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Contents

Summary

This thesis contributes to three major fields in the international finance literature: forward premium anomaly, monetary policy and exchange rate determination, and measuring monetary policy expectations from asset prices.

In the first chapter, I develop a production-based asset pricing model predicting that excess returns of currency carry trade compensate investors for the commodity price risk. Commodity producers differ in their exposure to the export price risk. Exchange rate-commodity price covariance, procyclical interest rates, negative price of exchange rate volatility, and countercyclical currency risk premium arise endogenously. Empirically, risk factors implied by the model explain up to 55% of time-series variation in carry trade returns across developed countries, and generate substantial risk- and transaction costs-adjusted returns as tradable strategies.

In the second chapter (jointly with Igor Pozdeev), we document a drift in exchange rates before monetary policy changes across major economies. Currencies tend to depreciate by 0.8% over ten days before policy rate cuts and appreciate by 0.5% before policy rate increases. We show that available fixed income instruments allow to forecast monetary policy decisions and thus that the drift is exploitable by investors. Buying (selling) currencies ten days in advance of predicted target rate hikes (cuts) earns on average a statistically significant excess return of over 40 basis points per ten-day period after trading costs. We further demonstrate that this return is robust to the choice of holding horizon and monetary policy forecast rule. Our results thus pose a major challenge for the risk-based explanations of the exchange rate dynamics.

In the third chapter (jointly with Igor Pozdeev), we document overnight index swaps (OIS) to be unbiased predictors of future short rates in developed economies, bearing no significant risk premium for maturities up to one year. We show that the OIS underlying overnight rates accurately reflect the target rates set by central banks. We extract the implied future target rates from the OIS prices to predict the outcome of monetary policy meetings around the world. In the US, a randomly selected triplet of a target rate hike, cut and no-change is correctly classified using the OIS-implied rates in 99.9 and 98% of cases five and ten days before a FOMC announcement respectively. We report similarly high prediction accuracy for other developed countries.

Zusammenfassung

Diese Arbeit trägt zu drei Hauptbereichen der Forschung der internationalen Finanzen bei: zum Thema der Forward-Prämie-Anomalie, der Geldpolitik und Wechselkursdynamik, sowie der Messung der geldpolitischen Erwartungen aus den Vermögenspreisen.

Im ersten Kapitel entwickle ich ein produktionsbasiertes Asset-Pricing-Modell, wo die Überschussrenditen des Carry-Trade-Handels die Anleger für das Rohstoffpreisrisiko entschädigen. Rohstoffproduzenten unterscheiden sich in ihrem Exposure gegenüber dem Exportpreisrisiko. Die Kovarianz zwischen Wechselkursen und Rohstoffpreisen, prozyklische Zinssätze, ein negativer Preis der Wechselkursvolatilität und antizyklische Währungsrisikoprämie entstehen endogen. Empirisch erklären die vom Modell implizierten Risikofaktoren bis zu 55% der Zeitreihenvariation der Carry-Trade-Renditen in den Industrieländern und generieren substanzielle risiko- und transaktionskostenbereinigte Renditen als handelbare Strategien.

Im zweiten Kapitel (gemeinsam mit Igor Pozdeev) dokumentieren wir einen Trend in den Wechselkurse vor Anpassungen der Geldpolitik in den Industrieländern. Die Währungen neigen dazu, innerhalb von zehn Tagen vor der Leitzinssenkung um 0.8% zu fallen und vor der Erhöhung der Leitzinsen um 0.5% zu steigen. Wir zeigen, dass verfügbare festverzinsliche Wertpapiere es erlauben, geldpolitische Entscheidungen zu prognostizieren und somit der Trend von Investoren ausgenutzt werden kann. Das Kaufen (Verkaufen) von Währungen zehn Tage vor den vorhergesagten Leitzinsanhebungen (-senkungen) liefert im Durchschnitt eine statistisch signifikante Rendite von mehr als 40 Basispunkten pro Zehn-Tage-Periode nach den Handelskosten. Darüber hinaus zeigen wir, dass diese Rendite robust gegenüber der Wahl der Haltefrist- und der geldpolitischen Prognose ist. Unsere Ergebnisse stellen somit eine grosse Herausforderung für die risikobasierten Erklärungen der Wechselkursdynamik dar.

Im dritten Kapitel (gemeinsam mit Igor Pozdeev) dokumentieren wir, dass Overnight Index Swaps (OIS) unverzerrte Prädiktoren für künftige kurzfristige Zinssätze in Industrieländern sind. Wir zeigen, dass die OIS keine signifikante Risikoprämie für Laufzeiten bis zu einem Jahr aufweisen, und dass die zugrunde liegenden Overnight-Sätze der OIS die von den Zentralbanken festgelegten Zielquoten genau widerspiegeln. Wir extrahieren die impliziten zukünftigen Zielzinssätze aus den OIS-Preisen, um das Ergebnis der geldpolitischen Gremien auf der ganzen Welt vorherzusagen. In den USA wird ein zufällig ausgewähltes Triplett einer Leitzinserhöhung, -kürzung und keiner Änderung korrekt unter Verwendung der OIS-implizierten Raten in 99.9 und 98% der Fälle fünf bzw. zehn Tage vor einer FOMC-Ankündigung klassifiziert. Wir dokumentieren eine ähnlich hohe Vorhersagegenauigkeit für andere Industrieländer.

Preface

This thesis consists of three chapters, each contributing to three major fields in the international finance literature: forward premium anomaly and risk-based explanations of the currency returns, monetary policy and exchange rate determination, and measuring monetary policy expectations from asset prices. Each chapter is structured as a separate working paper contributing to the research in one of the aforementioned areas. Below I provide a brief summary of the main research questions and highlight the key results.

In the first chapter titled ”Carry Trades and Commodity Price Risk in Production Economies”,[1] I develop a production-based asset pricing model predicting that excess returns of so-called carry trades, i.e. borrowing in low interest rate currencies and investing in high interest rate currencies, compensate investors for the commodity price risk. In my model exporters of commodities have heterogeneous exposures to the export price risk and show that this model can account for deviations from the uncovered interest parity (UIP) and thus for the forward premium anomaly and profitability of currency carry trades. The mechanics of the model can be summarized as follows: free international flows of investment combined with heterogeneity in revenues due to export tariffs, shipment costs or other frictions result in differential loadings of producers' pricing kernels on the common risk factor – commodity price, thus production in the foreign relatively insulated economy is less risky, leading to a lower foreign Sharpe ratio and hence to a positive expected return on the foreign currency. In bad times when commodity price uncertainty is high, interest rates in the domestic relatively exposed economy decrease by a greater amount than in the foreign insulated economy, simultaneously expected excess return on investment (equivalently Sharpe ratio) rises more domestically than abroad, thus commanding an increase in the currency risk premium, to make domestic investors indifferent between investing at home or abroad, rationalizing deviations from the UIP. Exchange rate-commodity price covariance, procyclical interest rates, negative price of exchange rate volatility, and countercyclical currency risk premium arise endogenously, ensuring absence of arbitrage between investment returns across countries.

I further provide broad empirical evidence supporting the theoretical model documenting strong commonality between the dynamics of commodity market and FX excess returns. I show that the aggregate commodity market risk is different from the aggregate FX market risk and possesses sizable explanatory power in capturing both time-series and cross-sectional variation of excess returns of carry trade portfolios and individual currencies through several distinct channels. Empirically, the risk factors implied by the model explain up to 55% of time-series variation in carry

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[1] The paper was awarded the 2017 SummerHaven Commodity Research Fellowship.

trade returns across developed countries, and generate substantial risk- and transaction costs-adjusted returns as tradable strategies.

Overall, the first chapter contributes to the growing literature on risk-based explanations of the forward premium anomaly and on relationships between currencies and other asset classes.

In the second chapter "Monetary Policy and Currency Returns: the Foresight Saga"[2] (joint with Igor Pozdeev), we study behavior of exchange rates around monetary policy announcements around the globe. Previous research has primarily focused on dynamics of asset prices around the announcements of the US Federal Open Markets Committee. In this paper, we bring the currencies and policy announcements of other developed countries into the picture. Our primary contribution is to document an economically and statistically significant drift in exchange rates several days in advance of changes in target policy rates across major economies. We show that a randomly selected currency is expected to depreciate against the USD by 80 basis points over the 10 days before before a randomly selected rate cut, and appreciate by 50 basis points in the opposite case, which is statistically significant at the 5% level. We find that the multiperiod appreciation before rate hikes and depreciation before rate cuts is a phenomenon common to most currencies – not only to the US dollar as documented in previous research. We further demonstrate that this drift can be exploited by investors as a trading strategy. Using overnight index swaps, we forecast upcoming rate changes and go long in currencies ten days in advance of an expected rate hike and short in those with an expected rate cut. The strategy features a statistically and economically significant excess return of over 40 basis points per event after transaction costs, a cumulative of 127 percent since late 2000.

Our second contribution is to point out that forecasting monetary policy direction is a classification problem and thus subject to the discretionary choice of the classification rule. The holding period is another "tweaker" for the trader or researcher to adjust. Thus, there exist many possible forecast-based trading strategies: one for each element of the Cartesian product of the set of possible classification rules and the set of possible holding periods. Since it is never clear *ex ante* which strategy specification will result in a significant return, the backward-looking bias might contaminate the inference. We construct a plethora of specifications and show that our findings are very robust: the average return across all specifications amounts to 80 percent since late 2000 while several specifications lead to as much as a 225 percent return and only a handful – to money loss.

We argue that robust and persistent returns of the pre-announcement trading pose a

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[2] This paper received the "Best Conference Paper Award 17" at the 10th FIW Research Conference on International Economics. It was also presented at the 7th Auckland Finance Meeting (2017) and 2017 Paris Financial Management Conference.

major challenge for the existing risk-based explanations of the exchange rate dynamics and highlight an important side effect of monetary policy decisions.

In the third chapter ”Overnight Index Swap Rates as Forecasts of Monetary Policy” (joint with Igor Pozdeev), we show that overnight index swaps (OIS) are perfect instruments for measuring expectations of financial markets' participants about the future path of the short-term rates in a number of developed economies. Given the close relation of short-term rates to policy target rates, the prices of OIS also embed information that allows to accurately forecast the outcomes of policy rate decisions. These two tasks are of major importance to practitioners, regulators and academics: for practitioners, the expected risk-free rate is an element of asset pricing and liquidity management; for regulators, it is an integral part of the forward guidance practice recently favored by monetary authorities across the globe; for academics, the interest in policy rate forecasts is sparked by the growing literature on the response of asset prices to policy rate changes. In the US, the task of measuring expectations about the future path of the short rate is well accomplished by the federal funds futures. However, to the extent of our knowledge there is no similar work on the market-based forecasts of short-term rates in economies other than the US, and our paper aims at filling this gap by studying the OIS-implied information about future interest rates and policy rate decisions.

In an OIS, one party agrees to pay a fixed rate, and the other a floating short rate compounded over the lifetime of the contract, the payments being exchanged at maturity of the swap. Each day, a new portion of the floating leg return is accumulated based on the current underlying rate level, while the fixed leg portion remains constant ever since the inception. First, we investigate if OIS rates can serve as a direct measure of the expected compounded underlying rates, which can only be the case if the difference between the two – effectively the return of the floating rate receiver – has historically been zero on average. At the one-month maturity, we estimate this return to be less than one basis point p.a. for all currencies in our sample except the Swiss franc (1.5 basis points). The average risk premium is economically insignificant, and most of the time statistically insignificant as well. For the US dollar swaps, the returns at different maturities are several times smaller than those documented for the federal funds futures in the previous literature. We conclude that the OIS rates are unbiased predictors of future cumulative underlying rates.

We then show that the OIS underlying overnight rates accurately reflect the target rates set by central banks, making the swaps capable of accurately forecasting the future course of monetary policy. We derive a set of assumptions needed to extract the implied future target rates from the OIS prices and validate them in the data. We demonstrate that the OIS-implied future target rates are capable of accurately predicting the outcomes of monetary policy meetings around the world. In the US, a randomly selected triplet of a target rate hike, cut and no-change is correctly classified using the

OIS-implied rates in 99.9 and 98 percent of cases five and ten days before a FOMC announcement respectively, which exceeds the prediction accuracy of the federal funds futures-implied rates. We report similarly high prediction accuracy for other developed countries.

Chapter 1

Carry Trades and Commodity Price Risk in Production Economies[*]

Dmitry Borisenko[†]

Abstract

A production-based asset pricing model predicts that excess returns of so-called ”carry trades”, i.e. borrowing in low interest rate currencies and investing in high interest rate currencies, compensate investors for the commodity price risk. Commodity producers differ in their exposure to the export price risk. Exchange rate-commodity price covariance, procyclical interest rates, negative price of exchange rate volatility, and countercyclical currency risk premium arise endogenously, ensuring absence of arbitrage between investment returns across countries. Empirically, risk factors implied by the model explain up to 55% of time-series variation in carry trade returns across developed countries, and generate substantial risk- and transaction costs-adjusted returns as tradable strategies.

Keywords: Currency Risk Premia, Carry Trades, Commodity Markets, Return Predictability

JEL Classification: E43, E52, E58, F31, G12

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1.1 Introduction

Currency carry trade – an investment strategy that borrows in currencies with low interest rates and invests in currencies with high interest rates – has been generating substantial returns punctuated by infrequent severe losses for over three decades. Uncovered interest rate parity (UIP), on the other hand, predicts that high interest rate currencies should depreciate relative to low interest rate currencies eliminating carry trade profits, thus the UIP or forward premium puzzle arises. A plausible theoretical framework aiming to solve the puzzle should either depart from rational expectations or assume time-varying currency risk premia. The latter explains carry trade profitability as a compensation for losses during "bad times". What are the common fundamental factors defining these "bad times" across carry trade currencies?

Structure of countries' export is one of such common factors. Net exporters of basic commodities (Australia, Canada, New Zealand or Norway) have on average higher interest rates than net exporters of manufactured goods (Japan or Switzerland). In contrast to the UIP prediction, this interest rate differentials are not offset by depreciation of commodity exporters' currencies, hence, leading to carry trades. Furthermore, the "commodity currencies" perform worse during commodity market slumps, suggesting a link between commodity prices and currency risk premium.

In this paper I develop a production-based asset pricing model which links currency risk premium to output prices. The model features free international flows of investment combined with heterogeneity in revenues due to export tariffs, shipment costs or other frictions, resulting in differential loadings of producers' pricing kernels on the common risk factor – commodity price, thus production in the foreign relatively insulated economy is less risky, leading to a lower foreign Sharpe ratio and hence to a positive expected return on the foreign currency. In bad times when commodity price uncertainty is high, interest rates in the domestic relatively exposed economy decrease by a greater amount than in the foreign insulated economy, simultaneously expected excess return on investment (equivalently Sharpe ratio) rises more domestically than abroad, thus commanding an increase in currency risk premium, to make domestic investors indifferent between investing at home or abroad, rationalizing deviations from the UIP. The model also explicitly takes in account the fact that commodities are traded in currencies foreign to commodity producers, the positive covariance between insulated exporters' spot exchange rates and commodity prices arises endogenously providing an additional level of insulation from commodity price shocks and leading to higher interest rate and currency risk premium. Similarly, higher exchange rate volatility destabilizes producer profits leading to lower currency excess returns, replicating the negative price of FX volatility observed in the data. The model thus provides a unified no-arbitrage framework that explains (i) procyclical interest rates and countercyclical risk premia, (ii) comovement of exchange rates and commodity prices, (iii) cross-sectional dispersion of interest rates and expected currency risk premium, and time-series variation in the latter, (iv) negative price of FX volatility documented by Menkhoff et al. (2012).

The argument of dual commodity price–exchange rate exposure is intuitively appealing – basic commodities are traded on centralized exchanges with prices quoted in currencies foreign to commodity producers (Chen and Rogoff (2003)). Therefore, if costs of production are paid in domestic currency,[1] commodity exporters face output price and exchange rate risks simultaneously. So, if currencies of these exporters appreciate (depreciate) as commodity prices rise (fall), the time-varying risk premium arises with "bad times" defined as low commodity prices. Figure 1.1 provides a simple graphical analysis of this claim, plotting average transaction costs-adjusted monthly return of the Lustig et al. (2011) HML_{FX} factor (which is a portfolio that is long in high forward discount currencies and short in low forward discount currencies) conditional on commodity market return (which is an equally weighted portfolio of 24 commodities from Moskowitz et al. (2012)). The left panel shows results for ten developed countries[2] and the right panel shows results for 24 countries[3] further referred to as *all* countries. Carry trade strategy clearly yields higher excess returns during high commodity prices state and perform poorly during commodity market slumps. This pattern is especially pronounced and monotonic for the developed countries, where HML_{FX} basically funds positions in Australian and New Zealand dollars with Japanese yen and Swiss franc. Spread in returns of carry trades between high and low commodity market return quartiles achieves sizable 17% and 14% p.a. for developed and all countries respectively.

The informal analysis above justifies the need for more rigorous theoretical and empirical examination of exchange rates–commodity prices interactions and their ability to account for the forward premium anomaly. Having a comprehensive model capturing joint dynamics of FX and commodity markets from producers' perspective is important for several reasons. First, it offers a novel rational risk-based explanation for the UIP puzzle and profitability of carry trades from the production-based asset pricing perspective, thus providing a link between FX premium and investment decisions in an economy. Second, understanding the interrelation between the two markets is important for policy making. For instance, in economies that rely heavily on exports of natural resources central banks can allocate FX reserves into assets denominated in currencies which covary negatively with commodity prices, thus creating a countercyclical buffer.

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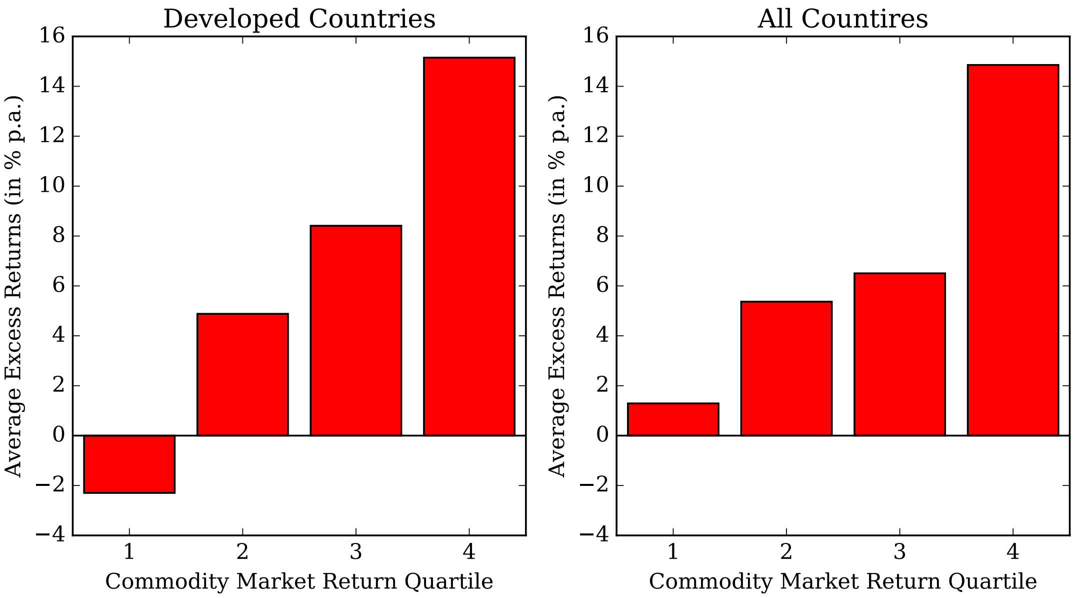
[1] Equivalently, if there is free trade in investment goods, so the law of one price holds and producers are indifferent between buying these goods at home or abroad.

[2] Australia, Canada, Denmark, Germany (spliced with euro after January 1999), Japan, New Zealand, Norway, Sweden, Switzerland, and United Kingdom.

[3] Developed plus Brazil, India, Indonesia, Israel, Malaysia, Mexico, Philippines, Poland, Russia, Singapore, South Africa, South Korea, Taiwan, Thailand.

Figure 1.1: Currency Carry Trade Excess Returns and Commodity Market Returns



This figure shows average monthly excess returns (annualized) of the carry trade factor (HML_{FX}) conditional on commodity market factor (COM) returns (four quartiles along the x-axis). The carry trade factor is the difference in excess returns of equally weighted portfolios of 20% of the highest forward discount currencies and 20% of the lowest forward discount currencies rebalanced every month. The commodity market factor is an equally weighted portfolio of spot rate returns of 24 commodities. The left panel shows results for developed countries, the right panel shows results for all countries. The sample is from December 1983 to October 2016.

The question is, however, why there is a positive relationship between commodity prices and carry trade profitability. I employ a production-based approach of Cochrane (1993), recovering stochastic discount factors from producers' first order conditions and deriving an analytical expression for currency risk premium and equilibrium spot exchange rate in the absence of international arbitrage. In my model there is unconstrained flow of investment goods across countries but commodity producers, whom I assume to be price takers, differ in their exposure to the commodity price risk – one may think of different export tariffs, shipment costs, costs of hedging, exerting market power, entering long term contracts, and so on, though I do not specify the exact source of these differences. Positive correlation between exchange rates and commodity prices then arises endogenously to remove arbitrage opportunities between physical investment returns. Intuitively, profits of the less exposed exporters grow (decline) less when commodity price rises (falls), therefore, their currencies should appreciate (depreciate). Similarly to the neoclassical growth model, my model arrives at the inverse relationship between stochastic discount factor of an economy and investment return. Therefore, volatility of the pricing kernel of the relatively insulated producer is lower than that of the relatively exposed one, thus commanding lower Sharpe ratios and higher currency risk premium consistent with results of Backus et al. (2001). The intuition behind this is that bad states of high commodity price uncertainty are worse for the exposed producer, hence commanding greater reduction in interest rates, comparing to the producer insulated from commodity price shocks, and leading to the deviations from the UIP and countercyclical currency risk premium.

I show that that the currency risk premium is linear in conditional variances of commodity price and spot exchange rate and their conditional covariance. In a benchmark two-country example, the commodity price is quoted in the curreny of the domestic producer, so she does not face exchange rate risk, while the foreign producer does (think of the U.S. vs. Canadian or Norwegian oil producers). In this case, model predicts that currency risk premium increases in commodity price–spot exchange rate covariance and decreases in spot exchange rate volatility. The impact of commodity price volatility depends on the two countries' relative exposure to the commodity price risk, so if the domestic economy is not exposed to this risk a negative effect is expected, and if both economies are equally exposed, the effect is zero. High degree of comovement between the foreign producer's exchange rate and commodity price stabilizes her profits, implying lower expected return on physical investment. This directly translates into the lower volatility of the pricing kernel and positive price of covariance risk in producer's currency, in order to remove arbitrage opportunities among productive assets across countries. The opposite reasoning applies to volatilities, which destabilize profits driving up the Sharpe ratios.

An additional important feature of the model unrelated to the UIP puzzle is predicted positive currency risk premium for insulated economies irrespective to the interest rate differential: the spot exchange rate equalizes investment return across countries, so in good times of high expected commodity returns and low commodity price uncertainty currencies of insulated producers appreciate to ensure absence of arbitrage between investment across countries, even though the insulated producer might have lower interest rate.

The theoretical implications of the model are supported by the data. I provide broad empirical evidence supporting the theoretical model documenting strong commonality between the dynamics of commodity market and FX excess returns. I show that the aggregate commodity market risk is different from the aggregate FX market risk and possesses sizable explanatory power in capturing both the time-series and cross-sectional variation in excess returns of carry trade portfolios and individual currencies. Following Cochrane (1991), I assume that in equilibrium firms' managers remove arbitrage opportunities between physical investment and stock market, so the corresponding returns are equalized. The portfolio going long in currencies of countries whose stock markets are insulated from commodity price shocks and shorting the exposed-stock market currencies (IME, or insulated-minus-exposed) delivers excess returns comparable in magnitude and significance to returns of carry trades. I also show that commodity and FX volatility, and covariance of exchange rate and commodity price are priced risks in the FX market. Combined, the stock market exposure, volatility, and covariance risks explain up to 55% of time-series variation in carry trades over the last thirty years. I further show that these commodity-based factors can generate substantial returns in excess of carry trades and transaction costs. The empirical results provide evidence in favor of the risk-based explanation of currency risk premium.

The remainder of the paper is organized as follows: Section 1.2 discusses the related literature, in Section 1.3 I derive the currency risk premium and equilibrium spot rate in a neoclassical investment model with smooth production technologies. Section 1.4 describes the data and portfolio construction methodology. Section 1.5 empirically assesses implications of the production-based model, starting with formal asset pricing tests and proceeding to profitability of commodity-related factors as tradable portfolios. Section 1.6 concludes.

1.2 Related Literature

This paper relates to the two major fields in the finance literature: production-based asset pricing and forward premium anomaly. In my theoretical model, I recover stochastic discount factors from firms' optimization problems with smooth production technologies, following Cochrane (1993) and Belo (2010). The production-based approach has proven to be successful in capturing key empirical facts about the US equity premium (Belo (2010), Jermann (2010)) and term structure of interest rates (Jermann (2013)). I contribute to this strand of research by applying the production-based approach to exchange rates. I also provide a direct link between currency risk premium and equity markets: following Cochrane (1991), I assume that in equilibrium firms remove arbitrage opportunities between returns on investment and stock markets, both domestically and abroad.

In the theoretical literature on forward premium anomaly, this paper is related to several studies. Ready et al. (2016) develop a general equilibrium model with trade specialization (commodity and final good producers) where commodity producers are insulated form the global productivity shocks by convex slowly adjusting shipping costs, so it is less costly to deliver the final good in "bad times", and hence, consumption in commodity producing countries is less risky giving rise to carry trades. Technically, this means that under standard CRRA utility the domestic pricing kernel is more volatile. In the simplest case of lognormal pricing kernels Backus et al. (2001) show that the currency risk premium equals half the difference of conditional variances of domestic and foreign log stochastic discount factors (SDFs). So a positive FX risk premium is observed, if the conditional variance of the domestic SDF is higher. Similarly, in my model different exposure of firm's revenues to commodity price risk results in cross-sectional dispersion in investment returns or marginal rates of transformation across countries.[4] My paper is, however, different in the following respect: throughout this paper I assume that revenue per unit of output sold is represented by a Cobb-Douglas aggregator $(P_t)^{\pi}\bar{P}^{1-\pi}$ $\pi \in [0,1]$, so each producer sells a (log) share π of her output at the competitive price P_t, and the complementary share at a predetermined price $\bar{P}$. Such revenue structure can arise due to different ability to hedge output price, long term contracts while also naturally admitting the convex procyclical shipment costs interpretation of Ready et al. (2016). In contrast to their study, I abstract from productivity shocks and assume producers to be price takers on the commodity market leaving the commodity price to be the only source of exogenous variation, thus allowing to express investment (equivalently, equity) and currency risk premium as functions of higher moments of commodity prices, exchange rates, and exposure parameter π all of which can be recovered from the abundant market data at higher frequencies. Therefore, instead of focusing on quantities like import ratios, I directly go to prices and returns. An additional feature of the proposed price aggregator is that once the predetermined component of $\bar{P}$ is allowed to vary through time (e.g. via staggered price setting), the model can be reformulated as a version of Campbell and Cochrane (1995) preferences with external habit formation, also capable to replicate UIP deviations, even if shocks in consumption across countries are i.i.d. as shown by Verdelhan (2010). I do not pursue this interpretation further focusing only on variation in commodity prices.

In this paper pricing kernels and investment returns in both foreign and domestic economies share a common component, explicitly depending on the commodity price. This feature is consistent with Brandt et al. (2006), who argue that SDFs should be highly correlated across countries in order to account for relatively smooth exchange rates and volatile equity premia.[5] Comovement of exchange rates and commodity prices also establishes a link to equilibrium models where currency risk premium arises as a compensation for small risk of economic "disaster".[6] I find that commodity returns have skewness comparable to that of carry trade returns, so if covariance is high enough, rapidly declining commodity prices can trigger carry trade crashes.

Overall, my study adds to the existing theoretical literature, offering a production-based point of view on the forward premium puzzle.

Although there is vast empirical evidence documenting violations of UIP and profitability of carry trades over more than past three decades (Hansen and Hodrick (1980),

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[4] Which are equivalent to marginal rates of substitution in the consumption-based asset pricing.

[5] Colacito and Croce (2011) specifically address this issue, their equilibrium model with Epstein and Zin (1989) preferences and a predictable component of consumption growth simultaneously accounts for volatile equity risk premia and smooth exchange rates. No-arbitrage models of Lustig et al. (2011), Lustig et al. (2014) also feature pricing kernels with a strong common component as the major source of variation.

[6] Gabaix (2008), Gourio et al. (2013) develop models that rely on disaster risk to replicate violations of the UIP. Ready et al. (2016) also report that allowing for disasters improves quantitative fit of their model.

Fama (1984)), relationships between exchange rates and commodity prices are investigated in a few number of studies. Chen and Rogoff (2003) report that exchange rates of "commodity currencies" (Australia, New Zealand and Canada) are strongly linked to the dollar price of their commodity exports. Ferraro et al. (2012) find that oil prices predict U.S.–Canada exchange rate, Bakshi and Panayotov (2013) show that returns of high-minus-low carry strategy are predictable by FX volatility and and prices of industrial commodities. I complement this evidence showing that in the production-based framework deviations from UIP arise conditionally on expected commodity price, and that empirically covariance of exchange rates and commodity prices is a priced risk.

This paper is also closely related to the literature on time-varying carry trade premium and its risk exposures. Brunnermeier et al. (2009) document role of volatility and funding liquidity in carry trade crashes. Lustig et al. (2011) find a negative price of global equity volatility innovations, and Menkhoff et al. (2012) present evidence of an inverse relationship between profitability of carry trades and global FX volatility innovations. Finally, Christiansen et al. (2011) show that returns of carry trades are lower and experience higher degree of commonality with stock market risk during high FX volatility regimes.

1.3 Exchange Rate and Commodity Prices: A Production-Based Approach

This section establishes a link between exchange rates and commodity prices from the production-based asset pricing perspective. I begin with an exporter's[7] optimization problem and business cycle properties of the stochastic discount factor and then derive currency risk premium and deviations from the uncovered interest parity in a no-arbitrage two-country example.

Standard production functions do not allow to transform output across states of nature, so the production possibilities frontier has a kink, and, therefore, the equilibrium marginal rate of transformation is not well defined. Cochrane (1993) introduces a framework where producers are able to transform output across states, thus the stochastic discount factor for the economy is identified by the equilibrium marginal rate of transformation. Belo (2010) further develops this approach and shows that the pricing kernel derived from producers' first order conditions is able to explain returns of US equity market size and value portfolios.

To grasp the idea of smooth production technologies, consider a standard production

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[7] I also solve the problem for an importer who uses commodity as a factor of production. Since the currency risk premium implications are similar, I discuss the importer's problem in the Supplementary Appendix.

function of the form:

$$Y_t(s) = \varepsilon_t(s)F(K_t),$$

where $Y_t(s)$, $\varepsilon_t(s)$, K_t are output, exogenous productivity level and capital (chosen at time $t-1$) respectively, $F(\cdot)$ is an increasing and concave function. Since $\varepsilon_t(s)$ is exogenous, choosing higher capital results in increase of output in all states. Cochrane (1993) suggests that producers have some control over the state-contingent productivity ε_t subject to the constraint:

$$1 \geq E_{t-1}[(\frac{\varepsilon_t}{\theta_t})^{\alpha}]^{\frac{1}{\alpha}},$$

where $\theta_t > 0$ is an underlying state-contingent level of productivity, and $\alpha > 1$ is a parameter which controls ability of the producer to transform output across states: as α rises, it becomes difficult to transform output, and $\alpha \to \infty$ corresponds to the standard production technologies which are Leontief across states, where $\varepsilon_t = \theta_t$ state by state.

1.3.1 The Commodity Exporter's Optimization Problem

Consider a competitive commodity producer with total revenue $(\frac{P_t}{S_t}Y_t)^{\pi}(\bar{P}Y_t)^{1-\pi}$, who sells $\pi \in [0,1]$ share of her log[8] output abroad at price P_t and $1-\pi$ at the fixed price $\bar{P}$ in units of domestic currency. Such revenue structure may arise if the producer is subject to export tariffs, keeps a part of her price risk hedged, has long-term contracts or receives subsidies. It also admits a convex trade costs interpretation similar to that of Ready et al. (2016): when commodity demand (and price) is high, costs of shipping an additional unit of commodity are also high. The producer operates in a small open economy and takes as given the prices P_t, $\bar{P}$, the nominal spot exchange rate S_t in units of foreign currency per unit of exporter's currency (so an increase in the spot exchange rate means appreciation of exporter's currency) and the nominal market-determined stochastic discount factor M_{t+1}. Upon realization of the output, its price, and the exchange rate, producer converts the foreign currency-denominated share of revenue into domestic currency, chooses the investment level I_t, and the next-period productivity ε_{t+1}. Profit, which equals revenue less investment cost, is then distributed to shareholders as dividends D_t. Let $V(K_t, \varepsilon_t)$ to be the present value of the commodity producer at the time t. The Bellman equation of the producer is:

$$V(K_t, \varepsilon_t) = \max_{\{I_t, \varepsilon_{t+1}\}} \{D_t + E_t[M_{t+1}V(K_{t+1}, \varepsilon_{t+1})]\} \tag{1.1}$$

---

[8] Although a solution for the linear specification in levels, i. e. *Total Revenue* $= [\pi\frac{P_t}{S_t} + (1-\pi)\bar{P}]Y_t$ is available, I assume the log-linear specification which is more analytically tractable.

subject to the constraints:

$$D_t = (\frac{P_t}{S_t}Y_t)^{\pi}(\bar{P}Y_t)^{1-\pi} - I_t, \quad \pi \in [0,1] \tag{1.2}$$

$$Y_t = \varepsilon_t F(K_t) \tag{1.3}$$

$$1 \geq E_t[(\frac{\varepsilon_{t+1}}{\theta_{t+1}})^{\alpha}]^{\frac{1}{\alpha}}, \quad \alpha > 1 \tag{1.4}$$

$$K_{t+1} = I_t \tag{1.5}$$

Where K_t is the stock of capital, which w.l.o.g. I assume to be fully depreciating, $F(K_t)$ is an increasing and concave production function, and θ_t is the underlying level of productivity. The first order conditions, derived in Appendix A, result in the following expression for the stochastic discount factor and investment return:[9]

$$M_{t+1} = \frac{1}{F_K(K_{t+1})}\frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}}(\frac{1}{\bar{P}})^{1-\pi}(\frac{S_{t+1}}{P_{t+1}})^{\pi} \tag{1.6}$$

$$R_{I,t+1} = F_K(K_{t+1})\varepsilon_{t+1}\bar{P}^{1-\pi}(\frac{P_{t+1}}{S_{t+1}})^{\pi} \tag{1.7}$$

1.3.1.1 Business Cycle Properties of the Stochastic Discount Factor

Since a reasonable stochastic discount factor should be countercyclical, the model economy has the following sensible properties: the price of exports P_t and exchange rate S_t are procyclical and countercyclical respectively. To further illustrate this issue, I consider an exporter with $\pi = 1$ (i.e. full exposure to the price and exchange rate risks) and assume that $\varepsilon_t = \theta_t$.[10] Plug the assumed values into 1.6, the stochastic factor for this economy is given by:

$$M_{t+1} = \frac{F(K_{t+1})}{F_K(K_{t+1})}\frac{1}{Y_{t+1}}(\frac{S_{t+1}}{P_{t+1}}) \quad \Leftrightarrow \quad \frac{P_{t+1}}{S_{t+1}}Y_{t+1} = \frac{F(K_{t+1})}{F_K(K_{t+1})}\frac{1}{M_{t+1}}$$

The first equality follows from the constraint 1.3. Further denote $P_{t+1}^D = P_{t+1}/S_{t+1}$ as price of exports expressed in domestic currency, hence $P_{t+1}^D Y_{t+1} \propto M_{t+1}^{-1}$ – nominal output is inversely proportional to the nominal SDF. The stochastic discount factor is countercyclical, thus implying a procyclical risk-free rate.

In order to focus on the relationships among the risk-free rate, exports price, and exchange rate, from now on, I assume that the productivity processes ε_{t+1}, θ_{t+1} are known at time t. For $\pi = 1$ taking expectations conditional on time t of the equation 1.6 and taking the second order Taylor expansion around $E_t[S_{t+1}]$, $E_t[P_{t+1}]$, yields the

---

[9] Note that in absence of arbitrage $E_t[M_{t+1}R_{I,t+1}] = 1$ which implies that constraint 1.4 is binding in equilibrium.

