Currency Volatility and Global Technological Innovation

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Abstract

We investigate the real effects of foreign exchange (FX) volatility on technological innovation. Using a 32-market, three-decade sample, we show that heightened FX volatility associates with significantly lower firm-level R&D expenditures, patents granted, and forward citations. The negative FX volatility-innovation relation can be attributed to precautionary savings needs and trade slowdown. The relationship is stronger for firms with financial constraints, with the use of foreign debt, and in more open economies; it is weaker for firms with derivatives hedging, with higher sales, and in countries with better financial development.

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1. Introduction

The foreign exchange (FX) market is the largest financial market in the world in terms of trading volume. According to the 2019 tri-annual survey by the Bank for International Settlements (BIS), the daily aggregate trading volume in global FX markets is over six trillion dollars.[1] Understanding the link between exchange rates and economic fundamentals is at the center of international finance (James, Marsh, and Sarno, 2012; Rossi, 2013); however, strong empirical evidence of the exchange rate-fundamentals connection remains lacking in the literature.[2] At the aggregate level, recent studies have documented the adverse effects of foreign exchange uncertainty on economic growth, productivity, and income (Frankel and Rose, 2002; Aghion, Bacchetta, Rancière, and Rogoff, 2009). At the firm level, excessive exchange rate volatility would increase uncertainty, which unavoidably impacts their operation and investment decisions.[3]

In this paper, we examine the effects of FX volatility on firm-level operations[4] from an important yet hitherto *unexplored* perspective: technological innovation.[5] The importance of technological innovation in promoting economic growth has been highlighted since the seminal studies of Solow (1957), Kydland and Prescott (1982), Romer (1986, 1990), and subsequent

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[1] https://www.bis.org/statistics/rpfx19_fx_annex.pdf

[2] The seminal work of Meese and Rogoff (1983) and a large number of ensuing studies thus highlight the scarcity of empirical evidence connecting economic fundamentals and exchange rate as an "exchange rate-fundamentals disconnect puzzle" (e.g. Mark, 1995; Flood and Taylor, 1996; Frankel and Rose, 2002; Cheung, Chinn and Pascual, 2005; Rogoff and Stavrakeva, 2008; Della Corte and Tsiakas, 2012). A few studies consider alternative theoretical models or econometric methods to explain the exchange rate-fundamentals disconnect puzzle, but results are mixed (Engel and West, 2005; Evans and Lyon, 2005; Bacchetta and van Wincoop, 2006; Abhyankar, Sarno and Valente, 2005). More recent studies provide more positive answers to the question (Gourinchas and Rey, 2007; Della Corte, Sarno and Sestieri, 2012; Della Corte, Riddiough, and Sarno, 2016; Filippou and Taylor, 2017; Colacito, Riddough, and Sarno, 2019).

[3] Early theoretical studies such as Shapiro (1975), Dumas (1978), Hodder (1982), and Bodnar, Dumas, and Marston (2002) suggest that exchange rate changes have considerable impacts on firm values and cash flows. Empirical studies, such as Jorion (1990), Amihud (1994), and Bartov and Badnor (1994), however, do not find significant evidence for the FX exposures. Bartram, Brown, and Minton (2010) highlight the importance of pass-through and hedging activities in reconciling the difference between theoretical and empirical exposures. Taylor, Wang, and Xu (2021) investigate the effect of exchange rate risk on firm capital investment.

[4] To be rigorous, here we mean the firm-year level operations because the sample is constructed as firm-year level. Throughout the entire paper, we write firm-level for *de facto* firm-year level variables for simplicity. Similarly, we write market-level for *de facto* market-year level variables.

[5] In this paper, we focus on the effect of volatility on innovation. We occasionally use the terms uncertainty and volatility (or risk) interchangeably, similarly to previous studies such as Bloom (2014). We recognize that several prior studies differentiate volatility from uncertainty. For instance, volatility and uncertainty could have different implications in the menu cost literature (e.g. Vavra, 2014), in studies for departures from full-information rational expectation (e.g. Coibion and Gorodnichenko, 2015), and in research about ambiguity (e.g. Backus, Ferriere, and Zin, 2015). In this paper, we do not intend to delve into the detail about differences between risk and uncertainty.

empirical studies.[6] At the firm level, innovation activities are generally regarded as one of the most critical long-term investments. Different from tangible and physical investments, innovation activities take a longer period to complete and are subject to much higher risk and uncertainty (Holmstrom, 1989; Hall and Lerner, 2010). Research and development (R&D) is an intangible investment that creates patents (and growth options) that determine firms' long-term value, which is different from capital expenditure that scales up firms' current production and contributes to short-term profits (Aghion, Angeletos, Banerjee, and Manova, 2010). Thus, R&D investment tends to be countercyclical, while physical investment tends to be procyclical (Aghion, Askenazy, Berman, Cette, and Eymard, 2012). Moreover, U.S. R&D has grown much faster than traditional physical investment: Skinner (2008) shows that, over the period from 1980 to 2005, U.S. listed firms' total capital expenditures increased by less than 50%, while their total R&D expenditures increased by about 250%; in 2005, their R&D expenditures were more than twice the amount of their capital expenditures.

There is, however, a lack of empirical evidence on the role of international finance on firm-level innovation activities. When prior studies examine the relationship between international trade and technology spillovers, they tend to focus on R&D spillovers (e.g. Fracasso and Marzetti, 2015). Moreover, as international collaboration and trade of technologies have grown rapidly relative to global GDP (Spulber, 2008), it is particularly important to examine the real effect of exchange rate volatility on firms' innovation activities. Thus, whether and how FX volatility influences firm-level R&D investments and patent outputs deserves further investigation.

We argue that FX volatility may deter firm-level innovation activities through two potential economic mechanisms: precautionary savings and trade slowdown. The idea of precautionary savings dates back to Keynes (1936), referring to the increase of cash savings to prepare for future higher uncertainty.[7] When FX volatility surges, firms engaging in foreign

[6] Prescott (1986) suggests that technology shocks explain more than half of post-war U.S. economic fluctuations, and Rosenberg (2006) documents that technology innovations can explain about 85% of economic growth around the world.

[7] Previous studies connect precautionary saving motives to current cash flow risk (Opler, Pinkowitz, Stulz, and Williamson, 1999), future risk (Carroll, Christopher, and Kimball, 2007), uninsurable investment risk (Sandri, 2010), or when firms facing

trading are concerned about their cash holdings for future business operations and may give up valuable investment projects. In comparison with physical investments, innovation activities require long-term investments but their outputs are highly uncertain and are hard to liquidate or collateralize, so that firms may not initiate these innovative projects or will have to abandon them to maintain day-to-day business operations when they are cash or credit constrained (e.g., Bloom and Van Reenen, 2002; Aghion, Angeletos, Banerjee, and Manova, 2010; Aghion, Askenazy, Berman, Cette, and Eymard, 2012). Moreover, such an effect can be amplified by the heightened costs of evaluating innovation projects in difficult times (Kerr and Nanda, 2015).

FX volatility may also increase trade frictions and slow down cross-border trade, which will particularly impact firms and economies that depend on international trade. Kenen and Rodrik (1986) argue that countries with higher short-term exchange rate volatility have lower international trade volume. Also, Aghion, Bacchetta, Rancière, and Rogoff (2009) show that a fixed FX regime is more beneficial to economic growth for economies with lower financial development. High-tech or innovative firms, especially those in emerging countries, will tend to be damaged by the slowdown of international trade to a greater extent if their operations rely on international trade and cross-border activities.[8] When an economy is more open, it is clearly more vulnerable to FX volatility (Rodrik, 2001), and so the innovation activities of firms in more open economies, compared to more inward-looking or closed economies, are more likely to be affected.

On the other hand, we also acknowledge that FX volatility may promote firm-level innovation activities for two potential reasons. First, under greater economic uncertainty, firms may be motivated to invest more in R&D and innovative projects because these investments help firms better withstand external shocks and competition (Bloom, Draca, and Van Reenen,

funding gaps (Acharya, Almeida, and Campello, 2007). Riddick and Whited (2009) show that income uncertainty affects savings more than external finance constraints. Stokey (2009) shows that volatility level changes behaviors in models of inaction or precautionary savings.

[8] With the expansion of emerging markets and the globalization of supply chains, firms' operations have been subject to currency volatility to a greater extent in recent decades (Dominguez and Tesar, 2006). Empirical evidence from the international economics literature has suggested that firms' cross-border activities, such as foreign direct investment (FDI) and international trade, are important factors in economic growth, productivity, and technology spillovers (Alfaro, Chanda, Kalemli-Ozcan, and Sayek 2004; Branstetter, 2006; Keller and Yeaple, 2009).

2016; Hombert and Matray, 2018). Second, due to the lower opportunity costs of innovation investments during recessions, R&D and innovative activities are expected to be countercyclical for firms *without* financial constraints (Aghion et al., 2010; Aghion et al., 2012); thus, when FX volatility drives an economic downturn, we may find a positive relationship between FX volatility and firm-level innovation.

In our empirical analysis, we consider an unbalanced panel of FX-exposed, innovative firms in 32 markets with available FX, financial, and patent data from 1989 to 2018. These firms have sales in foreign markets using different currencies (and therefore are FX-exposed) and have been granted at least one patent in our sample period (and therefore are innovative or patent-active). We measure a firm's innovation activities in a year using the following six variables: R&D expenditure scaled by total assets, log number of patents registered in the home patent office ("domestic patents"), log number of forward citations received by domestic patents ("domestic citations"), log number of patents registered in the US Patent and Trademark Office (USPTO) ("US patents"), log number of forward citations received by US patents ("US citations"), and a dummy variable indicating registration of at least one patent.

We construct firm-level exchange rate volatility to exploit the cross-firm, cross-year variation. We first calculate annually realized exchange rate volatility at the market level. Then we use the information about a firm's yearly sales to different markets to construct a weighted average measure of firm-specific FX volatility. This measure absorbs a firm's information concerning the geographical distribution of sales and the market-level FX volatility. This measure can also be viewed as a Bartik-style instrument (Bartik, 1991; Goldsmith-Pinkham, Sorkin, and Swift, 2020; Klepacz, 2021).[9]

Since the explanatory variable is at the firm level, we control for firm fixed effects to absorb the time-invariant firm characteristics. Moreover, we control for market-market-year fixed effects, which are stronger than market-year fixed effects in that not only are the macro

[9] We are grateful to an anonymous referee for pointing this out.

factors controlled for as in both fixed effects, but the bilateral factors are also controlled. For example, the trade tensions between two countries are controlled, and the two countries' corresponding policy moves are also controlled.

