−10.59**	**−1.09**	**−9.50**
	[−16.04]	[6.89]	[−18.47]	[−12.08]	[7.80]	[−15.22]	[−14.52]	[−3.63]	[−13.52]
Ret	**27.43**	**10.27**	**17.16**	**14.00**	**9.18**	4.81	**52.17**	**22.97**	**29.19**
	[5.28]	[4.61]	[3.33]	[2.80]	[3.67]	[0.86]	[3.66]	[4.35]	[2.29]
ΔVIX	**−0.20**	0.05	**−0.25**	**0.30**	0.12	0.18	**−0.63**	−0.14	**−0.49**
	[−1.78]	[0.80]	[−1.99]	[2.10]	[1.26]	[0.98]	[−2.73]	[−1.76]	[−2.57]

Announcement days are sorted by pre-announcement ΔVIX into "High" and "Low" in Panel A, and, in Panel B, by pre-announcement ΔVOV, where VoV is the volatility of realized volatility (reported in percent) estimated using high-frequency returns within the pre-announcement window. "High" containing announcement days ranked top 20% in VIX (VoV) reduction and "Low" containing the rest. "All 4 Macro" includes NFP, ISM, GDP, and FOMC, and "Ex FOMC" excludes FOMC from the four. Numbers significant at the 5% level are in bold. The sample period is from September 1994 to May 2018.

and both correlations are highly statistically significant at the 1% level.

Table 8 reports the joint dynamics of pre-announcement returns, ΔVoV, and ΔVIX along two dimensions. Panel A uses the pre-announcement changes in VIX as the information variable to divide the announcement days into high and low groups of uncertainty resolution and then reports their respective pre-announcement returns and ΔVoV. For the high group, the average drop in VoV is 2.34% and 5.11% for the four macroeconomic indicators and FOMC alone, respectively, and both are statistically significant at the 1% level. For the three non-FOMC macroeconomic indicators, the high-uncertainty events experience a 3.39% increase in VoV, but the estimate is not statistically significant. Overall, using ΔVIX as a measure of impact uncertainty, the high-uncertainty group experiences a reduction in ΔVoV as well. In other words, ΔVIX and ΔVoV indeed contain overlapping information with respect to impact uncertainty.

Panel B reverses the order and uses the pre-announcement changes in VoV as the information variable to divide the announcement days into high and low groups of uncertainty resolution. Specifically, we sort macroeconomic announcement days based on the pre-announcement changes in VoV and define the high-uncertainty group as the top 20% of the events with the largest reduction in VoV during the pre-announcement period, and the rest as the low-uncertainty group. As shown in Panel B of Table 8, the average pre-announcement return is 27.43 bps for the high-uncertainty group of the four macroeconomic announcements, significantly higher than that of the low-uncertainty group, which is 10.27 bps. The pattern is strong for FOMC but weaker for the three non-FOMC macroeconomic indicators. Similarly, VIX tends to decrease for the high-uncertainty groups identified by the reduction of VoV, except for the three non-FOMC macroeconomic indicators. For the four macroeconomic indicators and FOMC alone, the pre-announcement drop in VIX is 0.20 and 0.63 for the high uncertainty groups, with *t*-stats of −1.78 and −2.73, respectively. For the three non-FOMC macroeconomic indicators, VIX of the high-uncertainty events increases by 0.30 with a *t*-stat of 2.10.

Overall, the evidence suggests that, qualitatively, the pre-announcement drop in VoV is also useful in picking up macroeconomic announcements that have high uncertainty resolution. Compared with VIX, however, the results based on VoV are substantially weaker in both their economic magnitude and statistic significance. In particular, for non-FOMC macroeconomic indicators whose pre-announcement periods fall mainly in the overnight period, VoV could not identify the high-uncertainty resolution events reliably. The substantial measurement errors in the relatively quiet overnight period could also potentially contribute to the weaker empirical results from VoV.

Variance risk premium

Given that VIX reflects both expected variance and a risk premium for variance uncertainty, another proxy for impact uncertainty could be obtained by adjusting VIX for recent realized variance. Following Bollerslev et al. (2009), we first calculate the expected volatility as the squared root of the realized variance, which is the summation of the five-minute squared returns on the E-mini S&P 500 index futures covering the normal trading hours from 9:30 am to 4:00 pm (78 5-minute returns per day) along with the close-to-open overnight squared returns in a rolling 22-day window. We then calculate the variance risk premium (VRP_{22D}) as the differences between VIX and the realized volatility.