[10] The technological constraint 1.4 implies that such choice is always feasible.

following formula for the risk-free rate:

$$\begin{aligned} R_{f,t} &= \Psi_{t+1}\frac{1}{E_t[S_{t+1}P_{t+1}^{-1}]} \approx \\ &\approx \Psi_{t+1}\frac{E_t[P_{t+1}]^3}{E_t[S_{t+1}]E_t[P_{t+1}]^2 - cov_t(S_{t+1},P_{t+1})E_t[P_{t+1}] + E_t[S_{t+1}]Var_t[P_{t+1}]}, \end{aligned} \tag{1.8}$$

where $\Psi_{t+1} = [F_K(K_{t+1})\theta_{t+1}^{\alpha}/\varepsilon_{t+1}^{\alpha-1}]^{-1}$. Keeping all else equal, a higher covariance between exchange rate and commodity price requires higher interest rate to compensate investors for the export price risk – to see this consider a producer who fully hedges next period's commodity price but not the exchange rate. For simplicity abstract from costs of carry and assume that forward price of the commodity is determined under risk-neutrality: $F_t = R_{f,t}^{*}P_t$, where $R_{f,t}^{*}$ is the interest rate for the currency in which commodity is denominated. The conditional variance and covariance in equation 1.8 are zero and it reduces to a variant of the uncovered interest parity:

$$R_{f,t} = \Psi_{t+1}\frac{P_tR_{f,t}^{*}}{E_t[S_{t+1}]} \quad\Leftrightarrow\quad E_t[S_{t+1}] = \Psi_{t+1}P_t\frac{R_{f,t}^{*}}{R_{f,t}}$$

In absence of export price risk, a higher domestic or lower foreign interest rates lead to expected depreciation of domestic currency. In the next section I formally derive the equilibrium spot rate and currency risk premium in a two-country example and show how deviations form UIP may arise.

1.3.2 Currency Excess Returns and Interest Rate Differentials in Absence of Arbitrage

If the law of one price holds and there are no arbitrage opportunities, there exists a unique positive stochastic discount factor. Assume that markets are complete and denote foreign variables with $*$, then the nominal foreign and domestic stochastic discount factors are M_{t+1}^{*} and M_{t+1} respectively. The Euler equations for the foreign currency-denominated return R_{t+1}^{*} imply $E_t[M_{t+1}^{*}R_{t+1}^{*}] = E_t[M_{t+1}\frac{S_{t+1}}{S_t}R_{t+1}^{*}] = 1$, therefore, the gross return on the nominal exchange rate is:

$$\frac{S_{t+1}}{S_t} = \frac{M_{t+1}^{*}}{M_{t+1}} \tag{1.9}$$

Backus et al. (2001) show that for the lognormal SDFs and returns, the expected log currency excess return is equal to the half difference of conditional variances of the domestic and foreign log pricing kernels:

$$E_t[rx_{t+1}] = \frac{1}{2}Var_t[m_{t+1}] - \frac{1}{2}Var_t[m_{t+1}^{*}] \tag{1.10}$$

Under the lognormality assumption the domestic and foreign interest rates are given by:

$$
\begin{aligned}
r_{f,t} &= -logE_t[M_{t+1}] = -E_t[m_{t+1}] - \frac{1}{2}Var_t[m_{t+1}] \\
r^*_{f,t} &= -logE_t[M^*_{t+1}] = -E_t[m^*_{t+1}] - \frac{1}{2}Var_t[m^*_{t+1}]
\end{aligned}
$$

Since $E_t[m^*_{t+1}] - E_t[m_{t+1}] = E_t[\Delta s_{t+1}]$:

$$
r^*_{f,t} - r_{f,t} + E_t[\Delta s_{t+1}] = \frac{1}{2}Var_t[m_{t+1}] - \frac{1}{2}Var_t[m^*_{t+1}] = E_t[rx_{t+1}]
$$

In the production-based framework the exchange rate ensures absence of arbitrage opportunities between returns on domestic and foreign physical investment. Henceforth, I stick to the lognormality assumption and write the stochastic discount factors and investment returns derived in Appendix A as:

$$
\begin{aligned}
M_{t+1} &= \Xi_{t+1}(\frac{S_{t+1}/S_t}{P_{t+1}/P_t})^{\pi} \qquad (1.11) \\
R_{I,t+1} &= \Phi_{t+1}(\frac{S_{t+1}/S_t}{P_{t+1}/P_t})^{-\pi}, \qquad (1.12)
\end{aligned}
$$

Ξ_{t+1} and Φ_{t+1} are known at time t.[11] For a reference economy, not facing exchange rate risk, the stochastic discount factor and returns on physical investment are defined by equations 1.11 and 1.12 with S_{t+1}/S_t equal to 1.

Consider a domestic and a foreign economy taking commodity price as given with pricing kernels M_{t+1} and M^*_{t+1} determined by 1.11, let the domestic currency be the reference currency, in which the commodity price is quoted, and assume the domestic investor's perspective. Finally, denote natural logs with lower case letters, and normalize the predetermined variables Ξ_{t+1}, Φ_{t+1} to one in order to keep notation as transparent as possible.

1.3.2.1 Spot Return

In absence of international arbitrage, equation 1.9 implies:

$$
\Delta s_{t+1} = \pi^*\Delta s_{t+1} + (\pi - \pi^*)\Delta p_{t+1} \quad \Leftrightarrow \quad \Delta s_{t+1} = \frac{\pi - \pi^*}{1 - \pi^*}\Delta p_{t+1} \qquad (1.13)
$$

---

[11] $\Xi_{t+1} = \frac{1}{F_K(K_{t+1})}\frac{\varepsilon^{\alpha-1}_{t+1}}{\theta^{\alpha}_{t+1}}(\frac{1}{\bar{P}})^{1-\pi}(\frac{S_t}{P_t})^{\pi}$, and $\Phi_{t+1} = \varepsilon_{t+1}F_K(K_{t+1})\bar{P}^{1-\pi}(\frac{S_t}{P_t})^{-\pi}$. Alternatively one can assume joint independence of productivity processes $\theta_{t+1}, \varepsilon_{t+1}$ from commodity price which I further assume to be the only exogenous variable.

The spot return is a function of commodity price with coefficient determined by the countries' relative exposure to the export price risks. The denominator $1 - \pi^*$ is always non-negative, so the numerator $\pi - \pi^*$ determines the sign of the no-arbitrage coefficient.

The foreign spot exchange rate has positive loading on commodity return whenever $\pi^* < \pi$, that means the foreign economy is less exposed to the world prices. Intuitively, the currency of the less exposed exporter must appreciate since the spot rate changes offset the arbitrage opportunities between physical investment returns in the two countries – if the commodity price rises, the investment returns of the less exposed exporter increase less, than those of the more exposed producer, hence the currency of the less exposed economy appreciates.

However, in any no-arbitrage framework deviations from the uncovered interest parity and time-varying currency risk premium arise from time variation in the conditional higher moments of the pricing kernels.

1.3.2.2 Currency Risk Premium and Deviations from Uncovered Interest Parity

The excess log return for holding the foreign currency is the half difference between domestic and foreign stochastic discount factors:

$$E_t[rx_{t+1}] = \frac{1}{2}(\pi^2 - \pi^{*2})Var_t[\Delta p_{t+1}] - \frac{1}{2}\pi^{*2}Var_t[\Delta s_{t+1}] + \pi^{*2}cov_t[\Delta s_{t+1}, \Delta p_{t+1}] \quad (1.14)$$

The currency risk premium is driven by four components: *(i)*degree of insulation of exporters' revenues from commodity price shocks; *(ii)* commodity price volatility, whose impact depends on the countries' relative exposure to the commodity price risk and a negative loading is expected if the foreign economy is more exposed; *(iii)* spot exchange rate volatility which loads negatively – intuitively, when the spot rate volatility is high, the expected return on physical investment in the foreign economy is also high, which translates to the opposite effect on currency risk premium in order to remove arbitrage opportunities; *(iv)* covariance of exchange rate with commodity price – higher covariance insulates producers from export or import price risk, leading to lower expected return on physical investment and consequently to higher currency risk premium.

The interest rate differential is given by $r_t^* - r_t = -E_t[\Delta s_{t+1}] + E_t[rx_{t+1}]$, so the uncovered interest parity holds exactly if the conditional variances of the SDFs (or equivalently, the currency risk premium) are time-invariant. From 1.13 the spot exchange rate is a constant multiple of commodity price with coefficient determined by countries' export (or import) risk exposure parameters, plug the spot rate into equation 1.14

to obtain the risk premium in terms of commodity variance:

$$
\begin{aligned}
&r_t^* - r_t + E_t[\Delta s_{t+1}] = \qquad (1.15)\\
&= \left[\frac{1}{2}(\pi^2 - \pi^{*2}) - \frac{1}{2}\pi^{*2}\left(\frac{\pi - \pi^*}{1 - \pi^*}\right)^2 + \pi^{*2}\frac{\pi - \pi^*}{1 - \pi^*}\right] Var_t[\Delta p_{t+1}]
\end{aligned}
$$

Using the fact that $(\pi - \pi^*)/(1 - \pi^*) = E_t[\Delta s_{t+1}]/E_t[\Delta p_{t+1}]$, rearrange the equation above to obtain the expected change in exchange rate as a linear function of the interest rate differential:

$$E_t[\Delta s_{t+1}] = \frac{E_t[\Delta p_{t+1}]}{\kappa Var_t[\Delta p_{t+1}] - E_t[\Delta p_{t+1}]}(r_t^* - r_t) \qquad (1.16)$$

where $\kappa \geq 0$ is a constant[12] determined by the exposure parameters π, π^*.

The UIP slope coefficient equals minus one only if both economies are equally exposed, i.e. $\pi = \pi^*$ or commodity price is constant. In these cases profits are equal or there is no uncertainty in investment returns respectively, both resulting in the currency risk premium of zero. In other cases deviations from the UIP occur conditionally on the expected commodity return and its volatility. For example, if the expected change in commodity price is zero, so is the expected change in exchange rate, and currency risk premium is determined by the difference in interest rates, delivering higher returns on the currency of a less exposed country: according to equation 1.15 premium is strictly positive for any $\pi > \pi^*$.

The intuition behind this is that production in exposed economies is riskier than in insulated economies. Assume $\pi > \pi^*$, i.e. domestic producer has higher exposure to the commodity price risk. From 1.11 and 1.12 log investment return in each country equals minus log pricing kernel: $r_{I,t+1} = -m_{t+1}$, meaning that the pricing kernel of the domestic producer is more volatile and return to the domestic investment dominates the exchange rate dynamics. Upon realization of a positive commodity price shock, profit of the domestic producer rises more than profit of the foreign producer, and foreign currency appreciates to equalize investment returns in two countries: $r_{I,t+1} - r_{I,t+1}^* = m_{t+1}^* - m_{t+1} = \Delta s_{t+1}$. Similarly when the commodity price falls, return to investment decreases domestically more than abroad, thus commanding depreciation of the foreign currency.

Second, high commodity price uncertainty and low commodity returns correspond to low interest rates both domestically and abroad, furthermore the interest rate differential is always positive if the denominator in equation 1.16 is greater than zero, since the

---

[12] To arrive at 1.16 first factor out $\frac{\pi-\pi^*}{1-\pi^*}$ from the brackets on the right hand side of the previous equation, simplify terms in brackets to get $r_t^* - r_t + E_t[\Delta s_{t+1}] = \frac{\pi-\pi^*}{1-\pi^*}\left[\frac{\pi-2\pi\pi^*+\pi^*}{2(1-\pi^*)}\right] Var_t[\Delta p_{t+1}] = \frac{E_t[\Delta s_{t+1}]}{E_t[\Delta p_{t+1}]}\kappa Var_t[\Delta p_{t+1}]$.

spot rate always moves in the same direction as commodity price if the domestic economy is more exposed, as implied by 1.13. Intuitively, since the investment returns are tied to the exchange rates, variation in interest rates ensures equalization of expected log *excess* returns on investment domestically and abroad for a domestic investor borrowing at home. Note that expected log excess return on borrowing and investing domestically equals half the variance of the log SDF $\frac{1}{2}\pi^2 Var_t[\Delta p_{t+1}]$, if she invests abroad the expected log excess return in domestic currency is same as domestically:

$$-r_{f,t} + E_t[r^*_{I,t+1}] + E_t[\Delta s_{t+1}] = E_t[m_{t+1}] + \frac{1}{2}Var_t[m_{t+1}] - E_t[m^*_{t+1}] + E_t[m^*_{t+1} - m_{t+1}]$$

Which equals exactly half the variance of the domestic pricing kernel. So the domestic investor is indifferent between the two alternatives. During bad times when the commodity price uncertainty is high, volatility of the domestic pricing kernel and the risk premium on the domestic productive assets is also high and domestic interest rates are low. If the denominator in 1.16 is positive, the interest rate differential is also positive, thus the domestic investor expects positive currency risk premium. The currency risk premium is therefore countercyclical: in bad times the domestic interest rate is low and Sharpe ratio is high, simultaneously due to a relative insulation, foreign economy has higher interest rates and lower Sharpe ratios, thus the positive currency excess return is expected.

1.3.3 Summary of Implications of the Model

The equilibrium analysis above shows that the currency risk premium equation 1.14 can be reduced to a function of commodity volatility since it is the only exogenous variable, however it is useful to reinterpret results in terms of all four components as a number of testable predictions for relationships between commodity prices, spot exchange rates and currency risk premium:[13]

1. Higher degree of insulation of foreign producers' revenues implies appreciation of their currencies, since returns on similar investments should be equalized across countries.

2. High exchange rate–commodity price covariance economies offer higher interest rates to compensate investors for additional risk. Furthermore, higher covariance stabilizes producers' profits translating into positive currency risk premium in order to remove arbitrage opportunities between physical investments.

---

[13] The commodity prices are not country-specific while the exchange rates are. One can always read the equation 1.14 as: given exposure parameters π, π^*, stochastic processes for exchange rate and commodity price satisfying equations 1.13 and 1.14, ensure absence of international arbitrage.

3. By the similar no-physical-investment-arbitrage reasoning, lower spot exchange rate volatility leads to higher currency risk premium. High exchange rate volatility increases Sharpe ratios in the foreign economy, hence leading to negative currency risk premium.

4. The impact of commodity price volatility on currency risk premium is positive for insulated exporters and negative for exposed exporters. In a portfolio of currencies conditioned on commodity price volatility[14] exposure to the reference currency is eliminated, thus positive premium is expected. the impact of commodity price volatility should be lower in comparison with two other components of the risk premium, unless the reference economy has zero exposure.

5. Deviations from the uncovered interest parity occur conditionally on the expected commodity return – countries with higher degree of insulation from commodity price shocks deliver higher (lower) expected returns if commodity price is expected to rise (fall).

1.4 Data and Portfolio Construction

This section describes the data, computation of returns for currencies and commodities, and construction of factor portfolios.

1.4.1 Currencies

Similarly to Lustig et al. (2014), I collect daily FX spot, 1-month forward exchange rates for the following countries: Australia, Austria, Belgium, Brazil, Canada, Czech Republic, Denmark, Euro area, Finland, France, Germany, Greece, Hong Kong, Hungary, India, Indonesia, Ireland, Israel, Italy, Japan, Kuwait, Malaysia, Mexico, Netherlands, New Zealand, Norway, Philippines, Poland, Portugal, Russia, Singapore, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, Thailand, United Kingdom. The currency data collected by Reuters and Barclays come from Datastream and cover the period from October 1983 to October 2016. I exclude the euro area countries after January 1999, also I exclude Hong Kong and Saudi Arabia, since these countries have their currencies pegged to the US dollar over the course of the sample, and delete observations corresponding to episodes of large deviations from the covered interest parity: South Africa from the end of July 1985 to the end of August 1985; Malaysia from the end of August 1998 to the end of June 2005; Indonesia from the end of December 2000 to the end of May 2007. I follow the Cochrane (1991) argument that in complete

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[14] A portfolio investing in currencies that deliver higher excess returns when commodity price volatility is high, and funding the long position by currencies delivering lower excess returns.

markets firms remove arbitrage opportunities between return on physical investment and asset returns and proxy the former with stock market data. Specifically, I collect MSCI country stock market indices and drop currencies where stock market indices are unavailable or contain less than 5 stocks. I also splice German mark with euro and use MSCI Europe as the corresponding stock market,[15] which leaves me with 24 countries.[16]

I also consider a narrower subsample of the 10 most liquid currencies, including those of Australia, Canada, Denmark, Germany (spliced with euro after January 1999), Japan, New Zealand, Norway, Sweden, Switzerland, and United Kingdom. I further refer to this subsample as "developed countries". All exchange rates are expressed as units of foreign currency per United States dollar.

1.4.2 Commodities

Following Moskowitz et al. (2012), I cover 24 commodities, obtaining spot price series from Datastream: WTI Crude, Natural Gas, RBOB Gasoline spliced with Unleaded Gasoline, Fuel Oil, and Platinum from New-York Mercantile Exchange (NYMEX); Gold and Silver are from New-York Commodities Exchange (COMEX); Aluminium, Copper, Nickel, and Zinc are from London Metal Exchange (LME); Brent Crude, Gas Oil, Cotton, Coffee, Cocoa, and Sugar are from Intercontinental Exchange (ICE); Live Steers and Lean Hogs are from Chicago Mercantile Exchange (CME); Corn, Soyabeans, Soyameal, Soya Oil and Wheat are from Chicago Board of Trade (CBOT).

I am primarily interested in commonality in FX and commodity risks and not in performance of the commodity investments, hence I use commodity spot prices, not futures, due to the greater availability of data.

1.4.3 Portfolio Construction

1.4.3.1 Carry trade portfolios and transaction cost adjustment

I assume a US investor perspective and estimate monthly excess returns from holding foreign currency k as:

$$rx_{t+1}^{k} = i_{t}^{k} - i_{t} - \Delta s_{t+1}^{k} \approx f_{t}^{k} - s_{t+1}^{k} \tag{1.17}$$

---

[15] The vast majority of European currencies were pegged to or maintained a crawling band around the German mark (see Reinhart and Rogoff (2002) for classification of exchange rate regimes).

[16] Australia, Brazil, Canada, Denmark, Germany (spliced with euro after January 1999), India, Indonesia, Israel, Japan, Malaysia, Mexico, New Zealand, Norway, Philippines, Poland, Russia, Singapore, South Africa, South Korea, Sweden, Switzerland, Taiwan, Thailand, the United Kingdom.

where i^k and i denote foreign and domestic one-month interest rates, s^k and f^k denote the end-of-month log spot and forward exchange rates as units of foreign currency per US dollar. Assuming that the covered interest rate parity (CIP) holds,[17] the interest rate differential $i_t^k - i_t$ approximately equals forward discount $f_t^k - s_t^k$. At the end of each month t I form five carry trade portfolios, so that portfolio 1 (5) contains currencies with lowest (highest) forward discounts. I use the Menkhoff et al. (2012) transaction costs adjustment scheme, in which return is adjusted for bid–ask spread (BAS) once a currency enters or exists a portfolio. In the first month (November, 1983) investor opens positions in all available currencies and has to liquidate all positions in the last month (October, 2016). I adjust the portfolio of funding currencies (i.e. portfolio 1) and portfolios of investment currencies 2–5 for short and long position transaction costs respectively. Denote rx_{t+1}^l, rx_{t+1}^s as net returns for long and short positions, and a, b superscripts as ask and bid quotes respectively, the adjustment procedure is as follows: (i) $rx_{t+1}^l = f_t^b - s_{t+1}^a$, $rx_{t+1}^s = -f_t^a + s_{t+1}^b$ for a currency that enters a portfolio at month t and exits it at the end of the month; (ii) $rx_{t+1}^l = f_t^b - s_{t+1}$, $rx_{t+1}^s = -f_t^a + s_{t+1}$ or a currency that enters a portfolio at month t and remains in it at the end of the month; (iii) $rx_{t+1}^l = f_t - s_{t+1}^a$, $rx_{t+1}^s = -f_t + s_{t+1}^b$ for a currency that was already in the portfolio at the beginning of the month but exits it at the end of the month. As in Lustig et al. (2011), I denote the difference in returns of portfolios 5 and 1 as HML_{FX}.

1.4.3.2 Factor portfolios

Equation 1.14 implies positive risk premium for currencies whose excess returns load positively on commodity volatility and high exchange rate–commodity price covariance currencies, and a negative risk premium for exchange rate volatility. Furthermore, the model predicts positive currency risk premium for currencies of producers who are insulated from commodity price shocks (i.e. those with relatively low π^*). To quantify exposures to these risk factors, I run the following regressions for each currency k:

$$rx_t^k = \beta_{0,t}^k + \beta_{1,t}^k DOL_t + \beta_{2,t}^k COM_t + \beta_{3,t}^k \sigma_{c,t} + \beta_{4,t}^k \sigma_{fx,t} + u_t^k \tag{1.18}$$

$$r_t^k = \gamma_{0,t}^k + \pi_t^k (COM_t + \Delta s_t^k) + v_t^k, \tag{1.19}$$

where rx^k is the excess return on currency k; DOL_t is the dollar risk factor of Lustig et al. (2011), constructed as an equally weighted portfolio of excess returns against the US dollar; COM_t is the similarly constructed commodity market risk factor; $\sigma_{c,t}$ and $\sigma_{fx,t}$ are the aggregate commodity and FX volatilities, construction of which I discuss below in more detail; r_t^k is log return on country k's stock market (in local currency) which I

---

[17] Akram et al. (2008) show that CIP holds at daily and lower frequencies. On the other hand, Du et al. (2017) document substantial deviations from the CIP starting from the 2007-2009 financial crisis, linking the disconnect between money market- and FX derivatives implied interest rate differentials to banking regulation.

regress on commodity return in local currency (Δs_t^k is spot exchange rate depreciation). I include dollar risk to isolate the impact of commodity market risk on excess returns (the correlation between the long-only FX and commodity portfolios is 0.46 for the whole sample and 0.47 for the developed countries). I further use regression estimates (which include information up to the period t) as sorting variables for next period's currency excess returns. So, for instance, I form 5 commodity market risk exposure portfolios, where portfolio 1 invests in 20% of currencies with lowest commodity market covariance (i.e. lowest $\beta_{1,t}$), and portfolio 5 buys 20% of currencies with highest commodity market covariance. In a similar way I form portfolios for volatility and stock market exposure factors. Finally, I construct 4 high-minus-low factors: IME, or insulated-minus-exposed buying low commodity risk exposure currencies (measured by $\hat{\pi}^k$ from 1.19) and selling high exposure currencies; COV, VOL_C, VOL_{FX} which go long in high commodity market risk (commodity volatility, FX volatility) exposure currencies (i.e. currencies from fifth portfolios) and short currencies with low exposures to these risks (currencies from first portfolios).

Throughout the next section I build portfolios using both monthly and daily[18] data for estimation of equations 1.18, 1.19. I investigate the latter portfolios as tradable strategies and adjust them for transaction costs using the scheme described above.

1.4.3.3 Volatility Proxy

Following Bakshi and Panayotov (2013) and Menkhoff et al. (2012) I construct aggregate volatility proxies by averaging currency- or commodity-specific volatilities over the corresponding cross-section of assets. However in contrast to these studies I use volatility in levels and not volatility innovations since the latter implicitly assumes an ARCH-like process for the conditional variance. Therefore, I proxy global FX and commodity volatilities first by estimating rolling 3-month (66 days) variances of spot returns on currencies and commodities and then taking cross-sectional averages of these estimates.

1.4.4 Descriptive Statistics for Portfolios

Table 1.1 presents descriptive statistics for five carry trade portfolios, and for the HML_{FX} high-minus-low factor. The five carry trade portfolios in Table 1.1 show an established pattern of increasing mean return, kurtosis, autocorrelation, Sharpe ratios, and decreasing skewness both for developed countries in the top panel and for all countries in the bottom panel of the table.

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[18] In this case the left hand side of the equation 1.18 is spot return, and the dollar factor is an equally weighted portfolio of spot returns.

Table 1.1: Descriptive Statistics: Carry Trade Portfolios

Portfolio	1	2	3	4	5	HML_{FX}
Panel A: Developed countries						
Mean	−1.74	−0.40	2.22	0.96	4.80	6.54
	(1.89)	(1.89)	(1.72)	(1.78)	(2.30)	(1.93)
Median	−3.39	−0.62	4.01	2.39	4.45	9.10
Std. dev.	10.01	9.22	8.85	9.45	11.39	10.42
Skewness	0.13	0.11	−0.37	−0.55	−0.32	−0.90
Kurtosis	0.44	0.46	1.71	2.53	1.25	2.75
Sharpe ratio	−0.17	−0.04	0.25	0.10	0.42	0.63
AC(1)	0.01	0.05	0.08	0.05	0.12	0.09
	(0.05)	(0.05)	(0.05)	(0.06)	(0.06)	(0.08)
Panel B: All countries						
Mean	−2.16	−0.59	2.77	1.51	4.84	7.01
	(1.65)	(1.57)	(1.57)	(1.81)	(2.64)	(2.02)
Median	−2.98	−0.37	3.57	2.88	8.64	10.01
Std. dev.	8.44	7.89	8.34	8.80	12.28	10.93
Skewness	0.07	−0.01	−0.35	−0.50	−1.18	−1.16
Kurtosis	0.51	0.52	1.97	1.33	6.32	5.47
Sharpe ratio	−0.26	−0.08	0.33	0.17	0.39	0.64
AC(1)	0.04	0.03	0.05	0.11	0.12	0.07
	(0.05)	(0.05)	(0.05)	(0.07)	(0.06)	(0.07)

The table reports descriptive statistics of currency portfolios sorted monthly on previous period's forward discounts for developed countries (Panel A) and for all countries (Panel B). Portfolio 1 and 5 contain 20% of currencies with the lowest and highest $t-1$ forward discounts respectively. The last column (HML) is the long-minus-short portfolio which buys portfolio 5 and sells portfolio 1. All returns are excess returns in USD. Means, medians, standard deviations and Sharpe ratios are annualized. AC(1) denotes first order autocorrelation coefficient. Numbers in parentheses are the Newey and West (1987) HAC standard errors with optimal number of lags according to Newey and West (1994). Returns are monthly and the samples span period from December 1983 to October 2016.

Table 1.2 reports descriptive statistics (Panel A) and correlation matrices (Panel B) of commodity market risk COM and four high-minus-low portfolios. I sort these HML portfolios on the prior month's slope coefficient estimates from regressions 1.19 (IME) and 1.18 (COV, VOL_C, VOL_{FX}). I obtain the estimates from expanding window regressions, with minimum of 36 months of data required to produce the first estimate. The commodity market return has skewness of -0.81 comparable to those of HML_{FX} factors from Table 1.1, furthermore the COM factor's correlations with carry trades of 28% (for developed countries) and 29% (for all countries) imply that commodity market downturns can be partially responsible for carry trade crashes. This evidence is further supported by the high-minus-low commodity price – exchange rate covariance portfolio COV which also displays negative skewness and has even higher degree of commonality with carry trades (correlations around 50% for both samples). The COV factor also provides economically significant returns of 2.62 (developed countries) and 3.67 (all countries) though it reaches statistical significance at 5% level only in the latter sample. Although correlations of FX and commodity volatility factors with carry trades are in line with predictions of the model model, these factors do not provide provide any significant risk premiums. The insulated-minus-exposed factor IME delivers 3.56% p.a. (significant at 5% level) for the developed sample and neither economically nor statistically significant 1% p.a. for the all countries sample. The factor is also well correlated with carry trades.

Overall, the descriptive analysis above indicates strong commonality between FX and commodity markets. In the next section I first conduct formal asset pricing tests, investigating whether the proposed factors are capable of explaining time-series and cross-sectional variation in excess returns to carry trade portfolios and individual currencies. Then I examine the factors as tradable strategies using daily data and adjusting for transaction costs.

Table 1.2: Descriptive Statistics: Factor Portfolios

		Developed countries				All countries			
Portfolio	COM	IME	COV	VOL_C	VOL_{FX}	IME	COV	VOL_C	VOL_{FX}
Panel A: Descriptive statistics									
Mean	1.45	3.56	2.62	1.13	0.73	1.01	3.67	−0.20	−0.27
	(2.92)	(1.77)	(1.78)	(1.74)	(1.96)	(1.54)	(1.78)	(1.76)	(1.60)
Median	3.69	0.27	2.45	3.30	−1.33	1.00	4.99	1.59	−0.85
Std. dev.	13.72	9.71	10.02	9.79	9.44	7.82	8.81	8.38	8.28
Skewness	−0.82	0.19	−0.42	0.01	0.95	0.11	−0.12	−0.14	−0.04
Kurtosis	4.67	0.45	0.88	1.10	3.95	1.06	0.19	0.70	0.64
Sharpe ratios	0.11	0.37	0.26	0.12	0.08	0.13	0.42	−0.02	−0.03
AC(1)	0.13	0.06	0.01	−0.02	0.07	0.08	0.06	0.14	0.03
	(0.09)	(0.05)	(0.05)	(0.06)	(0.09)	(0.07)	(0.06)	(0.07)	(0.06)
Panel B: Correlation matrices									
COM						0.15	0.31	−0.03	−0.26
IME	0.15								
COV	0.28	0.70				0.58			
VOL_C	0.22	0.70	0.71			0.59	0.36		
VOL_{FX}	−0.25	0.08	−0.21	−0.11		−0.40	−0.49	−0.27	
HML_{FX}	0.28	0.39	0.52	0.32	−0.55	0.29	0.47	0.20	−0.24
$\rho(DOL, COM)$	0.47					0.46			

The table reports descriptive statistics and return correlations of commodity market portfolio COM, and four high-minus-low portfolios of currencies for developed countries (columns 3–6) and all countries (columns 7-10). IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high. The degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency. COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The coefficient estimates are obtained from expanding window regressions with 36 months required to produce the first estimate. The estimated coefficients are then lagged for one month for portfolio formation. Panel A reports descriptive statistics for Panel B reports correlations of monthly returns. The last two rows of Panel B report correlations with carry factor HML_{FX} and commodity market and dollar factor correlation DOL, which is a long-only equally-weighted portfolio of currency excess returns. All returns are excess returns in USD. Means, medians, standard deviations and Sharpe ratios are annualized. AC(1) denotes first order autocorrelation coefficient. Numbers in parentheses are the Newey and West (1987) HAC standard errors with optimal number of lags according to Newey and West (1994). Returns are monthly and the samples span period from January 1987 to October 2016.

1.5 Empirical Results

In this section I examine how well the time-series and cross-sectional variation in excess returns of carry trade portfolios and currencies can be explained by their degree of insulation from commodity price shocks, covariance with commodity market returns, global commodity and FX volatilities. I begin with time-series and cross-sectional pricing tests using factors from Table 1.2 as explanatory variables, and then examine factors as tradable strategies estimating parameters of equations 1.18, 1.19 from daily data and adjusting for transaction costs.

1.5.1 Asset Pricing Tests: Carry Trade Portfolios

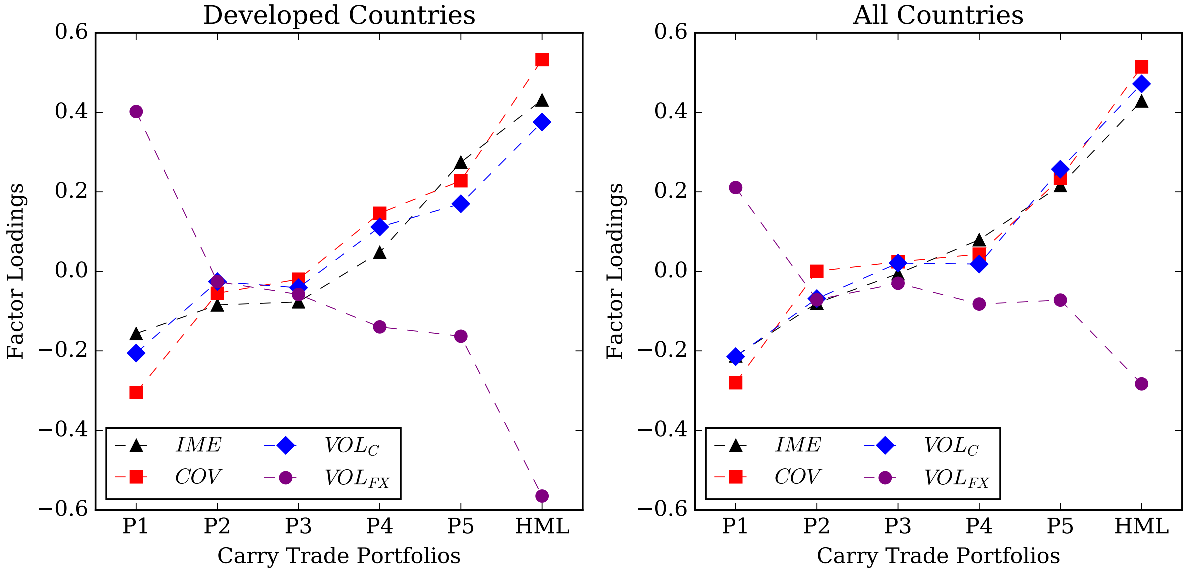
I run time-series regressions of five currency portfolios sorted on forward discounts and the carry trade HML_{FX} factor described in the previous section on average FX market excess return DOL, and four high-minus-low currency portfolios based on slope coefficients of local stock market returns on commodity market return in local currency (IME), and FX excess returns' on commodity market return (COV), global commodity volatility (VOL_C), and global FX volatility (VOL_{FX}):

$$rx_t^k = \alpha^k + \beta_1^k DOL_t + \beta_2^k IME_t + \beta_3^k COV_t + \beta_4^k VOL_{C,t} + \beta_5^k VOL_{FX,t} + \varepsilon_t \qquad (1.20)$$

Figure 1.2 presents slope estimates β_i^k, $i = 2, ...5$ from bivariate specifications of regression 1.20, where each regression includes the dollar factor and one of the four HML portfolios. The left panel shows results for developed countries and the right panel shows results for all countries. As implied by the risk premium expression 1.14 and its equilibrium version 1.15, the loadings of the carry trade portfolios increase monotonically (from the lowest forward discount portfolio P1 to the HML_{FX} factor) with degree of insulation from commodity price shocks, exchange rate – commodity market return covariance, and commodity volatility, and decrease with FX volatility for both samples.

Table 1.3 reports estimates of regression 1.20 including all five factors. Panel A shows results for developed countries and Panel B shows results for all countries. Numbers in parentheses are Newey and West (1987) standard errors with optimal number of lags selected according to Newey and West (1994). Pricing errors (intercepts) are in the first column and reported in % p.a., the last column contains adjusted R^2. The loadings pattern of bivariate regressions from Figure 1.2 generally holds in the multivariate specification, except for VOL_C in the developed countries sample and IME, VOL_{FX} in the all countries sample, due to the high degree of correlation between the factors. For the developed and all countries samples, the five factor model explains 55% and 31% of time-series variation in returns of carry trade strategy, reducing annual alphas by

Figure 1.2: Factor Loadings from Bivariate Regressions



This figure plots the factor loadings of of five carry trade portfolios and the long-minus-short HML_{FX} factor (along the x-axes) on four high-minus-low portfolios obtained from bivariate regressions on dollar factor DOL and one of the four portfolios IME, COV, VOL_C, VOL_{FX}. DOL is an equally-weighted long-only portfolio of currency excess returns; IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The coefficient estimates are obtained from expanding window regressions with 36 months required to produce the first estimate. The estimated coefficients are then lagged for one month for portfolio formation. The left panel depicts results for developed countries while the right panel shows results for all countries. All returns are monthly excess returns in USD and the samples span period from November 1986 to October 2016.

approximately 1.5% and 1.25% respectively.

Table 1.4 reports results of Fama and MacBeth (1973) two-stage regressions for the developed countries sample.[19] The test assets are five carry trade portfolios. In the first stage of the procedure I estimate in-sample time-series betas for each test asset and I do not include intercept in the the second stage regressions, since I include the DOL factor in each specification.[20] I report standard errors of factor risk prices λ's and χ^2-tests of joint significance of pricing errors with a Shanken (1992) correction for the fact that betas are estimated in the first stage and with a Newey and West (1987) adjustment with number of lags according to Newey and West (1994) (standard errors of risk premiums and p-values of χ^2-tests are in parentheses).

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[19] Results for the all countries sample are qualitatively and quantitatively similar and can be found in Table B.1 in Appendix B

[20] The DOL factor is effectively unrelated to the cross-section of carry trade portfolios' returns, thus being equivalent to a constant – see Burnside (2011), Lustig and Verdelhan (2007), Menkhoff et al. (2012) for further discussion.