We find that our FX volatility measure is associated with significant reductions in firm-level innovation activities after we control for firm and market-market-year fixed effects, exchange rate changes (i.e., the mean effect), as well as various firm-level characteristics. This negative relationship is not only statistically significant but also economically sizeable. Specifically, a one standard deviation increase in FX volatility is followed by a 7.3% decrease in R&D expenditure ratio, a 2% decrease in the number of domestic patents, a 0.3% decrease in the number of domestic citations, a 7.8% decrease in the number of U.S. patents, a 6.8% decrease in the number of U.S. citations, and a 21.4% decrease in the propensity to file a patent. In addition, a one standard deviation increase in FX volatility is also followed by a 1.7% increase in cash holdings, consistent with the precautionary saving motive. These decreases in innovation output are critical to firm value and growth, as pointed out in Griliches (1981), Harhoff, Narin, Scherer, and Vopel (1999), and Hall, Jaffe, and Trajtenberg (2005). In our robustness checks, we show that our results are unaffected when an alternative GARCH-based measure of FX volatility is employed.

We also explore the impact of FX volatility on other dimensions of innovation activities. We find that FX volatility is negatively associated with patent originality and exploration, while positively related to patent generality and exploitation. These findings suggest that FX volatility discourages long-term investment in innovation projects that are radical and different from firms' existing expertise, which confirms our argument based on risk avoidance. On the other hand, the positive relation with patent generality and exploitation can be attributed to firms' resource-shifting: firms under more volatile FX environments may shift their innovation focus to patent projects that are more general and exploitative because these projects' outputs are of lower uncertainty.

Our further tests provide supportive evidence for the two economic mechanisms (which are not mutually exclusive): precautionary savings needs and trade slowdown. Besides the evidence of the higher cash holdings following an increase in FX volatility, our cross-sectional interaction tests based on financial constraints, firm sales, foreign debt, and market financial development further support the precautionary savings needs interpretation. The negative impact is amplified for firms with higher financial constraints, lower sales, higher foreign debt, and for firms located in less developed financial markets. Higher FX volatility also leads to higher future earnings uncertainty, measured by the cross-sectional dispersion of analysts' forecasts. Therefore, there is strong evidence that firms are indeed concerned about the adverse effects of FX volatility. Our cross-sectional interaction tests based on the use of currency derivatives and the degree of economic openness support the trade slowdown explanation: innovation activities reduce more when firms do not use currency derivatives to hedge FX risk,[10] or when firms are in more open economies.

This paper adds new evidence to the literature on the real effects of FX volatility. Existing studies on FX volatility mainly focus on the asset pricing implications.[11] The present paper is arguably one of the first to analyze the impact of FX volatility on firm operations. Our analysis of firm-level R&D investment and patent output following FX volatility fills a gap in the economics literature and provides new insights into the exchange rate-fundamentals connection, which lacks empirical evidence in the past (Meese and Rogoff, 1983).[12] One potential reason for the "exchange rate-fundamentals disconnect puzzle" could be the

[10] Brown (2001) investigates the use of derivatives to hedge foreign exchange risks and shows that information asymmetry, facilitation of internal contracting, and competitive pricing concerns are potential motivations to hedge.

[11] Hansen and Hodrick (1980) and Fama (1984) attribute the empirical failure of UIP to the presence of risk premia in exchange rate changes. Hodrick (1989) investigates the link between macro and exchange rate volatility. Previous studies on the FX risk premia mainly focus on the time-series perspective. Since Lustig and Verdlhan (2007), an increasing number of studies investigate cross-sectional risk premia in the FX markets. Lustig, Roussanov, and Verdlhan (2011); Menkhoff, Sarno, Schemling, and Schrimpf (2012); Mancini, Ranaldo, and Wrampelmeyer (2013); Latteu, Maggiori, and Weber (2014); and Della Corte, Riddiough, and Sarno (2016), among others, introduce different risk factors in explaining currency risk premia. A few recent studies (Muller, Tahbaz-Salehi, and Vedolin, 2017; Berg and Mark, 2018; Husted, Roger, and Sun, 2018; Della Corte and Krecetov, 2019) also directly examine the link between different types of uncertainty and currency excess returns. Brunnermeier, Nagel, and Pedersen (2008); Menkhoff et al. (2012); Della Corte, Ramadorai, and Sarno (2016); and Lee and Wang (2019) already document the role of different forms of FX risk and uncertainty in pricing or predicting currency excess returns.

[12] Recent studies present further empirical evidence. Gourinchas and Rey (2007); Della Corte, Sarno and Sestieri (2012); and Della Corte, Riddiough, and Sarno (2016) suggest that global imbalances can predict exchange rate movements or price carry trade returns. Filippou and Taylor (2017) find that combined macro fundamentals are informative about currency risk premia. Colacito, Riddough, and Sarno (2019) find a strong link between currency excess return and relative strength of business cycle. Using a portfolio sorting approach, Sarno and Schemling (2014) show that exchange rates have strong predictive power for nominal fundamentals.

inaccurately measured and less frequently updated fundamental variables relative to exchange rates. Our firm-level R&D-based and patent-based variables appropriately reflect innovation inputs and performance in a timely manner, which effectively mitigates the measurement error issue in economic fundamentals.

From a broader perspective, this work is related to the debate on the stability and regulation of foreign exchange rates.[13] Given the crucial role of technological innovation in promoting economic growth, our findings imply that one reason for FX volatility to slow down economic growth is through reducing innovation activities and investments.

This paper also provides new evidence for the adverse effects of macroeconomic uncertainty on intangible investments, echoing the implications of Bloom, Bond, and Van Reenen (2007) and Aghion et al. (2010). Our results support the argument of Bloom and Van Reenen (2002) that government policies for reducing macroeconomic uncertainty are important for the accumulation and application of knowledge capital.[14] Moreover, different from prior studies that examine how physical investments are influenced by broadly defined economic uncertainty,[15] we focus on FX volatility, which is more specific and can thus be more precisely measured.

The rest of the paper is organized as follows. Section 2 describes the datasets and variables used in the empirical analysis. Section 3 presents the test results of the association between FX volatility and firm-level innovation activities. Section 4 discusses the mechanisms through

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[13] The proponents of a free market economy have argued that floating exchange rate regimes facilitate domestic economies to adjust production activities to minimize real output loss (Friedman 1953; Edwards and Levy Yeyati 2005). In addition, fixed exchange rate regimes may encourage protectionist policies and lead to inefficient resource allocation (Obstfeld and Rogoff 1995). However, there is also evidence suggesting that real exchange rate volatility has an adverse impact on industry-level productivity growth (Aghion et al., 2009). In addition, Frankel and Rose (2002) argue that stable exchange rates are beneficial to investment and international trade, and ultimately economic growth.

[14] Prior studies have discussed other sources of uncertainty that influence firm-level innovation decisions, such as uncertainty in appropriability related to intellectual property protection (Branstetter, Fisman, Foley, and Saggi, 2011; Branstetter and Saggi, 2011; Aghion, Howitt, and Prantl, 2015; Fang, Lerner, and Wu, 2017), financing uncertainty (Nanda and Rhodes-Kropf, 2013, 2017; Hsu, Tian, and Xu, 2014), and political uncertainty (Bhattacharya, Hsu, Tian, and Xu, 2017).

[15] Baker, Bloom, and Davis (2016) construct an economic uncertainty index based on the newspaper coverage frequency of terms related to "economic", "policy", and "uncertainty", and find it negatively influences aggregate investments and employment. Kim and Kung (2017) then provide firm-level evidence for the economic uncertainty on firm-level capital investment. On the other hand, political uncertainty, measured by election cycles, is also found to negatively affect firm-level capital investments (Julio and Yook, 2012; Gulen and Ion, 2016; Jens, 2017).

which FX volatility influences firm-level innovation activities. Section 5 concludes the paper.

2. Data and variable construction

2.1. Exchange rate data

We describe data sources and variable construction in this section. We obtain daily US-dollar (USD) denominated exchange rates from January 2nd, 1989 to December 29th, 2017 for 48 currencies from Datastream,[16] which has been used in the FX asset pricing literature such as Menkhoff et al. (2012). The USD exchange rate is directly quoted as the dollar price of foreign currency, so a higher exchange rate indicates an appreciation of the foreign currency.

2.2. Firm-level exchange rate volatility

We define the log exchange rate return in annual frequency as follows:

$$r_{m,t} = \Delta s_{m,t} = lnS_{m,t} - lnS_{m,t-1} \tag{1}$$

where $S_{m,t}$ refers to the exchange rate *m* (*m* indicates the market where the foreign currency is used) in year *t*, $\Delta s_{m,t}$ refers to log exchange rate return or change in year *t*.

We first construct a measure of market-level exchange rate volatility. There are different approaches to measure exchange rate volatility in the literature. Here, in our main analysis, we use the realized exchange rate volatility, constructed as follows:

$$Vol_{m,t} = \sqrt{\frac{1}{K}\sum_{k=1}^{K}\left(r_{m,t,k} - \overline{r_{m,t}}\right)^2} \tag{2}$$

where $Vol_{m,t}$ is the realized volatility for exchange rate *m* in year *t*, $r_{m,t,k}$ is the daily log return for exchange rate *m* on day *k* in year *t*. In the Appendix A, we consider an alternative

[16] The USD-based exchange rates from Datastream are available from October 1983. We focus our sample from 1989 onwards for two reasons. First, the number of currencies in the early period is small (e.g., the number of currencies in 1983 is only eight). Second, we need to match with the available cross-country firm-level data, which starts in 1989.

approach to measuring exchange rate volatility based on the GARCH model of Bollerslev (1986). Our results are robust across different volatility measures.

Based on the market-level volatility, we use detailed foreign sales information from FactSet Geographic Exposure about a firm's yearly sales to different markets to construct a firm-specific volatility as our main independent variable of interest.[17, 18] It is a sales-weighted average of market-level volatility (WEIGHTED_VOL) as follows,

$$Vol_{f,m,t} = \sum_{m=1}^{M} Vol_{m,t} * Exposure_{f,m,t} = \frac{\sum_{m=1}^{M} Vol_{m,t} Sales_{f,m,t}}{\sum_{m=1}^{M} Sales_{f,m,t}} \tag{3}$$

where the weight $Sales_{f,m,t}$ is calculated as the ratio of firm f's sales to market m in year t to its total sales (domestic sales are included) in the same year. To construct firm-level exchange rate volatility, we first obtain cross rates between the home country and the foreign market based on two USD-denominated exchange rates and then calculate realized volatility $Vol_{m,t}$ for the cross rates as in equation (2). Then we calculate firm-level volatility $Vol_{f,m,t}$ by weighting each cross-rate volatility by foreign sales to different markets as shown in equation (3).

This firm-level volatility measure is intuitive. If a firm's sales are mainly to a specific foreign market, then the exchange rate volatility for the paired currencies in the firm's domestic and main foreign sales market should affect the firm more, and hence have a higher weight. While different foreign exchange exposure measures have been introduced in the literature, such as the elasticity of firms' stock returns to exchange rate changes (Adler and Dumas,1984) or foreign sales (Allayannis and Weston, 2001; Allayannis, Lel, and Miller, 2012), we use the foreign sales to total sales ratio both for the data availability consideration and for a more

[17] For firms with foreign sales recorded to a general region without specifying a specific country, we assume transactions are conducted in US dollar. In an unreported analysis, we also consider the interaction of country-level exchange rate volatility and firm-level foreign sales to total sales ratio as the main independent variable. This method assumes all foreign transactions use USD, and hence the firm is only concerned about the volatility of USD exchange rate vs. the firm's home country.