The right panel of Fig. 5 plots the time-series of the estimated volatility and VIX. It is worth noting that the estimated volatility, based on the intraday returns in the past 22 days, is quite smooth and does not vary substantially at the daily frequency. As a result, the daily changes

Table 9
Predicting Return, using ΔVIX, and ΔVRP .

Y = Pre-Ann Return	All 4 Macro			Ex FOMC			FOMC Only		
X =	VIX	VRP_{22D}	VRP_{6D}	VIX	VRP_{22D}	VRP_{6D}	VIX	VRP_{22D}	VRP_{6D}
ΔX [−6, −1]	3.80***	2.21**	0.37	4.03***	2.48***	0.66	2.41	0.40	−2.22
	[3.18]	[2.58]	[0.56]	[2.76]	[2.61]	[0.96]	[1.63]	[0.22]	[−1.24]
Constant	13.80***	13.80***	13.80***	10.36***	10.36***	10.36***	28.45***	28.45***	28.45***
	[6.80]	[6.72]	[6.66]	[4.75]	[4.70]	[4.65]	[5.52]	[5.48]	[5.54]
Adj-R2 (%)	3.96	1.72	0.01	4.55	2.35	0.30	1.01	−0.57	1.66
Obs	862	862	862	698	698	698	164	164	164

Pre-announcement returns are regressed on lagged changes in VIX and VRP over a six-day window. VRP_{22D} is estimated as the difference between VIX and the realized volatility of a rolling 22-day window, where the realized volatility is the squared root of the realized variance which is the summation of the 22 × 78 within-day five-minute squared returns covering the normal trading hours from 9:30 am to 4:00 pm along with the close-to-open overnight squared returns in a rolling 22-day window. VRP_{6D} is estimated as the difference between VIX and the realized volatility of a rolling 6-day window. “All 4 Macro” includes NFP, ISM, GDP, and FOMC, and “Ex FOMC” excludes FOMC from the four. Returns are in basis points; ΔVIX and ΔVRP are in percent. The regressands are demeaned so that the intercept reflects the averages of returns. The reported t-stat’s use Newey-West standard errors, adjusting for serial correlations. The sample period is from September 1997 to May 2018.

in the variance risk premium (VRP_{22D}) is mainly driven by the variations in VIX, rather than the variations in the expected volatility. In fact, the correlation between the daily changes of VRP_{22D} and VIX is 0.92, highly statistically significant with a p-value smaller than 0.01%. To better capture volatility changes at the daily frequency, we also construct an alternative measure of the variance risk premium, VRP_{6D}, as the difference between VIX and the squared root of the summation of the five-minute squared returns over a 6-day window. Compared with VRP_{22D}, this six-day version of variance risk premium is more sensitive to the daily movement of volatility, but is also much noisier due to measure errors of the estimated daily volatility.

To investigate the information content of VRP with respect to impact uncertainty, we use the changes in VRP during the six-day accumulation period to predict the pre-announcement returns and contrast the predictability against that of VIX. The regression specification is similar to the setting of the predicative tests on VIX as reported in Table 7, except that we replace the cumulative change of VIX by the cumulative change of VRP_{22D} and VRP_{6D}. The results are reported in Table 9.

Compared with the predictability of VIX, VRP_{22D} could deliver similar, but weaker, results. Among macroeconomic announcement days, a one percent higher VRP_{22D} increase from day −6 to day −1 predicts a 2.21 bps higher stock return, statistically significant at the 5% level. The adjusted R-squared of the regression is 1.72%. The magnitudes of the coefficients and the R-squared are smaller than those based on the cumulative VIX changes. VRP_{6D}, on the other hand, could not predict future returns, most likely due to its noisy volatility component. Overall, the empirical evidences suggest that variance risk premium is a useful, but noisier proxy for heightened uncertainty than VIX.

Implied volatility of 10-Day SPX options

One issue of using VIX as a proxy for impact uncertainty is that VIX has a one-month horizon. On any date when the VIX is measured, several announcements could fall within that one-month horizon, all of which might have be influencing the VIX level on that day. We address this issue of mismatch in horizon in two dimensions.