Table 1.3: Time-Series Regressions: The Five-Factor Model

	α	DOL	IME	COV	VOL_C	VOL_{FX}	$\bar{R}^2$
Panel A: Developed countries							
P1	−2.41	0.94	−0.04	−0.23	0.04	0.36	0.86
	(0.76)	(0.03)	(0.04)	(0.05)	(0.05)	(0.04)	
P2	−0.93	0.91	−0.11	−0.03	0.08	−0.01	0.70
	(0.84)	(0.05)	(0.05)	(0.07)	(0.06)	(0.05)	
P3	0.92	0.98	−0.10	0.05	−0.01	−0.04	0.84
	(0.64)	(0.03)	(0.03)	(0.04)	(0.04)	(0.03)	
P4	0.05	1.00	−0.09	0.16	0.05	−0.09	0.79
	(0.77)	(0.04)	(0.05)	(0.05)	(0.05)	(0.04)	
P5	2.67	1.17	0.35	0.04	−0.13	−0.20	0.83
	(0.82)	(0.04)	(0.05)	(0.05)	(0.05)	(0.04)	
HML_{FX}	5.08	0.23	0.39	0.27	−0.17	−0.56	0.55
	(1.32)	(0.05)	(0.06)	(0.08)	(0.08)	(0.06)	
Panel B: All countries							
P1	−2.73	0.86	0.03	−0.22	−0.09	0.08	0.81
	(0.63)	(0.06)	(0.05)	(0.04)	(0.04)	(0.03)	
P2	−1.49	0.78	−0.13	0.03	−0.05	−0.12	0.69
	(0.82)	(0.04)	(0.06)	(0.04)	(0.05)	(0.04)	
P3	1.10	1.01	−0.05	0.03	0.03	−0.03	0.82
	(0.59)	(0.04)	(0.04)	(0.03)	(0.04)	(0.03)	
P4	0.42	0.97	0.10	−0.02	−0.06	−0.07	0.79
	(0.67)	(0.05)	(0.04)	(0.03)	(0.04)	(0.04)	
P5	3.03	1.35	0.01	0.20	0.18	0.09	0.74
	(0.94)	(0.11)	(0.06)	(0.08)	(0.07)	(0.05)	
HML_{FX}	5.75	0.49	−0.02	0.43	0.27	0.01	0.31
	(1.40)	(0.17)	(0.11)	(0.11)	(0.09)	(0.07)	

The table reports time-series regression estimates for the linear five-factor model. The factors in columns include the dollar risk (DOL), and four long-minus-short portfolios based on exposures of local stock markets to commodity price risk in local currency (IME), FX excess returns' slope coefficients to commodity market return (COM), global commodity volatility (VOL_C), and global FX volatility (VOL_{FX}). The coefficient estimates for portfolio formation are obtained from expanding window regressions with 36 months of data required to produce first estimate. The test assets are monthly excess returns of five carry trade portfolios and the high-minus-low carry trade factor HML_{FX} based on currencies from developed countries (Panel A) and all countries (Panel B). Standard errors of coefficients are estimated using Newey and West (1987) approach with optimal number of lags according to Newey and West (1994). First column reports annualized pricing errors (intercepts) in per cent per p.a. The last column shows adjusted R^2. All returns are monthly excess returns in USD. The sample is from January 1987 to October 2016.

The first four rows of Table 1.4 report results from bivariate specifications (DOL plus one of the four HML factors). As theoretically predicted, stock market exposure factor IME along with exchange rate–commodity price covariance COV and commodity volatility VOL_C deliver positive annual risk premiums of 12.36%, 9.19% and 12.41% respectively. The FX volatility factor's risk premium is -7.36% p.a. All premia estimates in bivariate setups are statistically significant at 5% level. Note, that DOL plus IME (the first row) is the only bivariate specification in which the null of pricing errors being jointly indistinguishable from zero can not be rejected. The next six rows report results from trivariate specifications (DOL plus all combinations of any two from the four factors). The results are similar to the bivariate specifications, though stock market exposure IME and exchange rate–commodity price covariance COV appear to dominate the global volatility factors. I do not go for four-factor regressions, since there are only 5 observations per cross-section which would result in having only one degree of freedom, and probably overfitting the model since number of regressors approaches the number of observations.

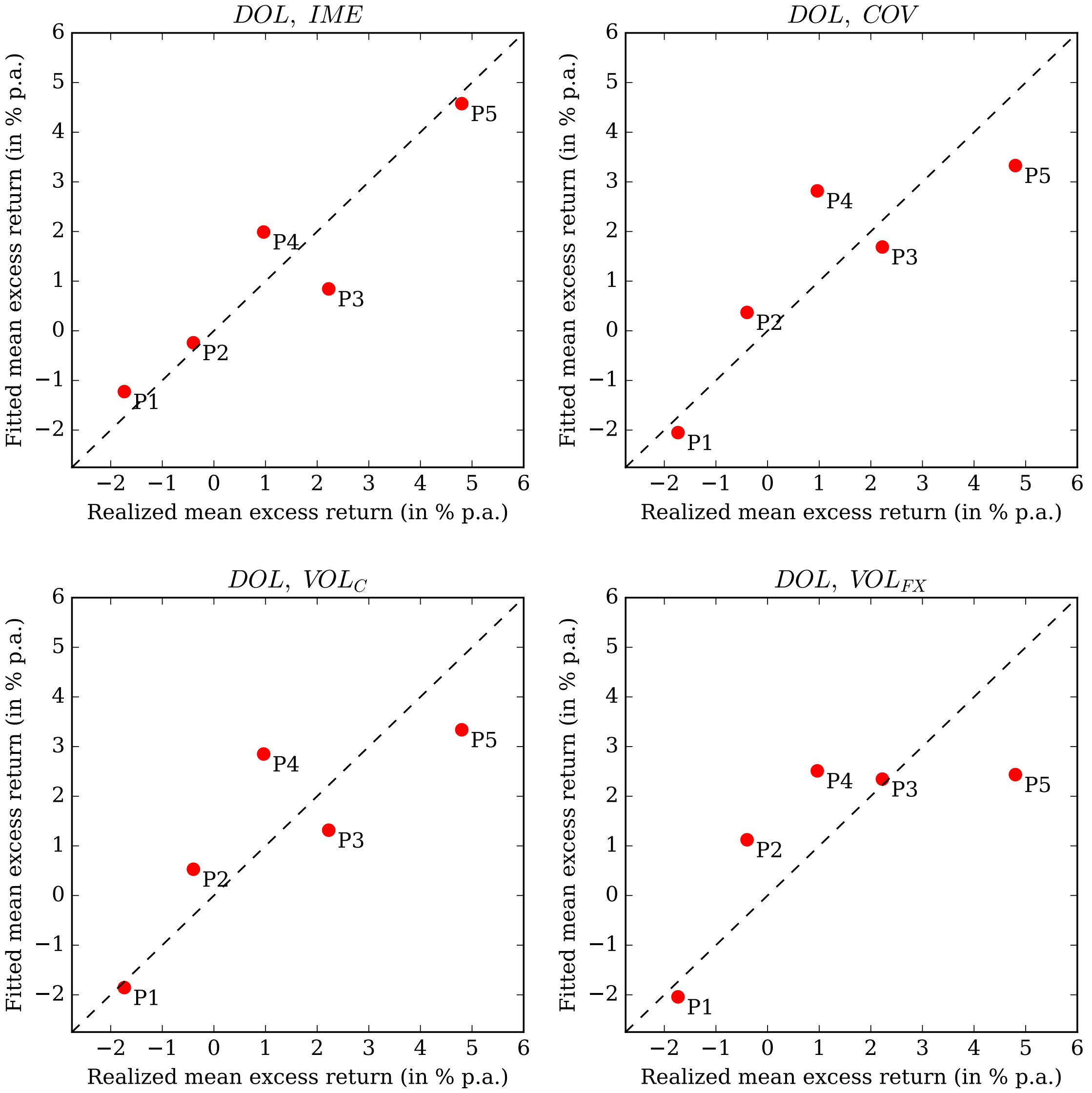
Table 1.4: Fama-MacBeth Regressions: Developed Countries

	DOL	IME	COV	VOL_C	VOL_{FX}	χ^2_{Sh}	χ^2_{NW}
λ	1.82	12.36				4.81	5.45
(Sh)	(1.47)	(4.21)				(0.19)	(0.14)
(NW)	(1.67)	(3.83)					
λ	1.88		9.19			6.47	12.47
(Sh)	(1.47)		(3.33)			(0.09)	(0.01)
(NW)	(1.47)		(3.24)				
λ	1.85			12.41		8.06	14.58
(Sh)	(1.47)			(4.83)		(0.05)	(0.00)
(NW)	(1.51)			(4.60)			
λ	1.94				−7.36	16.37	29.38
(Sh)	(1.47)				(2.72)	(0.00)	(0.00)
(NW)	(1.47)				(2.67)		
λ	1.82	11.99	9.21			4.21	5.82
(Sh)	(1.47)	(4.35)	(3.40)			(0.12)	(0.05)
(NW)	(1.70)	(3.45)	(3.45)				
λ	1.82	12.52		7.74		4.49	3.68
(Sh)	(1.47)	(4.19)		(4.92)		(0.11)	(0.16)
(NW)	(1.47)	(3.95)		(4.62)			
λ	1.82	10.79			−0.94	4.83	5.40
(Sh)	(1.47)	(4.73)			(3.09)	(0.09)	(0.07)
(NW)	(1.77)	(3.40)			(3.51)		
λ	1.93		8.48	−4.66		5.90	10.71
(Sh)	(1.46)		(3.60)	(12.85)		(0.05)	(0.00)
(NW)	(1.55)		(3.47)	(11.14)			
λ	1.86		13.47		2.05	6.79	9.39
(Sh)	(1.46)		(6.80)		(4.93)	(0.03)	(0.01)
(NW)	(1.75)		(5.21)		(4.56)		
λ	1.84			14.02	−0.76	8.13	12.74
(Sh)	(1.46)			(8.54)	(4.12)	(0.02)	(0.03)
(NW)	(1.74)			(7.01)	(4.04)		

This figure shows results of Fama and MacBeth (1973) regressions for bivariate and trivariate factor models for developed countries. The factors in columns include dollar risk (DOL, an equally-weighted long-only portfolio of currency excess returns), and one of four high-minus-low currency portfolios: IME, COV, VOL_C, VOL_{FX}. IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The test assets are monthly returns of five carry trade portfolios based on currencies from developed countries. The first stage estimates of time-series betas are obtained in-sample. The second stage regressions do not include intercept. Standard errors of factor risk prices λ and χ^2 test statistics for joint significance of pricing errors are estimated using both Newey and West (1987) HAC approach with optimal number of lags according to Newey and West (1994) and Shanken (1992) (Sh) correction. The factor risk prices λ and corresponding standard errors are in per cent per annum. All returns are in USD. The sample is from January 1987 to October 2016.

Finally, figures 1.3 and 1.4 illustrate the fit of the bivariate models plotting realized average excess returns to the five carry trade portfolios along the x-axis and the fitted average excess returns along the y-axis. Figure 1.3 and 1.4 present results for developed and all countries respectively. The four subplots in each figure proceed from top to bottom and from left to right (DOL plus IME, COV, VOL_C, VOL_{FX}).

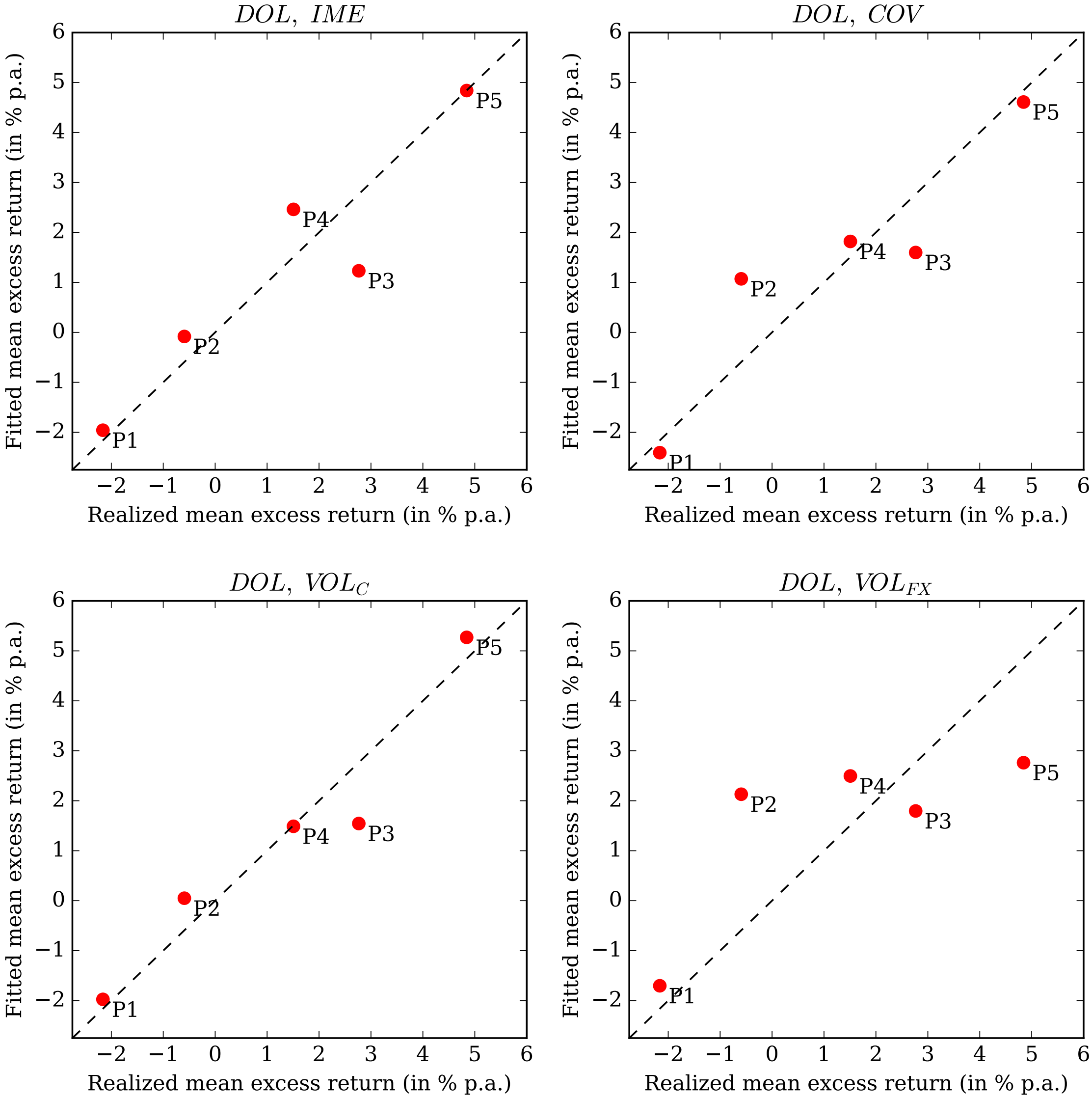
Figure 1.3: Pricing Error Plots: Carry Trade Portfolios, Developed Countries



This figure shows annualized pricing errors from Fama and MacBeth (1973) procedure for developed countries. Each plot reports pricing errors for a bivariate specification where factors include dollar risk (DOL, an equally-weighted long-only portfolio of currency excess returns), and one of four high-minus-low currency portfolios (clockwise from top-left) IME, COV, VOL_C, VOL_{FX}: IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The pricing errors are average residuals from Fama and MacBeth (1973) procedure with first-stage time-series regression estimates obtained in-sample. The test assets are monthly excess returns of five carry trade portfolios based on currencies from all countries. The sample is from November 1986 to October 2016.

Overall, as indicated by the tests, in both samples the stock market exposure factor provides the best fit, covariance and commodity volatility are on par underpricing the

Figure 1.4: Pricing Error Plots: Carry Trade Portfolios, All Countries



This figure shows annualized pricing errors from Fama and MacBeth (1973) procedure for all countries. Each plot reports pricing errors for a bivariate specification where factors include dollar risk (DOL, an equally-weighted long-only portfolio of currency excess returns), and one of four high-minus-low currency portfolios (clockwise from top-left) IME, COV, VOL_C, VOL_{FX}: IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The pricing errors are average residuals from Fama and MacBeth (1973) procedure with first-stage time-series regression estimates obtained in-sample. The test assets are monthly excess returns of five carry trade portfolios based on currencies from all countries. The sample is from November 1986 to October 2016.

high forward discount portfolio on average by 2% p.a., and FX volatility is capable of pricing only the low carry portfolio reasonably well.

1.5.2 Asset Pricing Tests: Developed Countries Excess Returns

In this section I repeat the asset pricing tests for individual currencies from the developed countries sample. Panels A and B in Table 1.5 summarize the time-series and cross-sectional tests respectively.

In general, commodity exporters like Canada, Australia and New Zealand and Norway load positively on the commodity market covariance factor COV, so their currencies appreciate with rising commodity prices. Conversely, importers of commodities like the Euro area, Japan, or Switzerland are negatively loaded to the commodity risk. Interestingly, there is a significant dispersion in loadings on the IME factor among the commodity exporting countries. Australia's and New Zealand's stock markets are much less exposed on average to the variation in commodity prices (in their local currencies) comparing to Norway and Canada, indicating that production in the former countries is less risky, thus commanding higher currency risk premium in line with equation 1.15. Indeed, a simple portfolio shorting half a dollar in Canadian dollar and Norwegian krone, and investing half a dollar in Australian and New Zealand dollars earns excess return of 2.7% p.a. with standard error of 1.2%. Finally, the loadings to the FX volatility reinforce the empirical evidence of Swiss franc and Japanese yen being safe haven currencies that appreciate during periods of high uncertainty in the foreign exchange markets.

The results of cross-sectional pricing tests in Panel B of Table 1.5 and pricing error plots in Figure 1.5 further corroborate findings for carry trade portfolios. Although failing to reach statistical significance, premia estimates have predicted signs and reasonable magnitude. Subplots in Figure 1.5 display pricing errors from Fama and MacBeth (1973) with number of regressors progressively expanded from univariate specification with the dollar risk only (top-left plot) to the five-factor model which includes all factors (bottom right plot). In the cross-section of excess returns of individual currencies, when comparing to the univariate specification with DOL only, the model improves fit of Australian and New Zealand Dollars, Japanese yen and Swedish krona, while underpricing Norwegian and Danish kroner and overpricing the euro.

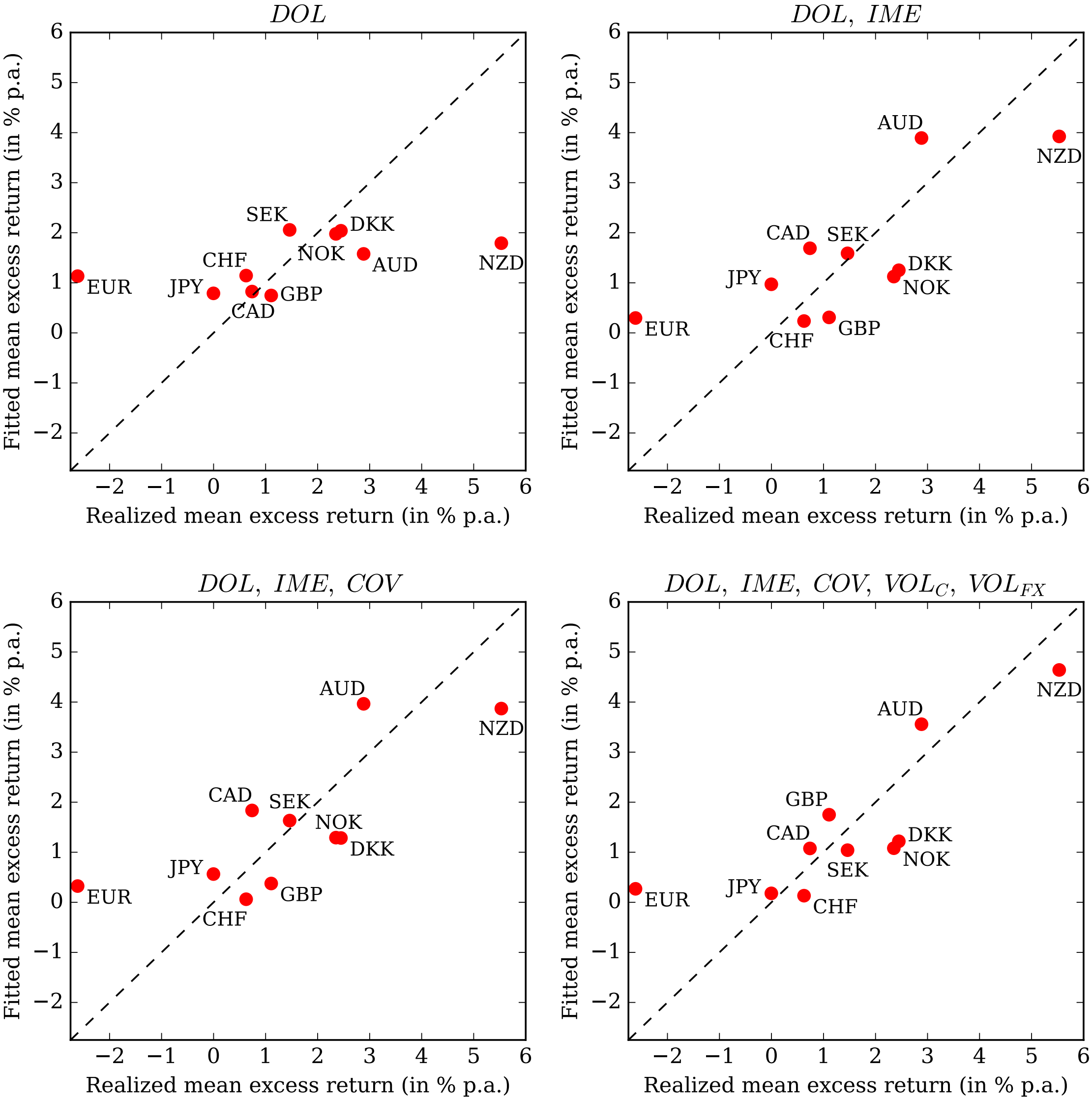
Overall, this section shows that the degree of insulation of local stock markets from commodity price shocks, covariance between exchange rates and commodity prices (also reflecting the degree of insulation from commodity price shocks in my model), and global FX and commodity volatility are priced factors both in time-series and cross-section of carry trade portfolios and (to lesser extent in terms of statistical significance) in excess returns of individual currencies. This results support the proposed theoretical model and corroborate earlier findings on local markets insulation of Ready et al. (2016), predictability of carry trades by commodity returns of Bakshi and Panayotov (2013) and negative price of FX volatility of Menkhoff et al. (2012).

Table 1.5: Asset Pricing Results: Excsess Returns of Developed Countries

	DOL	IME	COV	VOL_C	VOL_{FX}	α	$\bar{R}^2$
Panel A: Time-Series regressions							
Australia	1.04	0.35	0.23	0.22	−0.16	0.32	0.86
	(0.03)	(0.05)	(0.05)	(0.05)	(0.04)	(0.75)	
Canada	0.58	−0.11	0.17	0.32	−0.10	−0.00	0.59
	(0.04)	(0.05)	(0.05)	(0.06)	(0.04)	(0.74)	
Denmark	1.14	−0.22	−0.04	−0.04	−0.03	1.06	0.91
	(0.03)	(0.04)	(0.05)	(0.04)	(0.02)	(0.66)	
Euro	1.14	−0.24	−0.04	−0.04	−0.01	−2.79	0.90
	(0.03)	(0.05)	(0.05)	(0.05)	(0.02)	(0.76)	
Japan	0.75	0.16	−0.52	0.31	0.69	−1.76	0.74
	(0.07)	(0.08)	(0.08)	(0.07)	(0.04)	(0.98)	
New Zealand	1.10	0.56	0.25	−0.19	0.01	1.05	0.78
	(0.04)	(0.07)	(0.07)	(0.05)	(0.04)	(0.86)	
Norway	1.12	−0.44	0.16	0.04	−0.08	1.66	0.86
	(0.04)	(0.06)	(0.06)	(0.05)	(0.04)	(0.72)	
Sweden	1.20	−0.14	−0.13	0.07	−0.25	0.20	0.84
	(0.03)	(0.03)	(0.04)	(0.04)	(0.03)	(0.77)	
Switzerland	1.12	−0.01	−0.33	−0.10	0.12	0.16	0.85
	(0.04)	(0.06)	(0.06)	(0.05)	(0.03)	(0.75)	
United Kingdom	0.81	0.09	0.25	−0.59	−0.19	0.10	0.74
	(0.04)	(0.05)	(0.06)	(0.06)	(0.04)	(0.94)	
Panel B: FMB Regressions						χ^2_{Sh}	χ^2_{NW}
λ	1.83	3.05				134.7	37.84
(Sh)	(1.47)	(2.04)				(0.00)	(0.14)
(NW)	(1.47)	(2.03)					
λ	1.79		3.05			133.9	68.47
(Sh)	(1.47)		(2.17)			(0.00)	(0.00)
(NW)	(1.47)		(2.16)				
λ	1.81			2.47		131.8	40.53
(Sh)	(1.47)			(2.20)		(0.00)	(0.00)
(NW)	(1.55)			(2.23)			
λ	1.70				−1.05	135.4	59.82
(Sh)	(1.47)				(2.10)	(0.00)	(0.00)
(NW)	(1.61)				(2.32)		
λ	1.80	3.13	3.35	−0.33	0.83	128.8	36.50
(Sh)	(1.47)	(2.09)	(2.49)	(2.11)	(2.61)	(0.00)	(0.00)
(NW)	(1.68)	(1.75)	(2.63)	(2.18)	(2.98)		

This table reports pricing for the linear five-factor model. The factors in columns include the dollar risk (DOL), and four high-minus-low portfolios: IME (sorted on countries' stock market betas to commodity market return in local currency); COV, VOL_C, VOL_{FX} (sorted on betas of currency excess returns to commodity market return, global commodity and FX volatilities respectively). Betas estimates are obtained from expanding window regressions. The test assets are monthly excess returns of ten currencies from the 'developed countries' sample. Panel A reports estimates of time-series regressions, two last columns report annualized pricing errors in per cent and adjusted R^2. Standard errors of coefficients are estimated using Newey and West (1987) approach with optimal number of lags according to Newey and West (1994). All returns are monthly excess returns in USD. Panel B reports results of Fama and MacBeth (1973) regressions with first-stage time-series betas estimated in-sample and no intercepts in the second stage of the procedure. The factor risk prices λ and corresponding standard errors are in per cent per annum. Standard errors of factor risk prices λ and χ^2 test statistics for joint significance of pricing errors are estimated using both Newey and West (1987) (NW) approach with optimal number of lags according to Newey and West (1994) and Shanken (1992) (Sh) correction. The sample is from January 1987 to October 2016.

Figure 1.5: Pricing Error Plots: Excess Returns, Developed Countries



This figure shows annualized pricing errors from Fama and MacBeth (1973) procedure, with test assets being excess returns on currencies from developed countries. The factors are added sequentially, so that the top left panel plots pricing error when *DOL* (an equally-weighted long-only portfolio of currency excess returns) is the only factor; the top right panel adds *IME*, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high; the bottom left panel shows results for a three-factor model adding the *COV* portfolio; the bottom right plot presents results for the five-factor model further adding global FX and commodity volatility factors VOL_C and VOL_{FX}. COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The pricing errors are average residuals from Fama and MacBeth (1973) procedure with first-stage time-series regression estimates obtained in-sample. The sample is from November 1986 to October 2016.

1.5.3 Can the Commodity-Related Factors Generate Substantial Returns?

In the previous section I have shown that the proposed factors bear the signs which are in line with the model, and deliver premia of a reasonable economic magnitude in the cross-section. The time-series means, however are marginally statistically significant at best. In this section I turn to the data of higher granularity and examine whether the commodity-related factors are capable of generating substantial returns and to which extent this returns are affected by transaction costs.

First, I reestimate regressions 1.18, 1.19 using daily data, replacing the excess returns on the left hand side of 1.18 with spot rate returns and calculating the dollar factor over spot rate returns only. Then I estimate the daily data regressions over rolling windows varying in length from 22 days (one month) to 261 days (one year), form portfolios as in the previous section and adjust portfolios for transaction costs as discussed before. I also form two additional portfolios MIX_1 and MIX_2. MIX_1 is a long-minus-short portfolio establishing positions in currencies for month $t+1$ according to the previous month's z-score aggregated slope coefficient estimates: $z(\hat{\beta}^k_{2,t}) + z(\hat{\beta}^k_{3,t}) - z(\hat{\beta}^k_{4,t}) + z(\hat{\pi}^k_t)$, where z-score is computed over the cross-section of countries and FX volatility coefficient is taken with negative sign to represent positive expected return. Similarly, MIX_2 aggregates three slope coefficients $\hat{\beta}^k_i$, thus not taking the stock market exposure into account.

Figure 1.6 plots excess returns on the six portfolios from the stock market exposure factor IME at the top left subplot to the combined MIX_2 portfolio (bottom right) for the developed countries sample. The rolling window length (formation horizon) is along horizontal axes and the annualized mean excess returns are along vertical axes. Unadjusted returns are in black and red solid lines represent returns adjusted for transaction costs. Figure 1.7 plots Newey and West (1987) t-statistics of the mean excess return estimates, with optimal number of lags selected according to Newey and West (1994). The stock market exposure factor delivers unambiguously positive return for any formation horizon, even after adjustment for transaction costs, the IME factor earns more than 4% p.a. for formation horizons up to one year while also retaining statistical significance. Moreover for formation horizons from two to six months the portfolio displays returns comparable in magnitude and significance to those of carry trades. Covariance and volatility portfolios have higher spread between unadjusted and adjusted returns, comparing to the exposure portfolio, indicating more frequent rebalancing. So for example the spread in returns for the COV portfolio at the horizon of two months (44 days) is around 1.5% p.a. implying average transaction costs of 6.25 bps even if both legs of the portfolio are completely rebalanced each month, which is sizable for the FX market.[21] The COV and VOL_C portfolios nevertheless survive transaction cost adjustment (in statistical sense) for intermediate horizons of up to 6 and 3 months respectively with average excess returns of around 2.5% p.a. each. Similar to the findings of the previous section, FX volatility bears a small negative premium that does not survive transaction costs or achieve statistical significance. Both aggregated

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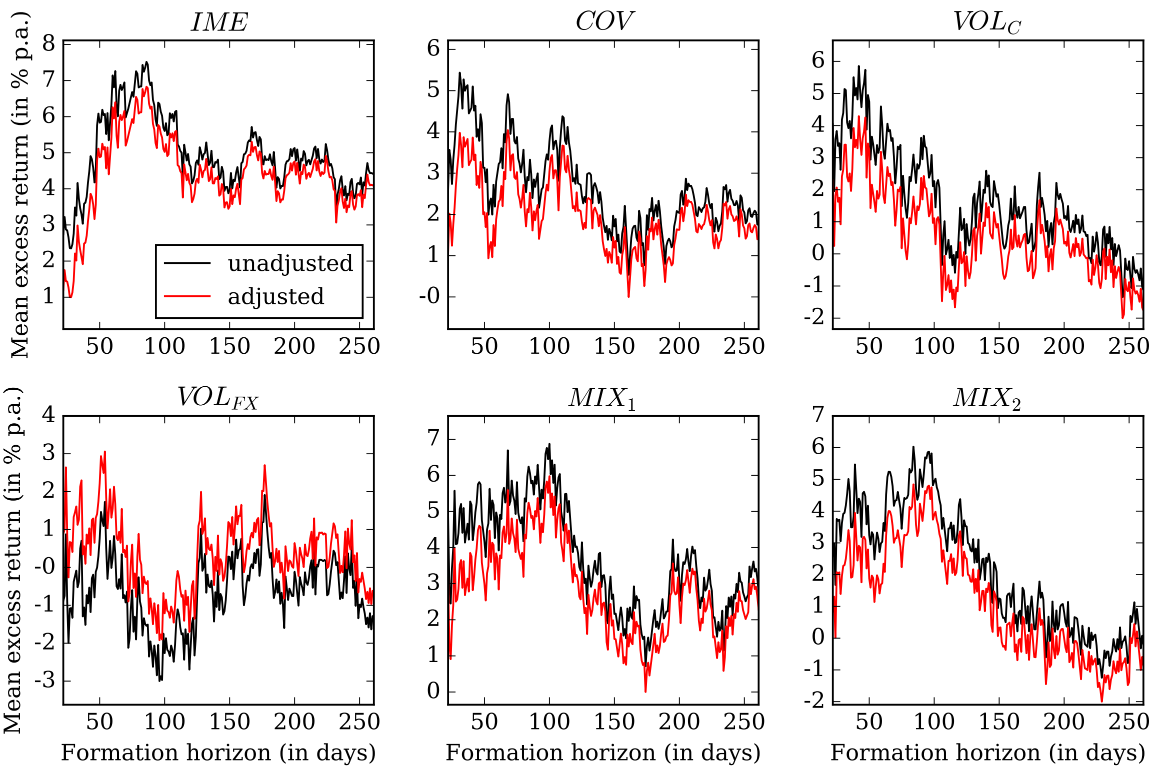
[21] I briefly comment on the Datastream's FX quotes at the end of this section.

portfolios provide positive significant returns for formation horizons up to half a year earning around 4% p.a. (MIX_1) and 3% p.a. (MIX_2).

Figure 1.6: Mean Excess Returns and Formation Horizon: Developed Countries

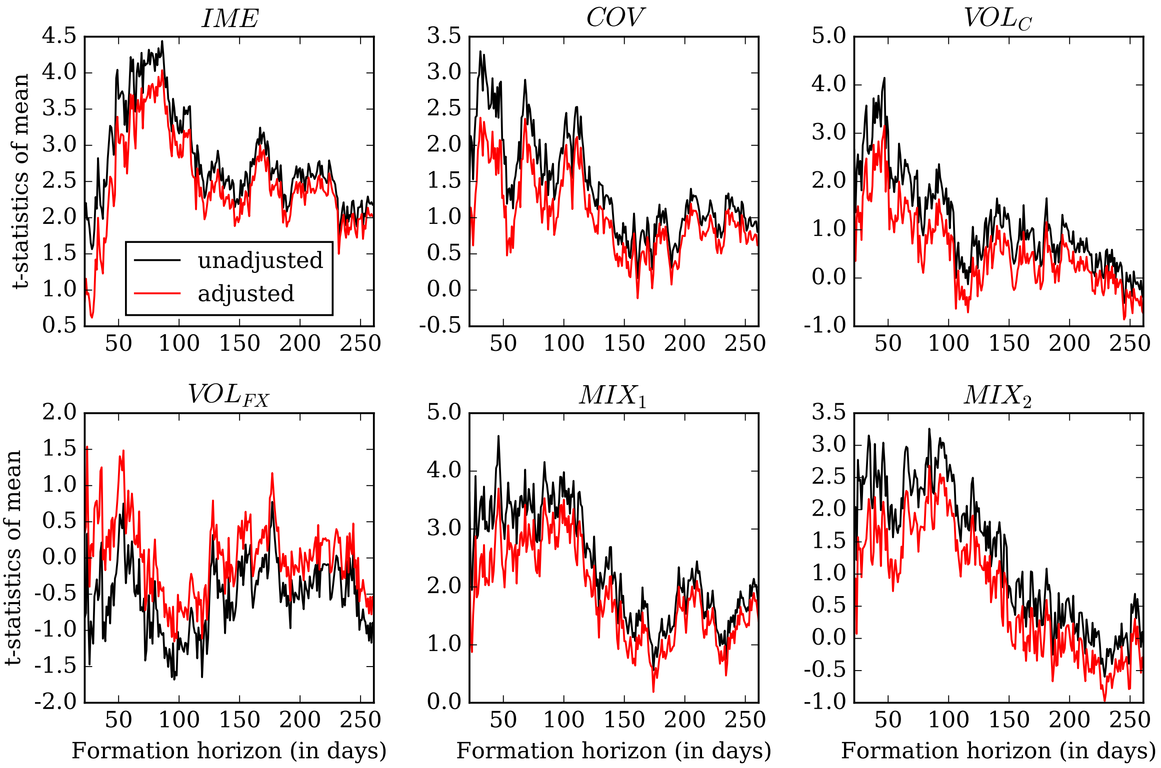


This figure plots mean excess returns in USD on factor portfolios (in % p.a.) against formation horizon (in days) for developed countries. The black lines represent returns unadjusted for transaction costs and red lines represent transaction costs-adjusted returns. All portfolios are sorted on the prior month's slope coefficients estimated from regressions 1.18, 1.19 using daily data. Length of the rolling estimation window (formation horizon) is along the x-axis in each subplot. The portfolios are (from top left to bottom right): IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. MIX_1 and MIX_2 are portfolios sorted on z-score aggregated slope coefficients from four factors and three factors (COV, VOL_C, VOL_{FX}) respectively with FX volatility taken with negative sign to represent positive premium. The sample is from March 1985 to October 2016.

Figures 1.8 and 1.9 repeat the analysis above for all countries. Results are qualitatively similar to the developed countries sample, however transaction costs are twice as high on average and level the trading profits. Only the IME portfolio is capable of delivering positive bid-ask spread-adjusted returns for formation horizons from 3 months to half a year, though its excess returns stay positive for all horizons considered (same behavior is observed for the COV factor and for VOL_C up to a horizon of approximately 9 months).