[18] Other studies, such as Berman, Martin, and Mayer (2012), rely on customs data to understand firm exchange rate exposure. However, these studies mainly focus on a single country. We instead aim to focus on the relation between exchange rate volatility and innovation in a cross-country firm-level analysis, and hence we construct a firm-level exchange rate volatility measure by combining country-level exchange rate volatility and firm-level foreign sales information.

accurate gauge of firm-level exposure to the volatility of different exchange rates.

The main advantage of the firm-level measure over the market-level measure is that it accounts for the cross-sectional heterogeneity of firms with different exposures to exchange rate volatility. The firm-level exchange rate volatility measure may also be interpreted as an example of a Bartik (1991)-style instrument. A conventional Bartik instrument is constructed using the interaction of the local industry share (exposures) and the national industry growth rates (common shocks) (Goldsmith-Pinkham, Sorkin, and Swift, 2020). Klepacz (2021) applies the Bartik approach to identify the effect of oil price volatility by interacting aggregate oil volatility with industry-specific oil usage. We suggest that the weighted average exchange rate volatility can be viewed as a general version of Bartik-style instrument as it captures firm exposure to multiple exchange rate volatilities and weighs them based on firm exposure, i.e., foreign sales, to each market.[19]

2.3. Currency derivatives usages and foreign debt

Firms involved in international trade may use currency derivatives to hedge against potential adverse fluctuations of the exchange rate (Brown, 2001). Following Allayannis et al. (2012), we hand-collect data on currency derivatives usage from annual reports from two sources. First, for those international firms listed in the U.S. exchanges, we collect data from report 20-F filed with the U.S. Securities and Exchange Commission (SEC). Second, for those non-U.S. listed international firms, we collect data from their annual reports downloaded from Reuters Eikon. We construct an indicator variable FX_DERI that equals one if a firm uses FX derivatives and zero otherwise. A firm is considered as using FX derivatives if we find keywords “derivative” and “hedging” in the firm’s annual report, and then further check whether “foreign exchange”, “exchange rate”, or “currency” appears within 100 words before or after “derivative”. Because only the international firms listed on the U.S. exchange file 20-

[19] The identifying assumption is that the exposure is exogenous conditional on observables. In an unreported analysis, we interact firm-specific exchange rate volatility, which includes information about firm exposure, with all other firm-level control covariates and find that our main results remain consistent.

F reports and only a few countries with firm annual reports available from the Reuters Eikon, our sample size in our analysis related to firms' use of currency derivatives is smaller than the sample used for the main analysis.

Firms with foreign debt may also react differently to exchange rate volatility. As direct, accurate firm-level foreign debt information is not available to the best of our knowledge, we closely follow Kalemli-Ozcan, Liu, and Shim (2021) to construct a firm-level foreign debt measure based on the market-level foreign debt. Specifically, we first construct a market-level foreign debt measure based on the non-financial sector debt share, calculated as the sum of FX loans and debt in the non-financial sector of a given market divided by the total debt (loans and debt) in the non-financial sector. Market-level FX loan and debt information is collected from the Global Liquidity indicator (GLI) database, while market-level total debt is collected from the Total Credit database, both of which are available from the Bank of International Settlements (BIS). Then we construct firm-level foreign debt by assuming each firm's foreign debt share is equal to the aggregate market-level foreign debt share. In a final step, we obtain firm-level foreign debt by multiplying firm-level total debt by foreign debt share.[20]

2.4. *Firm-level innovation measures*

In this paper, we construct six different measures of firm-level technological innovation, following the literature, to examine the impact of FX volatility on innovation activities through different perspectives. We first collect firms' annual R&D expenditure of all international public firms in 32 markets from the Compustat-Global and Worldscope; the details of both databases will be elaborated in Section 2.5. We construct the variable, RD_RATIO_AT, the annual R&D expenditure scaled by the lagged total asset, as the innovation input measure of

[20] While the same foreign debt share across firms within a country is a strong assumption, Kalemli-Ozcan, Liu, and Shim (2021) show that this firm-level foreign debt proxy is very close to true firm-level foreign debt for selected countries with available data. Hence, we view the approach as an appropriate way to measure firm-level foreign debt given the data availability concern. Other studies such as Kamil (2005) and Kalemi-Ozcan, Kamil, and Villegas-Sanchez (2016) use a dataset of detailed currency composition of firm's balance sheets; however, their dataset covers up to six Latin American countries only. Hence it does not fit our purpose for a large cross-country firm-level analysis. Therefore, we follow the approach of Kalemli-Ozcan, Liu, and Shim (2021) to construct firm-level foreign debt.

each firm-year observation.

In addition to R&D expenditure that captures innovation *input*, we also consider patent-based measures for innovation *output*. We consider both patent number and patent citation. Intuitively, a firm that files more applications and then receives a higher number of patents in a period is regarded as more innovative in *quantity*. However, merely counting the number of patents does not differentiate innovation outputs of different quality (Hsu, Tian, and Xu, 2014). Therefore, we follow the prior innovation economics literature (e.g., Aghion, Van Reenen, and Zingales, 2013) and use another innovation output measure based on patent citation, which is the number of forward citations received by these patents, reflecting a firm's innovation output in *quality*. This measure is also named "citation-weighted patent number" (e.g., Hall, Jaffe, and Trajtenberg, 2005) because it assigns a higher weight to patents that received more forward citations.

We collect each firm's domestic patents and their forward citations from subsequent patents in its home market from the REGPAT database that is based on the PATSTAT database.[21] Because the application and approval criteria of patent filing may vary in different countries, we also collect each firm's U.S. patents and their forward citations from subsequent patents in the USPTO using the patent database accessible from the University of Virginia.[22] We use the natural logarithm of one plus the number of a firm's patents registered in the domestic patent office (PATENT_DOM _LN), the number of forward citations received by those domestic patents (CITATION_DOM_LN), the number of patents registered in the USPTO (PATENT_US_LN), and the number of forward citations received by these U.S. patents (CITATION_US_LN). By considering each firm's patents and citations in its home market and in the U.S., we can capture global firms' innovation activities comprehensively. In addition, we also use a patent filing dummy, which equals one if a firm registers at least one international or U.S. patent in a given year and zero otherwise. The four measures of patent

[21] For each public firm in Compustat-Global and Worldscope, we match the firm's name to patent assignees that appear in the REGPAT database. Source: https://www.oecd-ilibrary.org/science-and-technology/the-oecd-regpat-database_241437144144

[22] The data can be access through the following link https://patents.darden.virginia.edu/get-data/. The detailed instructions for the data construction can be found in Bena, Ferreira, Matos, and Pires (2017).

numbers and citations mainly focus on the intensive margin of innovation. The patent filing dummy variable allows us to understand the extensive margin. Hence, we can examine how FX volatility affects the propensity of a firm to file a patent in the given year.

Besides these six measures for R&D, patents, and citations that are mainly about the *intensity* of innovation, we also consider four additional patent-based variables to understand more deeply how FX volatility affects the *direction* of innovation activities: First, we consider originality and generality. Following Hall, Jaffe, and Trajtenberg (2005), we measure each patent's originality and generality as follows: A patent's originality (generality) score is one minus the Herfindahl index of the technology section distribution of all the patents it cites (being cited). A patent's originality refers to the variety of technology classes on which it is based. On the other hand, a patent's generality refers to the variety of technology classes to which it can be applied. We then take the average of originality (generality) scores of all patents granted to a firm in a year to construct firm-level originality (generality) measure, which is denoted as ORIGINALITY (GENERALITY).[23]

Second, we consider a firm's exploration ratio and exploitation ratio. A higher exploration ratio implies that the majority of the backward citations made by a firm's patents are based on new knowledge outside of its existing expertise. A higher exploitation ratio implies that the majority of the backward citations made by a firm's patents are based on old knowledge within a firm's existing expertise. To construct these two variables, we follow the three-step procedure from Benner and Tushman (2002) and Gao, Hsu, and Li (2018). We first calculate the percentage of backward citations made by each patent applied for by firm *f* in year *t* that are based on existing expertise (defined as the combination of firm *f*'s portfolio of patents from year *t-5* to year *t-1* and the backward citations made by these patents). Then, a patent is categorized as "exploratory" ("exploitative") if more than or equal to 60% of its backward citations are outside of (within) firm *f*'s existing expertise as defined in the first step. Finally,

[23] We thank an anonymous referee for suggesting to us that we focus on the average of originality (generality) scores of all patents to construct the firm-level originality (generality) measure.

we calculate firm *f*'s exploration ratio (EXPLORE_RATIO) in year *t* as the number of exploratory patents granted to the firm in year *t* divided by its total number of patents in the same year, and its exploitation ratio (EXPLOIT_RATIO) in year *t* as the number of exploitative patents granted to the firm in year *t* divided by its total number of patents in the same year.

2.5. Sample construction

Our sample firms and firm-level financial variables are collected from Compustat Global and Worldscope. Compustat Global date begins in 1986 and covers financial statement data of over 24,000 publicly traded companies in global markets for more than 80 countries. Worldscope covers over 40,000 public firms in more than 50 developed and emerging markets. Both databases are widely used in corporate finance research in an international setting.

To construct our sample, we first merge the two databases to obtain a comprehensive set of international firms. Second, we restrict our sample to those firms with sales in foreign markets using different currencies (who therefore are FX-exposed) and being granted at least one patent in our sample period (and therefore are innovative). We impose the foreign sales condition because we want to focus on the direct impact of FX volatility on those firms with foreign currency usage. We impose the condition of patent granting because we want to ensure that our sample firms are patent-active (Aghion, Van Reenen, and Zingales, 2013); if a firm has never been granted a patent in the whole sample period, we have reason to believe that it does not intend to innovate (or file patents) in any case.

The initial Compustat-Global-Worldscope sample has 746,800 firm-year observations. After merging with firm-level foreign sales information from FactSet Geographic Exposure, we are left with 80,400 firm-year observations because a majority of firms do not have foreign sales. The sample further reduces to 49,005 firm-year observations after merging with the FX volatility constructed from daily currency prices from Datastream, because the daily data are missing in many markets in the early days although yearly exchange rate information is available every year. After merging with the financial variables, patent and citation data from

REGPET and USPTO, and keeping only firms with at least one patent granted, our final sample for the main empirical analysis contains 10,624 firm-year observations, covering 1,519 unique firms in 32 markets from 1989 to 2018. The Appendix A Table A1 provides precise details for all variables. Table A2 lists the coverage of observations in 32 markets.[24] Table 1 offers summary statistics of main variables.