First, it should be emphasized that our measure of impact uncertainty is the *change* in VIX, either during the six-day accumulation window or during the pre-announcement window. As a result, the information content of ΔVIX focuses mostly on the upcoming event. In theory, ΔVIX is not as precise as a one-day variance swap but a close approximation.

Second, we test the robustness of our results using the implied volatility of the 10-day at-the-money S&P 500 index options (IV_{10D}) provided by OptionMetrics. The 10-day implied volatility is interpolated from a fitted smooth volatility surface based on the prices of various S&P 500 index options with different maturities and moneyness. With shorter maturity than VIX, the dynamics of the 10-day option implied volatility are likely to be driven more by the upcoming announcement than by other events. Changes in the 10-day option implied volatility are highly correlated with changes in VIX. Specifically, the correlation between ΔVIX and ΔIV_{10D} is 0.94 and highly significant.

We test the predictability of the accumulation-period changes of ΔIV_{10D} for pre-announcement returns. Similar to our tests based on the build-up of VIX, we sort announcement days into high- and low-uncertainty groups based on the build-up of the 10-day SPX options implied volatility during the accumulation period. “High” refers to a subgroup of announcement days with the highest 20% increase of ΔIV_{10D} during the accumulation period, “Low” refers to the rest of announcement days. Overall, the results based on ΔIV_{10D} are very similar to those based on ΔVIX, in terms of both magnitudes and statistical significance. For brevity, the empirical results are not included in the paper. Interested readers can refer to the Section C of the Online Appendix for further details.

5. Empirical results: unanticipated heightened uncertainty

In addition to pre-scheduled announcements, heightened uncertainty can also be triggered unexpectedly.

Table 10
Average Daily S&P 500 Index Returns Realized on Heightened VIX Days .

$\mathrm{VIX}_t - \mathrm{VIX}_{t-1} \geq$ Cutoff ($\eta = 0$)				$\mathrm{VIX}_t - \mu^{\eta}_{t-1} \geq$ Cutoff ($\eta = 0.15$)				$\mathrm{VIX}_t - \mu^{\eta}_{t-1} \geq$ Cutoff ($\eta = 0.30$)			
Cutoff (%)	N Days (/year)	Ret_{t+1} (bps)	T-stat	Cutoff (%)	N Days (/year)	Ret_{t+1} (bps)	T-stat	Cutoff (%)	N Days (/year)	Ret_{t+1} (bps)	T-stat
1994–2018				**1994–2018**				**1994–2018**			
4.0	3.9	**58.91**	2.07	4.0	4.1	49.63	1.73	4.0	4.5	**65.68**	2.29
3.5	5.4	38.17	1.65	3.5	5.4	**51.34**	2.19	3.5	5.9	**58.18**	2.56
3.0	7.7	**42.70**	2.46	3.0	7.8	**52.92**	3.08	3.0	8.5	**57.22**	3.24
2.5	11.1	**36.58**	2.83	2.5	11.1	**46.06**	3.34	2.5	11.6	**34.56**	2.50
2.0	15.9	**24.03**	2.45	2.0	16.0	**29.38**	2.80	2.0	16.4	**28.30**	2.70
1.5	24.6	**19.63**	2.68	1.5	24.5	**16.64**	2.14	1.5	25.4	**19.92**	2.70
1.0	39.7	**10.34**	2.01	1.0	39.3	**11.70**	2.17	1.0	41.2	**11.80**	2.23
0.5	68.0	**7.87**	2.28	0.5	68.1	**7.14**	2.02	0.5	68.6	**7.24**	2.05
0.0	117.9	3.47	1.46	0.0	116.7	4.33	1.85	0.0	115.3	**6.06**	2.53
1986–2018				**1986–2018**				**1986–2018**			
4.0	3.6	35.98	1.19	4.0	3.7	36.29	1.18	4.0	4.0	52.64	1.74
3.5	4.9	22.29	0.95	3.5	4.9	38.67	1.58	3.5	5.3	45.65	1.93
3.0	6.9	30.55	1.73	3.0	7.0	**43.14**	2.41	3.0	7.6	**48.04**	2.71
2.5	9.8	**29.35**	2.27	2.5	9.9	**39.45**	2.86	2.5	10.4	**29.45**	2.17
2.0	14.3	16.94	1.78	2.0	14.4	**24.51**	2.42	2.0	14.9	**21.70**	2.16
1.5	22.2	**14.22**	2.07	1.5	22.2	12.30	1.68	1.5	23.0	**15.56**	2.23
1.0	36.5	6.59	1.41	1.0	36.7	8.83	1.82	1.0	38.2	**9.71**	2.03
0.5	65.4	4.84	1.62	0.5	65.2	5.33	1.73	0.5	65.7	5.79	1.88
0.0	118.6	3.03	1.54	0.0	117.7	**4.03**	2.05	0.0	115.8	**5.07**	2.51