It is important to understand that exchange rate quotes reported by Datastream are

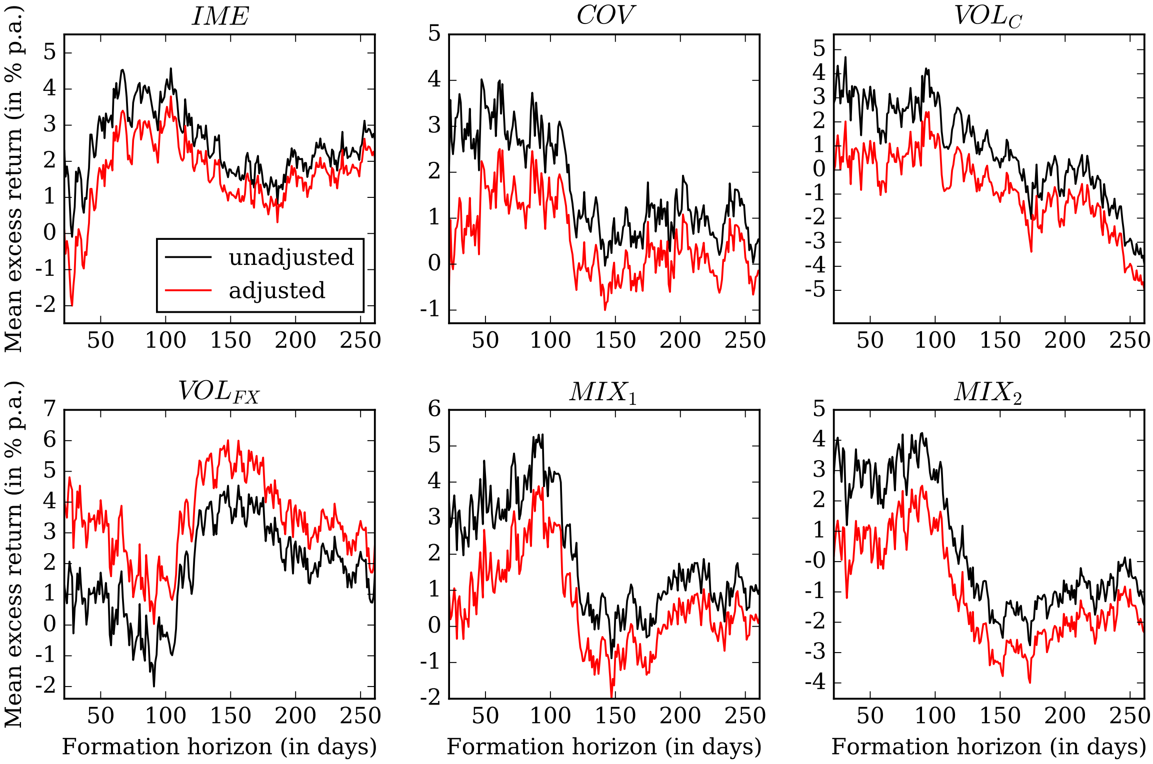
Figure 1.7: Significance of Mean Excess Returns and Formation Horizon: Developed Countries



This figure plots t-statistics of mean excess returns on factor portfolios (in % p.a.) against formation horizon (in days) for developed countries. The black lines represent returns unadjusted for transaction costs and red lines represent transaction costs-adjusted returns. All portfolios are sorted on the prior month's slope coefficients estimated from regressions 1.18, 1.19 using daily data. Length of the rolling estimation window (formation horizon) is along the x-axis in each subplot. The portfolios are (from top left to bottom right): IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. MIX_1 and MIX_2 are portfolios sorted on z-score aggregated slope coefficients from four factors and three factors (COV, VOL_C, VOL_{FX}) respectively with FX volatility taken with negative sign to represent positive premium. The reported statistics are estimated using Newey and West (1987) approach with optimal number of lags according to Newey and West (1994). The sample is from March 1985 to October 2016.

not the actual quotes observed in the FX market and tend to overstate the real transaction costs. So for example, according to Datastream data Australian dollar (against USD) had bid-ask spread of 10 bps for spot prices and 13 bps for forward prices over the whole sample, and of 5 bps and 7 bps for the period from January 2010 to October 2016. Overall, the results of this section provide additional evidence supporting the theoretical model, moreover, for the most liquid currencies the proposed factors are capable of delivering substantial transaction costs-adjusted returns. The remaining question is, however, whether profits from these portfolios can be attributed to the carry trades and other factors or they constitute separate sources of currency risk

Figure 1.8: Mean Excess Returns and Formation Horizon: All Countries



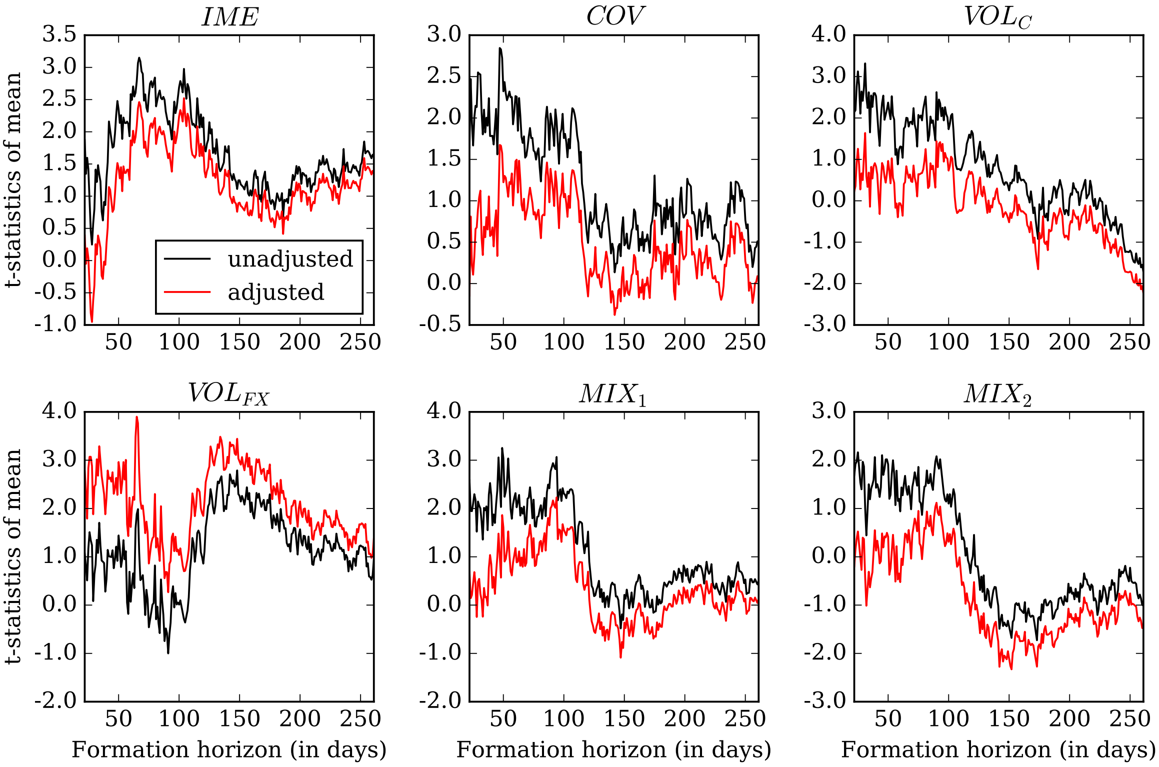
This figure plots mean excess returns in USD on factor portfolios (in % p.a.) against formation horizon (in days) for all countries. The black lines represent returns unadjusted for transaction costs and red lines represent transaction costs-adjusted returns. All portfolios are sorted on the prior month's slope coefficients estimated from regressions 1.18, 1.19 using daily data. Length of the rolling estimation window (formation horizon) is along the x-axis in each subplot. The portfolios are (from top left to bottom right): IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. MIX_1 and MIX_2 are portfolios sorted on z-score aggregated slope coefficients from four factors and three factors (COV, VOL_C, VOL_{FX}) respectively with FX volatility taken with negative sign to represent positive premium. The sample is from March 1985 to October 2016.

premium.

1.5.4 Are Those Premia Different from Carry Trades?

Table 1.6 reports results of time-series regressions with the commodity-related portfolios from the previous section as test assets and the carry trade portfolio HML_{FX} as an explanatory variable. The four commodity-related FX factors are based on the estimates of slope coefficients from regressions with estimation window of 66 days, and returns to these portfolios along with returns of HML_{FX} are adjusted for transaction costs. Panel A reports estimates for the developed countries and panel B reports esti-

Figure 1.9: Significance of Mean Excess Returns and Formation Horizon: All Countries



This figure plots t-statistics of mean excess returns on factor portfolios (in % p.a.) against formation horizon (in days) for all countries. The black lines represent returns unadjusted for transaction costs and red lines represent transaction costs-adjusted returns. All portfolios are sorted on the prior month's slope coefficients estimated from regressions 1.18, 1.19 using daily data. Length of the rolling estimation window (formation horizon) is along the x-axis in each subplot. The portfolios are (from top left to bottom right): IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. MIX_1 and MIX_2 are portfolios sorted on z-score aggregated slope coefficients from four factors and three factors (COV, VOL_C, VOL_{FX}) respectively with FX volatility taken with negative sign to represent positive premium. The reported statistics are estimated using Newey and West (1987) approach with optimal number of lags according to Newey and West (1994). The sample is from March 1985 to October 2016.

mates for all countries. Each row shows results of a regression of one of the five high-minus-low portfolios on the other four plus the dollar risk. The first column of the table reports annualized pricing errors (intercepts) in % p.a. The last column shows adjusted R^2. Standard errors of coefficients are in parentheses and estimated using Newey and West (1987) approach with optimal number of lags according to Newey and West (1994).

Note, that the proportion of explained variance is lower, comparing to the results using monthly data (in Table 1.3), indicating that estimation on lower frequency better captures time-series variation in interest rates, which are the major source of profitability of carry trades. As expected, both IME and HML_{FX} factors load positively and significantly on each other and on the covariance factor COV. Furthermore, in the developed sample, both portfolios still generate positive and significant risk-adjusted returns of over 4% p.a. and jointly explain returns on the exchange rate-commodity price covariance portfolio COV. Interestingly, the commodity volatility portfolio is essentially unrelated to anything except for the dollar risk, while still earning a significant premium of 4% p.a. In the all countries sample, returns of IME and COV portfolios do not provide significant risk-adjusted returns when controlling for each other and carry trades, which remain profitable. The positive risk-adjusted return of the FX volatility VOL_{FX} factor is primarily caused by the transaction cost adjustment (see the bottom left plot of Figure 1.8)

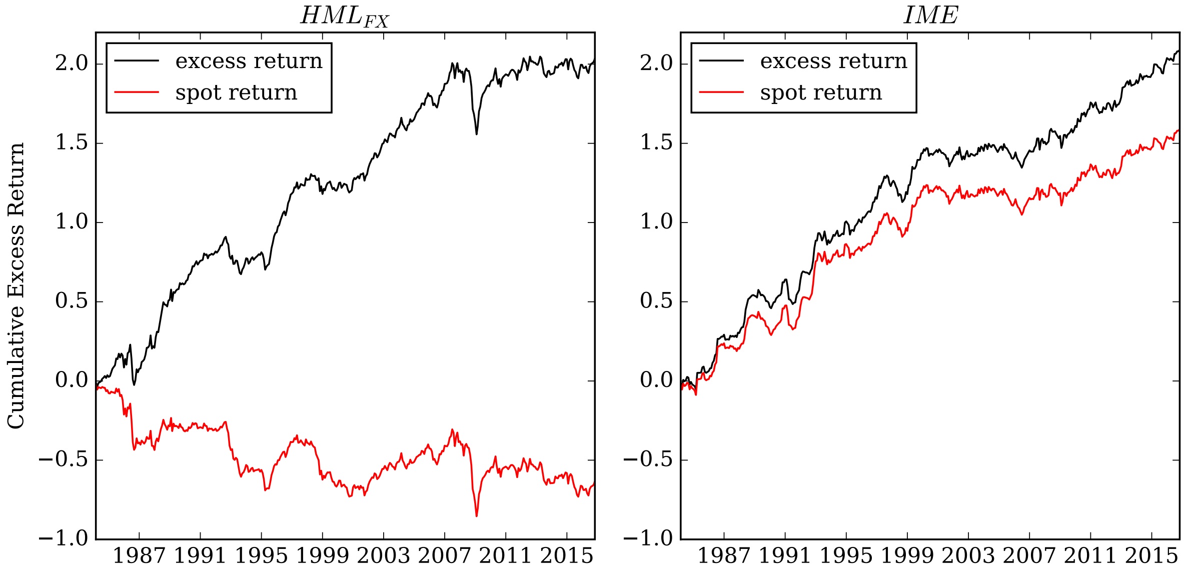
Table 1.6: Time-Series Regressions: Commodity Factors as Test Assets

	α	DOL	IME	COV	VOL_C	VOL_{FX}	HML_{FX}	$\bar{R}^2$
Panel A: Developed Countries								
IME	4.25	0.03		0.14	−0.01	0.03	0.15	0.08
	(1.66)	(0.07)		(0.06)	(0.06)	(0.07)	(0.08)	
COV	0.26	−0.03	0.18		−0.09	−0.02	0.23	0.11
	(1.64)	(0.07)	(0.08)		(0.08)	(0.06)	(0.08)	
VOL_C	4.01	−0.16	−0.01	−0.08		−0.11	−0.08	0.06
	(1.72)	(0.07)	(0.07)	(0.07)		(0.11)	(0.07)	
VOL_{FX}	−0.63	0.12	0.05	−0.02	−0.13		0.12	0.04
	(1.79)	(0.08)	(0.12)	(0.07)	(0.11)		(0.12)	
HML_{FX}	4.67	0.12	0.21	0.26	−0.10	0.11		0.14
	(1.72)	(0.09)	(0.11)	(0.09)	(0.09)	(0.12)		
Panel B: All countries								
IME	1.51	0.16		0.15	0.05	0.04	0.20	0.13
	(1.71)	(0.09)		(0.07)	(0.04)	(0.05)	(0.07)	
COV	2.13	−0.27	0.24		−0.09	−0.07	−0.01	0.06
	(2.11)	(0.09)	(0.12)		(0.10)	(0.07)	(0.13)	
VOL_C	0.79	−0.02	0.07	−0.07		0.12	−0.11	0.03
	(1.54)	(0.07)	(0.06)	(0.08)		(0.16)	(0.08)	
VOL_{FX}	3.43	0.08	0.06	−0.06	0.13		−0.00	0.02
	(1.46)	(0.06)	(0.08)	(0.07)	(0.18)		(0.09)	
HML_{FX}	4.80	0.33	0.35	−0.01	−0.15	−0.00		0.15
	(1.76)	(0.10)	(0.13)	(0.14)	(0.12)	(0.11)		

The table reports time-series regression estimates for five linear five-factor models. Panel A reports estimates for developed countries and panel B reports estimates for all countries. Each row shows results of a regression of one of the five high-minus-low portfolios on the other four plus the dollar risk (DOL, an equally-weighted long-only portfolio of currencies against USD). The five high-minus-low factors include: carry trades HML_{FX}, buying high interest rate currencies, while funding this position with low interest rate currencies, and four factors based on estimated slope coefficients from regressions of local stock market return on commodity return in local currency – IME; and currency spot returns on commodity market return, global FX and commodity volatility (COV, VOL_C, and VOL_{FX} respectively). The slope coefficients are estimated from rolling regressions with window of 66 days (3 months) and then lagged by one month for the portfolio formation. All portfolios are adjusted for transaction costs. All returns are monthly excess returns in USD. Standard errors of coefficients (in parentheses) are estimated using Newey and West (1987) approach with optimal number of lags according to Newey and West (1994). First column reports annualized pricing errors (intercepts) in per cent per p.a. The last column shows adjusted R^2. The sample is from May 1984 to October 2016.

The analysis above suggests that, the commodity-based factors are related, but not equivalent to carry trades, thus representing additional sources of risk and return in the FX market, and that this return is substantial at least for the most liquid currencies, where transaction costs are low. Figure 1.10 illustrates these claims by plotting transaction cost-adjusted spot returns and excess returns of the carry trade portfolio HML_{FX} (left plot) and of the exposure factor IME as calculated for the Table 1.6 (right plot). Apparently, the portfolios are very different in terms of source of gains: on average, carry trade excess returns come exclusively from the interest rate differential, and high forward discount currencies depreciate while low forward discount currencies appreciate. The IME gets the bulk of its return from spot rate appreciation, in line with equation 1.15 which predicts positive risk premium for insulated currencies regardless the sign of the interest rate differential.

Figure 1.10: Carry Trades vs. Stock Market Exposure: Developed Countires



This figure plots currency excess returns (in black) and spot returns (in red) to the HML_{FX} and IME factors (left and right plots respectively). The HML_{FX} portfolio invests in currencies with high previous month's forward discount, funding this position with low interes rate currencies. The IME, or insulated-minus-exposed, portfolio buys currencies of countries with low degree of comovement between local stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high. The degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency. The slope coefficient is estimated from rolling regressions with window of 66 days (3 months) and then lagged by one month for the portfolio formation. Returns are ajusted for transaction costs and expressed in USD. The sample spans period from February 1986 to October 1987.

The results in the two previous sections further reinforce the evidence I obtain from the monthly data. The commodity-based risk factors can be exploited as tradable strategies earning substantial risk-adjusted returns, though the magnitude of these returns is highly affected by transaction costs, especially for the all countries sample. Also I show that despite sharing similarities with carry trades, the commodity-based factors represent different aspect of the currency risk premium.

1.6 Conclusions

In this paper I examine the impact of commodity prices on currency risk premium and profitability of carry trades – trading strategies, stemming from the forward premium anomaly, i.e. tendency of high interest rate currencies to appreciate, generating positive excess returns. I develop a production-based no-arbitrage framework where exporters of commodities have heterogeneous exposures to the export price risk and show that this model can account for deviations from the UIP.

The mechanics of the model can be summarized as follows: free international flows of investment combined with heterogeneity in revenues due to export tariffs, shipment costs or other frictions result in differential loadings of producers' pricing kernels on the common risk factor – commodity price, thus production in the foreign relatively insulated economy is less risky, leading to a lower foreign Sharpe ratio and hence to a positive expected return on the foreign currency. In bad times when commodity price uncertainty is high, interest rates in the domestic relatively exposed economy decrease by a greater amount than in the foreign insulated economy, simultaneously expected excess return on investment (equivalently Sharpe ratio) rises more domestically than abroad, thus commanding an increase in the currency risk premium, to make domestic investors indifferent between investing at home or abroad, rationalizing deviations from the UIP.

The model also explicitly takes in account the fact that commodities are traded in currencies foreign to commodity producers, so higher covariance between spot exchange rate and commodity prices provides an additional level of insulation from commodity price shocks and leads to higher interest rate and currency risk premium. Similarly, higher exchange rate volatility destabilizes producer profits leading to lower currency excess returns, replicating the negative price of FX volatility observed in the data. An additional important feature of the model unrelated to the UIP puzzle is predicted positive currency risk premium for insulated economies irrespective of the interest rate differential: the spot exchange rate equalizes investment return across countries, so in good times of high expected commodity returns and low commodity price uncertainty currencies of insulated producers appreciate to ensure the absence of arbitrage between investment across countries.

I provide broad empirical evidence supporting the theoretical model documenting strong commonality between the dynamics of commodity market and FX excess returns. I show that the aggregate commodity market risk is different from the aggregate FX market risk and possesses sizable explanatory power in capturing both time-series and cross-sectional variation of excess returns of carry trade portfolios and individual currencies through several distinct channels. I further link both FX and commodity markets to equity markets across the world, using the Cochrane (1991) argument that investment return equals stock return in equilibrium. I show that among the most liquid currencies the portfolio going long in currencies of countries whose stock markets are insulated from commodity price shocks and shorting exposed stock market currencies delivers excess returns comparable in magnitude and significance to returns of carry trades. I also show that commodity and FX volatility, and covariance of exchange rate and commodity price are priced factors in the FX market. These empirical findings contribute to the rational, risk-based view on the currency risk premium and forward premium puzzle.

Future studies can extend the production-based framework. In this paper I abstract from analyzing impact of productivity and ability of producers to transform output across states on the currency risk premium and focus only on the common component of countries' pricing kernels. Further research can address the country-specific components, examining the model's ability to quantitatively match the stylized facts about equity and currency risk premia.

Appendix A

Exporter's Optimization Problem

Let $V(K_t, \varepsilon_t)$ be the present value of commodity producer at the time t. The Bellman equation of the producer is:

$$V(K_t, \varepsilon_t) = \max_{\{I_t, \varepsilon_{t+1}\}} \{D_t + E_t[M_{t+1}V(K_{t+1}, \varepsilon_{t+1})]\} \tag{A.1}$$

subject to the constraints:

$$D_t = (\frac{P_t}{S_t}Y_t)^{\pi}(\bar{P}Y_t)^{1-\pi} - I_t, \quad \pi \in [0, 1] \tag{A.2}$$

$$Y_t = \varepsilon_t F(K_t) \tag{A.3}$$

$$1 \geq E_t[(\frac{\varepsilon_{t+1}}{\theta_{t+1}})^{\alpha}]^{\frac{1}{\alpha}}, \quad \alpha > 1 \tag{A.4}$$

$$K_{t+1} = I_t \tag{A.5}$$

Where M_{t+1} is the stochastic discount factor, K_t is the fully depreciating stock of capital, $F(K_t)$ is an increasing and concave production function, P_t is the price level of output (commodity) in units of commodity market currency, $\bar{P}$ is some fixed price level in exporter's currency, $\pi \in [0, 1]$ captures share of output sold abroad so if $\pi = 1$, S_t is the nominal exchange rate in units of commodity market currency per unit of exporter's currency (so an increase in the spot exchange rate means appreciation of exporter's currency), ε_t is the level of productivity, and θ_t is the underlying productivity. Upon realization of the output, its price, and the exchange rate, producer converts the revenue into domestic currency, chooses the investment level I_t, and the next-period productivity ε_{t+1}. Profit, which equals revenue less investment cost, is then distributed to shareholders as dividends D_t. Denote μ_t, λ_t to be the Lagrange multipliers associated with technological and capital accumulation constraints A.4, A.5 respectively. The first order conditions with respect to investment , capital stock at time $t + 1$, and productivity level are:

$$\frac{\partial}{\partial I_t} : -1 + \lambda_t = 0 \tag{A.6}$$

$$\frac{\partial}{\partial K_{t+1}} : E_t[M_{t+1}V_k(K_{t+1}, \varepsilon_{t+1})] - \lambda_t = 0 \tag{A.7}$$

$$\frac{\partial}{\partial \varepsilon_{t+1}} : M_{t+1}V_\varepsilon(K_{t+1}, \varepsilon_{t+1}) - \mu_t \alpha \frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}} = 0 \tag{A.8}$$

In equilibrium, the technological constraint A.4 is binding, therefore, the expectation in the last term of the equation A.8 equals 1. The envelope conditions are:

$$V_k = (\frac{P}{S})^{\pi}(\bar{P})^{1-\pi}\varepsilon F_K(K) \tag{A.9}$$

$$V_\varepsilon = (\frac{P}{S})^{\pi}(\bar{P})^{1-\pi}F(K) \tag{A.10}$$

Combining the first order conditions with respect to investment and capital (A.6, A.7) with the envelope condition with respect to capital (A.9) yields the standard asset pricing formula for investment return:

$$E_t[M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi}\varepsilon_{t+1}F_K(K_{t+1})] = E_t[M_{t+1}R_{I,t+1}] = 1 \tag{A.11}$$

Plug the productivity envelope condition A.10 into equation A.8, multiply both sides by ε_{t+1} and take expectation conditional on time t to obtain the following expression which defines the Lagrange multiplier μ_t:

$$E_t[M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi}\varepsilon_{t+1}F(K_{t+1})] = \mu_t\alpha E_t[(\frac{\varepsilon_{t+1}}{\theta_{t+1}})^{\alpha}] = \mu_t\alpha, \tag{A.12}$$

The last equality follows from the fact, that the technological constraint is binding in equilibrium. Plug μ_t back into equation A.8 to obtain:

$$M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi}F(K_{t+1}) = E_t[M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi}\varepsilon_{t+1}F(K_{t+1})]\frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}} \tag{A.13}$$

Since the capital stock K_{t+1} is predetermined at time t, the previous equation may be written as:

$$M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi} = E_t[M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi}\varepsilon_{t+1}]\frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}} \tag{A.14}$$

Finally, rearranging equation A.11 as $E_t[M_{t+1}(\frac{P_{t+1}}{S_{t+1}})^{\pi}(\bar{P})^{1-\pi}\varepsilon_{t+1}] = \frac{1}{F_K(K_{t+1})}$ and plugging the expectation into the previous equation, yields an expression for the stochastic discount factor:

$$M_{t+1} = \frac{1}{F_K(K_{t+1})}\frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}}(\frac{1}{\bar{P}})^{1-\pi}(\frac{S_{t+1}}{P_{t+1}})^{\pi} \tag{A.15}$$

Appendix B

Additional Asset Pricing Tests

Table B.1: Fama-MacBeth Regressions: All Countries

	DOL	IME	COV	VOL_C	VOL_{FX}	χ^2_{Sh}	χ^2_{NW}
λ	1.32	14.48				4.87	7.21
(Sh)	(1.37)	(4.56)				(0.18)	(0.07)
(NW)	(1.67)	(4.07)					
λ	1.29		12.77			7.02	7.65
(Sh)	(1.37)		(3.59)			(0.07)	(0.05)
(NW)	(1.67)		(3.42)				
λ	1.25			13.71		3.16	4.04
(Sh)	(1.37)			(4.51)		(0.37)	(0.26)
(NW)	(1.67)			(3.98)			
λ	1.38				-13.88	27.62	11.26
(Sh)	(1.37)				(3.93)	(0.00)	(0.01)
(NW)	(1.5)				(3.80)		
λ	1.30	12.33	11.16			1.98	7.35
(Sh)	(1.37)	(6.33)	(3.32)			(0.37)	(0.03)
(NW)	(1.67)	(5.74)	(3.12)				
λ	1.25	8.56		13.81		2.71	3.81
(Sh)	(1.37)	(5.61)		(6.36)		(0.26)	(0.15)
(NW)	(1.64)	(4.98)		(5.54)			
λ	1.32	14.72			-5.72	4.25	6.89
(Sh)	(1.37)	(5.15)			(3.71)	(0.12)	(0.03)
(NW)	(1.71)	(4.61)			(3.73)		
λ	1.24		6.58	14.86		3.50	4.34
(Sh)	(1.37)		(3.83)	(8.64)		(0.17)	(0.11)
(NW)	(1.69)		(3.77)	(7.82)			
λ	1.31		13.42		1.11	3.42	6.39
(Sh)	(1.37)		(4.09)		(5.62)	(0.18)	(0.04)
(NW)	(1.72)		(3.79)		(5.56)		
λ	1.25			13.71	-4.94	3.24	4.14
(Sh)	(1.37)			(5.08)	(3.77)	(0.20)	(0.13)
(NW)	(1.71)			(4.54)	(3.82)		

This figure shows results of Fama and MacBeth (1973) regressions for bivariate and trivariate factor models for all countries. The factors in columns include dollar risk (DOL, an equally-weighted long-only portfolio of currency excess returns), and one of four high-minus-low currency portfolios: IME, COV, VOL_C, VOL_{FX}. IME, or insulated-minus-exposed, is the portfolio buying currencies of the countries with low degree of comovement between stock prices and commodity prices in local currency, and selling currencies of the countries where degree of comovement is high (the degree of comovement is determined as a slope coefficient from regression of stock market returns on commodity returns in local currency); COV, VOL_C, VOL_{FX} are portfolios sorted on betas from time-series regressions of currency excess returns on commodity market return, global commodity and FX volatilities respectively. The test assets are monthly returns of five carry trade portfolios based on currencies from all countries. The first stage estimates of time-series betas are obtained in-sample. The second stage regressions do not include intercept. Standard errors of factor risk prices λ and χ^2 test statistics for joint significance of pricing errors are estimated using both Newey and West (1987) HAC approach with optimal number of lags according to Newey and West (1994) and Shanken (1992) (Sh) correction. The factor risk prices λ and corresponding standard errors are in per cent per annum. All returns are in USD. The sample is from January 1987 to October 2016.

Appendix C

Supplementary Appendix

C.1 Importer's Optimization Problem

Consider an importer who buys the commodity X in the international market and uses it as a factor of production. The Bellman equation for the importer is:

$$V(K_t, X_t, \varepsilon_t) = \max_{\{I_t, X_t \varepsilon_{t+1}\}} \{D_t + E_t[M_{t+1} V(K_{t+1}, X_{t+1}, \varepsilon_{t+1})]\} \tag{C.1}$$

subject to the constraints:

$$D_t = Y_t - I_t - \frac{P_t}{S_t}(X_t + G(X_t, \bar{X})) \tag{C.2}$$

$$Y_t = \varepsilon_t F(K_t, X_t) \tag{C.3}$$

$$1 \geq E_t[(\frac{\varepsilon_{t+1}}{\theta_{t+1}})^{\alpha}]^{\frac{1}{\alpha}}, \quad \alpha > 1 \tag{C.4}$$

$$K_{t+1} = I_t \tag{C.5}$$

$$F(K_t, X_t) = K_t^{\gamma} X_t^{1-\gamma}, \quad \gamma \in [0, 1] \tag{C.6}$$

$$G(X_t, \bar{X}) = \frac{\beta}{2} \bar{X} (\frac{X_t - \bar{X}}{\bar{X}})^2 \tag{C.7}$$

Where X_t is the demand for commodity, $\bar{X}$ is some reference commodity input level, so that deviations from this level induce convex adjustment costs $G(X_t, \bar{X})$. In contrast to the exporter's problem, the production function depends on the input chosen at the period of output realization and the stochastic discount factor can be derived analytically only for a limited number of production functions – for example, there is no explicit solution for the CES function. I assume the Cobb-Douglas function with constant returns to scale and introduce convex adjustment costs in order to account for the limited substitutability between capital and commodity. So, for example, if demand for commodity is below the reference level, additional costs might be induced by underutilization of production capacities or by penalty paid under a take-or-pay contract. If the demand exceeds the reference level, the costs might arise due to a within-period commodity storage fee or purchasing additional quotas for burning fossil fuels, if commodity is, for instance, oil or natural gas. The other variables and mechanics of the problem are similar to those of the exporter.

Let μ_t, λ_t be the Lagrange multipliers associated with technological and capital accumulation constraints C.5, C.4 respectively. The first order conditions with respect to the current period's investment and commodity input and the next period's capital stock and productivity level are:

$$\frac{\partial}{\partial I_t} : -1 + \lambda_t = 0 \tag{C.8}$$

$$\frac{\partial}{\partial K_{t+1}} : E_t[M_{t+1} V_k(K_{t+1}, X_{t+1}, \varepsilon_{t+1})] - \lambda_t = 0 \tag{C.9}$$

$$\frac{\partial}{\partial \varepsilon_{t+1}} : M_{t+1} V_\varepsilon(K_{t+1}, X_{t+1}, \varepsilon_{t+1}) - \mu_t \alpha \frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}} = 0 \tag{C.10}$$

$$\frac{\partial}{\partial X_t} : \varepsilon_t F_X(K_t, X_t) - \frac{P_t}{S_t}(1 + G_X(X_t, \bar{X})) = 0 \tag{C.11}$$

Where F_X, G_X are partial derivatives of the production and costs functions respectively. In equilibrium the technological constraint C.4 is binding, therefore the expectation in the last term of the equation C.10 equals 1. The envelope conditions are:

$$V_k = \varepsilon F_K(K, X) \tag{C.12}$$

$$V_\varepsilon = F(K, X) \tag{C.13}$$

Combining the first order conditions with respect to investment and capital C.8, C.9 with the envelope condition with respect to capital C.12 yields the standard asset pricing formula for investment return:

$$E_t[M_{t+1} \varepsilon_{t+1} F_K(K_{t+1}, X_{t+1})] = E_t[M_{t+1} R_{I,t+1}] = 1 \tag{C.14}$$

Plug the productivity envelope condition C.13 into equation C.10, multiply both sides by ε_{t+1} and take expectation conditional on time t to obtain the following expression which defines the Lagrange multiplier μ_t:

$$E_t[M_{t+1} \varepsilon_{t+1} F(K_{t+1}, X_{t+1})] = \mu_t \alpha E_t[(\frac{\varepsilon_{t+1}}{\theta_{t+1}})^{\alpha}] = \mu_t \alpha, \tag{C.15}$$

The last equality follows from the fact, that the technological constraint is binding in equilibrium. Plug μ_t back into equation C.10 to obtain:

$$M_{t+1} F(K_{t+1}, X_{t+1}) = E_t[M_{t+1} \varepsilon_{t+1} F(K_{t+1}, X_{t+1})] \frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}}$$

Under the Cobb-Douglas technologies $F(K, X) = K^{\gamma} X^{1-\gamma}$, $F_K(X, K) = \gamma K^{\gamma-1} X^{1-\gamma}$, equation C.14 implies:

$$E_t[M_{t+1} \varepsilon_{t+1} K_{t+1}^{\gamma} X_{t+1}^{1-\gamma}] = \frac{K_{t+1}}{\gamma} = E_t[M_{t+1} \varepsilon_{t+1} F(K_{t+1}, X_{t+1})]$$

The two previous equations yield the stochastic discount factor:

$$M_{t+1} = \frac{1}{\gamma} \frac{\varepsilon_{t+1}^{\alpha-1}}{\theta_{t+1}^{\alpha}} K_{t+1}^{1-\gamma} X_{t+1}^{\gamma-1} \tag{C.16}$$

For the assumed production technology and adjustment costs, the first order condition for commodity input C.11 is:

$$\varepsilon_t (1-\gamma) K_t^{\gamma} X_t^{-\gamma} = \frac{P_t}{S_t} (1 + \beta \frac{X_t - \bar{X}}{\bar{X}})$$

Denote k, x, p, s as the natural logarithms of capital, commodity demand, commodity price, and spot exchange rate respectively, take logs, assuming that $\beta(X_t - \bar{X})/\bar{X}$ is small:

$$log(\varepsilon_t (1-\gamma)) + \gamma k_t - \gamma x_t \approx p_t - s_t + \beta \frac{X_t - \bar{X}}{\bar{X}} \approx p_t - s_t + \beta x_t - \beta \bar{x}$$

Solving for the log demand x_t and exponentiating yields:

$$X_t = [\varepsilon_t (1-\gamma) K_t^{\gamma} \bar{X}^{\beta} S_t P_t^{-1}]^{\frac{1}{\beta+\gamma}}$$

Finally, plug the optimal demand for commodity into equation C.16 to obtain the stochastic discount factor in terms of the commodity price and exchange rate:

$$M_{t+1} = \frac{\varepsilon_{t+1}^{\alpha - \frac{1+\beta}{\beta+\gamma}}}{\theta_{t+1}^{\alpha}} \frac{(1-\gamma)^{\frac{\gamma-1}{\beta+\gamma}}}{\gamma} (\frac{K_{t+1}}{\bar{X}})^{\frac{\beta(1-\gamma)}{\beta+\gamma}} (\frac{S_{t+1}}{P_{t+1}})^{\frac{\gamma-1}{\beta+\gamma}} \tag{C.17}$$

In contrast to the exporter, the exchange rate and commodity price are now pro- and countercyclical respectively, the other properties are similar. Write the SDF from equation C.17 as $M_{t+1} = \Psi_{t+1}(S_{t+1}/P_{t+1})^{(\gamma-1)(\beta+\gamma)}$, assuming Ψ_{t+1} is known at time t, the risk-free rate is:

$$R_{f,t} \approx \tag{C.18}$$

$$\frac{\Psi_{t+1}}{\mu_{s,t}^{\omega}\mu_{p,t}^{-\omega} + \frac{1}{2}(\omega^2 \mu_{s,t}^{\omega-2}\mu_{p,t}^{-\omega}\sigma_{s,t}^2 + \omega(\omega+1)\mu_{s,t}^{\omega}\mu_{p,t}^{-\omega-2}\sigma_{p,t}^2 - 2\omega^2\mu_{s,t}^{\omega-1}\mu_{p,t}^{-\omega-1}\sigma_{sp,t})},$$

where $\omega = (\gamma-1)/(\beta+\gamma)$ and $\mu_{s,t}$, $\mu_{p,t}$, $\sigma_{s,t}^2$, $\sigma_{p,t}^2$, $\sigma_{sp,t}$ are time t expectations, variances and covariance of the corresponding variables at $t+1$. Note that equation C.18 also applies to a general exporter with exposure π, in such case $\omega = \pi$. For both importers and exporters, keeping other things equal, higher variance of exchange rate and its lower covariance with commodity price command lower interest rates. The impact of commodity price variance on the risk-free rate is always non-positive for exporters – since $\pi \in [0,1]$, $\omega(1+\omega) \geq 0$, implying lower interest rates as commodity price variance increases. For importers, however, it depends on sign of $(\gamma - 1)/(\beta + \gamma) + 1$ – this term is negative if $\gamma < (1-\beta)/2$, so in absence of adjustment costs the share of capital in output should be less than 0.5, therefore if β is not too large the negative impact is expected.