3. Empirical analysis

3.1. Baseline results

In this section, we empirically examine whether firm-specific FX volatility affects firm-level innovation activities in the following years. The baseline model is presented as follows:

$$Innov_{f,m,t+k} = \alpha + \beta VOL_{f,m,t} + \mathrm{X}_{f,m,t} + \Phi_f + \Phi_{m,m',t} + \epsilon_{f,m,t+k}\,, \tag{4}$$

in which $VOL_{f,m,t}$ (WEIGHTED_VOL) refers to our firm-level measure of FX volatility for firm *f* in market *m* in year *t*. $Innov_{f,m,t+k}$ refers to measures of innovation activities of firm *f* in market *m* in year *t+k*. We set $k = 1$ when the dependent variable is the ratio of R&D to the total asset (RD_RATIO_AT), meaning that we look at the effects of the current year's FX volatility on the next year's R&D expenses. As the innovation input may take years to produce *granted* patents,[25] we set $k = 4$ when the dependent variables are the following patent output measures based on the *granted* year: the natural logarithm of one plus domestic patents number (PATENT_DOM_LN) and citations (CITATION_DOM_LN), the natural log of one plus US patents number (PATENT_US_LN) and citations (CITATION_US_LN), as well as a dummy variable that the firm registers at least one domestic or U.S. patent (FILE_PATENT_DUMMY).

[24] These 32 markets are: Australia, Austria, Belgium, Brazil, Canada, Switzerland, Germany, Denmark, Spain, Finland, France, Great Britain, Greece, Hong Kong, India, Ireland, Israel, Italy, Japan, Korea, Mexico, Netherland, Norway, New Zealand, Poland, Russia, Singapore, Slovenia, Sweden, Thailand, Taiwan, and South Africa.

[25] Pakes and Griliches (1984) and Pakes and Schankerman (1984) have documented that the average time lag between R&D input and patent applications ranges between one and two years, and Hall, Jaffe, and Trajtenberg (2005) suggest that the average time lag between patent applications and grants is about two years. For international patents, de Rassenfosse and Jaffe (2018) show that roughly 80% of patents granted by the European Patent Office are filed within one year of the start of corresponding R&D projects.

In addition, to test the impact of FX volatility on firm cash holding in the next year, we also use the ratio of cash holding on total asset (CASH_RATIO_AT) in year *t+1* as a dependent variable.

$X_{f,m,t}$ denotes a vector of firm-level control variables including firm-specific exchange rate changes (WEIGHTED_FX_RATE_CHANGE), and other firm characteristics.[26] We also control for firm fixed effects (Φ_f) to absorb all omitted variables that are related to specific firms. An important feature for our identification strategy is to include the *market-market-year* joint fixed effects ($\Phi_{m,m',t}$). This practice allows us to absorb not only all time-varying, market-specific variables, such as market-level macro variables like market-level intellectual property protection (Branstetter, Fisman, Foley, and Saggi, 2011; Branstetter and Saggi, 2011; Aghion, Howitt, and Prantl, 2015; Fang, Lerner, and Wu, 2017), financial development (Hsu, Tian, and Xu, 2014), and policy uncertainty (Bhattarcharya et al., 2017), but also all time-varying and bilateral variables for each pair of markets (m, m') such as bilateral trade tensions and political conflicts. Hence, we do not need to include market-level control variables explicitly. We cluster standard errors at the market level.

Table 2 presents our main empirical results about the effects of FX volatility on technological innovation. Columns (1) to (7) report the main regression results concerning the effects of FX volatility on innovation activities. We show that high FX volatility is associated with higher firm cash holdings, which is consistent with firms' precautionary saving motives when the exchange rates they face are more volatile. In line with our premise, FX volatility is consistently and negatively associated with innovation activities. As shown in Column (2), higher FX volatility is followed by lower R&D expenditure. The negative effect is not only

[26] The firm-specific exchange rate change (WEIGHTED_FX_RATE_CHANGE) is defined similarly to the firm-specific exchange rate volatility. Specifically, we calculate annual exchange rate change using log exchange rate return for each pair of currencies between the home country where the firm is located and the foreign market. Then we calculate the weighted average of country-level exchange rate changes to obtain the firm-specific exchange rate change. The weight is calculated as the ratio of foreign sales to total sales. The weighted exchange rate change represents changes in units of basket of currencies for a unit of home currency. A higher value corresponds to the appreciation of the home currency and the depreciation of the basket of foreign currencies. In addition, we control for an extensive list of firm-level control variables (more detailed definitions are provided in Appendix Table A1). These variables include Tobin's Q (TobinQ), earnings before interest, taxes, depreciation and amortization (EBITDA), standard deviation of EBITDA (EBITDA_VOL), pretax book income (PTBI), volatility of pretax book income (PTBI_VOL), long-term debt (LEVERAGE), firm loss dummy (LOSS), the change in sales (SGA_DELTA), natural logarithm of total assets (TOTAL_ASSETS_LN), and firm age (FIRM_AGE).

statistically significant but also economically meaningful. A one standard deviation increase of firm-level exchange rate FX volatility is associated with a 7.3% drop in the R&D ratio.[27] This is consistent with our proposition that, when firms face a volatile exchange rate, they tend to reduce their investment in innovation activities.

FX volatility is also negatively associated with innovation outputs. For example, a one standard deviation increase of FX volatility is followed by a drop of 7.8% and 6.8% in the U.S. patent number and citations,[28] respectively, and a 21.4% reduction in the propensity to file at least one patent.[29] Although these estimates are inferred from firm-level data, in aggregate they may become a big reduction in innovative activities that will have a long-term impact on economic growth. On the other hand, in terms of the value-enhancing effect of these patent metrics, prior studies have estimated that producing one more patent increases a firm's market value by 2% to 3% (Hall, Jaffe, and Trajtenberg, 2005). In addition, earning one more citation per patent in the USPTO record is worth an approximate US$1 million (Harhoff, Narin, Scherer, and Vopel, 1999; Hall, Jaffe, and Trajtenberg, 2005). In contrast, the coefficients of exchange rate changes (WEIGHTED_FX_RATE_CHANGE) are mixed with both positive and negative signs and vary across innovation measures to a great extent. Hence, our findings support the view that exchange rate volatility rather than the exchange rate change (the level effect) matters more for firm-level innovation activities.

In addition, we use daily exchange rate returns over the year to estimate FX volatility using the GARCH model by Bollerslev (1986) as a robustness check. Table IA1 in the Internet Appendix shows that the negative FX volatility-innovation relation remains when GARCH volatility is used. Therefore, our results are not restricted to a specific volatility measure.

Our main results employ the firm-level exchange rate volatility and the market-market-

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[27] The figure -7.3% is calculated as -0.0871(coefficient)*0.02(standard deviation of the independent variable)/0.02(mean of the dependent variable).

[28] The percentage change of the de-logged dependent variable is $e^{\beta \Delta x} - 1$. The figure -7.8% is calculated as (the exponential of -4.095 (coefficient) * 0.02(standard deviation of the independent variable) – 1). The figure -6.8% is calculated as (the exponential of -3.528 (coefficient) * 0.02(standard deviation of the independent variable) – 1).

[29] The percentage -21.4% is calculated as -1.794(coefficient)*0.02(standard deviation of the independent variable)/0.17(mean of the dependent variable).

year joint fixed effects to mitigate the potential endogeneity concerns. In the Internet Appendix, we provide additional results using two major historical events in the FX markets to further enhance the identification. We consider the change of exchange rate regime from fixed to float and from float to fixed. We also analyze the collapse of the European Exchange Rate Mechanism (ERM) in 1992. Both of these two additional identification tests support our main findings and strengthen the causal interpretation of our results. For space consideration, these results are reported in Tables IA2 and IA3 in the Internet Appendix. We provide more discussions about these results in in the Internet Appendix.

3.2. Other innovation measures

Our results so far rely on the number and citations of patents granted to measure the quantity and quality of innovation outputs. In this section, we consider four additional patent characteristics to further understand how FX volatility affects firms' choices of innovation projects. These four patent characteristics are: generality, originality, exploration ratio, and exploitation ratio. As discussed in Section 2.4, generality refers to patents being cited by a wide class of technologies, originality refers to patents that cite a wide class of technologies, the exploration ratio refers to the use of knowledge beyond the firm's existing expertise, and the exploitation ratio refers to the use of knowledge within the firm's existing expertise. Our analysis is as follows:

$$InnovChar_{f,m,t+4} = \alpha + \beta VOL_{f,m,t} + X_{f,m,t} + \Phi_f + \Phi_{m,m',t} + \epsilon_{f,m,t+4} \quad (5)$$

where $InnovChar_{f,m,t+4}$ denotes one of these four patent characteristics (generality, originality, exploration ratio, and exploitation ratio). As before, we control for firm-level variables, add firm fixed and market-market-year fixed effects, and cluster standard errors at the market level.

Table 3 reports the empirical results of this analysis. We find that these four patent characteristics are associated with FX volatility in different directions. FX volatility is negatively associated with originality and the exploration ratio, and is positively associated with generality and the exploitation ratio. A one standard deviation increase in FX volatility is followed by 13.5% and 11% reductions in originality and the exploration ratio, respectively, and 4.0% and 16.7% increases in generality and the exploitation ratio, respectively.[30] The negative coefficients for originality and exploration are fairly intuitive because higher FX volatility discourages long-term risk tolerance in innovation and reduces long-term investment that is radical and different from firms' existing expertise. On the other hand, the positive coefficients for generality and the exploitation ratio can be attributed to the fact that more general and exploitative patents are safer choices and create lower uncertainty for firms, which could be more favorable under more volatile environments.

4. Mechanisms

4.1. Precautionary savings needs

As Keynes (1936) noted, firms have a precautionary motive to hold cash as a buffer against adverse conditions or to meet future investment needs. On the other hand, large cash holdings allow firms to undertake valuable projects that might otherwise be bypassed (e.g., Myers and Majluf, 1984). When FX volatility surges, firms are concerned about future profits and cash flows and may thus delay their investments and initiatives to enhance their precautionary savings. In comparison with physical investment, innovation activities are more sensitive to firms' precautionary savings because they require long-term investments and thus demand stable funding and cash flows. As prior studies have shown that macroeconomic uncertainty causes firms to delay innovative projects or abandon ongoing ones to ensure their liquidity and survival (e.g., Bloom and Van Reenen, 2002; Aghion et al., 2010; Aghion et al., 2012), FX

[30] The percentage 4.0% is calculated as 0.000275 (coefficient)*0.02(standard deviation of independent variable)/0.0014(mean of dependent variable). 16.7% is calculated as 0.00708(coefficient)*0.02(standard deviation of independent variable)/0.0008(mean of dependent variable). 13.47% is calculated as 0.0214 (coefficient)*0.02(standard deviation of independent variable)/0.0032(mean of dependent variable). 11% is calculated as 0.15(coefficient)*0.02(standard deviation of independent variable)/0.03(mean of dependent variable).

volatility requires firms to hold more precautionary savings and thus discourages firms' innovation activities. Moreover, it is difficult for firms to collateralize their innovation outputs that often take the form of intellectual property (Brown, Fazzari, and Petersen, 2009), and such difficulty increases firms' needs for precautionary savings under macroeconomic uncertainty triggered by volatile FX environments; thus, FX volatility further reduces firms' incentive to invest in innovation activities.