Reported under Ret_{t+1} are average daily returns on the S&P 500 index realized on heightened VIX days. Day $t+1$ is predicted as an heigthened VIX day if $\mathrm{VIX}_t - \mu^{\eta}_{t-1} \geq$ Cutoff, where $\mu^{\eta}_{t-1} = (1-\eta)\sum_{\tau=0}^{t-1}\eta^{\tau}\mathrm{VIX}_{t-\tau-1}$ is the exponentially weighted moving average of past VIX and smoothing is controled by the decay factor η. When $\eta = 0$, there is no smoothing and $\mu^{\eta}_{t-1} = \mathrm{VIX}_{t-1}$. "N Days" measures the average number of such "Heightened VIX" days per year. The sample period is from September 1994 to May 2018 for the top panel and January 1986 to May 2018 for the bottom panel. The sample standard deviation of daily changes in VIX is 1.59% for the first sample from September 1994 to May 2018 and is 2.16% for the second sample period from January 1986 to May 2018.

In this section, we expand the implications of our model beyond the scheduled announcements to include such unanticipated heightened uncertainty. According to Prediction 6 of our model, following unanticipated heightened uncertainty, there should be reversals in VIX and positive stock returns as the uncertainty resolves. Effectively, this exercise serves as an out-of-the-sample test of the key mechanism of our model by showing that heightened uncertainty, regardless of its origin, brings risk as well as risk premium to the market.

To capture episodes of unanticipated heightened uncertainty, we take advantage of our model's prediction that changes in VIX are a gauge of impact uncertainty.[24] In the context of our model, a large spike in VIX on a single day can be viewed as a condensed, sped-up version of the slow accumulation of VIX in anticipation of a scheduled announcement. Following this observation, we focus mainly on daily changes in VIX, defined by

$$\Delta\mathrm{VIX}_t = \mathrm{VIX}_t - \mathrm{VIX}_{t-1}.$$

Our data sample for studying surprise VIX hikes is larger, starting in January 1986 and ending in May 2018. For the early period from 1986 through 1989, we use the "old VIX" index (VXO), and after that we use the current form of VIX index. To compare with macroeconomic announcements, we also report results for the sub-period from September 1994 to May 2018.

Over the full sample, $\Delta\mathrm{VIX}_t$ has a slightly negative but insignificant mean, and a standard deviation of 2.16%. The events surrounding the 1987 stock market crash significantly affect the distribution of $\Delta\mathrm{VIX}_t$, resulting in extreme values in its skewness and kurtosis. Taking out October 1987, the sample standard deviation of $\Delta\mathrm{VIX}_t$ is 1.51%, skewness is close to 1 (with a t-stat of 2.77), and kurtosis is 24 (with a t-stat of 6.09). Overall, the distribution of $\Delta\mathrm{VIX}_t$ is marked by large movements in the tails, with sudden spikes in VIX being more frequent and larger in magnitude than sudden reductions in VIX. Our objective in this section is to use the tail events associated the sudden spikes in VIX to capture heightened uncertainty in financial markets and measure the premium for heightened uncertainty.

At the close of trading day t, we define day $t+1$ as a heightened VIX day, if $\Delta\mathrm{VIX}_t$ is larger than a predetermined constant cutoff value. As shown in Table 10, different cutoff values allow us to focus on the different parts of the tail distribution of $\Delta\mathrm{VIX}_t$, with higher cutoff resulting in fewer heightened VIX days. For the post-1994 sample period, a cutoff value of 2.5% yields an average of 11.1 heightened VIX days per year, comparable to the monthly frequency of NFP, ISM, and GDP, while a higher cutoff value of 3.0% results in an average of 7.7 heightened VIX days per year, comparable to the FOMC frequency. Rather interestingly, the corresponding next-day returns, as reported under Ret_{t+1} in Table 10, are 36.59 and 42.70

[24] Given the close connection among return, variance, and VIX, it is natural to ask whether heightened uncertainty can be captured by sudden drops in price or sudden increase in its variance. In the context of our model, this is not the case. We provide further empirical tests in Section D of the Online Appendix.