Except for some special cases, equation C.18 does not admit a closed form solution for the expected spot rate. Overall, the production-based approach above leads to several implications without making any distributional or no-international-arbitrage assumptions: ceteris paribus, lower interest rates are implied by *(i)* low covariance between exchange rate and commodity price; *(ii)* high exchange rate volatility; *(iii)* higher commodity price volatility, unless the importer's adjustments costs are high.

C.2 Currency Excess Returns and Interest Rate Differentials in Absence of Arbitrage: General Case

If the law of one price holds and there are no arbitrage opportunities, there exists a unique positive stochastic discount factor. Assume that markets are complete and denote foreign variables with $*$, then the nominal foreign and domestic stochastic discount factors are M^*_{t+1} and M_{t+1} respectively. The Euler equations for the foreign currency-denominated return R^*_{t+1} imply $E_t[M^*_{t+1}R^*_{t+1}] = E_t[M_{t+1}\frac{S_{t+1}}{S_t}R^*_{t+1}] = 1$, therefore, the gross return on the nominal exchange rate is:

$$\frac{S_{t+1}}{S_t} = \frac{M^*_{t+1}}{M_{t+1}} \tag{C.19}$$

Backus et al. (2001) show that for the lognormal SDFs and returns, the expected log currency excess return is equal to the half difference of conditional variances of the domestic and foreign log pricing kernels:

$$E_t[rx_{t+1}] = \frac{1}{2}Var_t[m_{t+1}] - \frac{1}{2}Var_t[m^*_{t+1}] \tag{C.20}$$

Under the lognormality assumption the domestic and foreign interest rates are given by:

$$r_{f,t} = -logE_t[M_{t+1}] = -E_t[m_{t+1}] - \frac{1}{2}Var_t[m_{t+1}]$$
$$r^*_{f,t} = -logE_t[M^*_{t+1}] = -E_t[m^*_{t+1}] - \frac{1}{2}Var_t[m^*_{t+1}]$$

Since $E_t[m^*_{t+1}] - E_t[m_{t+1}] = E_t[\Delta s_{t+1}]$:

$$r^*_{f,t} - r_{f,t} + E_t[\Delta s_{t+1}] = \frac{1}{2}Var_t[m_{t+1}] - \frac{1}{2}Var_t[m^*_{t+1}] = E_t[rx_{t+1}]$$

In the production-based framework the exchange rate ensures absence of arbitrage opportunities between returns on domestic and foreign physical investment. Henceforth, I stick to the lognormality assumption and write the stochastic discount factors and investment returns derived in Appendix A as:

$$M_{t+1} = \Xi_{t+1}(\frac{S_{t+1}/S_t}{P_{t+1}/P_t})^{\omega} \tag{C.21}$$

$$R_{I,t+1} = \Phi_{t+1}(\frac{S_{t+1}/S_t}{P_{t+1}/P_t})^{-\omega}, \tag{C.22}$$

where $\omega = \pi$ for exporters and $\omega = \frac{\gamma-1}{\beta+\gamma}$ for importers, Ξ_{t+1} and Φ_{t+1} are known at time t.[1] For a reference economy, not facing exchange rate risk, the stochastic discount factor and returns on physical investment are defined by equations C.21 and C.22 with S_{t+1} equal to 1.

Consider a domestic and a foreign economy with pricing kernels M_{t+1} and M^*_{t+1} determined by C.21, let the domestic currency be the reference currency, in which the commodity price is quoted, and assume the domestic investor's perspective. Finally, denote natural logs with lower case letters, and normalize the predetermined variables Ξ_{t+1}, Φ_{t+1} to one in order to keep notation as transparent as possible.

In absence of international arbitrage, equation C.19 implies:

$$\Delta s_{t+1} = \omega^* \Delta s_{t+1} + (\omega - \omega^*)\Delta p_{t+1} \quad \Leftrightarrow \quad \Delta s_{t+1} = \frac{\omega - \omega^*}{1 - \omega^*}\Delta p_{t+1} \tag{C.23}$$

The spot return in equation C.19 is a function of commodity price with coefficient determined by the countries' relative exposure to the export (or import) price risks. The denominator $1 - \omega^*$ is non-negative for exporters and strictly positive for importers, so the numerator $\omega - \omega^*$ determines the no-arbitrage coefficient.

For instance, if both the foreign and the domestic economies are exporters, the foreign spot exchange rate has positive loading on commodity return whenever $\omega^* < \omega \Leftrightarrow \pi^* < \pi$, that means the foreign economy is less exposed to the world prices. Intuitively, the currency of the less exposed exporter must appreciate since the spot rate changes offset the arbitrage opportunities between physical investment returns in the

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[1] For exporters $\Xi_{t+1} = \frac{1}{F_K(K_{t+1})}\frac{\varepsilon^{\alpha-1}_{t+1}}{\theta^{\alpha}_{t+1}}(\frac{1}{\bar{P}})^{1-\pi}(\frac{S_t}{P_t})^{\pi}$, and $\Phi_{t+1} = \varepsilon_{t+1}F_K(K_{t+1})\bar{P}^{1-\pi}(\frac{S_t}{P_t})^{-\pi}$; for importers $\Xi_{t+1} = \frac{\varepsilon_{t+1}^{\alpha-\frac{1+\beta}{\beta+\gamma}}}{\theta^{\alpha}_{t+1}}\frac{(1-\gamma)^{\frac{\gamma-1}{\beta+\gamma}}}{\gamma}(\frac{K_{t+1}}{\bar{X}})^{\frac{\beta(1-\gamma)}{\beta+\gamma}}(\frac{S_t}{P_t})^{\frac{\gamma-1}{\beta+\gamma}}$, and $\Phi_{t+1} = \varepsilon_{t+1}^{\frac{\beta+1}{\beta+\gamma}}\gamma(1-\gamma)^{\frac{1-\gamma}{\beta+\gamma}}K_{t+1}^{\gamma-1+\gamma\frac{1-\gamma}{\beta+\gamma}}\bar{X}^{\beta\frac{1-\gamma}{\beta+\gamma}}(\frac{S_t}{P_t})^{\frac{1-\gamma}{\beta+\gamma}}$

two countries – if the commodity price rises, the investment returns of the less exposed exporter increase less, than those of the more exposed producer, hence the currency of the less exposed economy appreciates.

For two importing economies the commodity price loading is positive if $(\gamma - 1)/(\beta + \gamma) > (\gamma^* - 1)/(\beta^* + \gamma^*)$. For instance, if the shares of capital in output are equal $\gamma = \gamma^*$, the positive loading occurs if the foreign economy faces lower adjustment costs of commodity input $\beta^* < \beta$ – so the foreign economy experiences a greater degree of substitutability between capital and imported commodity and therefore the price of commodity has larger impact on physical investment returns which is offset by appreciation of the exchange rate similar to the two exporters case.

Interestingly, the no-arbitrage loading of the spot rate on the commodity price for the domestic importer - foreign exporter case is always negative, since with an increase in the commodity price, importer's and exporter's investment returns fall and rise respectively. It is possible to generalize the production-based framework to produce a positive no-arbitrage importer-exporter commodity price loading – the straightforward way is to model each country both as exporter of some goods and importer of others akin to Ready et al. (2016) (the spot rate - commodity price coefficient will then depend on import adjustment costs and covariance between import and export prices). However, in any no-arbitrage framework deviations from the uncovered interest parity and time-varying currency risk premium arise from time variation in the conditional higher moments of the pricing kernels. This means that even if exporters' currencies are expected to depreciate, they can still earn positive risk premium . As an illustration consider a simplified example where both domestic importer and foreign exporter operate under the same currency, so the exporter's pricing kernel does not explicitly depend on spot exchange rate. The (real) risk premium is therefore:

$$E_t[rx_{t+1}] = \frac{1}{2}(\omega^2 - \pi^{*2})Var_t[\Delta p_{t+1}] \tag{C.24}$$

It is clear, that the exporter's currency earns positive risk premium if $|\omega| > |\pi|$. The rest of the risk premium implications and reasoning are very similar to the two exporters case discussed in the main text of the paper.

Chapter 2

Monetary Policy and Currency Returns: the Foresight Saga[*]

Dmitry Borisenko[†] and Igor Pozdeev[‡]

Abstract

We document a drift in exchange rates before monetary policy changes across major economies. Currencies tend to depreciate by 0.8 percent over ten days before policy rate cuts and appreciate by 0.5 percent before policy rate increases. We show that available fixed income instruments allow to accurately forecast monetary policy decisions and thus that the drift is foreseeable and exploitable by investors. Our baseline specification of a trading strategy constructed by going long in currencies against USD before predicted local interest rate hikes and short in currencies before predicted cuts earns on average a statistically significant excess return of over 40 basis points per ten-day period after trading costs. We further demonstrate that this return is robust to the choice of holding horizon and monetary policy forecast rule. Our results thus pose a major challenge for the risk-based explanations of the exchange rate dynamics and highlight an important side effect of monetary policy decisions.

Keywords: Monetary Policy, Policy Expectations, Predictability, Overnight Index Swap, Foreign Exchange.

JEL Classification: E43, E52, E58, F31, G12

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2.1 Introduction

By 2001, the central banks of most developed countries had adopted the practice of a fixed number of scheduled meetings per year, each culminating in a decision about the policy rate – most often a short-term rate. The decision would then by virtue of the expectation hypothesis propagate through the yield curve and eventually find its way into the domestic currency return, as documented in the vast literature on the uncovered interest parity and carry trade strategies. This indirect effect of monetary policy on exchange rates has been extensively studied; the direct, or immediate, relation has overgrown with anecdotal evidence – such as the January 2015 rate cut by the Swiss national bank trying to prevent a rapid appreciation of the franc – but been far less researched.

Mueller et al. (2017) were the first to document the abnormal positive return of being long in foreign (from the perspective of an American investor) currencies in the hours around FOMC announcements. They find that the effect is more pronounced for the high interest rate currencies, and that a simple *ex post* conditioning on the sentiment of policy decisions allows to improve the strategy performance. Karnaukh (2016) conducts similar research in the low-frequency dimension. She reports that the US dollar (synthetic exchange rate of the USD vs. a basket of currencies) tends to depreciate days before Federal funds rate cuts and appreciate before rate hikes. Using the rates implied in the Federal funds futures' prices to bet on the direction of the upcoming target rate change several days in advance, she constructs a strategy of high profitability between 1994 and 2015.

In this paper, we bring the currencies and policy announcements of other developed countries into the picture. Our primary contribution is to document an economically and statistically significant drift in exchange rates several days in advance of changes in target policy rates across major economies. We show that a randomly selected currency is expected to depreciate against the USD by 80 basis points over the 10 days before before a randomly selected rate cut, and appreciate by 50 basis points in the opposite case, which is statistically significant at the 5% level. We find that the multiperiod appreciation before rate hikes and depreciation before rate cuts is a phenomenon common to most currencies – not only to the US dollar, as shown by Karnaukh (2016). We further demonstrate that this drift can be exploited by investors as a trading strategy. Using overnight index swaps, we forecast upcoming rate changes and go long in currencies ten days in advance of an expected rate hike and short in those with an expected rate cut. The strategy features a statistically and economically significant excess return of over 40 basis points per event after transaction costs, a cumulative of 127 percent since late 2000.

Our second contribution is to point out that forecasting monetary policy direction is a classification problem and thus subject to the discretionary choice of the classification rule. The holding period is another "tweaker" for the trader or researcher to adjust. Thus, there exist many possible forecast-based trading strategies: one for each element of the Cartesian product of the set of possible classification rules and the set of possible holding periods. Since it is never clear *ex ante* which strategy specification will result in a significant return, the backward-looking bias discussed i.a. in Bailey and Lopez de Prado (2014) might contaminate the inference. We construct a plethora of specifications and show that our findings are very robust: the average return across all specifications amounts to 80 percent since late 2000 while several specifications lead to as much as a 225 percent return and only a handful – to money loss. Interestingly, when treated in the same way, the dollar-FOMC pre-announcement drift of Karnaukh (2016) is found to be less significant, averaging slightly below of zero across all specifications.

Our third contribution is to the literature on forecasting future policy rates. While evidence on the predictive power of the Fed funds futures is abundant (Krueger and Kuttner (1996) and Piazzesi and Swanson (2008), to name a few), this paper is to our knowledge the first extensive treatment of how overnight index swaps (OIS) can be used with the same purpose. We find that policy rate forecasts extracted from OIS rates have been most accurate since mid-2000s. For example, out of 20 rate increases and 13 rate cuts which happened in the USA in the bespoke period, 19 and 10 respectively could be correctly predicted by the OIS-implied rates twelve days in advance, which is on par with the Federal funds futures scoring 19 and 11 respectively.

Still, as we use only the market prices of one certain instrument, our forecasts are based on an information set that is surely narrower than that of the real-world market participants.[1] Thus our results are likely to be conservative.

Our paper thus extends the strand of literature on responses of asset prices to macroeconomic announcements. For the stock market, Lucca and Moench (2015) find strong positive returns of the S&P500 index around FOMC announcements. In contrast to the main finding of their paper, we show that exchange rates do not respond to the upcoming rate hikes and cuts in the same manner. Cieslak et al. (2016) report that the stock returns in the US are cyclical and centered on the FOMC meetings. For bonds, Hördahl et al. (2015) investigate the movements of the yield curve after the release of major U.S. macroeconomic announcements, and Kontonikas et al. (2016) study the dynamics of the corporate bond returns after monetary policy shocks. For the FX market, the above mentioned papers by Mueller et al. (2017) and Karnaukh (2016) are the major references. In contrast to many of these papers however, ours covers only target rate decisions among all monetary policy announcements and is silent about unconventional policy tools. Although the latter have enjoyed elevated popularity since

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[1] Additional sources of information are the prices of other fixed income derivatives, analysts' surveys and often the regulators' own words. For example, Norges Bank adds monetary policy projections with an own view on the future policy rates in its quarterly reports.

2008 and although the FX patterns that we document might actually be shaped by announcements of policy easing and tightening, which include but are not limited to target rate changes,[2] predicting the sentiment of a generic announcement is much more difficult and subject to data manipulation than predicting a rate hike or cut. In a way, we concentrate on a subset of monetary policy announcements, arguably the most important one which in addition we can measure *ex ante* for many currencies in a unified way, while leaving the rest for future research.

What could explain our results? Standard asset pricing theory links excess returns to systematic risks which can not be diversified away thus commanding a risk premium. Policy announcements provide markets with information about authorities' future actions. Recent theoretical models of Ai and Bansal (2016) and Pástor and Veronesi (2013) tie these information releases to the risk premium compensating investors for uncertainty regarding the path of the future policy.

It is difficult to reconcile our findings with these risk-based explanations: first, we show that excess return earned before the announcement day dwarfs the announcement day returns documented by Mueller et al. (2017); second, the pre-announcement drift in exchange rates does not appear before the announcements at which no policy rate change was implemented; third, our finding of monetary policy shifts being highly predictable leaves little room for the uncertainty resolution argument.

Alternative theories feature inattentive investors, infrequent rebalancing decisions and other impediments to perfect markets. Duffie (2010) develops a limited participation model with heterogeneous agents where the "inattentive" investors trade less frequently than "professional intermediaries". In this setup, the aggregate level of risk does not change before scheduled events, unlike its distribution among the investor types, with intermediaries bearing a larger share, thus demanding compensation for the risk. As Lucca and Moench (2015) point out, it is not clear in the setup of Duffie (2010), why it would be optimal for inattentive investors to sell their positions out to intermediaries instead of maintaining their holdings and reaping the premium.

Bacchetta and Van Wincoop (2010) present an overlapping generations model where infrequent rebalancing decisions stem from the costs of active portfolio management. In their setup, agents optimally stick to passive currency management if costs of active management are prohibitively high. The infrequent rebalancings in turn lead to the delayed exchange rate overshooting with depreciation of foreign currency over several periods after an interest rate cut implemented by the foreign central bank. Although the setup of Bacchetta and Van Wincoop (2010) helps to rationalize the persistence in

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[2] For example, on January 22, 2015 the ECB announced its expanded asset purchase programme with actual purchases starting in March 2015 simultaneously leaving the key rates unchanged. The euro depreciated against USD by more than 2 percent over ten days preceding the announcement and by more than one percent on the announcement day. Although OIS correctly predicted no target rate change they completely missed the more important unconventional component of the announcement.

currency returns, it does not explain why the drift appears before changes in interest rates.

The rest of the paper is organized as follows. Section 2.2 outlines the methodology of event studies, policy expectations recovery and trading strategy construction; Section 2.3 summarizes the data used; Section 2.4 presents our findings; Section 2.5 concludes.

2.2 Methodology

This section describes the empirical design of our study. First, we outline the methodology of event studies in a multicurrency framework. Then, we discuss the payoff structure of overnight index swaps and federal funds futures, and describe the techniques to extract the implied future interest rates. The section concludes with the description of the spot and excess returns of a trading strategy and related costs.

2.2.1 Event Study

To detect the pre-announcemnt drift in the currency markets, we use an event study framework.

Event studies in finance have not changed much since Fama et al. (1969). In our case the test assets are exchange rates, and the events are monetary policy announcements of respective regulators, such that each test asset is associated with multiple events. Two choices are important in the design of any event study: of the event window span, and of the model for what is considered "normal" as opposed to "abnormal".

The former choice is dictated by the possible duration of the exercised effect and by the necessity to retain an "uncontaminated" portion of the sample for inference purposes. Mostly interested in the pre-announcement dynamics of the assets, we choose the period of 10 days before and 5 days after each announcement as the event window, using the rest of the sample for estimation. We also exclude the event day from both samples, thus differentiating between the pre-event and post-event windows.

We use the constant mean model discussed i.a. in Brown and Warner (1980) as the model for the "normal" currency returns, the mean being zero. This way, abnormal returns are the same as returns. We will briefly discuss the quality of this model towards the end of this subsection.

Define $d_{i,k}$ to be the date of announcement $k \in \{1, \ldots, K\}$ relating to currency $n \in \{1, \ldots, N\}$. As discussed above, the event window spans w_b days before and w_a days after $d_{i,k}$. We cut the series of (dollar) returns of currency i into k subsamples of length

$w_a - w_b$). We reindex these subsamples to have incremental ordinal indexes

$$\{s\} = \{w_b, \dots, -1, 0, +1, \dots, w_a\},$$

understood to denote s days after an event: for example, the day of event will have index 0, and the day corresponding to two days before it will have index -2.

A cumulative abnormal return (CAR) is defined as:

$$R^{ca}_{i,k,s} = \begin{cases} \sum\limits_{t=s}^{-1} R_{i,k,t} & s < 0, \\ \sum\limits_{t=+1}^{s} R_{i,k,t} & s > 0, \end{cases} \tag{2.1}$$

such that the s-period CAR before an event is understood to be realized by buying the currency in period $-s$ and selling it in period -1; the return after an event is realized by buying the currency in period 1 and selling it in period s after the event. In what follows we will concentrate our attention on the pre-announcement returns.

The average cumulative abnormal return is defined as the average over events and over currencies of the cumulative return in equation (2.1):

$$\overline{R^{ca}_s} = \frac{1}{NK} \sum_{i=1}^{N} \sum_{k=1}^{K} R^{ca}_{i,k,s} \tag{2.2}$$

The variance of $\overline{R^{ca}_s}$ is calculated as the average variance of individual $R^{ca}_{i,k,s}$, based on the assumption that the latter are i.i.d. Seemingly restrictive, this assumption appears more realistic after acknowledging two facts: first, for each country, monetary policy decisions are spread out in time, which justifies independence over K; second, across countries, they are not synchronized (and most often out of phase), which mitigates potential dependence over N. The variance of individual $R^{ca}_{i,k,s}$ is calculated for each k based on the variance realized since the previous event window ended and using the the zero-mean assumption, such that the estimate is biased upwards.[3] Appendix A outlines the inference in detail.

2.2.2 Recovering Implied Rates

The literature on assessing the expectations about future monetary policy actions from observable asset prices is vast: for example, Krueger and Kuttner (1996), Kuttner (2001)

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[3] We also calculate bootstrapped confidence bands as a robustness check of the assumptions (details are given in Appendix A): All in all, these turn out to be less conservative than the parametric ones, such that the average cumulative returns appear more significant at all holding horizons. We attribute this to the fact that the estimate of the variance in equation (A.8) is biased upwards, and that the average autocorrelation across the spot returns is slightly negative. These results are available on request.

and Karnaukh (2016) use the federal funds futures, Cochrane and Piazzesi (2002) employ the one-month eurodollar deposit rate. Gürkaynak et al. (2007) compare the predictive power of rates implied by a variety of traded assets in forecasting future monetary policy actions in the US. Our contribution to this strand of literature is two-fold. First, the empirical evidence on predictability of target rate changes primarily considers the United States. We find that the changes in policy rates are also predictable in the major economies outside the US. Second, Gürkaynak et al. (2007) report the federal funds futures to provide the best market-based measure of near-term monetary policy expectations. Since the federal fund futures contracts are unique to the United States, we recover expected policy rates from the overnight index swaps (OIS) which so far did not receive much attention in the literature on policy rates prediction, despite they and their underlying rates have been gaining popularity in derivative pricing and monetary policy practice.[4] We show the OIS-implied rates to be accurate predictors of the future monetary policy actions in the other countries, performing on par with the federal funds futures in the US. In the rest of this section we describe the payoff structure and extraction of the expected future policy rates from the federal funds futures and OIS contracts; and discuss limitations of the OIS-implied rates as forecasting tools and how our methodology addresses these issues.

Overnight index swaps (OIS) are fixed/floating interest rate swaps where the floating leg pays the cumulative return on an underlying rate, e.g. the effective federal funds rate in the US or the SONIA in the UK. At the settlement day T the payoff of the floating leg of an OIS with notional amount of \$1 and start date tomorrow (day 1) is:

$$\pi^T = \prod_{t=1}^{T}(1 + r_t) - 1, \tag{2.3}$$

where t is the first day of the swap, r_s is the annualized underlying rate. The buyer will pay a fixed rate called the swap rate w_t, which is known at the inception of the swap, so the net payoff at maturity equals π^T.

In the absence of arbitrage opportunities, the price of the swap[5] today (day 0) with start date tomorrow (day 1) is equal to the risk-neutral expectation of (2.3):

$$w_0 = \mathrm{E}_0\left[\pi^T\right] = \mathrm{E}_0\left[\prod_{t=1}^{T}(1 + r_t) - 1\right], \tag{2.4}$$

where the expectation is taken under the risk-neutral measure. Let us assume a policy meeting takes place at date t^*, and the rate r^* announced at the meeting becomes effec-

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[4] For example in April 2017 the Bank of England recommended SONIA as the sterling near risk-free reference rate benchmark, furthermore Hull and White (2013) argue that for derivatives pricing OIS rates are superior to the traditional LIBOR rates.

[5] The actual prices are quoted in annualized terms, but we use rates per period equal to the maturity of the contract (e.g. monthly) to avoid cumbersome formulas.

tive at $t^* + 1$. We also assume the current rate stays constant until the announcement, and the rate then set prevails from the effective date until the expiration of the contract. That said, equation (2.4) can be rewritten as:

$$\begin{aligned} w_0 &= \mathrm{E}_0 \left[\prod_{s=1}^{t^*} (1 + r_0) \prod_{t=t^*+1}^{T} (1 + r^*) - 1 \right] \\ &= (1 + r_0)^{t^*} \mathrm{E}_0 \left[(1 + r^*)^{T-t^*} \right] - 1, \end{aligned} \tag{2.5}$$

Neglecting the Jensen's inequality, we arrive at the expected rate at the announcement date:

$$\mathrm{E}_0 \left[r^* \right] = \left((w_0 + 1)(1 + r_0)^{-t^*} \right)^{\frac{1}{T-t^*}} - 1 \tag{2.6}$$

A potentially severe drawback of the OIS as forecasting tools is that their underlying rates can differ from central bank operational targets. For example, the bulk of liquidity in the Eurozone and Sweden is provided via repurchase agreements with maturity of one week, which, given the unsecured nature of the OIS underlying rates, may result in future rate forecasts being contaminated by term, credit and liquidity premium. Our analysis implicitly addresses this problem, as we forecast rates over horizons of maximum of 15 days using one-month swaps. With a reasonable assumption that the potential risk premia do not vary much over short periods of time, the current rate would be as contaminated as the predicted future rate. Given that our findings are based on rate *changes*, constant or very persistent premium would cancel in the short run. Indeed, we find for the majority of currencies that the average difference between the OIS-implied and realized post-announcement future rates does not exceed one basis point, with mean absolute error ranging from 3.4 to 8.9 basis points. The second limitation is that even if the OIS are unbiased predictors of the underlying rate, they still would be a systematically biased predictor of the target rate if the two rates comove imperfectly. We partially alleviate this issue by focusing on the predicted *direction* of target rate changes and not on point estimates of the future rate. We demonstrate in the data, that OIS are capable of accurately predicting the direction of target change and that profits from forecast-based pre-announcement trading are similar to those based on the perfect foresight.

Federal funds futures are traded on the Chicago Mercantile Exchange (CME) and pay the average effective federal funds rate over the month at the corresponding month's end with the rate being carried forward over weekends. The payoff from holding a futures for delivery in month m is thus:

$$\pi^m = \frac{1}{T_m} \sum_{s \in m} r_s, \tag{2.7}$$

where T_m is the number of calendar days in month m. Two major advantages of these contracts are their high liquidity and zero counterparty risk because of the daily marking-to-market. Krueger and Kuttner (1996) and Gürkaynak et al. (2007) find the futures-implied rate to be an accurate predictor of the near-term monetary policy shifts in the US.

Similarly to OIS we start with the time t risk-neutral price of the federal funds futures contract with delivery in month m:

$$f_t^m = \frac{1}{T_m} \mathrm{E}_t \left[\sum_{s \in m} r_s \right], \tag{2.8}$$

Assuming that the Fed funds rate on average remains at the same level between consecutive FOMC meetings, it is straightforward to extract the expectation of the rate set at the next meeting. Since there are 8 meetings in a year, two scenarios are possible before any meeting k taking place in month m: either the next calendar month will witness another meeting $k+1$, or the next month is "free" of meetings. In the second case the expected rate set at meeting k is the price of the futures contract expiring in the month $m+1$. Otherwise the expected rate is a combination of the settlement price of the previous contract and today's price of this month's contract:

$$\mathrm{E}_t \left[r^k \right] = \begin{cases} 100 - f_t^{m+1}, & (k+1) \notin (m+1) \\ \frac{T_m}{T_m - t} \left(f_t^m - \frac{t}{T_m} f_{T_{m-1}}^{m-1} \right), & (k+1) \in (m+1) \end{cases} \tag{2.9}$$

2.2.3 Trading Strategy

We construct a simple trading strategy based on expected shifts in policy rates. Assuming a US investor's perspective, for a foreign central bank's target rate decision announced on day T we forecast the new policy rate on day $T-h-2$, and establish a position in the corresponding currency at the end of the next day $T-h-1$ to avoid any potential overlap between interest rate derivatives and currencies. The position is then held for h days and liquidated one day before the announcement at $T-1$. Should a rate hike be expected, we go long in the foreign currency vs. USD, should a rate cut be expected, we go short in the foreign currency vs. USD, and open no position otherwise. The log spot return over h periods realized at time $T-1$ is therefore:

$$R_{T-1}(h) = d_{T-h-2} \sum_{t=T-h}^{T-1} (r_t) = d(h) r(h), \tag{2.10}$$

where r_t is the daily currency log spot return and d_{T-h-2} is a categorical variable, capturing the $T-h-2$ expectation of the policy rate change on the announcement day and is equal to 1 if a hike is expected, -1 if a cut is expected and 0 otherwise. Conversely for the FOMC announcements we buy (sell) USD against an equally-weighted portfolio of currencies – the dollar index – if increase (decrease) in the federal funds rate is expected.

We recover the expected policy rates from the OIS contracts and federal funds futures using equations (2.6) and (2.9). With an exception of the US, the underlying rates for OIS differ from the policy rates set by central banks, hence the derivatives-implied expectations of the latter can be in addition to time-varying risk premia[6] contaminated with noise. To address this issue, we define the expected change in the target rate $\mathrm{E}_{T-h-2}\left[\Delta i_T\right]$ as the difference between the derivatives-implied rate expected to prevail after the announcement and the corresponding underlying rate with both rates averaged over the five preceding days.[7] We further employ a simple rule to evaluate the expected shift in the target rate by defining the categorical variable d_{T-h-2} as:

$$d(h,\tau) = \begin{cases} 1, & \text{if } \mathrm{E}_{T-h-2}\left[\Delta i_T\right] > \tau, \text{ rate hike expected} \\ 0, & \text{if } \left|\mathrm{E}_{T-h-2}\left[\Delta i_T\right]\right| \leq \tau, \text{ no change expected} \\ -1, & \text{if } \mathrm{E}_{T-h-2}\left[\Delta i_T\right] < -\tau, \text{ rate cut expected} \end{cases}$$

where τ is a threshold level. Denote $a = 1, ..., A$ to be a chronological sequence of all policy rate announcements for every currency, the cumulative US dollar return on the aggregate strategy as of announcement a can be written as:

$$R_a(h,\tau) = \sum_{a=1}^{A} \left[d_a(h,\tau) r_a(h)\right], \tag{2.11}$$

Throughout this paper we employ the holding period and threshold of 10 days and 10 basis points as the baseline values. We further demonstrate that our results are robust to the variation in these parameters.

The strategies constructed this way admit cross-sectional leverage: if signals in different countries are separated by a period shorter than the holding period, we do not split the invested capital, but multiply it. This is a computationally convenient and realistic setup given the preponderance of leveraged transactions on the FX markets. The US Commodity Futures Trading Commission allows for a 50:1 leverage in the off-exchange retail FX forex trading,[8] which corresponds to a possibility of opening 50 positions in our setup. The average leverage for the baseline strategy that we construct is 1.38, and it is less than or equal to 2 on 94% of all days. In Appendix D we provide a detailed description of how deleveraged strategies are constructed, and show that our

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[6] Although given our short policy rate forecast horizons the risk premium is of a lesser concern, Piazzesi and Swanson (2008) document the predictable time-varying risk premium in the federal funds futures of maturities higher than one month.

[7] The choice of the smoothing window is inconsequential for our results.

[8] Or 30:1 leverage on-exchange currency futures trading, 50:1 in the commercial bank forex trading and 200:1 in the offshore off-exchange retail forex trading.

findings are robust to restricting leverage.

A zero-cost foreign exchange trading requires investors to pay (or receive) the interest rate differential between the base currency and the counter currency. A common way in the academic literature to calculate the h-period excess return is to take the difference between the (log of) spot price in period $t+h$ and the price of a forward contract with maturity h opened in period t:

$$
\begin{aligned}
rx_{t+h} &= \log S_{t+h} - \log F_{t\to h}, &(2.12)\\
&= \underbrace{\log S_{t+h} - \log S_t}_{\Delta s_{t+h}} + \underbrace{\log S_t - \log F_{t\to h}}_{d_t}, &(2.13)
\end{aligned}
$$

where Δs_t is the spot return, and d_t should under the Covered interest parity be equal to the interest rate differential. However, as forward prices are readily obtainable for a limited number of maturities only (e.g. one week, two weeks, etc.), but our task is to construct a strategy with the holding period of *several days*, we turn to the foreign exchange swaps which allow to earn the interest rate differential on the daily basis. In fact, foreign exchange swaps are the most traded instrument on the FX market, with the turnover in short-term swaps (maturity of under seven days) and spot transactions approaching USD 1.6 trillion for each of the instruments, exceeding the daily turnover of forward contracts of *any* maturity by a factor of two (BIS (2016a)). Most of the FX positions are usually opened out of speculative interest and eventually reversed before the actual delivery of the transacted currency takes place. Until then every position kept open at 5pm New York time is being rolled over: the delivery is then postponed by one day, and the price of the contract is adjusted by adding the tom/next swap points. The tom/next swap points are closely linked to the interest rate differential between the two legs of the FX position and are positive (negative) if the interest rate in the base currency is lower (higher) than that in the counter currency, in which case the holding period return on the position rolled over falls (rises) *ceteris paribus*.

Now, imagine postponing the delivery for h periods: in this case the end-of period log-return is:

$$
rx_{t+h} = \log S_{t+h} - \log(S_t + \sum_{\tau=1}^{h} w_\tau), \qquad (2.14)
$$

where w_τ is the tom/next swap points. Seen at time t, the same return is expected to be achieved by selling short an h-day forward and closing the position at its expiration. Hence, the change in the opening price by the time the position is closed can be *ex ante* thought of as the forward premium or discount, which brings us back to equation (2.13). In Appendix C we discuss the plausibility of this approach and compare it on the monthly frequency to the more common technique in (2.13).

2.3 Data

In this section we describe our dataset. First we provide a brief overview of monetary policy implementation procedures across the major economies, then we describe our currency and fixed income data.

2.3.1 Announcements of Central Banks

In the 1990s central banks started to adopt the policy of announcing target interest rate changes on pre-scheduled dates. We collect data on policy rate announcements for the following countries: United States, United Kingdom, Australia, Canada, New Zealand, Switzerland, Sweden, Norway and the Eurozone. Our sample spans the period from November 2000 to March 2017. By November 2000, all countries in the sample adopted the practice of interest rate announcements on pre-scheduled dates. In our analysis, we consider currency-events satisfying the following conditions: (i) the announcement schedule of the corresponding central bank should be published in advance of the monetary policy meetings; (ii) an interest rate level or range should be an operational target of the central bank; (iii) explicit exchange rate targeting is not part of the monetary policy framework. Conditions (i, ii) emphasize our focus on announcements with outcomes that can be forecasted in a systematic way several days beforehand, condition (i) also rules out meetings occurring outside of the schedule. Condition (iii) ensures we do not run into endogeneity problems and forces us to leave out Denmark: since 1999, the country's monetary policy objective has been to maintain a fixed exchange rate regime against the euro, such that Danmarks Nationalbank does not even have a schedule for policy decisions, therefore also violating condition (i).[9] Due to violation of condition (iii) we also exclude Switzerland for the period of the minimum exchange rate to the euro (from September 2011 to January 2015). We exclude Japan, since the Bank of Japan has been switching between different monetary policy tools over the past 20 years, and satisfied condition (ii) for a limited number of

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[9] When the ECB implements a change in interest rates, Danmarks Nationalbank typically responds with a similar change on the same date. More importantly, in order to maintain the currency peg, the bank resorts to unilateral rate changes in response to persistent changes in the euro-krone exchange rate, explicitly acknowledging it in the announcements. Furthermore, the unilateral rate changes are not scheduled and hence not known to investors in advance. See Spange and Toftdahl (2014) for a detailed overview of Denmark's fixed exchange rate policy. In unreported results we find that the krone's behavior around the ECB announcements is indistinguishable of that of the euro.

time intervals over the course of our sample.[10,11] Below we provide a brief summary of targets and announcement schedules for the central banks in the sample.

Australia. The Reserve Bank of Australia began to announce the target rate decisions on pre-scheduled dates in 1981. The monetary policy meetings usually occur eleven times a year. Between 1990 and 1996 the Bank changed the Cash rate on 21 occasions from which ten cuts and two hikes were implemented outside the scheduled Board's meetings. There were two further unscheduled cuts in 1997. Until 1998, from time to time the Board gave the Governor discretion to implement a change in the cash rate in an agreed manner. From 1998 onwards, the Bank sticks to its schedule of announcing decisions on the first Tuesday of each Month except January. Before 2008 RBA announced the interest rate decision on the day following the meeting day simultaneously with the new policy coming into effect. Starting from 2008, the decision is announced on the meeting day and becomes effective on the following day.

Canada. The Bank of Canada introduced pre-scheduled interest rate announcements in November 2000. The announcements take place eight times a year with decision becoming effective on the announcement day.

Eurozone. The European Central Bank (ECB) held a monetary policy meeting twice a month from 1999 to 2001, then once a month from 2002 to 2015, switching to a six-week cycle in 2015. The ECB targets three rates: (i) the deposit facility which allows banks to place deposits at the ECB; (ii) the marginal lending facility which offers overnight loans to the Eurozone's banking system; (iii) the main refinancing operations (or MRO) rate at is the rate at the ECB injects and withdraws liquidity using repo operations, normally, with a maturity of one week. The Bank announces its interest rate decisions on the meeting day, the changes in policy become effective on the day set at the meeting, usually from the next day to a week.