In the main analysis, we have already observed the increase in firms' cash holdings following the surge of FX volatility. In this section, we implement further tests based on a series of variables related to the need for precautionary savings, including financial constraints, firm sales, foreign debt, financial development, and future earnings forecast dispersions, to examine the precautionary savings need mechanism.

4.1.1. Financial constraints

Based on the precautionary saving need, the negative FX volatility-innovation relation is expected to be stronger for firms with tightened financial constraints. Intuitively, when a negative shock like FX volatility hits, constrained firms that are short of internal funds and external financing sources are more likely to cut long-term risky investments unrelated to day-to-day operations, and instead hold more cash. The idea is also consistent with the premise of Aghion et al. (2010) that firms are less willing to make long-term investments (such as innovations) when facing tight credit constraints. To test this proposition, we estimate the following model:

$$\begin{aligned} Innov_{f,m,t+k} = \alpha + \beta_1 VOL_{f,m,t} * KZ_{f,m,t} + \beta_2 VOL_{f,m,t} \\ +\beta_3 KZ_{f,m,t} + \mathrm{X}_{f,m,t} + \Phi_f + \Phi_{m,m\prime,t} + \epsilon_{f,m,t+k} \,. \end{aligned} \tag{6}$$

The model specification augments the baseline model in equation (4) by adding a measure of financial constraints $KZ_{f,m,t}$ (KZ_INDEX), the Kaplan and Zingales (1997) financial constraint index based on financial statement data, and its interaction term with FX volatility. A higher value of the KZ index implies a higher level of financial constraints.

Table 4 reports results considering financial constraints. We find that the interaction term is consistently negative (positive) and significant for innovation measures (cash holdings). These empirical results are consistent with our argument that the negative effects of FX volatility on technological innovation are strengthened when firms face higher levels of financial constraints and that these firms save more cash (which reflects their higher precautionary savings needs). These results are also consistent with Kerr and Nanda (2015) who suggest that the effect of uncertainty on innovations is stronger for more financially constrained firms.

4.1.2. Firm sales

Besides the KZ index, a more traditional measure of financial constraint is firm size, measured by total sales in our cross-country sample. Large firms are usually less constrained as they are more likely to have multiple financing channels, while small firms are more likely to face tighter financial constraints. To test how the effect of FX volatility is associated with firm size, we consider the following specification,

$$\begin{aligned} Innov_{f,m,t+k} = \alpha + \beta_1 VOL_{f,m,t} * Sales_{f,m,t} + \beta_2 VOL_{f,m,t} \\ + \beta_3 Sales_{f,m,t} + \mathrm{X}_{f,m,t} + \Phi_f + \Phi_{m,m\prime,t} + \epsilon_{f,m,t+k}\,, \end{aligned} \quad (7)$$

where $Sales_{f,m,t}$ is the natural logarithm of total sales (SALES_LN) and all other features are similar to the specifications above.

Table 5 reports the results of this empirical analysis. We find that the estimated coefficients of the interaction term ($VOL_{f,m,t} * Sales_{f,m,t}$) are consistently positive and significant for firms' innovation activities as the dependent variables, and negative and significant for firms' cash holdings. These findings show that for larger firms that are less subject to precautionary savings needs under economic uncertainty, the negative (positive) impact of FX volatility on innovation (cash saving) is mitigated. In contrast, smaller firms tend to have tightened financial constraints under economic uncertainty, and are more affected by FX volatility and thus reduce (increase) innovation (cash) more strongly.

4.1.3. Foreign debt

Firms could also be more sensitive to FX volatility through issuing foreign debt (e.g., Aguiar, 2005; Salomao and Varela, 2021). Higher FX volatility leads to more volatile foreign debt value, hence increasing the risk and uncertainty associated with debt obligations. Therefore, when FX volatility is high, firms with more foreign debt require more cash holdings to take precautions, and relatively speaking, face tighter financial constraints. As a result, they may be more reluctant to invest in long-term and risky technological innovation, and instead, they tend to hold more cash to sustain daily firm operations. Therefore, we expect the effect of FX volatility on firm innovation to be stronger for firms with a higher degree of foreign debt issuance.

Unlike other accounting variables, foreign debt information is not directly observed in standard financial statements to the best of our knowledge. We thus closely follow Kalemli-Ozcan, Liu, and Shim (2021) and construct a firm-level foreign debt proxy (FX_DEBT_RATIO_AT) based on the market-level foreign debt ratio and the firm-level total debt ratio. The analysis is confined to a smaller sample of countries with available data. We consider the following regression specification,

$$\begin{aligned} Innov_{f,m,t+k} = \alpha + \beta_1 VOL_{f,m,t} * FX\_DEBT\_RATIO\_AT_{f,m,t} + \beta_2 VOL_{f,m,t} \\ + \beta_3 FX\_DEBT\_RATIO\_AT_{f,m,t} + \mathrm{X}_{f,m,t} + \Phi_f + \Phi_{m,m',t} + \epsilon_{f,m,t+k}. \end{aligned} \tag{8}$$

The model specification is similar to that of the previous subsection, except that we consider the interaction of FX volatility and foreign debt ($VOL_{f,m,t} * FX\_DEBT\_RATIO\_AT_{f,m,t}$).

Table 6 presents the empirical results of this analysis. The interaction term between FX volatility and foreign debt is negative and significant for innovation activities and is positive and significant for cash holdings. These findings are consistent with our proposition that using foreign debt amplifies the adverse impact of FX volatility on technological innovation and induces more cash savings for precautionary motives.

4.1.4. Financial development

Firms located in countries with different levels of financial development may react to FX volatility differently. Aghion et al (2009) suggest that the effect of exchange rate volatility on economic growth depends on financial development. They document that the negative effect of exchange rate volatility concentrates on countries with less developed financial markets, as firms in these countries find it more difficult to acquire financing due to poor credit conditions. To investigate how financial development plays a role in the effects of FX volatility on technological innovation, we consider the following model,

$$Innov_{f,m,t+k} = \alpha + \beta_1 VOL_{f,m,t} * FinDev_{f,t} + \beta_2 VOL_{f,m,t} \\ + X_{f,m,t} + \Phi_f + \Phi_{m,m',t} + \epsilon_{f,m,t+k}\,, \tag{9}$$

where $FinDev_{f,t}$ (Financial_DEVT) is the ratio of credit by banks and other financial institutions to the private sector relative to GDP, as in Levine, Loayza, and Beck (2000) and Aghion et al (2009). The specification is similar to those of previous subsections, except for replacing the appropriate mechanism variable with our financial development variable. Financial development is a market-level variable, and the standalone variable is *absorbed* by the market-market-year fixed effects.

Table 7 reports the empirical results. The interaction term is positive and significant for innovation measures and is negative and significant for cash holdings. These findings are consistent with our argument that the adverse effect of FX volatility on innovation is effectively mitigated in economies with a higher level of financial development. Better-developed credit markets in these economies facilitate firms' external financing, reduce firms' financial constraints, and hence encourage their long-term risky innovation investments. Meanwhile, firms in these economies have less need to save in order to increase cash balances for precautionary purposes. Moreover, we also show that the coefficients of FX volatility remain negative and significant in all columns for innovation-related dependent variables, and their economic magnitude is larger than that of the coefficients of the interaction term. This finding suggests that the negative effect of FX volatility on innovation cannot be fully mitigated by financial market development. Hence, FX volatility represents a distinctive determinant of variations in firm-level technological innovation.

4.1.5. FX volatility and dispersions of earnings forecasts

An implicit assumption of the precautionary savings needs mechanism is that FX volatility makes expected earnings more volatile; thus, firms tend to save more cash in order to avoid the adverse effects of possibly more volatile earnings on corporate activities. This discussion leads to another testable assumption that FX volatility indeed results in more volatile expected earnings.

Empirically, since variables obtained from financial statements are only available at a low frequency (quarterly or annually), a direct estimation (either parametric or nonparametric measure) of earnings volatility requires a very long sample, and the resulting estimate may be inaccurate. Therefore, in this section, we use analyst forecast dispersion of earnings, calculated by the cross-sectional standard deviation of analysts' forecast earnings per share (EPS), obtained from IBES, scaled by the mean forecast, to measure earnings uncertainty. Intuitively, when future earnings of firms are relatively stable, forecasts by different analysts tend to converge. Instead, when futures earnings are highly uncertain, the cross-sectional heterogeneity of analysts' forecasts becomes stronger. Therefore, we expect that FX volatility is positively associated with future earnings dispersion, and estimate the following specification:

$$EarningDisp_{f,m,t+1} = \alpha + \beta VOL_{f,m,t} + X_{f,m,t} + \Phi_f + \Phi_{m,m\prime,t} + \epsilon_{f,m,t+1}\,, \tag{10}$$

where we simply replace the dependent variable in the baseline model with our measure of earnings forecasts dispersion $EarningDisp_{f,m,t+1}$ (PREDICTED_EPS_DISPERSION).

Table 8 presents regression results. In line with our conjecture, FX volatility is indeed positively associated with one-year-ahead earnings forecasts dispersion. The positive relation is statistically significant and economically meaningful. A one standard deviation increase in

FX volatility is associated with a 35% increase in analysts' earnings forecasts dispersion relative to its mean in the next year.[31]

To summarize, therefore, our results reported in this section—based on financial constraints, firm sales, foreign debt, financial development, and earnings dispersion—collectively confirm the explanation based on precautionary savings needs for the negative association between FX volatility and technological innovation.

4.2. *Trade slowdown*

FX volatility may increase trade frictions and slow down cross-border trade, which negatively impacts firms and economies that depend on international trade. As shown in Aghion et al. (2009), a fixed FX regime is more beneficial to economic growth for economies with lower financial development. Since high-tech or innovative firms rely on international trade and cross-border activities to a greater extent, they are also hurt the most by trade slowdowns due to FX volatility (Kenen and Rodrik, 1986). Moreover, recent years have witnessed the rapid growth of international collaboration and trade of technologies (Spulber, 2008). High FX volatility may therefore impede high-tech firms exporting their products and importing innovation input materials, which likely leads to lower patent outputs. In this section, we examine how FX volatility influences innovation activities more when firms do not use currency derivatives to hedge FX risk, or when firms are based in more open economies, as these firms are affected to a great extent by the slowdown of international trade.