Table 11
Predicting Return and ΔVIX by VIX Build-up .

	Return		ΔVIX	
ΔVIX [−6, −1]	2.96***	0.33	−0.07***	−0.02**
	[3.60]	[0.40]	[−6.87]	[−2.04]
ΔVIX [−6, −1] × Macro		5.43**		−0.09**
		[1.99]		[−2.43]
ΔVIX[−6, −1] × HVIX		6.69*		−0.13**
		[1.69]		[−2.30]
Macro		15.44***		−0.32***
		[3.76]		[−6.17]
HVIX		13.85		−0.23
		[0.63]		[−0.61]
Constant	3.60**	−0.76	0.00	0.09***
	[2.48]	[−0.46]	[0.01]	[3.91]
Adj R-Sqr(%)	0.64	1.65	2.07	4.08
Obs	5972	5972	5971	5971

Daily returns on the S&P 500 index and changes in VIX are regressed on lagged changes in VIX over a six-day window. “Macro” is a dummy variable for NFP, ISM, GDP and FOMC announcement days. “HVIX” is a dummy variable for heightened VIX days selected based on exponentially weighted moving average of past VIX with the decay factor η equals to 0.3. Returns are in basis points and ΔVIX are in percent. ΔVIX[-6, −1] is demeaned so that the intercept reflects the average returns and ΔVIX. The reported t-stat's use Newey-West standard errors, adjusting for serial correlations. The sample period is from September 1994 to May 2018.

basis points, respectively, and both statistically significant. This result confirms the prediction of our model: following heightened uncertainty, the stock market experiences positive and significant return. Moreover, the higher the uncertainty, the stronger the risk premium.

To further improve our results and smooth out the potential noise in daily changes in VIX, we compare VIX_t relative to its exponentially weighted moving average $\mu^{\eta}_{t-1} = (1-\eta)\sum_{\tau=0}^{t-1}\eta^{\tau}\text{VIX}_{t-\tau-1}$, with η serving as the decay factor. At the close of trading day t, we define day $t+1$ as a heightened VIX day if $\text{VIX}_t - \mu^{\eta}_{t-1}$ is greater than a cutoff value. When $\eta = 0$, there is no smoothing, $\mu^{\eta}_{t-1} = \text{VIX}_{t-1}$, and we are back to the simple ΔVIX_t version. As shown in the right two panels of Table 10, smoothing the past VIX helps improve our results, especially for the early sample that includes the late 1980s. For example, keeping the same cutoff value of 3% as before, smoothing the past VIX with a decay factor of $\eta = 0.30$ yields an average of 7.6 heightened VIX days per year, comparable to the FOMC frequency, and the average return realized on such heightened VIX days is 48.04 basis points and significant.

We hypothesize that the underlying mechanism driving the joint dynamics of return and uncertainty on heightened VIX days is similar to that for pre-scheduled macroeconomic announcements.[25] To test this common mechanism, we use the six-day cumulative change in VIX observable on day −1 as a predictor to predict the day-0 stock returns and VIX changes, including announcement days as well as non-announcement days. In other words, we are examining the predictability of the cumulative buildup in VIX in a unified framework. The results are reported in Table 11. We use one dummy variable, Macro, to single out the scheduled macroeconomic announcement days (NFP, ISM, GDP and FOMC), and another dummy variable, HVIX, to single out the heightened VIX days and interact these dummies with the predictor.

For both macroeconomic announcements and HVIX days, a higher buildup in VIX predicts a higher stock return and a subsequent VIX drop, and the magnitudes of the predictability are quite similar. Specifically, a 1% increase in VIX buildup prior to a macroeconomic announcement predicts a 5.43 bps increase in day-0 stock return and a 0.09% decline in VIX, while the respective numbers for HVIX are 6.69 bps increase in day-0 stock return and 0.13% decline in VIX. By comparison, for normal days excluding the pre-scheduled announcements and HVIX days, the respective numbers are 0.33 bps increase in day-0 stock return, statistically insignificant, and a 0.02% decline in VIX. Overall, these results are consistent with our model's prediction that the predictability of VIX buildup is uniquely linked to the presence of heightened uncertainty, either anticipated as in the case of macroeconomic announcements or unanticipated as in the case of VIX hikes. In both cases of heightened uncertainty, the same risk-return dynamics is driving the behavior of return and VIX.