New Zealand. The Reserve Bank of New Zealand announces its Official Cash Rate on pre-scheduled meetings since April 1999. The bank holds around eight policy meetings a year, with the interest rate decisions becoming effective on the announcement day.

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[10] On March 19th 2001 the Bank of Japan abandoned targeting of the uncollaterallized overnight call rate (MUTAN), leaving the rate to be determined by the market. The MUTAN was expected to be capped from above by *the official discount rate* on the Lombard-type lending facility where eligible financial institutions could receive loans posting eligible collateral. Simultaneously, the main operating target for monetary policy was changed to current account balances at the Bank of Japan. Subsequently, the Bank resumed targeting the average call rate on March 9th 2006, switched to targeting a band on October 5th 2010, and abandoned interest rate targeting in favor of monetary base targeting on April 4th 2013. Finally, the Bank introduced negative interest rates on the current account balances on January 29th 2016 (effective from February 16th) and "yield curve control" on September 21st 2016 as additional policy measures. See also Kuttner (2014) for a comprehensive overview of Japan's monetary policy from 1980 to 2012.

[11] Over the course of our sample during the periods when the Bank of Japan had the overnight rate as its operational target, there were only two target rate hikes (in 2006 and 2007), and three rate cuts (one in 2001 and two in 2008). While these data points are unlikely to alter our main results, we nevertheless consider this discretionary choice as a limitation to our dataset.

Norway. Norges Bank started to announce interest rate decisions on pre-scheduled meetings on June 16th 1999. The meetings took place once a month until June 2000 when the monetary policy meetings began to occur once every six weeks. The decision is normally announced on the day of the meeting and becomes effective on the next day.

Sweden. The Riksbank adopted the policy rate announcements on pre-scheduled meetings on October 6th 1999, with the first meeting in the February 2000. Since then and until 2008 the Bank held monetary policy meetings once every six to eight weeks. From 2008 onwards the Riksbank holds six ordinary monetary policy meetings per year. The decision is normally announced on the day following the day of the meeting and becomes effective in a week.

Switzerland. In contrast to other central banks mentioned here which target overnight rates, the Swiss National Bank operates on the higher maturity region of the yield curve, targeting the 3-month Swiss Franc Libor. Since 2000 the Bank abandoned money supply targeting in favor of interest rate targeting. Policy meetings take place four times a year with decision becoming effective immediately. From September 2011 to January 2015 the SNB focused its monetary policy on sustaining the exchange rate cap to the euro.

United Kingdom. In June 1998 the Bank of England received autonomy over the monetary policy. The Bank's Monetary Policy Committee (MPC) held meetings every month until September 2016, since then the official interest rate is reviewed eight times a year. The interest rate decision is announced on the day following the MPC meeting day and comes into effect on the next day.

United States. Since February 1994, the Federal Open Markets Committee (FOMC), a part of the Federal Reserve System overseeing the monetary policy in the United States, announces its decisions on eight pre-scheduled meetings a year. The target range for the Federal funds rate is announced on the second day of the meeting and becomes effective on the following day. For a detailed description of the FOMC meetings and statement releases see e.g. Lucca and Moench (2015) and references therein.

Table 2.1 reports summary of the scheduled policy announcements for the central banks discussed above. The second and third columns show the fixed announcement schedule adoption date and the key policy rates respectively. The last three columns report the total number of announcements and the numbers of hikes and cuts in policy rates of each central bank. The joint sample is from November 2001, when the Bank of Canada adopted the fixed schedule, to March 2017. The period of Swiss franc – euro cap (from September 2011 to January 2015) is excluded for Switzerland.[12] The total

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[12] Note that exclusion of the Swiss franc for the period of the exchange rate cap does not have any impact on the the event study results – the only two target rate changes implemented within the cap period were announced at unscheduled meetings. Furthermore, to counter appreciation of the franc the

numbers of hikes and cuts are 155 and 180 respectively, resulting in the sample size well above the total number of all events for the FOMC announcements considered in the previous literature.

We further consider the scheduled monetary policy meetings only, although some extraordinary meetings became known to market participants well in advance (e.g. the meeting of Norges Bank on October 15, 2008 was announced on October 8th). First, the policy actions undertaken during unscheduled meetings constitute a small fraction of all target rate changes.[13] Second, we aim to keep our results conservative and robust to outliers by ruling out extreme events like the September 2001 terrorist attacks and the coordinated interest rate cut by a number of central banks on October 8th 2008.

Table 2.1: Central Banks' Policy Meetings Summary

Country	Announcements since	Target Rate	Events	Hikes	Cuts
Australia	1980s	Cash Rate	180	19	24
Canada	Nov-2000	Target for the Overnight Rate	131	18	25
Eurozone	Jan-1999	Main Refinancing Operation Rate	202	11	20
New Zealand	Apr-1999	Official Cash Rate	130	23	22
Norway	Jun-1999	Sight Deposit Rate	128	21	23
Sweden	Oct-1999	Repo Rate	110	24	23
Switzerland	Jan-2000	3-month CHF LIBOR	52	9	5
United Kingdom	Jun-1998	Bank Rate	196	10	20
United States	Feb-1994	Federal Funds Rate	132	20	18
Total Events			1254	155	180

This table summarizes the policy announcements across countries. The first three columns contain countries, date of adoption of interest rate target announcements on prescheduled dates by the countries' central banks, and the corresponding interest rates respectively. The last three columns contain the total number of meetings, and the numbers of hikes and cuts for each country. The sample spans period from November 2001 when all countries adopted target rate announcements on fixed dates to March 2017, and considers shceduled announcements only. The period of Swiss franc – euro peg (September 2011 to January 2015) is omitted.

2.3.2 Exchange Rates and Currency Returns

We use Bloomberg daily spot exchange rates against USD for the following countries: Australia, Canada, Japan, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the Eurozone. We collect the quotes for different fixing times to ensure that the announcement day is not overlapped for any of the currencies. Thus we use 5pm London fixing time for the Eurozone, Norway, Sweden, Switzerland, and the United

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Swiss National Bank conducted foreign exchange interventions outside the 2011–2015 period in 2009, 2010, and 2016. Excluding these years or even the entire currency does not affect our results: as we demonstrate below, the Swiss franc tends to weakly appreciate before rate cuts and depreciate before hikes.

[13] With a notable exception of Switzerland, where roughly three quarters of the target rate changes from 2000 to 2017 were implemented during unscheduled meetings.

Kingdom; 5pm New York time for Canada and the US; 8pm Tokyo time for Australia and New Zealand. Respective bid and ask prices are used to adjust for the trading costs. The long and short tom/next swap points are also from Bloomberg: except for AUD, EUR, GBP and NZD, these are quoted as units of foreign currency per unit of USD, such that we have to convert them first to conform with the perspective of a US investor.

For the FOMC announcements we construct the dollar index – an equally weighted portfolio of currency returns against USD, with each currency, including JPY, fixed at 5pm New York time.

2.3.3 Overnight Index Swaps and Federal Funds Futures

We collect 1-month swap rates from Bloomberg and use rates from Datastream where Bloomberg quotes are unavailable. The availability of the OIS data is as follows: the Eurozone since January 1999; United Kingdom and Switzerland since late 2000; Australia, Canada, and the US since August 2001; New Zealand and Sweden since September 2002.

The overnight rates underlying the OIS are the federal funds effective rate for the US, SONIA for the UK, RBA Cash Rate for Australia, Official Cash Rate for New Zealand, CORRA for Canada, TOIS fixing for Switzerland, STIBOR for Sweden, and EONIA for the Eurozone.[14] The data on these rates is from Bloomberg.

In order to assess predictive power of the OIS-implied rates we also collect the data on the federal funds futures contracts considered to be staple in the literature. This data comes from the Chicago Mercantile Exchange.

2.4 Results

In this section we present the empirical results of the paper. We begin with documenting a pre-announcement drift in currency returns preceding shifts in monetary policy around the world. We then demonstrate that this drift is exploitable by investors first, by showing that monetary policy actions are predictable and second, that a trading strategy aiming to forecast future monetary policy action and then buy (sell) currencies whose monetary authorities are expected to raise (cut) their policy rates earns substantial returns.

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[14] There are no overnight interest rates data available for Norway.

2.4.1 Drift in Spot Exchange Rates Before Announcements

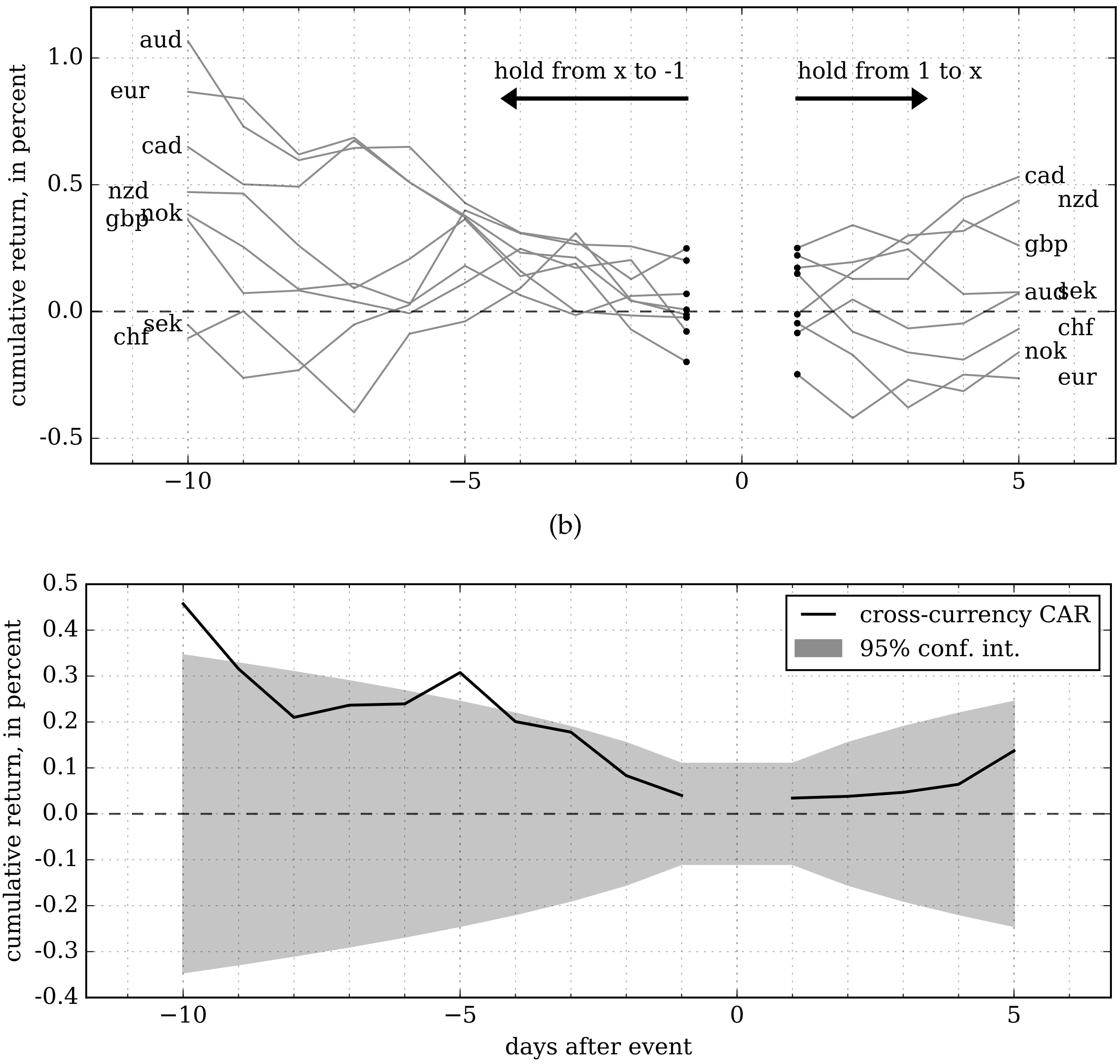
Figures 2.1 and 2.2 depict the results of the event study, with events being announcements of the local central banks to raise and cut the target interest rate respectively, and the test assets being spot returns of the currencies of the corresponding countries. As shown in the bottom panel of Figure 2.1, a randomly selected currency before a randomly selected rate hike is expected to appreciate by 50 bps over ten days, 30 bps over five days, and 10 bps on the day before the event day. The individual cumulative spot returns are presented in the upper panel, making it evident that of all currencies, only the Swedish krona and the Swiss frank slightly depreciate on average over the ten-day period ahead of rate hikes. The pattern is reversed before rate cuts, as can be seen in the lower panel of Figure 2.2: in this case, a currency is expected to depreciate by about 70 bps over ten days, half that over five days, and 10 bps on the pre-announcement day. The average return is significant at the 5% level for periods of all lengths.

As seen in the figures, currencies experience a statistically significant and economically large drift in the direction of the policy rate changes, more pronounced in the case of rate cuts. The spot exchange rates begin to move at least ten days in advance of the central banks' announcements. Interestingly, the drift mostly dissipates, and the abnormal returns evaporate in the post-announcement period. As a robustness check, in Appendix B we redo the same exercise using two different counter currencies – GBP and JPY – rather than USD, and confirm an equally strong significant downward trend before interest rate cuts, and an upward yet insignificant trend before hikes.

In Figures 2.3 and 2.4, we contrast the observed patterns in the spot returns to those around the FOMC announcements. In general, the effect of the Fed policy rate changes on the foreign currencies is opposite in sign to that of the local rate changes: an average foreign currency tends to depreciate against the US dollar before the Fed funds rate is increased, and appreciate in the opposite scenario. However, this effect only manifests itself over a short period of time, and no significant cumulative appreciation or depreciation can be detected earlier than four days ahead of events. The effect is also weaker economically: the average depreciation before the Fed funds rate hikes is lower in magnitude than that before the local rate cuts at any considered horizon, and the average appreciation in the opposite case is lower for 7 out of 10 horizons.

Given the magnitude of the abnormal returns and the horizon over which the drift manifests itself, the natural question is to what extent the market participants are able to exploit it in a trading strategy. To exploit the pre-announcement drift, investors need to be able to accurately predict upcoming monetary policy actions and earn significant return after accounting for transaction costs. We address this issue in the rest of the section.

Figure 2.1: **Exchange rates around local interest rate hikes.**


(a)

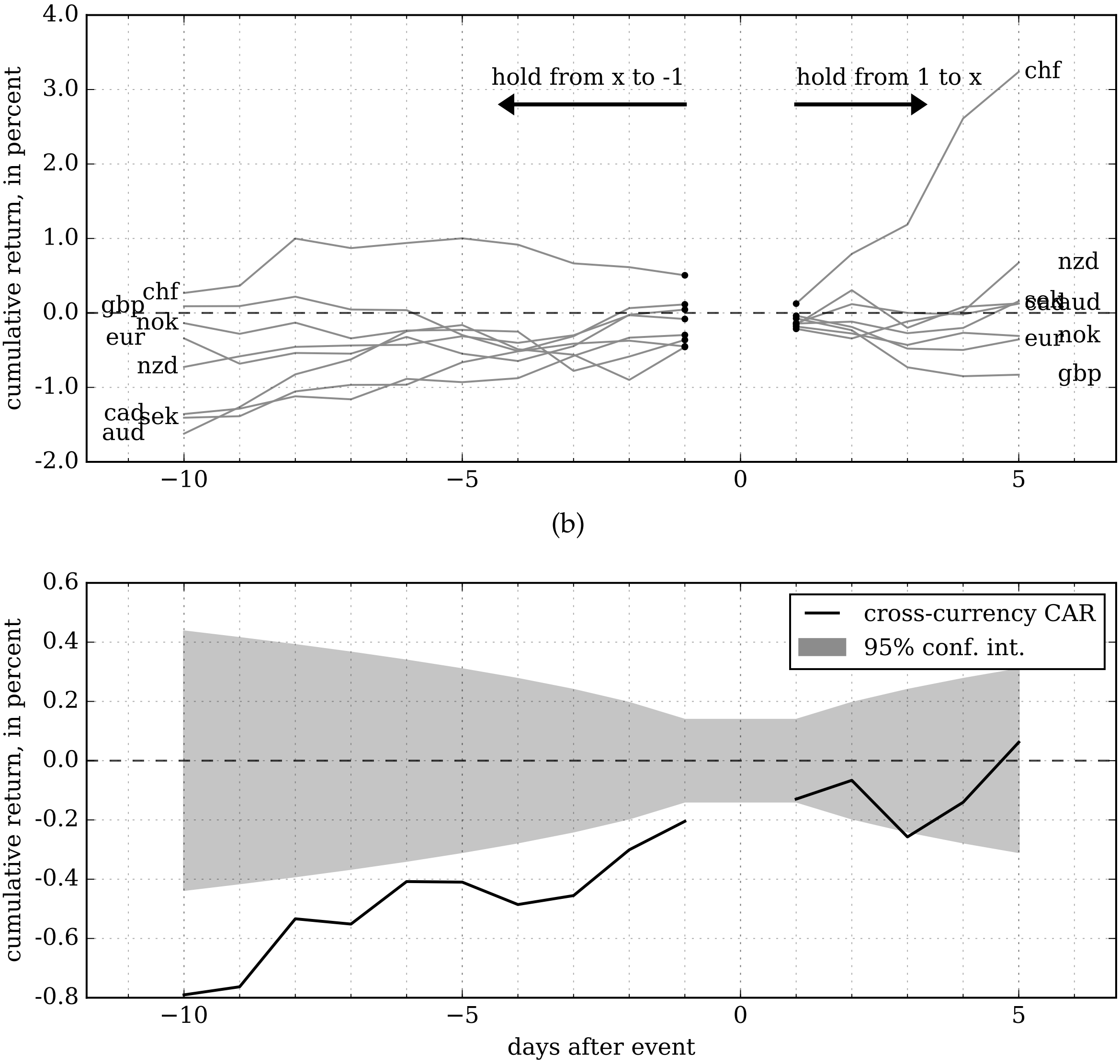
(b)

This figure depicts cumulative currency returns around interest rate hikes announced by the local central banks. Panel 2.1a shows returns on individual currencies and Panel 2.1b shows the average return over all currencies weighted in proportion to the number of hikes each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency x days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for x days, whereby x is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in USD. The sample includes AUD, CAD, CHF, EUR, GBP, NOK, NZD and SEK for the period from November 2000 to March 2017, thus covering a total of 135 hikes.

2.4.2 Recovering Monetary Policy Expectations

Using the 1-month OIS and the forecast horizon of 12 days (for the 10-day holding period to be possible), we estimate the reference rates expected to prevail after each announcement. Figure 2.5 shows the error plots constructed thereof. The post-announce-

Figure 2.2: **Exchange rates around local interest rate cuts.**



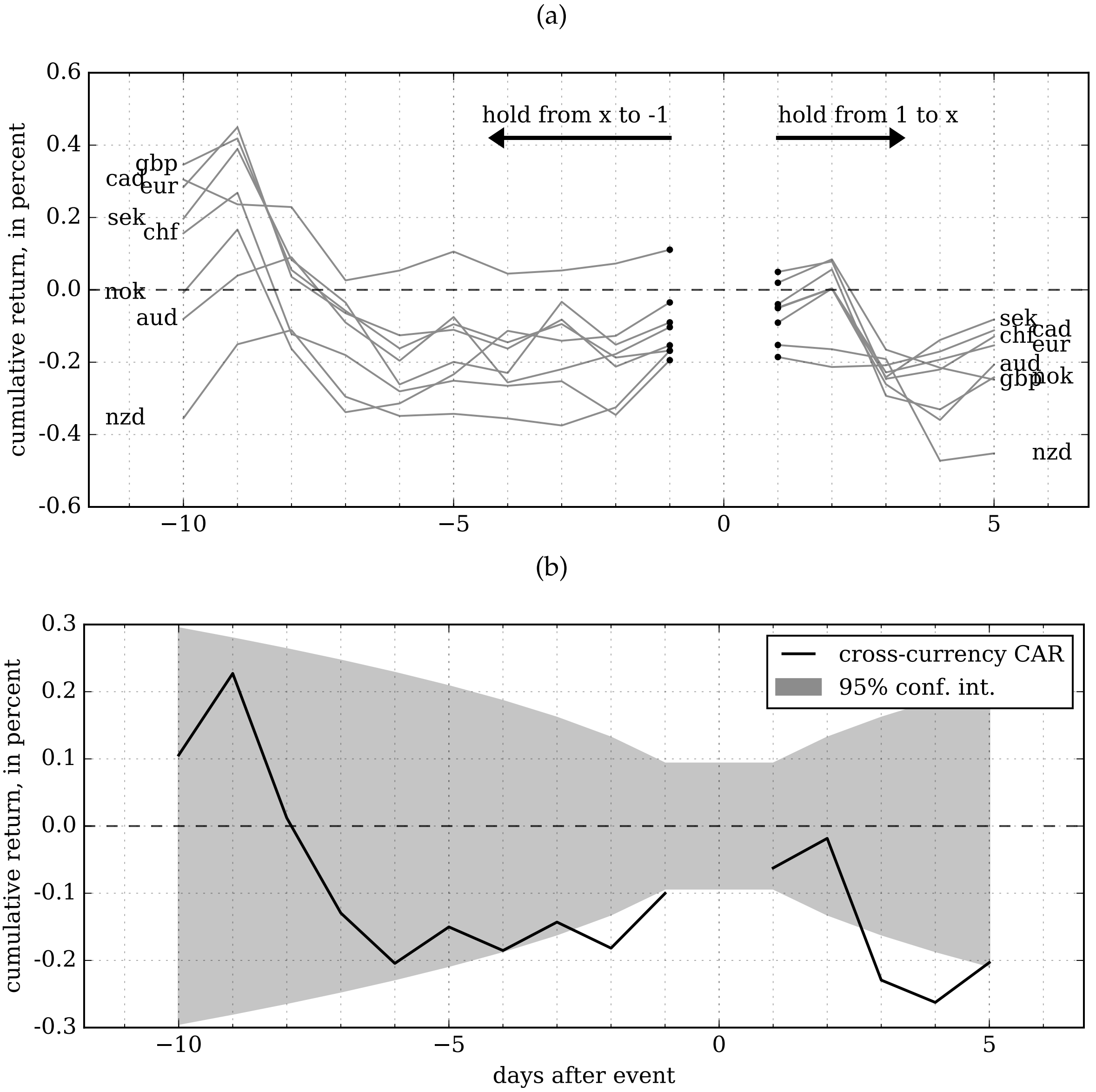
(a)

(b)

This figure depicts cumulative currency returns around interest rate cuts announced by the local central banks. Panel 2.2a shows returns on individual currencies and Panel 2.2b shows the average return over all currencies weighted in proportion to the number of cuts each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency *x* days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for *x* days, whereby *x* is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in USD. The sample includes AUD, CAD, CHF, EUR, GBP, NOK, NZD and SEK for the period from November 2000 to March 2017, thus covering a total of 162 cuts.

ment rates can be forecast with a mean absolute error below 10 bps, the highest differences occurring for Switzerland and the Eurozone. The mean error (not reported here) rarely exceeds 1 bps and reaches the maximum of 4 bps in the case of Switzerland. As a comparison, the lower right panel depicts the forecasts of the federal funds rate calculated using the Fed funds futures: these exhibit a slightly higher mean absolute

Figure 2.3: **Exchange rates around the Fed funds rate hikes.**

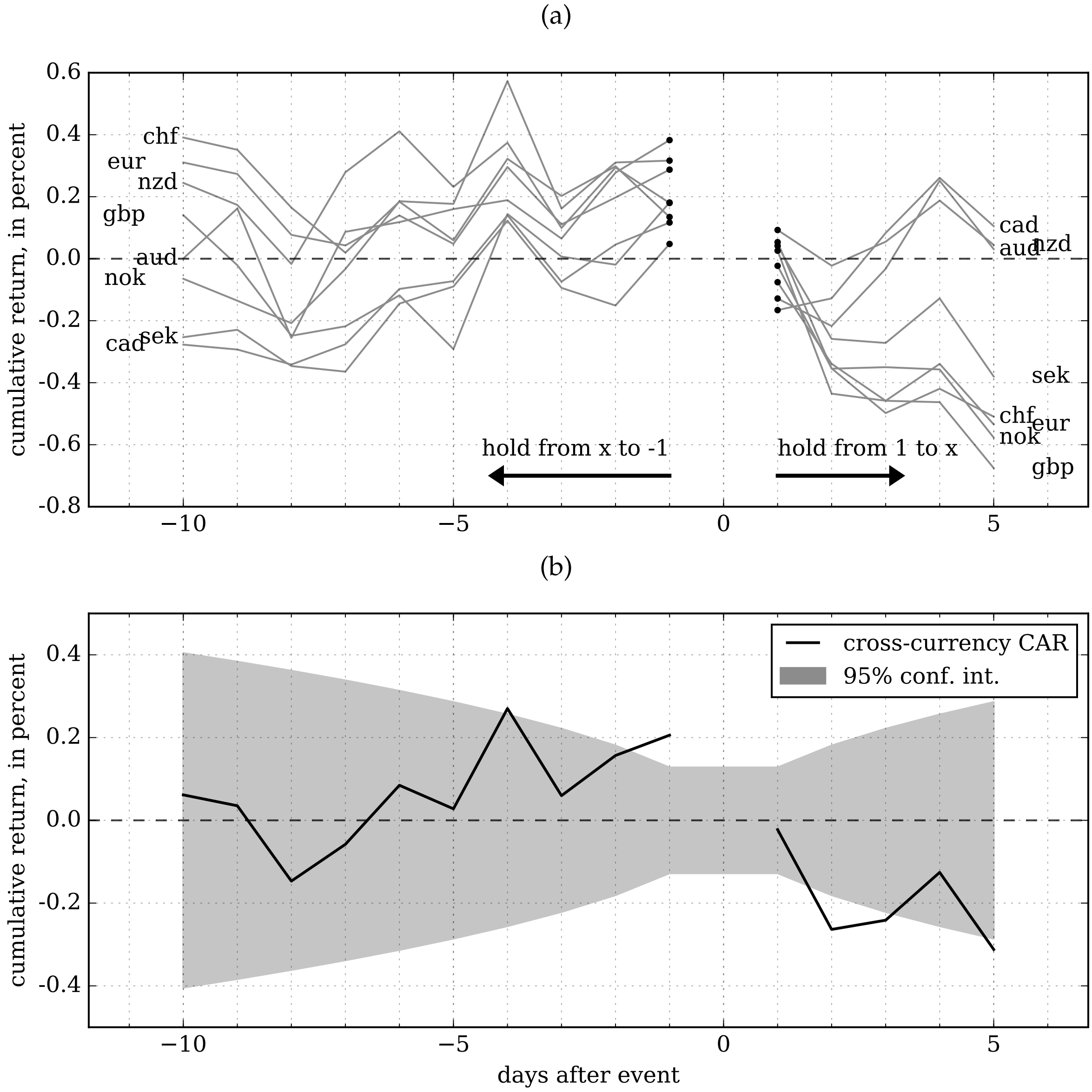


This figure depicts cumulative currency returns around around the Fed funds rate hikes announced by the FOMC. Panel 2.1a shows returns on individual currencies and Panel 2.1b shows the average return over all currencies weighted in proportion to the number of hikes each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency *x* days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for *x* days, whereby *x* is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in USD. The sample includes AUD, CAD, CHF, EUR, GBP, NOK, NZD and SEK for the period from November 2000 to March 2017, thus covering a total of 18 hikes.

error, but overall are as strong a predictor of the policy shifts.

Being interested not in the level of implied rates per se, but rather in the direction which the implied rates imply (no pun implied), in Figure 2.6 we show the confusion matrices corresponding to each error plot above. We use the threshold of 10 bps to separate expected cuts from hikes, the same 12-day forecasting horizon, and 5 days

Figure 2.4: **Exchange rates around the Fed funds rate cuts.**


(a)

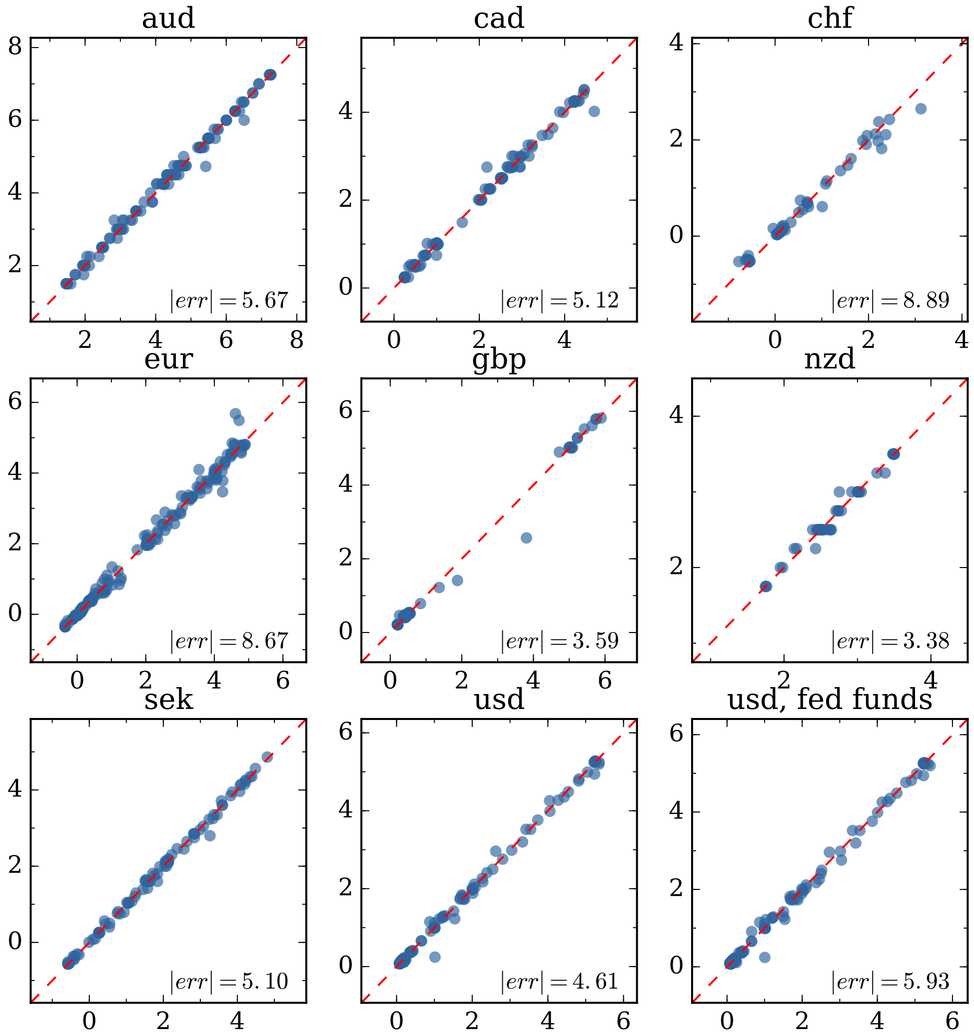
(b)

This figure depicts cumulative currency returns around the Fed funds rate cuts announced by the FOMC. Panel 2.2a shows returns on individual currencies and Panel 2.2b shows the average return over all currencies weighted in proportion to the number of cuts each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency x days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for x days, whereby x is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in USD. The sample includes AUD, CAD, CHF, EUR, GBP, NOK, NZD and SEK for the period from November 2000 to March 2017, thus covering a total of 18 cuts.

to average the implied and the underlying rates. The "worst" cases of forecasting a direction opposite to the announced are almost absent in the sample: these are located in the southwest and northeast corners of the matrices and never exceed 1. The ratio of correctly predicted directions is high, the worst being the one for rate cuts in Sweden.

Interestingly, rate cuts appear to be predictable with a lower accuracy than rate hikes.

Figure 2.5: **Forecasting interest rates.**



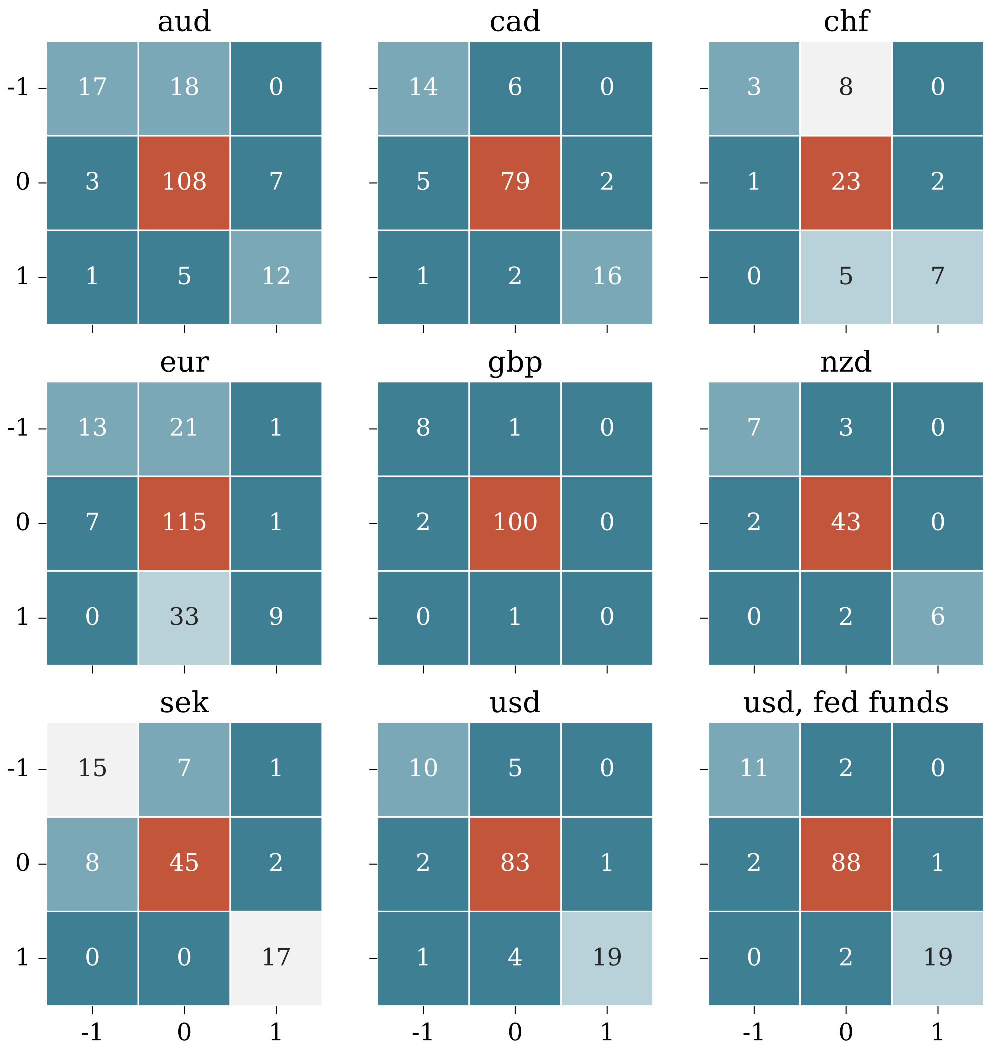
This figure compares the expected reference rates recovered before announcements to the actual post-announcement rates. We use 1-month OIS rates and the forecast horizon of 12 days to recover the implied rates. They are compared to a 12-period average of the post-announcement rates. The x-axis keeps the expected, and the y-axis – the realized rates, in percent p.a. The value reported in the lower right corner of each subplot is the mean absolute forecast error, in basis points. In the lower right panel the OIS as the material for recovering the expectations are substituted with the Fed funds futures. The sample period is different for each currency.

This is partly because they tend to happen in times of economic distress, when both the prices of OIS and the underlying rates become volatile and subject to large risk premia, such that the forecasts get distorted.

As in Figure 2.5, the bottom right panel refers to the Fed funds futures-based predictions. Since 2001, just one more cut was correctly predicted by the Fed funds futures.

Overall, using the information implied in the OIS rates to predict the upcoming monetary policy decisions is justified *ex post* by low absolute errors and a high percentage of correctly captured change directions. Not reported here are the outcomes of the forecasting exercise with different values of the forecasting horizon and threshold. In

Figure 2.6: **Forecasting policy rate decisions.**



aud	-1	0	1
-1	17	18	0
0	3	108	7
1	1	5	12

cad	-1	0	1
-1	14	6	0
0	5	79	2
1	1	2	16

chf	-1	0	1
-1	3	8	0
0	1	23	2
1	0	5	7

eur	-1	0	1
-1	13	21	1
0	7	115	1
1	0	33	9

gbp	-1	0	1
-1	8	1	0
0	2	100	0
1	0	1	0

nzd	-1	0	1
-1	7	3	0
0	2	43	0
1	0	2	6

sek	-1	0	1
-1	15	7	1
0	8	45	2
1	0	0	17

usd	-1	0	1
-1	10	5	0
0	2	83	1
1	1	4	19

usd, fed funds	-1	0	1
-1	11	2	0
0	2	88	1
1	0	2	19

This figure shows the confusion matrices of the policy rate forecasts. A rate hike (cut) is expected 12 days before announcements if the 5-day moving average of the implied rate at that day is by 10 bps higher (lower) than the similarly smoothed reference rate. Entry (x, y) (x denotes rows) in any such matrix contains the number of cases when direction x was predicted, and direction y announced. In each matrix, the column sum is the total number of decisions to decrease the policy rate, keep it unchanged and raise respectively. Higher numbers are highlighted with a warmer color. In the lower right panel the OIS as the material for recovering the expectations are substituted with the Fed funds futures. The sample period is different for each currency.

general, the prediction accuracy increases as the horizon shrinks (and vice versa).