4.2.1. Hedging with currency derivatives

Exposure to FX risk may be actively managed by using currency derivatives. Therefore, firms may react differently to FX volatility, depending on whether they use currency derivatives to hedge. For firms using currency derivatives to hedge, their cross-border trading is expected to be less affected by FX volatility. Therefore, the negative impact of FX volatility

[31] The percentage 35% is calculated as 3.808 (coefficient)*0.02(standard deviation of the independent variable)/0.22 (mean of the dependent variable).

on innovation tends to be alleviated for these firms that suffer less from trade slowdown. On the other hand, other firms may not use currency derivatives to hedge possibly because of the lack or insufficient supply of specific financial instruments with which to hedge in some markets. These firms cannot actively manage foreign exchange exposure and hence FX volatility is likely to affect their cross-border trading as well as innovation more severely. To empirically test the impact of hedging, we consider the following specification:

$$Innov_{f,m,t+k} = \alpha + \beta_1 VOL_{f,m,t} * Deri_{f,m,t} + \beta_2 VOL_{f,m,t} \\ +\beta_3 Deri_{f,m,t} + X_{f,m,t} + \Phi_f + \Phi_{m,m\prime,t} + \epsilon_{f,m,t+k} \quad (11)$$

where $Deri_{f,m,t}$ is an indicator variable that equals one if the firm uses currency derivatives (FX_DERI) and zero otherwise. We focus on the interaction term ($VOL_{f,m,t} * Deri_{f,m,t}$): we expect the interaction term to be positive and significant for innovation measures, as using currency derivatives for hedging is expected to mitigate the adverse effect of FX volatility on firm-level innovation activities.

Table 9 reports that the coefficients for the estimated interaction term between exchange rate volatility and derivative usage are indeed positive and significant for innovation measures and are negative and significant for cash holdings. Besides supporting the trade slowdown mechanism, the results of Table 9 also support the view that the use of currency derivatives effectively mitigates the need to hold more cash for precautionary savings needs.

4.2.2. Economic openness

We next investigate the role of economic openness in the FX volatility-innovation relation. Firms in more open economies tend to be more affected by the international business environment, and hence their innovation activities may be deterred more when FX volatility is high. We expect that the effect of FX volatility to be stronger for more open economies. We therefore consider the following model specification:

$$Innov_{f,m,t+k} = \alpha + \beta_1 VOL_{f,m,t} * Open_{m,t} + \beta_2 VOL_{f,m,t} \\ +X_{f,m,t} + \Phi_f + \Phi_{m,m',t} + \epsilon_{f,m,t+k}\,. \quad (12)$$

This specification is again similar to our previous model specifications, except that we focus on the interaction term between FX volatility and economic openness ($Open_{m,t}$). We use the import-export to GDP ratio (IMP_EXP_RATIO) based on data from World Bank to construct a market-level economic openness measure: the higher the ratio, the more open is the economy. Similar to the financial development proxy, economic openness is also a market-level variable, hence the standalone variable is absorbed by the market-market-year fixed effects.

As shown in Table 10, we find that the estimated coefficients for the interaction term between FX volatility and economic openness are negative and significant for innovation measures and are positive and significant for cash holdings. These findings are consistent with our argument that firms located in more open economies reduce their innovation activities because it is more difficult for them to acquire materials and to sell innovative products abroad.

5. Conclusion

This paper empirically investigates the real effects of FX volatility from the perspective of technological innovation. Using a firm-specific measure of currency volatility, we provide cross-market firm-level evidence that FX volatility is a significant determinant of innovation activity. FX volatility negatively affects both innovation inputs (R&D expenditure) and innovation outputs (number of patents granted and patent citations). It also reduces the propensity of a firm to fill a patent. Higher FX volatility also raises firms' cash holdings for precautionary purposes. Moreover, FX volatility depresses innovation originality and exploration, while encouraging innovation generality and exploitation.

We also explore potential economic mechanisms that may explain the negative FX volatility-innovation relation. The negative relation is stronger for firms with a higher degree of financial constraints, smaller firm size, higher foreign debt, and for firms located in countries with less developed financial markets. Higher FX volatility is also followed by more dispersed analyst earnings forecasts. All these findings support a mechanism based on firms' precautionary savings need under volatile FX environments. On the other hand, we also find that the negative FX volatility-innovation relation is mitigated by firms' usage of currency derivatives for hedging purposes and is amplified by economic openness. These findings are consistent with a trade slowdown mechanism.

Overall, this paper provides firm-level evidence for the effects of foreign exchange volatility, a particularly important source of macroeconomic uncertainty, on corporate technological innovation that has important implications for industrial organization and economic growth.

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Table 1 Summary Statistics

Dependent Variables	Obs	Mean	Std	Median
CASH_RATIO_AT	8,928	0.17	0.13	0.13
CITATION_DOM_LN	10,624	0.05	0.36	0.00
CITATION_US_LN	10,624	0.26	1.03	0.00
EXPLOIT_RATE	10,624	0.00	0.02	0.00
EXPLORE_RATE	10,624	0.03	0.15	0.00
FILE_PATENT_DUMMY	10,624	0.17	0.37	0.00
GENERALITY	10,624	0.00	0.02	0.00
ORIGINALITY	10,624	0.00	0.03	0.00
PATENT_DOM_LN	10,624	0.10	0.57	0.00
PATENT_US_LN	10,624	0.47	1.33	0.00
PREDICTED_EPS_DISPERSION	4,668	0.22	0.65	0.12
RD_RATIO_AT	10,624	0.02	0.07	0.01
Independent Variables	**Obs**	**Mean**	**Std**	**Median**
WEIGHTED_ERM_SHOCK	250	0.00	0.01	0.00
WEIGHTED_FIXED_TO_FLOAT	10,624	0.00	0.02	0.00
WEIGHTED_FLOAT_TO_FIXED	10,624	0.00	0.02	0.00
WEIGHTED_GARCH_VOL	10,421	0.04	0.06	0.02
WEIGHTED_NEWS_UNCERTAINTY	9,650	1.45	1.59	0.85
WEIGHTED_ROSSI_FORECAST_UNCERTAINTY	10,094	0.28	0.22	0.25
WEIGHTED_VOL	10,624	0.02	0.02	0.02
Interaction Variables	**Obs**	**Mean**	**Std**	**Median**
KZ_INDEX	9,462	-0.22	2.26	0.33
FINANCIAL_DEVT	9,500	141.42	38.35	160.36
FX_DEBT_RATIO_AT	965	0.01	0.01	0.01
FX_DERI	2,923	0.28	0.45	0.00
IMP_EXP_RATIO	9,607	47.25	31.37	35.60
SALES_LN	10,345	20.61	2.04	20.62
Control Variables	**Obs**	**Mean**	**Std**	**Median**
WEIGHTED_FX_RATE_CHANGE	10,624	0.00	0.02	0.00
EBIDTA	10,624	0.09	0.08	3.14
EBIDTA_VOL	10,624	0.05	0.05	0.10
FIRM_AGE	10,624	2.99	0.51	0.00
LEVERAGE	10,624	0.13	0.13	0.05
LOSS	10,624	0.13	0.34	0.03
PTBI	10,624	0.05	0.10	0.00
PTBI_VOL	10,624	0.05	0.06	1.07
SGA_DELTA	10,624	0.00	0.07	20.67
TOBINQ	10,624	1.38	0.97	1.07
TOTAL_ASSETS_LN	10,624	20.85	2.09	20.67

Table 2: Currency Volatility and Innovation

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	CASH_RATIO_AT	RD_RATIO_AT	PATENT_DOM_LN	CITATION_DOM_LN	PATENT_US_LN	CITATION_US_LN	FILE_PATENT_DUMMY
WEIGHTED_VOL	0.141**	-0.0871**	-1.046***	-0.157***	-4.095***	-3.528***	-1.794***
	(2.469)	(-2.249)	(-7.846)	(-4.581)	(-7.956)	(-4.249)	(-5.293)
WEIGHTED_FX_RATE_CHANGE	-0.0684**	0.0833	-0.0819	-0.000783	1.398***	1.045***	0.215*
	(-2.394)	(1.594)	(-1.014)	(-0.0135)	(4.525)	(5.205)	(1.768)
TOBINQ	0.0122**	2.92e-05	-0.00457	0.00409	-0.0233	-0.0129	-0.00621
	(2.426)	(0.0125)	(-0.413)	(0.811)	(-0.543)	(-0.545)	(-0.401)
EBIDTA	-0.00681	0.0340	-0.211**	-0.0653	1.394	0.528	0.167
	(-0.0452)	(1.280)	(-2.591)	(-0.422)	(1.404)	(1.039)	(1.092)
EBIDTA_VOL	0.171***	-0.0150	-0.0689	-0.117	0.680**	0.517	0.180*
	(4.599)	(-0.428)	(-0.430)	(-0.838)	(2.145)	(1.328)	(1.890)
PTBI	0.0981*	0.00988	0.0914	0.00926	-0.559***	-0.0240	-0.0737
	(1.772)	(0.458)	(0.798)	(0.426)	(-3.043)	(-0.146)	(-1.622)
PTBI_VOL	-0.0872	0.000831	0.211	0.146	0.664	-0.168	0.231
	(-1.690)	(0.0202)	(1.667)	(1.401)	(1.102)	(-0.556)	(1.390)
LEVERAGE	-0.0127	0.00676	0.0287	0.0183	0.162	-0.0356	0.00873
	(-0.719)	(1.249)	(1.007)	(1.558)	(0.795)	(-0.429)	(0.293)
LOSS	0.00354*	0.00122**	-0.00973	-0.00421	-0.00748	-0.0132	0.00322
	(1.774)	(2.109)	(-1.275)	(-1.077)	(-0.167)	(-0.321)	(0.253)
SGA_DELTA	-0.0226	-0.00838	0.0249	0.0389*	0.133*	0.0581	-0.0383*
	(-0.549)	(-0.560)	(0.707)	(1.734)	(1.722)	(0.406)	(-2.038)
TOTAL_ASSETS_LN	-0.0440***	-0.00457***	0.0258	0.0165	0.104***	0.0551	0.0330
	(-3.244)	(-3.562)	(0.534)	(0.247)	(3.233)	(1.402)	(1.394)
FIRM_AGE	0.0548***	-0.00505	0.0466	0.0403	2.091**	1.269***	0.485*
	(4.392)	(-0.601)	(0.435)	(1.615)	(2.433)	(3.372)	(1.917)
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,928	10,624	10,624	10,624	10,624	10,624	10,624
R-squared	0.909	0.949	0.832	0.902	0.800	0.835	0.809

Notes: This table presents the effects of firm-specific currency volatility on firm innovation. The sample is at the firm-year level. The dependent variables listed in the table headers are cash holding and innovation measures in year *t+1* (Columns 1 and 2) or *t+4* (Columns 3 to 7), including cash to total asset ratio (CASH_RATIO_AT), R&D expenses to total assets ratio (RD_RATIO_AT), natural logarithm of home country-registered patent number (PATENT_DOM_LN), natural logarithm of home country-registered patents' forward citation (CITATION_DOM_LN), natural logarithm of US-registered patent number (PATENT_US_LN), natural logarithm of US-registered patents' forward citation (CITATION_US_LN), and firm patent file dummy (FILE_PATENT_DUMMY). The independent variable of interest is the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales. In all regressions, we control firm-year characteristics including firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE), Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 3: Innovation Characteristics