6. Conclusions

We find that the U.S. stock market earns a large overnight return right before important macroeconomic announcements, including NFP, ISM, and GDP, with no increase in conventional risk measures. The large pre-announcement returns are qualitatively and quantitatively similar to the pre-FOMC announcement drift documented by Lucca and Moench (2015). Moreover,

[25] To illustrate this common mechanism, we also plot the patterns of cumulative returns and VIX around heightened VIX days in Figure A.1 of the Online Appendix. The timing is matched to that for the scheduled announcements.

for all four macroeconomic announcements, the pre-announcement return-to-variance ratio far exceeds the post-announcement counterparts, strongly suggesting that distinct types of risk premia are realized around the announcement window.

To explain this common pattern, we propose a two-risk model in which, in addition to the directional news risk itself, uncertainty about the magnitude of its market impact is the second risk. Importantly, this impact uncertainty is resolved before the news risk itself is fully resolved at the announcement. In the model, VIX emerges as a measure of impact uncertainty and return variance gives the standard measure of news risk. The model then generates the empirical pattern that pre-announcement return and return-to-risk ratio are much larger than their post-announcement counterparts. Moreover, the model yields clear predictions on the joint dynamics of return, variance and VIX surrounding an announcement. In particular, heightening of uncertainty concerning an announcement is captured by a rise in VIX in the accumulation period; it brings a contemporaneous price drop, and leads to a high pre-announcement drift accompanied by a large drop in VIX, reflecting the resolution of the impact uncertainty. Using the overnight period right before the announcement as the pre-announcement period and several days prior as the accumulation period, we empirically confirm all these predictions. Finally, analogous to the anticipated rise of uncertainty ahead of macroeconomic announcements, we find that large surprise spikes of VIX are also followed by higher stock returns and VIX reversals in the next day.

Exploring alternative explanations for the positive pre-announcement returns, we first consider the hypothesis of news leakage, and do not find much support that the positive pre-announcement returns are driven by news leakage prior to the formal announcements. As shown in the model, if news, including its leakage, is driving the risk and returns, then the return-to-variance ratio will be the same for the pre- and post-announcement periods, counter to the empirical facts documented in this paper. Another testable implication of the leakage hypothesis is that it will lead to positive correlation in pre- and post-announcement returns, which we do not find.[26] Finally and perhaps most important, the four macroeconomic releases (NFP, GDP, ISM, and FOMC) with significant pre-announcement returns have very different release processes, some of which are carefully designed to prevent leakage. It will be difficult to envision a unified leakage mechanism behind all of them. We also examine the extent to which institutional tradings near the market close (Lou et al. (2019)) could impact the pre-announcement returns. To make sure that our results are not driven by the institutional trading right before the market close, we shift the starting time of the pre-announcement window from the original 4:00 pm to 3:30 pm and re-calculate the pre-announcement returns for the four macroeconomic releases. We find that our results on pre-announcement returns remain robust.[27]

In conclusion, we have developed a framework of heightened uncertainty in anticipation of important macroeconomic announcements and used it to organize and reconcile the joint intertemporal behavior of returns, risks, and return-to-risk tradeoffs in the financial markets surrounding important news events. The large risk premiums these announcements bring to the market and their fast realization raise interesting questions about the underlying forces driving such a process, their impact on investors, and potential alternative designs for the production and release process of the announcement information.[28] In addition, we also find similar risk and return patterns for unanticipated heightened uncertainty as captured by VIX hikes at daily time windows. This further suggests that a more general underlying mechanism may be driving the high-frequency risk-return dynamics. We leave these questions for future research.