2.4.3 Is the Pre-Announcement Drift Exploitable by Investors?

We start with spot returns, thus recasting the results of the event study in the beginning of this section as a trading strategy. Figure 2.7 plots the cumulative performance of a strategy in which the investor goes long in currencies whose monetary authorities are expected to raise the policy rate, and short in currencies with expected interest rate cuts. Panel 2.7a shows the return plotted against time and Panel 2.7b shows the return plotted event-by-event. The solid line represents cumulative return of the forecast-based strategy, while the dashed line represents cumulative return of an investor with perfect foresight. The investor makes a decision whether to open a position twelve days ahead of the announcement. The rate change is forecast as the difference between the implied post-announcement rate extracted from the OIS and the underlying rate with both rates averaged over the five previous days. The investor establishes a position only if this difference exceeds a threshold of ten basis points in absolute value. For each predicted target rate change the FX position is held for ten days and liquidated one day ahead of the corresponding announcement. For the FOMC announcements the position in USD is established against the dollar index. The sample is from November 2001 to March 2017. The numbers in the upper panel report the mean return, its standard error (both in basis points) and the Sharpe ratio per one holding period. The standard error is Newey and West (1987) HAC with optimal number of lags according to Newey and West (1994). The upper panel of figure 2.7 also plots returns of the perfect foresight strategy for the same sample (that is, the dashed line basically plots the return earned if the OIS-based forecasts were 100% accurate).

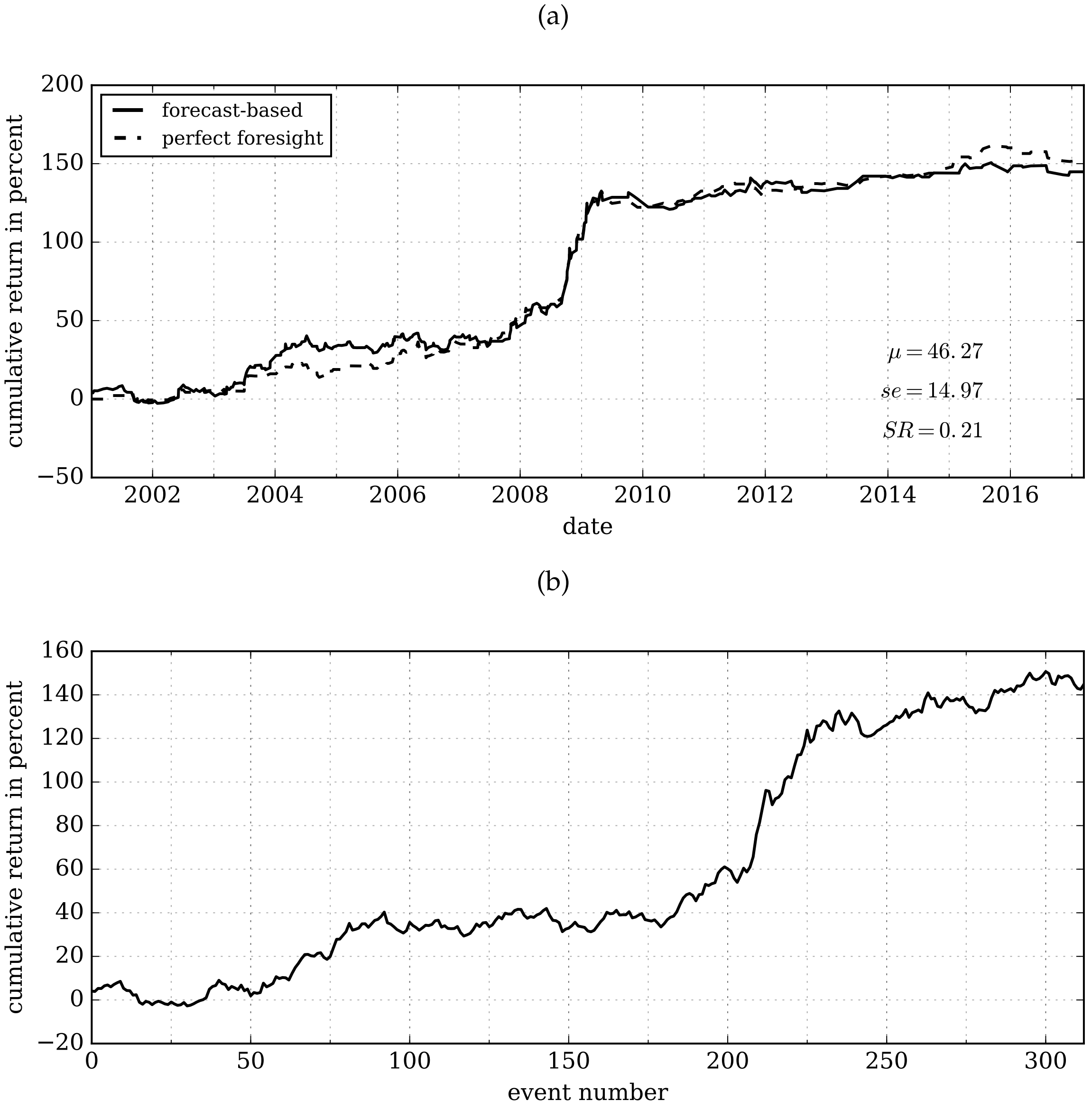
Over 16.5 years, the simple strategy based on the expected monetary policy shifts generated a total spot return of 145% with the average per-event return of 46.27 basis points (with t-statistic of over 3) and a ten-day Sharpe ratio of 0.21, outperforming its perfect foresight counterpart by less than 10% over the course of the sample. Consistent with the event study results, the spot exchange rates tend to front-run impending rate changes, and the high predictability of monetary policy allows to profitably exploit it.

To check that the strategy performance is not shaped by a handful of extreme events, in the bottom panel of Figure 2.7 we plot the performance on the event line instead of the timeline. As can be seen, the strategy also delivers stable and positive returns event-by-event. Given the economic and statistical significance of our results we go on to investigate their robustness to the choice of the holding period and threshold.

Now, we bring the trading strategy closer to a real-life application. First, we account for the bid-ask spread by opening long positions at the ask and short ones at the bid price, and liquidating the open positions at bid and ask respectively. Second, we make all open spot positions subject to rollovers at the end of the trading day, using bid and ask quotes of tom/next swap points.

Figure 2.8 plots the performance of the baseline strategy with the holding period of ten days and the threshold level of ten basis points. The cumulative return of the forecast-based strategy drops by approximately 20 percentage points to 127%, and per-event return falls to 40.66 basis points, remaining statistically significant at the 1% level. A similar reduction is observed for the strategy based on the perfect target rate change predictions. The bottom panel plots performance event by event. Similarly to the re-

Figure 2.7: **Pre-announcement trading (spot returns): cumulative performance.**



This figure depicts the cumulative return on a trading strategy buying (selling) currencies against USD in anticipation of local interest rate hikes (cuts). The position is established 11 days in advance of each announcement day if the forecast interest rate change exceeds 10 basis points in absolute value. The position is then held for 10 days and liquidated on the day preceding the announcement day. The rate change is forecast 12 days before the announcement day as the difference between the OIS-implied rate averaged over the five previous days and the corresponding underlying rate averaged over the same horizon. Panel 2.7a shows the return plotted against time and Panel 2.7b shows the return plotted event-by-event. The numbers in Panel 2.7a are mean return, its standard error (both in basis points) and the Sharpe ratio per one holding period. The standard error is Newey and West (1987) HAC with optimal number of lags according to Newey and West (1994). The returns are spot returns in USD on the following currencies AUD, CAD, CHF, EUR, GBP, NZD, SEK, and the dollar index. The sample is from November 2000 to March 2017.

sults reported for the spot rate, the performance is not driven by a small number of outliers: the surge in returns during the acute stage of the 2007–2009 financial crisis merely reflects the correctly predicted worldwide target rate cuts accompanied by depreciation of the corresponding currencies. Simply discarding the period of the apparent (in the time domain) spike, that is from September 2008 to September 2009, reduces the per-event return and its standard error to 24.30 and 12.02 basis points respectively, and the ten-days Sharpe ratio to 0.13.

In order to control for the uncertainty in the choice of the threshold and holding period and address the data snooping problem, we generate a universe of 375 trading strategies with holding periods ranging from 1 to 15 days and threshold levels ranging from 1 to 25 basis points. Figure 2.9 plots the results of this exercise. Only two strategies generated negative return over the course of the sample. In fact, the bottom decile of strategies by cumulative performance consists exclusively of strategies with holding period of one and two days, implying higher impact of transaction costs. We address the impact of holding period and target rate forecast threshold in more detail later in this section.

We further check if our results can be explained by the FOMC pre-announcement drift of the dollar factor documented by Karnaukh (2016). Figure 2.10 repeats the analysis in Figure 2.9 for the FOMC announcements and the dollar index only. Over the whole universe of 375 strategies buying and selling the dollar index around the US interest rates hikes and cuts, the average performance is almost exactly zero, indicating that the FOMC pre-announcement drift does not drive our results and making our evidence qualitatively different from that in previous studies.[15]

Table 2.2 presents descriptive statistics for a subset of pre-announcement trading strategies buying (selling) currencies against USD in anticipation of local interest rate hikes (cuts) plotted Figure 2.9. Each column reports statistics for a decile strategy in the empirical distribution of the whole set's cumulative performance (Panel A) and mean return per day of position open (Panel B). For each decile strategy first two rows show the corresponding holding period h (in days) and threshold level τ in basis points. Means, standard errors, medians, and standard deviations are in basis points. Before computing descriptive statistics, each reported strategy is (de-)leveraged to the 10-day holding period by multiplying its returns by the ratio of 10 to strategy's holding period. The Sharpe ratios are scaled by square root of the same ratio to represent the 10-day holding period.

All reported strategies positive average return ranging from to 9 to 48 basis points per predicted target rate change after transaction costs. In general, the returns are positively skewed, and statistical significance increases with holding period, so does the cumulative performance. As we previously demonstrated in the event study, the drift in exchange rates persists over several periods prior to the announcement, therefore the relative impact of transaction costs on the return would be higher for trading strate-

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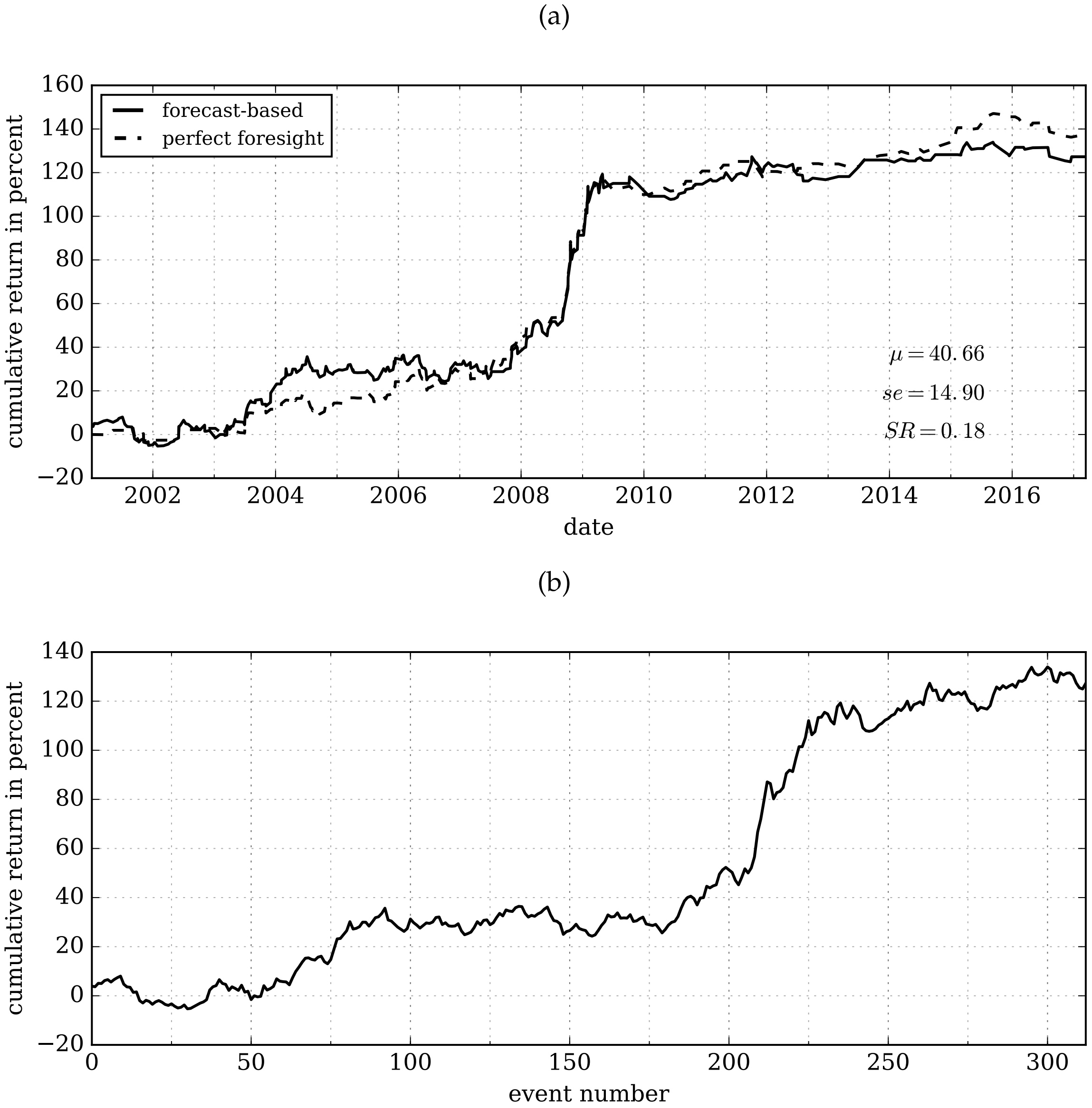
[15] Similar to Karnaukh (2016) we observe economically and statistically significant pre-announcement drift for a number of strategies trading the dollar index around FOMC announcements, primarily with short holding periods, it is unclear however whether investors could have learned the corresponding holding period and threshold values.

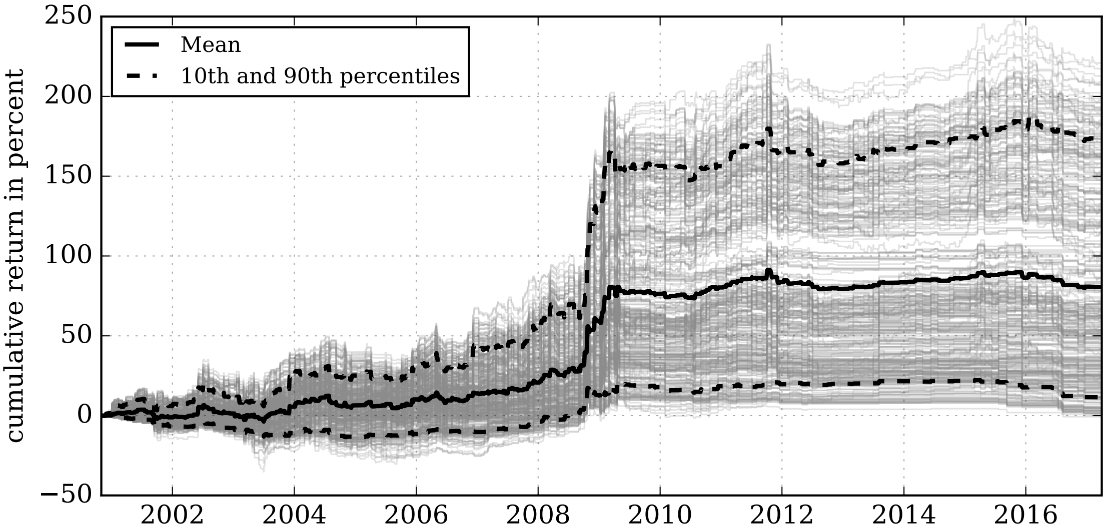
Figure 2.8: **Pre-announcement trading (bid-ask adjusted excess returns): strategy performance.**



This figure depicts the cumulative return on a trading strategy buying (selling) currencies against USD in anticipation of local interest rate hikes (cuts). The position in the spot rate is established 11 days in advance of each announcement day, only if the forecast interest rate change exceeds 10 basis points in absolute value. The position is then rolled over using tom/next swaps for 10 days and liquidated at the spot rate on the day preceding the announcement day. The rate change is forecast 12 days before the announcement day as the difference between the OIS-implied rate averaged over the five previous days and the corresponding underlying rate averaged over the same horizon. Panel 2.8a shows the return plotted against time and Panel 2.8b shows the return plotted event-by-event. The numbers in Panel 2.8a are mean return, its standard error (both in basis points) and the Sharpe ratio per one holding period. The standard error is Newey and West (1987) HAC with optimal number of lags according to Newey and West (1994). The returns are bid-ask spread-adjusted excess returns in USD on the following currencies AUD, CAD, CHF, EUR, GBP, NZD, SEK, and the dollar index. The sample is from November 2000 to March 2017.

gies with low holding periods. Furthermore, Panel B of Table 2.2 shows that trading around announcements where market participants are more certain about shift in the

Figure 2.9: **Pre-announcement trading (bid-ask adjusted excess returns): robustness to the choice of holding period and threshold.**

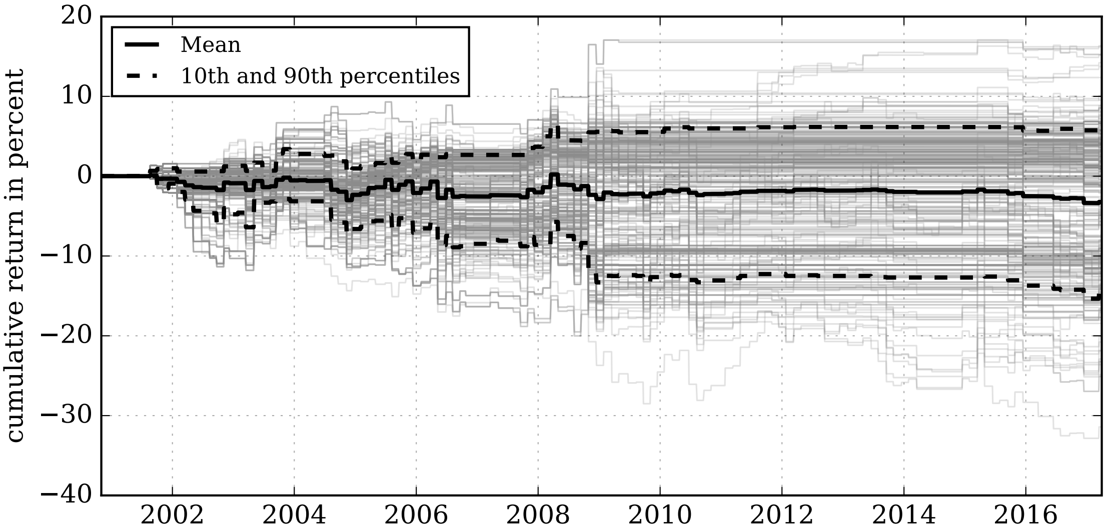


This figure plots cumulative returns on 375 trading strategies buying (selling) currencies against USD in anticipation of local interest rate hikes (cuts) for various holding horizons and expected policy rate cutoff levels. In the case of expected policy rate hike, the strategy $S^k(h, \tau)$ buys currency k against USD (or buys the dollar index for the FOMC announcements). The position in the spot rate is established $h+1$ days in advance of the announcement day, only if the difference between the average OIS-implied post-announcement rate over the days $h+2, ..., h+6$ exceeds the average corresponding underlying rate over the same horizon by τ or more. Similarly, the currency is sold if an interest rate cut is expected and the implied rate is below the underlying rate by at least τ basis points. The position is rolled over for h days using tom/next swaps and liquidated at the spot rate on the day preceding the announcement day. The set of trading strategies (plotted in gray) is generated for $h \in [1, 15]$ and $\tau \in [1, 25]bps$, the solid black line depicts the cross-sectional mean across all trading strategies and the dashed black lines represent the 1st and 9th empirical deciles of the distribution of the cumulative returns at each point of time. The returns are bid-ask spread-adjusted excess returns in USD on the following currencies AUD, CAD, CHF, EUR, GBP, NZD, SEK, and the dollar index. The sample is from November 2000 to March 2017.

policy rates (that is when the hypothetical investor uses higher threshold for forecasting the future rate) earn, on average, higher return.

Overall, the trading strategy exercise provides evidence of the short-horizon predictability of currency returns. This drift can not be attributed to the behavior of the dollar index before the target rate announcements documented in the previous literature. Furthermore, we demonstrate that the drift is perfectly exploitable by investors who face transaction costs and have to roll their spot positions overnight. It is important to point out, that some of the strategies admit leverage due to overlapping holding periods among predicted target rate changes for different currencies. In Appendix D we further demonstrate that our results also robust to restricting leverage.

Figure 2.10: **Pre-announcement trading (bid-ask adjusted excess returns, FOMC and the dollar index only): robustness to the choice of holding period and threshold.**



This figure plots cumulative returns on 375 trading strategies buying (selling) the dollar index in anticipation of interest rate hikes (cuts) in the US for various holding horizons and expected policy rate cutoff levels. In the case of expected policy rate hike, the strategy $S(h, \tau)$ buys the dollar index. The position is established $h + 1$ days in advance of the FOMC announcement day, only if the difference between the average OIS-implied post-announcement rate over the days $h + 2, ..., h + 6$ exceeds the average effective federal funds rate over the same horizon by τ or more. Similarly, the currency is sold if an interest rate cut is expected and the implied rate is below the underlying rate by at least τ basis points. The position is rolled over for h days using tom/next swaps and liquidated at the spot rate on the day preceding the announcement day. The set of trading strategies (plotted in gray) is generated for $h \in [1, 15]$ and $\tau \in [1, 25]bps$, the solid black line depicts the cross-sectional mean across all trading strategies and the dashed black lines represent the 1st and 9th empirical deciles of the distribution of the cumulative returns at each point of time. The returns are bid-ask spread-adjusted excess returns in USD on the the dollar index including the following currencies: AUD, CAD, CHF, EUR, GBP, JPY, NOK, NZD, SEK. The sample is from November 2000 to March 2017.

2.5 Conclusion

We describe a persistent pattern in the dynamics of exchange rates before policy rate announcements of respective central banks: currencies start to moderately appreciate days before declared interest rate hikes, and significantly depreciate before rate cuts. Given that a transparent monetary policy favored by most regulators since 2000s begets a high predictability of policy rate changes, we show that the pattern is profitably exploitable on the FX market. We document that policy rate decisions can be accurately forecast with information embedded in overnight index swaps, more so when the best classification rule is known in advance. However, the multitude of possible classification rules makes it difficult to accurately backtest trading strategies. We show that the final payoff of the strategies can be sensitive to the choice of the rule. Still, the payoff of the trading strategy that we construct using the OIS-implied information and a cross-section of currencies remains positive and large whatever the specification.

Table 2.2: Pre-Announcement Trading: Descriptive Statistics

Decile	1	2	3	4	5	6	7	8	9
Panel A: Deciles of cumulative performance									
h	1	8	7	7	7	10	11	13	14
τ	12	9	23	16	1	22	14	6	4
mean	41.20	9.26	38.51	33.09	12.61	46.66	39.05	22.62	20.12
(s.e)	(66.04)	(15.13)	(31.62)	(22.44)	(9.78)	(22.78)	(15.85)	(10.50)	(9.75)
median	21.15	12.72	27.57	40.00	23.71	38.20	35.21	23.18	21.24
std.	1129.3	250.9	325.6	300.6	270.3	228.3	213.4	203.1	189.5
skew.	1.08	0.49	0.81	0.63	−0.11	0.86	0.59	0.30	0.12
kurt.	7.09	2.89	3.64	3.13	2.80	3.13	1.29	1.62	1.85
Sharpe	0.12	0.04	0.14	0.13	0.06	0.20	0.17	0.10	0.09
count	277	320	127	216	713	172	278	502	614
Panel B: Deciles of average daily return									
h	1	13	12	15	5	13	10	4	11
τ	6	1	5	9	16	11	15	23	18
mean	12.64	19.15	23.14	27.46	32.73	35.89	39.09	43.59	48.04
(s.e)	(58.17)	(8.64)	(10.20)	(10.74)	(25.09)	(12.75)	(18.01)	(41.32)	(17.95)
median	−3.98	16.45	22.23	22.24	20.71	31.66	47.95	16.01	38.79
std.	1086.8	203.5	208.5	190.1	421.8	201.2	226.0	529.1	215.9
skew.	0.81	0.14	0.31	0.38	−0.17	0.42	0.57	0.89	0.71
kurt.	6.80	1.73	1.51	2.18	10.12	2.17	2.20	12.19	1.39
Sharpe	0.04	0.08	0.10	0.12	0.11	0.16	0.17	0.13	0.21
count	367	743	508	467	230	372	248	143	229

This table reports descriptive statistics for a subset of pre-announcement trading strategies buying (selling) currencies against USD in anticipation of local interest rate hikes (cuts) plotted Figure 2.9. In the case of expected policy rate hike, the strategy $S^k(h, \tau)$ buys currency k against USD (or buys the dollar index for the FOMC announcements). The position in the spot rate is established $h + 1$ days in advance of the announcement day, only if the difference between the average OIS-implied post-announcement rate over the days $h + 2, ..., h + 6$ exceeds the average corresponding underlying rate over the same horizon by τ or more. Similarly, the currency is sold if an interest rate cut is expected and the implied rate is below the underlying rate by at least τ basis points. The position is rolled over for h days using tom/next swaps and liquidated at the spot rate on the day preceding the announcement day. The set of trading strategies is generated for $h \in [1, 15]$ and $\tau \in [1, 25] bps$. Each column reports statistics for a decile strategy in the empirical distribution of the whole set's cumulative performance (Panel A) and mean return per day of position open (Panel B). For each decile strategy first two rows show the corresponding holding period h (in days) and threshold level τ in basis points. Means, standard errors, medians, and standard deviations are in basis points. Before computing descriptive statistics, each reported strategy is (de-)leveraged to the 10-day holding period by multiplying its returns by the ratio of 10 to strategy's holding period. The Sharpe ratios are scaled by square root of the same ratio to represent the 10-day holding period. The returns are bid-ask spread-adjusted excess returns in USD on the following currencies AUD, CAD, CHF, EUR, GBP, NZD, SEK, and the dollar index. The sample is from November 2000 to March 2017.

Our findings are difficult to reconcile with the existing theories of the determinants of exchange rates. Robust returns of the pre-announcement trading that we see might be a consequence of a gradual resolution of uncertainty about the approaching policy change and heterogeneous agents entering the currency market one by one as soon as their risk aversion allows to place a bet. The more risk averse investors would in this case enter the market last, when the monetary policy uncertainty is low, and the less risk averse ones would enter earlier, thus constantly buoying the demand for the currency. An attack at modeling the mechanism behind our findings would be a logical continuation of the research on the dependency between monetary policy and exchange rates.

Appendix A

Event study

Cutting and pivoting the sample of abnormal returns of currency i results in the following matrix:

$$R_i = \begin{bmatrix} R_{i,1,w_b} & R_{i,2,w_b} & \dots & R_{i,K,w_b} \\ R_{i,1,(w_b+1)} & R_{i,2,(w_b+1)} & \dots & R_{i,K,(w_b+1)} \\ \vdots & \vdots & \ddots & \vdots \\ R_{i,1,w_a} & R_{i,2,w_a} & \dots & R_{i,K,w_a} \end{bmatrix} \tag{A.1}$$

where each row corresponds to a cross-section of returns a certain number of days after a generic event. Return $R_{i,k,s}$ is thus read as "return of currency i in period s after event k".

As already stated in Section 2.2, a cumulative abnormal return (CAR) is defined as:

$$R^{ca}_{i,k,s} = \begin{cases} \sum_{t=s}^{-1} R_{i,k,t} & s < 0, \\ \sum_{t=+1}^{s} R_{i,k,t} & s > 0, \end{cases} \tag{A.2}$$

The average-across-events CAR is defined as:

$$\overline{R^{ca}_{i,s}} = \frac{1}{K} \sum_{k=1}^{K} R^{ca}_{i,k,s} \tag{A.3}$$

which corresponds to the average across columns of matrix (A.1). Finally, the average-across-assets CAR is the average-across-events CARs averaged across the assets:

$$\begin{aligned} \overline{R^{ca}_{s}} &= \frac{1}{N} \sum_{i=1}^{N} \overline{R^{ca}_{i,s}} \\ &= \frac{1}{NK} \sum_{i=1}^{N} \sum_{k=1}^{K} R^{ca}_{i,k,s} \\ &= \frac{1}{NK} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{t=s}^{-1} R_{i,k,t} \end{aligned} \tag{A.4}$$

in the pre-announcement case.

Distributional properties of $\overline{R^{ca}_{s}}$ are derived from equation (A.4). For the mean:

$$\mathrm{E}\left[\overline{R^{ca}_{s}}\right] = \frac{1}{NK} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{t=s}^{-1} \mathrm{E}\left[R_{i,k,t}\right] = 0 \tag{A.5}$$

under the constant mean zero model for the abnormal return. For the variance, note that:

$$\mathrm{var}\left[\sum_{m=1}^{M} x_m\right] = \sum_{m=1}^{M} \mathrm{var}\left[x_m\right] + 2\sum_{i\neq j} \mathrm{cov}\left[x_i, x_j\right], \tag{A.6}$$

which is simply equal to the first addend on the right-hand side if the cross-covariances are all zero. Given that policy announcements in any particular country are widely dispersed through time, the covariances stemming from the sum over k in equation (A.4) vanish. So do those stemming from the sum over i since the announcements made by the regulators of different countries are not synchronized and only rarely coincide. The inter-temporal covariances stemming from the sum over t are minuscule on the FX markets at the daily frequency, so we treat them as being zero. With that in mind:

$$\mathrm{var}\left[\overline{R_s^{ca}}\right] = \frac{1}{(NK)^2} \sum_{i=1}^{N} \sum_{k=1}^{K} \sum_{t=-s}^{-1} \mathrm{var}\left[R_{i,k,t}\right] \tag{A.7}$$

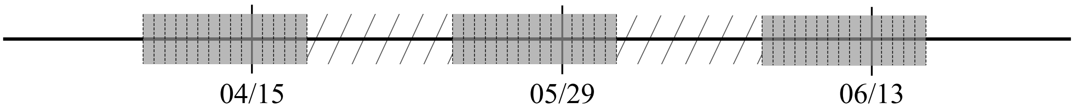
We estimate $\mathrm{var}\left[R_{i,k,t}\right]$ as the variance of returns of currency i in the period between two consecutive event windows, which given the zero-mean assumption discussed earlier amounts to:

$$\mathrm{var}\left[R_{i,k,t}\right] = \frac{1}{T} \sum_{t=s_0}^{s_1} R_{i,t}^2 \tag{A.8}$$

$$s_0 = d_{i,k-1} + w_a + 1$$

$$s_1 = d_{i,k} - w_b - 1$$

where T is the number of periods between the two event windows. This rather cumbersome formula in reality represents a very simple concept depicted below:



Here three events related to currency i are dated with $d_{i,1} = 04/15$, $d_{i,2} = 05/29$, and $d_{i,3} = 06/13$. The gray shaded area around each corresponds to (w_b, w_a) days around each event, and a hatched area before each event window is used for estimation of the variance of abnormal returns around that event.

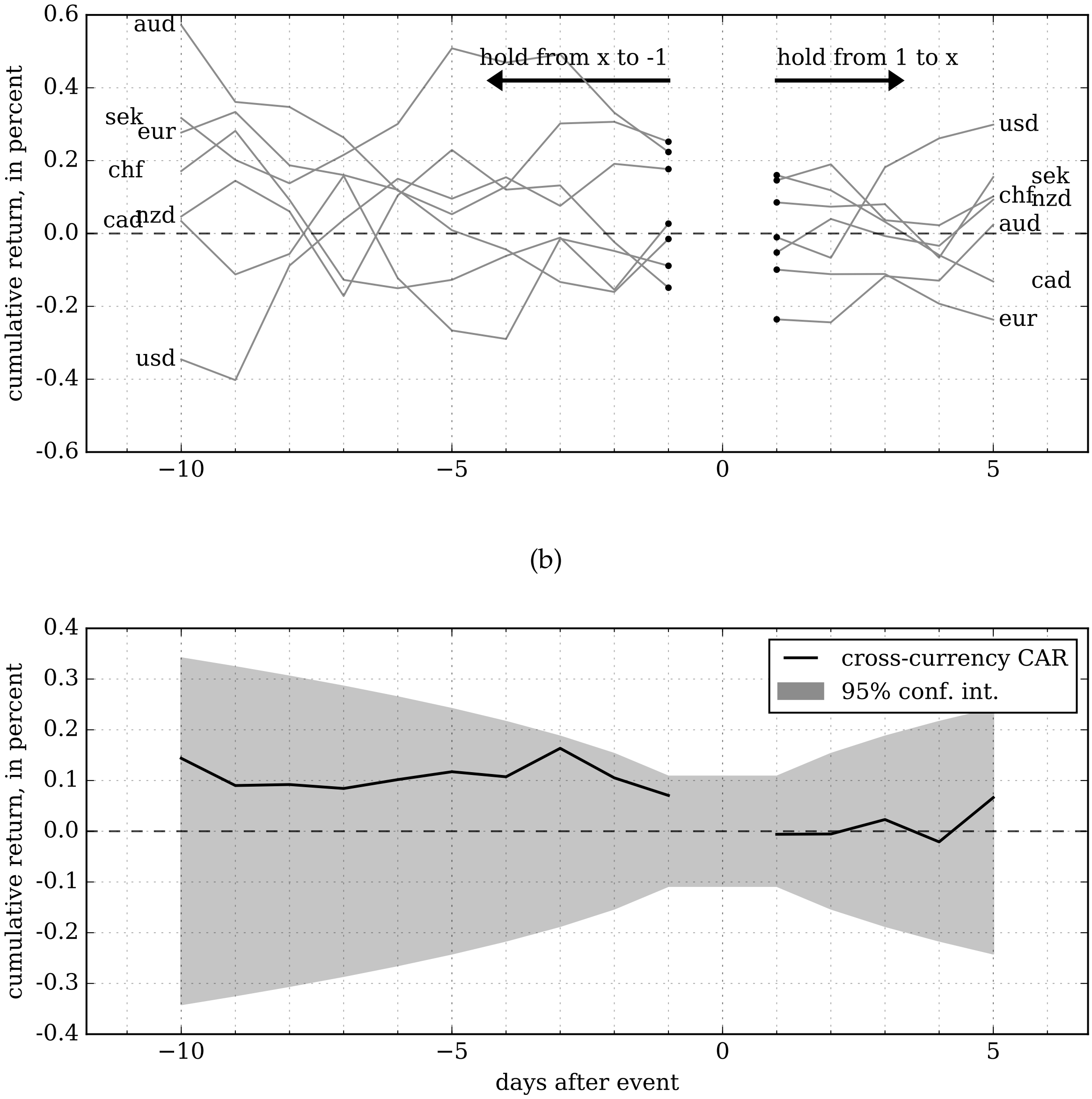
In addition and as a robustness check, we compute bootstrapped confidence bands. We first drop all event windows (w_b, w_a) from the matrix of returns irrespective of the monetary policy decision, thus leaving "gaps" in the matrix. Second, on each iteration of the bootstrapping procedure, we fill these gaps with resampled blocks of the same matrix to preserve the time-series correlation as much as possible; we then block-bootstrap a new history of returns with block size being equal to the length of the event window; we use the resulting history to calculate the average cumulative return in equation (A.4). Third, we collect M such averages and take their 2.5% and 97.5% percentiles as the lower and upper borders of the resulting confidence band respectively.

Appendix B

Event study, different counter currencies

We repeat the event study using GBP and JPY instead of USD as the counter currency. With a different counter currency, two things change when compared to Figures 2.1 and 2.2: first, the events associated with the new currency ”disappear”, and second, the USD appears as an additional currency. The results are presented in Figures B.1 and B.2 (with GBP as the counter currency) and B.3-B.4 (with JPY as the counter currency), and are supportive of our previous findings: the appreciation before interest rate hikes is not pronounced, unlike the depreciation before cuts. Over the 10-day pre-event period the currencies depreciate vs. GBP (JPY) by 60 (100) basis points, which is statistically significant at the 5% level.