	(1) GENERALITY	(2) EXPLOIT_RATIO	(3) ORIGINALITY	(4) EXPLORE_RATIO
WEIGHTED_VOL	0.00275*	0.00708***	-0.0214**	-0.150***
	(1.870)	(3.037)	(-2.219)	(-3.669)
WEIGHTED_FX_RATE_CHANGE	-0.000869	-0.00241***	0.00397	-0.0232
	(-1.130)	(-3.046)	(1.182)	(-1.064)
TOBINQ	0.000542	-0.000157	-0.00125	-0.00287
	(1.579)	(-1.152)	(-1.337)	(-0.689)
EBIDTA	0.00107	0.00629*	-0.00260	-0.00950
	(1.211)	(1.942)	(-0.612)	(-0.269)
EBIDTA_VOL	-0.00341	0.0113	0.00281	0.0777
	(-0.700)	(1.096)	(0.210)	(1.120)
PTBI	-0.00158*	-7.14e-05	0.00243	0.0153
	(-1.879)	(-0.0759)	(1.280)	(0.823)
PTBI_VOL	0.00337	-0.00626	0.00167	-0.00259
	(1.312)	(-1.028)	(0.262)	(-0.0831)
LEVERAGE	-0.00168*	-0.000414***	-0.00375	0.00980
	(-1.700)	(-2.857)	(-1.063)	(1.101)
LOSS	6.47e-05	0.000503***	-5.43e-05	-0.00645*
	(0.418)	(4.339)	(-0.137)	(-1.987)
SGA_DELTA	0.00262	-0.00230	0.00283	0.0142
	(1.171)	(-0.918)	(1.022)	(0.883)
TOTAL_ASSETS_LN	-0.000972	-0.000108	0.000658	0.0202
	(-1.379)	(-0.669)	(0.388)	(1.013)
FIRM_AGE	0.00284***	0.000715	0.00130	-0.0498
	(2.917)	(0.826)	(0.249)	(-1.569)
Constant	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes
Observations	10,624	10,624	10,624	10,624
R-squared	0.930	0.932	0.867	0.872

Notes: This table presents the effects of firm-specific currency volatility on firm innovation characteristics. The sample is at the firm-year level. The dependent variables listed in the table headers are innovation characteristics measures in year *t+4*, including GENERALITY, EXPLOIT_RATIO, ORIGINALITY, and EXPLORE_RATIO that are defined in Table A1. The independent variable of interest is the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales. In all regressions, we control firm-year characteristics including firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE), Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 4: Financial Constraints

	(1) CASH_RATIO_AT	(3) RD_RATIO_AT	(5) PATENT_DOM_LN	(6) CITATION_DOM_LN	(7) PATENT_US_LN	(8) CITATION_US_LN	(9) FILE_PATENT_DUMMY
WEIGHTED_VOL * KZ_INDEX	0.0963**	-0.0222**	-0.477***	-0.119**	-1.360***	-1.011***	-0.487***
	(2.645)	(-2.343)	(-4.601)	(-2.550)	(-6.843)	(-4.143)	(-4.505)
WEIGHTED_VOL	-0.0104	-0.0243	-1.425***	-0.343***	-5.075***	-4.238***	-1.901***
	(-0.228)	(-0.969)	(-7.671)	(-6.171)	(-21.10)	(-8.334)	(-9.974)
KZ_INDEX	-0.0154***	0.000545***	0.00945***	0.00277	0.00963	0.0229***	0.00634
	(-5.425)	(3.112)	(3.124)	(1.344)	(0.762)	(3.997)	(1.290)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,160	9,462	9,462	9,462	9,462	9,462	9,462
R-squared	0.922	0.955	0.868	0.949	0.816	0.857	0.827

Notes: This table presents the heterogeneous effects of firm-specific currency volatility on the innovation of firms with different degrees of financial constraints. The sample is at the firm-year level. The dependent variables listed in the table headers are the same as in Table 2. The independent variables of interests include 1) the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales, 2) the Kaplan-Zingales Index that measures the firm financial constraint (KZ_INDEX), and 3) the interaction term of 1) and 2). In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 5: Firm Sales

	(1) CASH_RATIO_AT	(3) RD_RATIO_AT	(5) PATENT_DOM_LN	(6) CITATION_DOM_LN	(7) PATENT_US_LN	(8) CITATION_US_LN	(9) FILE_PATENT_DUMMY
WEIGHTED_VOL * SALES_LN	-0.0745**	0.0307***	0.782***	0.376***	4.442***	1.820*	1.019***
	(-2.520)	(3.629)	(4.540)	(3.854)	(3.393)	(2.005)	(4.014)
WEIGHTED_VOL	1.632**	-0.688***	-16.04***	-7.412***	-91.73***	-38.37**	-21.87***
	(2.467)	(-3.667)	(-4.481)	(-3.601)	(-3.407)	(-2.091)	(-4.245)
SALES_LN	0.00575	0.00652*	0.0138	0.00757*	0.0368	0.0720**	-0.00205
	(1.302)	(1.945)	(1.265)	(1.761)	(1.001)	(2.380)	(-0.215)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,697	10,345	10,345	10,345	10,345	10,345	10,345
R-squared	0.915	0.965	0.864	0.927	0.803	0.851	0.816

Notes: This table presents the heterogeneous effects of firm-specific currency volatility on the innovation of firms with different degrees of sales. The sample is at the firm-year level. The dependent variables listed in the table headers are the same as in Table 2. The independent variables of interests include 1) the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales, 2) natural logarithm of net sales or revenues (SALES_LN), and 3) the interaction term of 1) and 2). In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 6: Foreign Debt

	(1) CASH_RATIO_AT	(3) RD_RATIO_AT	(5) PATENT_DOM_LN	(6) CITATION_DOM_LN	(7) PATENT_US_LN	(8) CITATION_US_LN	(9) FILE_PATENT_DUMMY
WEIGHTED_VOL * FX_DEBT_RATIO_AT	55.35***	-41.39**	-110.6***	-28.27**	-61.32***	-9.493***	-80.91***
	(7.592)	(-3.272)	(-4.096)	(-3.833)	(-5.522)	(-4.863)	(-4.328)
WEIGHTED_VOL	-0.665***	0.593***	1.030**	0.202**	0.813***	-1.204***	0.858***
	(-50.78)	(4.429)	(3.934)	(3.181)	(6.588)	(-17.16)	(4.878)
FX_DEBT_RATIO_AT	-2.773**	-2.218***	4.052**	0.850**	0.476***	0.860**	1.295**
	(-2.782)	(-7.847)	(3.541)	(3.745)	(4.456)	(3.019)	(3.042)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	810	965	965	965	965	965	965
R-squared	0.876	0.659	0.960	0.995	0.978	0.981	0.939

Notes: This table presents the heterogeneous effects of firm-specific currency volatility on the innovation of firms with different degrees of foreign debt. The sample is at the firm-year level. The dependent variables listed in the table headers are the same as in Table 2. The independent variables of interests include 1) the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales, 2) a measure of firm-level foreign debt (FX_DEBT_RATIO_AT), calculated as the ratio of total foreign debt to total debt in the market level scaled by firm total debt, then scaled by total asset 3) the interaction term of 1) and 2). In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 7: Financial Development

	(1) CASH_RATIO_AT	(3) RD_RATIO_AT	(5) PATENT_DOM_LN	(6) CITATION_DOM_LN	(7) PATENT_US_LN	(8) CITATION_US_LN	(9) FILE_PATENT_DUMMY
WEIGHTED_VOL * FINANCIAL_DEVT	-0.0111***	0.00174**	0.0434***	0.0198**	0.155***	0.145**	0.0587***
	(-6.038)	(2.722)	(4.388)	(2.612)	(3.749)	(2.522)	(2.823)
WEIGHTED_VOL	1.710***	-0.333***	-6.265***	-2.836**	-22.07***	-22.15**	-9.420**
	(6.306)	(-2.882)	(-4.035)	(-2.390)	(-3.015)	(-2.422)	(-2.650)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,015	9,500	9,500	9,500	9,500	9,500	9,500
R-squared	0.917	0.912	0.852	0.902	0.818	0.847	0.819

Notes: This table presents the heterogeneous effects of firm-specific currency volatility on the innovation of firms in countries with different degrees of financial development. The sample is at the firm-year level. The dependent variables listed in the table headers are the same as in Table 2. The independent variables of interests include 1) the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales, and 2) the interaction of firm-specific currency volatility and a measure of financial development calculated as credit provided by banks and other financial institutions to private sectors, scaled by GDP (FINANCIAL_DEVT). In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables, such as FINANCIAL_DEVT itself). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 8: Dispersion of Analyst Earnings Forecasts

	(1) PREDICTED_EPS_DISPERSION
WEIGHTED_VOL	3.808***
	(3.997)
Control	Yes
Constant	Yes
Market*Market*Year FE	Yes
Firm FE	Yes
Cluster at Market Level	Yes
Observations	4,668
R-squared	0.657

Notes: This table presents the effects of firm-specific currency volatility on the cross-sectional dispersion of analyst forecasts of earnings of the firm. The sample is at the firm-year level. The dependent variable listed in the table header is the standard deviation of analyst forecast EPS scaled by mean values of the forecast (PREDICTED_EPS_DISPERSION), defined in Table A1. The independent variable of interest is the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales. In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 9: Hedging of FX Derivatives

	(2) CASH_RATIO_AT	(3) RD_RATIO_AT	(5) PATENT_DOM_LN	(6) CITATION_DOM_LN	(7) PATENT_US_LN	(8) CITATION_US_LN	(9) FILE_PATENT_DUMMY
WEIGHTED_VOL * FX_DERI	-0.485***	0.300***	1.469***	0.637***	4.562***	3.716***	2.177***
	(-4.655)	(3.297)	(3.040)	(2.966)	(3.934)	(2.921)	(5.670)
WEIGHTED_VOL	-0.306	-0.249	-1.743***	-0.535	-9.738***	-9.455**	-5.747***
	(-0.443)	(-1.616)	(-2.793)	(-0.974)	(-4.402)	(-2.616)	(-10.40)
FX_DERI	0.0109	-0.00291	-0.0883*	-0.0434	0.00447	0.0251	-0.0289
	(1.588)	(-1.434)	(-1.787)	(-1.238)	(0.0926)	(0.567)	(-1.601)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2,368	2,923	2,923	2,923	2,923	2,923	2,923
R-squared	0.955	0.957	0.928	0.930	0.953	0.960	0.940

Notes: This table presents the heterogeneous effects of firm-specific currency volatility on the innovation of firms with and without using FX derivatives to hedge. The sample is at the firm-year level. The dependent variables listed in the table headers are the same as in Table 2. The independent variables of interests include 1) the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales, 2) a dummy variable that equals one if the firm uses foreign exchange derivatives to hedge (FX_DERI)), and 3) the interaction term of 1) and 2). In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Table 10: Economic Openness