Appendix A. Proofs

Equilibrium price at $t = 0$

Let $J_0 = E[J_1]$. Then,

$$\frac{dJ_0}{d\theta_0} = -e^{-\alpha[W_0+\theta_0(\bar{D}-P_0)]-\alpha^2 Q(\theta_0,\delta)} \frac{1}{1+\alpha^2\lambda Q(\theta_0,\delta)} \cdot \left\{ -\alpha(\bar{D}-P_0) + \alpha^2(1-\delta+\delta\theta_0)\lambda_0 + \frac{\alpha^2\lambda(1-\delta+\delta\theta_0)}{1+\alpha^2\lambda Q(\theta_0,\delta)} \right\} \tag{A.1}$$

where $Q(\theta_0, \delta)$ is given by (11). Setting the above expression to zero and substituting in $\theta_0 = 1$, we obtain (15). It is easy to check that the second-order condition holds, i.e., $\frac{d^2 J_0}{d\theta_0^2} < 0$. In particular, write $dJ_0/d\theta_0 = J_0 K$, where K is the expression in the curly bracket of (A.1). Then $d^2 J_0/d\theta_0^2 = (dJ_0/d\theta_0)K + J_0 dK/d\theta_0 = J_0 K^2 + J_0 dK/d\theta_0$. Note that K is strictly increasing in θ_0 and $J_0 < 0$. So $d^2 J_0/d\theta_0^2 < 0$.

Mean and variance of returns

From the stock prices at $t = 0, 1$ given in (15) and (8), the mean of the return in period 1 is:

[26] In Section E of the Online Appendix, we report the correlation between pre- and post-announcement returns and discuss its implications for the leakage hypothesis.

[27] Also informative are the patterns of the E-mini S&P 500 index futures prices increasing gradually over time during the pre-announcement window (Fig. 1). If the positive pre-announcement return is entirely due to institutional selling at the previous day's close and individual buying immediately before the announcement, we should expect the futures prices to stay relatively stable overnight and jump only immediately before the release time.

[28] To the extent that the resolution of uncertainty is a result of learning, a possible direction for future research is to use granular, micro-level data to uncover investors' behavior around these announcements. For example, using clicks on news articles, Benamar et al. (2021) find strong evidence of learning by investors in the overnight period before nonfarm payroll releases. Since the release process of macroeconomic announcements is often endogenous, its design can significantly affect the informational efficiency of the market. As an example, Hu et al. (2017) examine how tiered release of macroeconomic indicator such as ISM can substantially impact the price discovery process.

$$\begin{aligned}\mathrm{E}[R_1] &= \alpha\lambda_0 + \frac{\alpha\lambda}{1-\frac{1}{2}\alpha^2\lambda} - \alpha(1-\delta)\mathrm{E}[\sigma^2] \\ &= \delta\alpha(\lambda_0+\lambda) + \frac{\frac{1}{2}\alpha^3\lambda^2}{1-\frac{1}{2}\alpha^2\lambda} > 0,\end{aligned} \tag{A.2}$$

where we have used the fact that $\mathrm{E}[\sigma^2] = \lambda_0 + \lambda$. The variance of the return is:

$$\begin{aligned}\mathrm{V}[R_1] &= \mathrm{V}[\sigma\varepsilon_1 - \alpha(1-\delta)\sigma^2] = \mathrm{E}\big[[\sigma\varepsilon_1 - \alpha(1-\delta)\sigma^2]^2\big] \\ &\quad - \big(\mathrm{E}[\sigma\varepsilon_1 - \alpha(1-\delta)\sigma^2]\big)^2 \\ &= \delta(\lambda_0+\lambda) + \alpha^2(1-\delta)^2\lambda^2.\end{aligned} \tag{A.3}$$

Likewise, the mean and variance of the return over the second period are:

$$\mathrm{E}[R_2] = \mathrm{E}[\sigma\varepsilon_2 + \alpha(1-\delta)\sigma^2] = \alpha(1-\delta)(\lambda_0+\lambda) > 0, \tag{A.4}$$

$$\begin{aligned}\mathrm{V}[R_2] &= \mathrm{V}[\sigma\varepsilon_2 + \alpha(1-\delta)\sigma^2] = \mathrm{E}\big([\sigma\varepsilon_2 + \alpha(1-\delta)\sigma^2]^2\big) \\ &\quad - \big(\mathrm{E}[\sigma\varepsilon_2 + \alpha(1-\delta)\sigma^2]\big)^2 \\ &= (1-\delta)(\lambda_0+\lambda) + \alpha^2(1-\delta)^2\lambda^2,\end{aligned} \tag{A.5}$$

Deriving Proposition 3

From the expected returns over period 1 and 2, given in (19) and (20), we can see that for a sufficiently large λ, in particular when it approaches its upper bound $2/\alpha^2$, the expected return for the first period can be very large. Thus, we want to find a threshold λ^* such that when λ exceeds this threshold, the expected return and return to variance ratio for the first period are higher than those for the second period.

First, $\mathrm{E}[R_1] > \mathrm{E}[R_2]$ is equivalent to:

$$\frac{\frac{1}{2}\alpha^3\lambda^2}{1-\frac{1}{2}\alpha^2\lambda} > (1-2\delta)\alpha(\lambda_0+\lambda). \tag{A.6}$$

Since $\delta \in [0,1]$, a sufficient condition for this inequality to hold is:

$$\frac{\frac{1}{2}\alpha^3\lambda^2}{1-\frac{1}{2}\alpha^2\lambda} > \alpha(\lambda_0+\lambda). \tag{A.7}$$

Next, we explore a sufficient condition for $RVR_1 > RVR_2$. First, we note that

$$RVR_2 = \frac{\alpha(\lambda_0+\lambda)}{(\lambda_0+\lambda) + \alpha^2(1-\delta)\lambda^2} < \alpha. \tag{A.8}$$

Moreover,

$$RVR_1 = \frac{\alpha\delta(\lambda_0+\lambda) + \frac{1}{2}\alpha^3\lambda^2/(1-\frac{1}{2}\alpha^2\lambda)}{\delta(\lambda_0+\lambda) + \alpha^2(1-\delta)^2\lambda^2}. \tag{A.9}$$

A lower bound of RVR_1 can be obtained by making δ-related terms as small as possible in the numerator and making δ-related terms as large as possible in the denominator. Thus, a sufficient condition for $RVR_1 > RVR_2$ is:

$$\frac{\frac{1}{2}\alpha^3\lambda^2/(1-\frac{1}{2}\alpha^2\lambda)}{(\lambda_0+\lambda) + \alpha^2\lambda^2} > \alpha. \tag{A.10}$$

Reorganizing the terms gives the following:

$$\frac{\frac{1}{2}\alpha^3\lambda^2}{1-\frac{1}{2}\alpha^2\lambda} - \alpha^3\lambda^2 > \alpha(\lambda_0+\lambda). \tag{A.11}$$

Comparing (A.7) with (A.11), we see that the latter implies the former. Thus, we only need to focus on (A.11), which is equivalent to:

$$\frac{\lambda(\frac{1}{2}\alpha^4\lambda^2 - 1)}{1-\frac{1}{2}\alpha^2\lambda} > \lambda_0. \tag{A.12}$$

Now we impose a lower bound on λ:

$$\frac{\sqrt{2}}{\alpha^2} < \lambda < \frac{2}{\alpha^2} \tag{A.13}$$

where the upper bound is simply (4). Then, for λ satisfying (A.13), we have

$$\begin{aligned}\frac{\lambda(\frac{1}{2}\alpha^4\lambda^2 - 1)}{1-\frac{1}{2}\alpha^2\lambda} &= \frac{\frac{1}{2}\lambda\big(\alpha^2\lambda+\sqrt{2}\big)\big(\alpha^2\lambda-\sqrt{2}\big)}{1-\frac{1}{2}\alpha^2\lambda} \\ &> \frac{(2/\alpha^2)\big(\alpha^2\lambda-\sqrt{2}\big)}{1-\frac{1}{2}\alpha^2\lambda}.\end{aligned} \tag{A.14}$$

Thus, a sufficient condition for (A.12) is

$$\frac{(2/\alpha^2)\big(\alpha^2\lambda-\sqrt{2}\big)}{1-\frac{1}{2}\alpha^2\lambda} > \lambda_0, \tag{A.15}$$

which holds if

$$\lambda > \frac{\sqrt{2}/\alpha^2 + \lambda_0/2}{1+\alpha^2\lambda_0/4} = \frac{\sqrt{2}}{\alpha^2} + \frac{\big(2-\sqrt{2}\big)\lambda_0}{4+\alpha^2\lambda_0} \equiv \lambda^*(\lambda_0). \tag{A.16}$$

This gives Proposition 3 and $\lambda^*(\lambda_0) \in \big[\sqrt{2}/\alpha^2, 2/\alpha^2\big)$.

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jfineco.2021.09.015.

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