	(1) CASH_RATIO_AT	(2) RD_RATIO_AT	(3) PATENT_DOM_LN	(4) CITATION_DOM_LN	(5) PATENT_US_LN	(6) CITATION_US_LN	(7) FILE_PATENT_DUMMY
WEIGHTED_VOL * IMP_EXP_RATIO	0.00872***	-0.00447**	-0.117**	-0.0469**	-0.922**	-0.578**	-0.231**
	(2.990)	(-2.361)	(-2.569)	(-2.682)	(-2.052)	(-2.131)	(-2.264)
WEIGHTED_VOL	-0.326***	0.134**	3.556**	1.687***	30.24**	18.43**	6.555**
	(-2.859)	(2.272)	(2.442)	(3.138)	(2.221)	(2.179)	(2.046)
Control	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Constant	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Market*Market*Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Cluster at Market Level	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	8,712	9,607	9,607	9,607	9,607	9,607	9,607
R-squared	0.913	0.974	0.846	0.913	0.813	0.846	0.818

Notes: This table presents the heterogeneous effects of firm-specific currency volatility on the innovation of firms with different degrees of economic openness. The sample is at the firm-year level. T The dependent variables listed in the table headers are the same as in Table 2. The independent variables of interests include 1) the firm-specific currency volatility (WEIGHTED_VOL), calculated as market-level realized volatility weighted by the ratio of foreign sales in a specific market to total sales, 2) the sum of imports and exports of goods and services scaled by GDP (IMPORT_EXPORT_RATIO), and 3) the interaction term of 1) and 2). In all regressions, we control for firm-level exchange rate changes (WEIGHTED_FX_RATE_CHANGE) and other firm-year characteristics including Tobin's Q, EBITDA, EBITDA_VOL, PTBI, PTBI_VOL, LEVERAGE, LOSS, SGA_DELTA, TOTAL_ASSETS_LN, and FIRM_AGE that are defined in Table A1. We also control for the firm fixed effects to absorb all firm-specific omitted variables, and market-market-year effects, which should absorb all time-varying and pairwise markets specific variables (including market-specific variables). Standard errors are clustered at the market level. Robust t-statistics are in parentheses. ***, ** and * denotes 1%, 5% and 10% statistical significance.

Appendix A: Additional Tables

Table A1: Variable Definition

Variable Name	Definition	Source
Dependent Variables		
CASH_RATIO_AT	Cash and Short-Term Investment (ITEM2001) / lagged Total Assets (ITEM2999).	*Worldscope, Compustat Global*
CITATION_DOM_LN	Natural logarithm of one plus the number of forward citations of domestic patents granted to a firm.	*REGPAT*
CITATION_US_LN	Natural logarithm of one plus the number of forward citations of US patents granted to a firm.	*Univ of Virginia USPTO NBER*
EXPLOIT_RATIO	The number of exploitative patents granted to a firm divided by the total number of patents granted in a year. This measure is constructed in three steps following Benner and Tushman (2002).	*REGPAT*
EXPLORE_RATIO	The number of exploratory patents granted to a firm divided by the total number of patents granted in a year. This measure is constructed in three steps following Benner and Tushman (2002).	*REGPAT*
FILE_PATENT_DUMMY	Dummy variable that equals one if firm files at least one international or US patent and zero otherwise.	*REGPAT Univ of Virginia USPTO NBER*
GENERALITY	The average of generality scores of all patents granted to a firm in a year. The generality score for a patent is defined as one minus the Herfindahl Index of the three-digit technology class distribution of all subsequent patents that cite the focal patent.	*REGPAT*
ORIGINALITY	The average of originality scores of all patents granted to a firm in a year. The originality score for a patent is defined as one minus the Herfindahl Index of the three-digit technology class distribution of all prior patents cited by the focal patent.	*REGPAT*
PATENT_DOM_LN	Natural logarithm of one plus the number of domestic patents granted to a firm.	*REGPAT*
PATENT_US_LN	Natural logarithm of one plus the number of US patents granted to a firm.	*Univ of Virginia USPTO NBER*
PREDICTED_EPS_DISPERSION	Standard deviation of the analyst forecast on EPS.	*IBES*
RD_RATIO_AT	Research & Development Expense (ITEM1201) scaled by lagged Total Assets (ITEM2999).	*Worldscope, Compustat Global*

Independent Variables		
FINANCIAL_DEVT	Credit provided by banks and other financial institutions to private sectors (% of GDP), as in *Levine et al (2000).*	*World Bank*
FX_DEBT_RATIO_AT	Firm-level foreign currency debt / Total Assets (ITEM2999). Firm-level foreign currency debt is calculated following *Kalemli-Ozcan et al (2021).*	*Worldscope, Compustat Global, World Bank, BIS*
FX_DERI	Dummy variable that equal one if we find keywords "derivative" and "hedging" in the annual report and then find that "foreign exchange", "exchange rate", or "currency" appears 100 words before or after "derivative", and zero otherwise.	*Reuters Eikon, SEC Edgar*
IMP_EXP_RATIO	Imports of goods and services + Exports of goods and services (% of GDP).	*World Bank*
KZ_INDEX	Kaplan-Zingales Index = -1.001909 * $ITEM1551_{t-1}$ / $ITEM2501_{t-1}$ + 0.2826389 * ($ITEM2999_t$ + $ITEM7210_t$ - $ITEM3501_t$) / $ITEM2999_t$ + 3.139193 * ($ITEM8221_t$ / 100) -39.3678 * $ITEM4052_t$ / $ITEM2501_{t-1}$ - 1.314759 * $ITEM2001_t$ / $ITEM2501_{t-1}$	*Worldscope, Compustat Global, Lamont, Polk, and Saá-Requejo (2001)*
SALES_LN	Natural logarithm of Total Sales or Revenues (ITEM1001) in USD.	*Worldscope, Compustat Global*
WEIGHTED_ERM_SHOCK	Sales-weighted average of dummy variable 1(ERM), which is defined as one if a firm sells to the UK or Italy in 1992 or after and zero otherwise. The firm-year level variable is then the weighted average of country-level dummy variable, and the weight is calculated as firm foreign sales in each market to total sales ratio.	*FactSet Geographic Exposure*
WEIGHTED_FIOAT_TO_FIXED	Sales-weighted average of dummy variable 1(float to fixed), which is defined as one if a currency changes from a floating to a fixed regime in a year and zero otherwise. The firm-year level variable is then the weighted average of country-level dummy variable, and the weight is calculated as firm foreign sales in each market to total sales ratio.	*Worldscope, Compustat Global, FactSet Geographic Exposure, Ilzetzki et al (2019)*
WEIGHTED_FIXED_TO_FLOAT	Sales-weighted average of dummy variable 1(fixed to float), which is defined as one if a currency changes from a floating to a fixed regime in a year and zero otherwise. The firm-year level variable is then the weighted average of country-level dummy variable, and the weight is calculated as firm foreign sales in each market to total sales ratio.	*Worldscope, Compustat Global, FactSet Geographic Exposure, Ilzetzki et al (2019)*

WEIGHTED_GARCH_VOL	Sales-weighted average of GARCH volatility, which is defined as volatility calculated based on the GARCH model using daily exchange rate return data over the year. The firm-year level variable is then the weighted average of country-level GARCH volatility, and the weight is calculated as firm foreign sales in each market to total sales ratio.	*Worldscope, Compustat Global, FactSet Geographic Exposure, Datastream*
WEIGHTED_VOL	Sales-weighted average of realized volatility, which is defined as volatility calculated based on sample standard deviation using daily exchange rate return data over the year. The firm-year level variable is then the weighted average of country-level realized volatility, and the weight is calculated as firm foreign sales in each market to total sales ratio.	*Worldscope, Compustat Global, FactSet Geographic Exposure, Datastream*

Control Variables

WEIGHTED_FX_RATE_CHANGE	Sales-weighted average of exchange rate change, which is log exchange rate return. The firm-year level variable is then the weighted average of country-level exchange rate return for pairwise currencies between the home country and the foreign market, and the weight is calculated as firm foreign sales in each market to total sales ratio.	*Worldscope, Compustat Global, FactSet Geographic Exposure, Datastream*
TOBINQ	Tobin's Q, calculated as (Total Assets (ITEM2999) + Market Capitalization (ITEM7210) - Stockholders Equity (ITEM3501)) / Total Assets (ITEM2999).	*Worldscope, Compustat Global*
EBIDTA	Mean of (Earnings Before Interest (ITEM18198) / lagged Total Assets (ITEM2999)) over the last five years.	*Worldscope, Compustat Global*
EBIDTA_VOL	Standard deviation of (Earnings Before Interest (ITEM18198) / lagged Total Assets (ITEM2999)) over the last five years.	*Worldscope, Compustat Global*
FIRM_AGE	Natural logarithm of firm age.	*Worldscope, Compustat Global*
LEVERAGE	Long-Term Debt (ITEM3251) / lagged Total Assets (ITEM2999).	*Worldscope, Compustat Global*
LOSS	Dummy variable that equals one if the firm reports a loss (Income Before Extraordinary Items (ITEM1551) < 0) in any of the last three fiscal years and zero otherwise.	*Worldscope, Compustat Global*
PTBI	Pretax Income (ITEM1401) / lagged Total Assets (ITEM2999).	*Worldscope, Compustat Global*

PTBI_VOL	Standard deviation of (Pretax Income (ITEM1401) / lagged Total Assets (ITEM2999)) over the last five years.	*Worldscope, Compustat Global*
SGA_DELTA	The change in (Sales (ITEM1001) / Total Assets (ITEM2999)) over the prior fiscal year.	*Worldscope, Compustat Global*
TOTAL_ASSETS_LN	Natural logarithm of Total Assets (ITEM7230) in USD.	*Worldscope, Compustat Global*

Table A2: List of Markets

Country (Headquarter)	Num Firm	Num Obs	Year Start	Year End
AUS	79	545	1990	2018
AUT	25	176	1994	2018
BEL	12	60	1994	2018
BRA	7	41	1999	2018
CAN	58	372	1990	2018
CHE	21	171	1989	2018
DEU	52	282	1990	2018
DNK	19	118	1994	2018
ESP	5	37	2001	2018
FIN	20	139	1994	2018
FRA	59	305	1990	2018
GBR	95	603	1990	2018
GRC	2	8	2004	2017
HKG	1	11	2005	2017
IND	96	739	2002	2018
IRL	2	7	2009	2017
ISR	12	45	1998	2018
ITA	22	98	1989	2018
JPN	805	6,121	1998	2018
KOR	29	92	2001	2018
MEX	2	14	1994	2004
NLD	11	49	1992	2018
NOR	15	53	1993	2018
NZL	18	156	1990	2018
POL	1	5	2014	2018
RUS	1	9	2004	2012
SGP	4	31	2003	2017
SVN	1	1	2007	2007
SWE	24	183	1990	2018
THA	1	8	2009	2018
TWN	12	58	2010	2018
ZAF	8	87	2002	2018
Total	1,519	10,624	1989	2018

Note: This table lists the countries and regions of our sample firms in the main analyses, as well as the number of firms, the number of observations, the first and the ending year of the sample of each market.