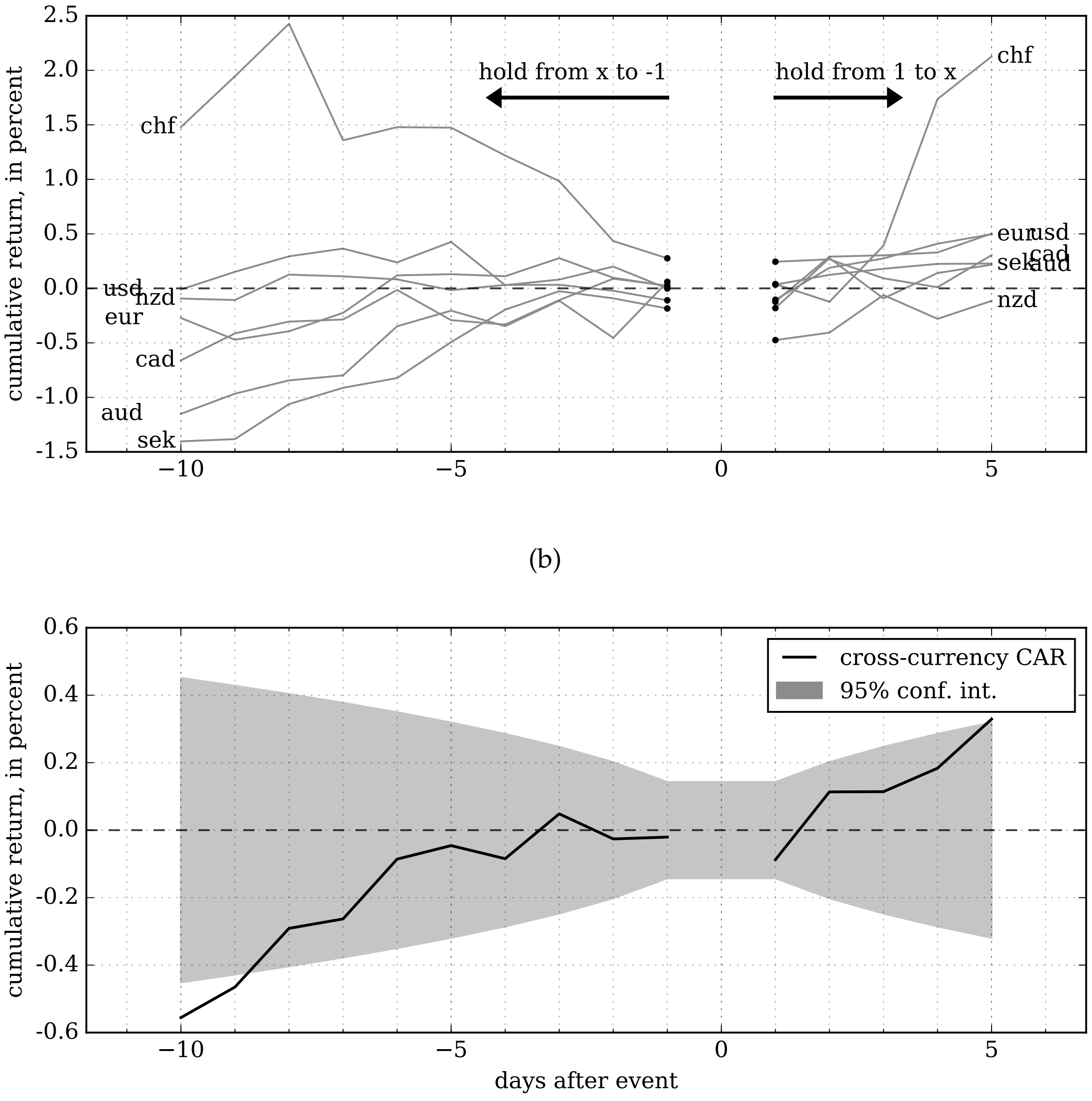
Figure B.1: **Exchange rates around local interest rate hikes (counter currency GBP).**


(a)

(b)

This figure depicts cumulative currency returns around interest rate hikes announced by the local central banks, with the counter currency being GBP. Panel B.1a shows returns on individual currencies and Panel B.1b shows the average return over all currencies weighted in proportion to the number of hikes each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency *x* days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for *x* days, whereby *x* is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in GBP. The sample includes AUD, CAD, CHF, EUR, NOK, NZD, SEK and USD for the period from November 2000 to March 2017.

Figure B.2: **Exchange rates around local interest rate cuts (counter currency GBP).**

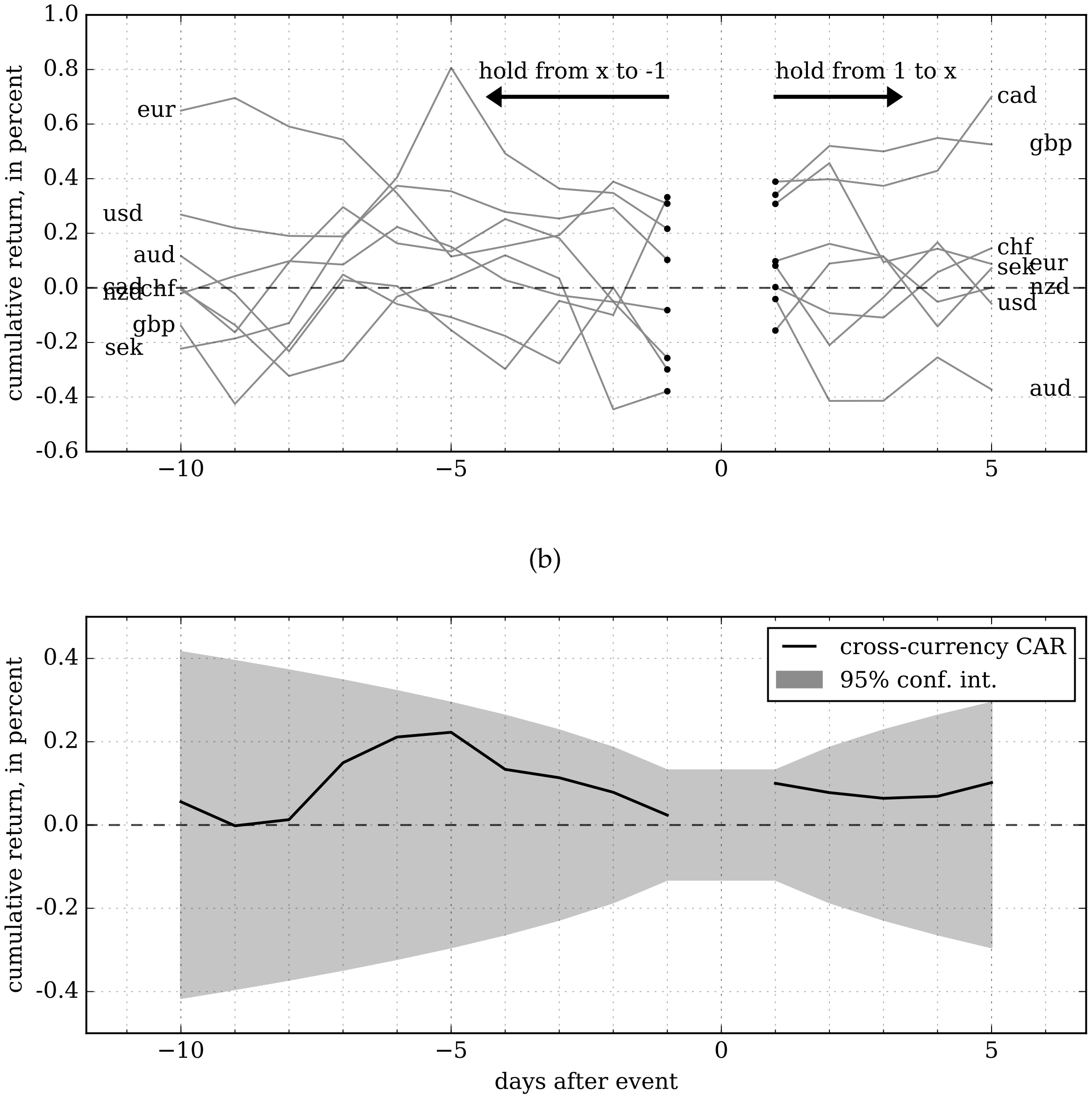

(a)

(b)

This figure depicts cumulative currency returns around interest rate cuts announced by the local central banks, with the counter currency being GBP. Panel B.2a shows returns on individual currencies and Panel B.2b shows the average return over all currencies weighted in proportion to the number of cuts each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency x days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for x days, whereby x is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in GBP. The sample includes AUD, CAD, CHF, EUR, NOK, NZD, SEK and USD for the period from November 2000 to March 2017.

Figure B.3: **Exchange rates around local interest rate hikes (counter currency JPY).**

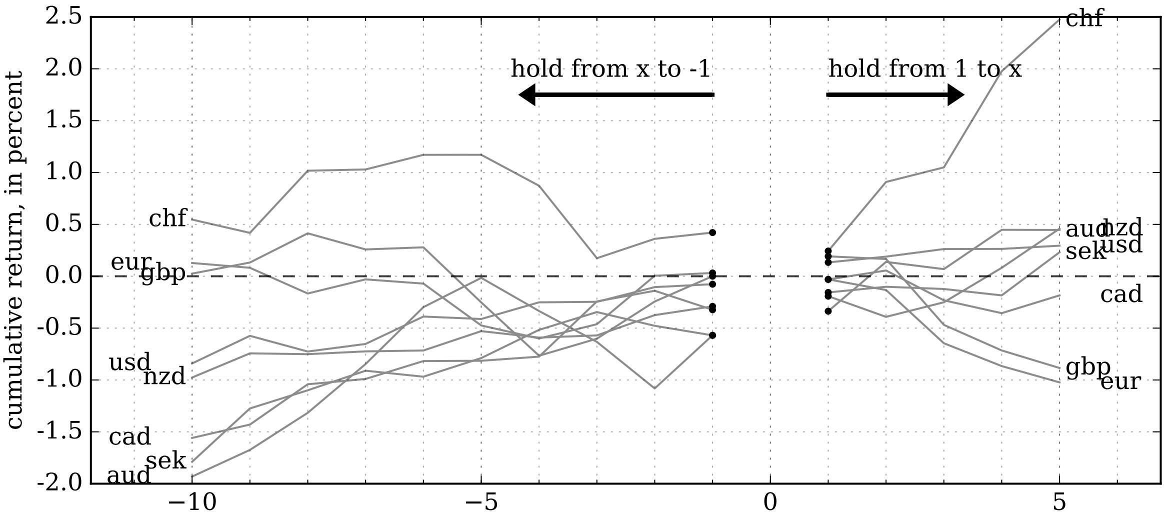
(a)



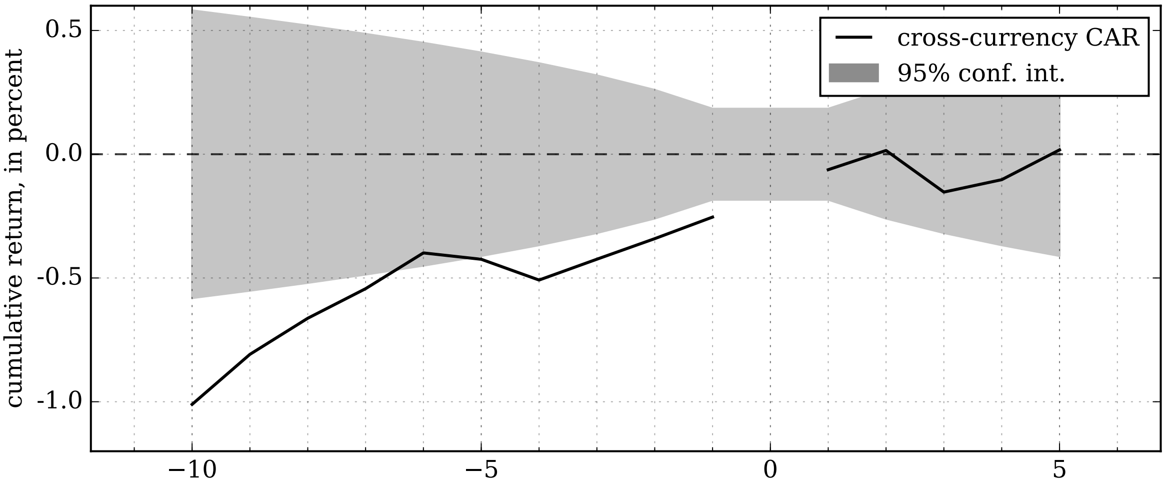
This figure depicts cumulative currency returns around interest rate hikes announced by the local central banks, with the counter currency being JPY. Panel B.3a shows returns on individual currencies and Panel B.3b shows the average return over all currencies weighted in proportion to the number of hikes each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency x days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for x days, whereby x is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in JPY. The sample includes AUD, CAD, CHF, EUR, jpy, NOK, NZD, SEK and USD for the period from November 2000 to March 2017.

Figure B.4: **Exchange rates around local interest rate cuts (counter currency JPY).**

(a)



(b)



This figure depicts cumulative currency returns around interest rate cuts announced by the local central banks, with the counter currency being JPY. Panel B.4a shows returns on individual currencies and Panel B.4b shows the average return over all currencies weighted in proportion to the number of cuts each currency experienced. The announcement day is marked by zero. A pre-announcement spot return is realized by opening a long position in the currency x days and reversing it one day before the announcement; the post-announcement returns are realized by opening a long position in the currency on the first day following the announcement and holding it for x days, whereby x is read off the abscissa. The shaded area in the bottom panel represents the 95% confidence interval for the average value around zero. All returns are spot returns in JPY. The sample includes AUD, CAD, CHF, EUR, GBP, NOK, NZD, SEK and USD for the period from November 2000 to March 2017.

Appendix C

Swap points vs. forward discounts

Recall that the monthly excess log-return on a currency pair is:

$$\begin{aligned} rx_{t+1} &= s_{t+1} - f_t \\ &= s_{t+1} - s_t + s_t - f_t \\ &= \Delta s_{t+1} + d_t, \end{aligned} \tag{C.1}$$

where Δs_{t+1} is the log spot return, d_t is the forward discount, approximately equal to the interest rate differential, and t is understood to index months. On the other hand, the same return is expected to be achieved by rolling over a spot position from t to $t+1$, assuming a total of h days in the month:

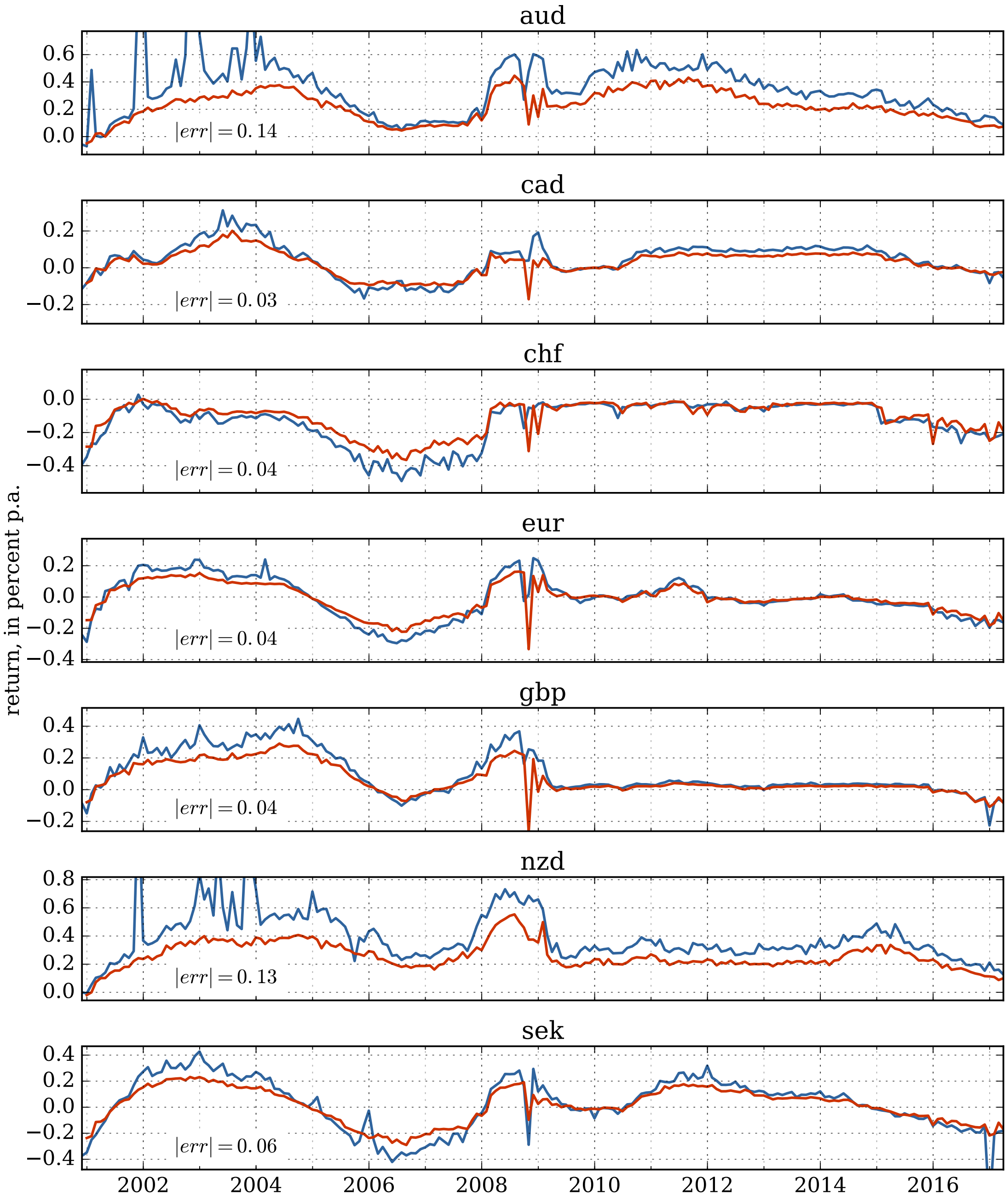
$$\widehat{rx}_{t+1} = \log S_{t+1} - \log(S_t + \sum_{\tau=1}^{h} w_\tau), \tag{C.2}$$

We could use the Taylor expansion of $\log(S_{t+1} + \sum_{\tau=1}^{h} w_\tau)$ around S_t (since the second addend is usually very small on the frequencies higher than the monthly) to rewrite equation (C.2) as follows:

$$\begin{aligned} \widehat{rx}_{t+1} &= \log S_{t+1} + \frac{1}{S_t} \sum_{\tau=1}^{h} w_\tau - \log S_t \\ &= \Delta s_{t+1} + \widehat{d}_t, \\ \widehat{d}_t &= \frac{1}{S_t} \sum_{\tau=1}^{h} w_\tau \end{aligned} \tag{C.3}$$

Obviosuly, asking how close $\widehat{rx}_t$ is to rx_t is tantamount to asking if the previous month's forward discounts are accurate predictors of their next month's cumulative daily counterparts. The wedge – if any – should be driven by both the failure of the expectation hypothesis and omnipresent market frictions. Without claim at a rigorous study of this wedge, which would be beyond the scope of our work, and rather as a quick check that it is small, in Figure C.1 we compare d_t from equation (C.1) $\hat{d}_t$ from equation (C.3). Though the cumulative daily rollovers are more volatile and would thus introduce additional noise to the excess return series, they closely follow the monthly forward discounts. The maximum mean absolute difference between the two series occurs for AUD and reaches 0.14% p.a., which is negligible compared to the magnitudes of returns of the strategies that we construct.

Figure C.1: **Daily tom/next swap points vs. 1-month forward discounts.**



This figure shows the part of the FX monthly excess return, in percent p.a., attributed to the interest rate differential between the respective currency and the US Dollar. The colder-colored line depicts the case of opening a spot position at the beginning of each month and rolling it over daily until the end of the month. Because of missing data, the average over the non-missing observations within each month is taken and multiplied by 30 to arrive at the monthly figure. The warmer-colored line depicts the case of an investor entering a short forward contract at the end of the previous month and closing it at month's end. The number in the lower left corner stands for the mean absolute difference between the two series, in percent p.a. All quotes are mid quotes from November 2000 to March 2017.

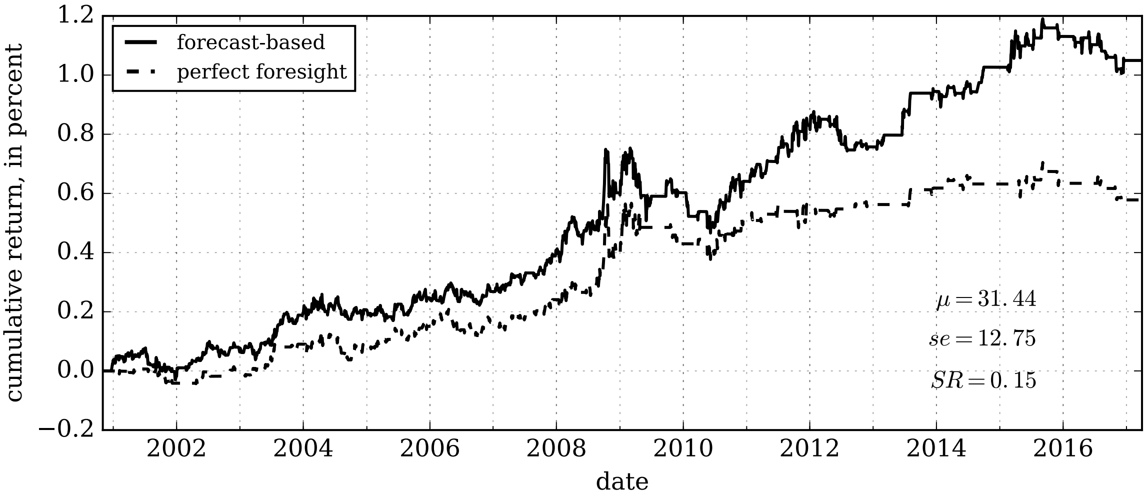
Appendix D

Restricting leverage

Although funding constraints for foreign exchange speculation are rather lax, we demonstrate that our results are not driven by higher amount of leverage before profitable trades and lower leverage before the unprofitable ones. We repeat the trading strategy exercise for a leverage-constrained investor.

Figure D.1 plots the cumulative unrealized profit and loss (i.e. the liquidation value of all open positions in excess of initial equity) of the baseline strategy. At the beginning of the sample we endow the investor with one US dollar of equity, and require her to fully collateralize all open positions on the *net* basis, that is for a dollar of equity she is allowed to hold one dollar long and one dollar short in different currencies. At each portfolio rebalancing, first, we calculate the margin closeout value which is the sum of the portfolio balance and the unrealized profits and losses; then we allocate an equal (in absolute terms) share of the closeout value to all currencies that are required to be held according to signals. A leveraged portfolio would have opened positions sum up to a multiple of the margin closeout value; we restrict leverage to 1 to make the strategy comparable with the popular long-short strategies on the FX market. We conduct every transaction at the London fixing time to avoid any overlaps in the positions. Furthermore, when local predicted signals conflict with the FOMC signals, the former are given priority over the latter. For example, if an interest rate hike is predicted both in the US and Australia, the portfolio is long AUD and short every other currency. With leverage excluded, the cumulative performance exceeds 100 percent over the whole sample which corresponds to about 6.5 percent per year. The average ten-day return of 31.44 basis points is statistically significant at the 1% level, having the *t*-statistic of 2.47.

Figure D.1: **Pre-announcement trading with restricted leverage (bid-ask adjusted excess returns): policy rate expectations.**



This figure depicts the cumulative unrealized profit and loss of a trading strategy buying (selling) currencies against USD in anticipation of local interest rate hikes (cuts). The position in the spot rate is established 11 days in advance of each announcement day, only if the forecast interest rate change exceeds 10 basis points in absolute value. The position is then rolled over using tom/next swaps for 10 days and liquidated at the spot rate on the day preceding the announcement day. The rate change is predicted 12 days before the announcement day as the difference between the OIS-implied rate averaged over the five previous days and the corresponding underlying rate averaged over the same horizon. The numbers refer to the mean, standard error of the mean (both in basis points) and the Sharpe ratio of daily log changes in market value of the portfolio scaled to 10 days to represent the average holding period. The standard error is Newey and West (1987) HAC with optimal number of lags according to Newey and West (1994). The unrealized profit and loss is in USD and accounts for bid-ask spread. The sample includes AUD, CAD, CHF, EUR, GBP, NZD, SEK, JPY, NOK, with the last two being traded around FOMC announcements only. The sample is from November 2000 to March 2017.

Chapter 3

Overnight Index Swap Rates as Forecasts of Monetary Policy*

Dmitry Borisenko[†] and Igor Pozdeev[‡]

Abstract

Despite growing popularity of overnight index swaps (OIS), which are used by practitioners and regulators as a tool of measuring markets' expectations of future monetary policy, these instruments have gained limited attention from academics. In this paper, we document OIS to be unbiased predictors of future short rates in developed economies, bearing no significant risk premium for maturities up to one year. We show that the OIS underlying overnight rates accurately reflect the target rates set by central banks, making the swaps capable of accurately forecasting the future course of monetary policy. We extract the implied future target rates from the OIS prices to predict the outcome of monetary policy meetings around the world. In the US, a randomly selected triplet of a target rate hike, cut and no-change is correctly classified using the OIS-implied rates in 99.9 and 98 percent of cases five and ten days before a FOMC announcement respectively, which exceeds the prediction accuracy of the federal funds futures- and LIBOR-implied rates. We report similarly high prediction accuracy for other developed countries.

Keywords: Monetary Policy, Policy Expectations, Predictability, Overnight Index Swap, Foreign Exchange.

JEL Classification: E43, E52, E58, F31, G12

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3.1 Introduction

Gauging the expected path of the short-term rate is crucial for financial market participants and regulators. The former use the (expected) risk-free rate as a key element of derivatives pricing, while the latter need to assess the market expectations about the future course of monetary policy. Federal funds futures contracts[1] have become a staple for predicting the future path of the short rate in the US among both practitioners and academics. However, no similar exchange-traded instrument is available in other major economies. Recently, overnight index swaps (OIS) [2] have become an important tool to take a view on the outcome of monetary policy meetings and to value securities using OIS rates as a risk-free benchmark. The question whether OIS rates provide an accurate measure of the expected future short rate has not been thoroughly researched.

Introduced to the markets worldwide in the early 2000s, OIS have enjoyed growing notional values and high degree of liquidity. In 2016 OIS comprised 50, 40 and 30 percent of the total interest rate swap (IRS) turnover in the Australian dollar, US dollar, and the euro (Kreicher et al. (2017)), with the average daily total IRS turnover in this year being 105, 898, and 445 USD billion respectively, up from 4, 100, and 173 USD billion in 2001 (BIS (2016b)). Similarly to the federal funds futures, the bulk of OIS liquidity is concentrated in maturities of less than one year (Fleming et al. (2012), Ehlers and Eren (2016)). Furthermore, since the 2007-2009 financial crisis reliability of LIBOR as a "risk-free" benchmark rate has been repeatedly questioned by practitioners and regulators. Indicative nature of quotes, absence of active underlying markets and thus proneness to manipulation, led the rate to be phased out in 2021. With the imminent demise of LIBOR, investment community is looking for an alternative benchmark. Hull and White (2013) provide formal arguments favoring OIS rates over LIBOR as risk-free benchmarks for discounting derivatives. In April 2017 the Bank of England recommended SONIA (the underlying rate for the sterling OIS) as the near risk-free reference rate benchmark. International Swaps and Derivatives Association started to promote OIS rates as such benchmarks by advancing standardization of collateral and margin requirements for the swaps, in particular by proposing to use cash as the sole eligible collateral for variation margin, thus bringing the OIS closer to their exchange-traded counterparts in terms of credit risk (ISDA (2013)).[3] The standardization in interest rate OTC derivatives, on the other hand, is furthered by authorities and regulators seeking to reduce systemic risks and thus promoting central counterparty (CCP) clearing of

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[1] The federal funds futures contracts are traded at the Chicago Mercantile Exchange. A month M federal funds futures contract settles at the average effective federal funds rate over the month M.

[2] An OIS is an over-the-counter interest rate swap where the floating leg pays the underlying overnight rate compounded over lifetime of the contract, for example in case of the US the underlying is the effective federal funds rate.

[3] Sundaresan et al. (2017) provide an extensive discussion of reasons behind the low credit risk and liquidity premium in OIS contracts. They also provide plethora of examples of OIS rates adopted for discounting among clearing houses and derivative trading venues.

OTC derivatives. Wooldridge (2016) estimates the total amount of interest rate derivatives to be cleared via CCP to have increased from 40 to 85 percent from 2004 to 2016, with around 80 percent of all interest rate swaps cleared centrally in 2016. Despite their increasing likeliness to exchange-traded interest rate instruments and rising popularity among practitioners and regulators, OIS have gained little attention from academics.

In this paper, we show that OIS rates are unbiased predictors of future short rates in major economies. In particular, we demonstrate that for the most liquid maturities from one month two one year, OIS bear neither statistically nor economically significant risk-premium with a few exceptions: for the period from early 2000s to June 2017 excess return on one-year OIS contracts ranges from 3 basis points for Australia (statistically insignificant) to 26 basis points for Switzerland (significant at 1% level), with the USD one-year OIS having statistically insignificant excess return of 20 basis points. We provide empirical evidence that the OIS underlying overnight rates closely follow the interest rate targets set by central banks. Thus, taking into account the absence of risk premium, we argue that OIS are accurate predictors of the future course of monetary policy. We further exploit this predictability to extract the implied future target rates before monetary policy meetings. In a statistical classification framework we show that the implied policy rates extracted from the OIS contracts can accurately predict the outcome of monetary policy meetings around the world. So for instance, in the US a randomly selected triplet of target rate hike, cut, and no-change is correctly inferred from OIS rates in 99.9 and 98 percent of the cases five and ten days before a FOMC announcement respectively. The federal funds futures-implied rates give the prediction accuracy of 99.8 and 94.5 percent for the same horizons, and the LIBOR-implied rates correctly infer the direction of the target rate change only in 43 and 36 percent of the cases. We report similarly high prediction accuracy for the other developed countries.

Our study extends the literature on measuring monetary policy expectations from market prices. Market-based predictions are found to be superior both to those produced by macroeconomic models such as Taylor rules (Evans (1998)) and time-series models (Gürkaynak et al. (2007)). Gürkaynak et al. (2007) also demonstrate that federal funds futures dominate other market instruments in terms of predictive power. Federal funds futures have been a popular tool among academics and practitioners to gauge the expected short rate path,[4] however, Piazzesi and Swanson (2008) demonstrate that fed funds futures contain significant time-varying risk premium and thus need a proper adjustment to be unbiased forecasts of the future short rate. We contribute to this strand of literature by taking the monetary policy prediction exercise to the international setting and examining eight major economies whose central banks employ interest rates targeting as monetary policy tool. First, we find that, although

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[4] Krueger and Kuttner (1996), Sack (2004), Kuttner (2001), Bernanke and Kuttner (2005), Piazzesi and Swanson (2008) are a few academic studies. The CME FedWatch Tool uses the futures contracts to compute the probability of target rate changes in the upcoming FOMC meetings.

generally positive, the risk premium in the prices of OIS of maturities up to one year is neither economically nor statistically significant for all countries except Switzerland.[5] In that respect, OIS rates are unbiased predictors of own future compound interest rates. Second, we link the OIS underlying and target rates of respective central banks, by showing that the former closely follow the latter. Hence, we find OIS rates to be an adequate tool for recovery of monetary policy expectations.

Our second contribution is to provide a convenient venue for further research on behavior of asset prices around target rate decisions. There is growing literature documenting abnormal dynamics of asset returns around monetary policy announcements. Lucca and Moench (2015) and Mueller et al. (2017) document significant excess returns on the US large cap stocks and portfolio of currencies against USD before the FOMC announcements, Cieslak et al. (2016) find cyclicality in the US stock returns with the cycle spanned by the FOMC meetings. Karnaukh (2016) further incorporates monetary policy expectations derived from federal funds futures showing that dollar appreciates (depreciates) against a portfolio of currencies several days in advance of anticipated US target rate hikes (cuts). Her analysis thus recognizes predicting the outcome of monetary policy meetings as a classification problem with discrete set of outcomes.[6] Building on our findings and using a statistical classification framework with a threshold-based rule, we demonstrate that the OIS-implied expected rates are capable of accurately predicting the direction of target rate changes in developed countries, with predictive power being on par with that of federal funds futures in the US.

The remainder of the paper is structured as follows. Section 3.2 describes the payoff structure of OIS contracts, computation of excess returns and our dataset as well as provides empirical evidence of OIS bearing no significant risk premium in the major economies. In this section we also demonstrate that the overnight rates underlying the OIS are tightly linked to the target rates set by central banks, thus providing evidence of OIS being accurate predictors of the future course of monetary policy. Section 3.3 presents the methodology of recovering the expected target rate changes from the prices of OIS, takes a closer look at the required assumptions, and assesses the forecasting power of the implied rates in predicting the outcomes of upcoming target rate decisions. Section 3.4 concludes.

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[5] With an exception of Australia and New Zealand where target rates are held constant between monetary policy meetings and overnight rates correspond exactly to the target rates, the target rates are either allowed to float within a band like the federal funds rate in the US, or not explicitly tied to OIS underlying rates at all, with an extreme example being Switzerland whose monetary authority targets the 3-month Swiss franc LIBOR.

[6] Mueller et al. (2017) also report diverging patterns in currency returns against USD immediately after the FOMC announcements resulting in target rate changes – dollar appreciates after hikes, and depreciates otherwise.

3.2 Excess Returns on Overnight Index Swaps

An Overnight Index Swap (OIS) is a contract requiring one party to pay the other the accumulated underlying rate – most often an overnight rate such as the federal funds rate in the US – in exchange for a predetermined fixed rate payment. OIS are priced based on the expectation of the future rate and have zero value at inception, hence the expected return from entering into such a contract can be thought of as a risk premium, which we find to be statistically and economically insignificant for most OIS specifications in our sample. The OIS underlying rates often coincide with the target rates in respective countries; when they do not, we show that the two are tightly linked. When indexed with the target rates instead of the true underlying rates, the prices of OIS are still found to be unbiased predictors of the future compound rate levels.

3.2.1 Overnight Index Swaps

In an OIS, one party agrees to pay a fixed rate, and the other a floating short rate accumulated over the lifetime of the contract, the payments being exchanged at maturity of the swap.[7] Each day, a new portion of the floating leg return is accumulated based on the underlying rate level which is determined according to the local market conventions – this process is called "fixing" – while the fixed leg portion is a constant negotiated at inception. By the risk-neutral pricing argument, the fixed leg rate of an OIS of maturity m negotiated at time t is determined as follows:

$$\begin{aligned} W_{m,t} &= \mathrm{E}_t\left[\prod_{s\in S_{m,t}}(1+r_s\delta_s)\right], \\ W_{m,t} &:= 1 + w_{m,t}D_m, \end{aligned} \tag{3.1}$$

where the expectation is taken under the risk-neutral measure, $w_{m,t}$ is the annualized fixed rate, D_m is the contract-specific day count factor such as Act/360 for USD OIS, $S_{m,t}$ is the set of all fixing days (usually banking days in the respective country) until the swap matures, r_s is the per-day fixing rate on day s, and δ_s is the "length of overnight", or one plus the number of bank close days following day s. For example, if s is Friday and the next Monday is not a bank holiday, $\delta_s = 3$; if the next Monday is a bank holiday, but the Tuesday is not, $\delta_s = 4$ and so on. For two OIS contracts on different currencies traded on the same day, S_m and D_m will be different. The differences come from the fixing and trading conventions of the underlying rates such as the holiday calendar, the effective date and the fixing lag. For example, for a sterling OIS traded on October 15th the first fixing occurs on the same day (effective date equal to

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[7] The OIS are subject to netting, that is notional is not exchanged, furthermore at the maturity the difference between the two legs is transferred to the counterparty with the positive payoff.

quote date), while for a USD OIS it occurs in two business days (effective date two days away from quote date). This means that the one-month sterling OIS has the effective lifetime from October 15th to November 15th, while its dollar counterpart starts accruing the floating rate on October 17th and matures on November 17th (provided that October 16th and 17th are banking days in the US). The fixing lag refers to the number of days between the fixing day of the floating leg an the value date of the underlying. For instance, the effective federal funds rate for a given day is published by the Federal Reserve Bank of New York on the following day, on the other hand the underlying rates for the Swiss franc and Swedish krona are tomorrow/next rates, hence the rate from the previous day is used for fixing.

We collect the fixed leg rates and the corresponding underlying rates of OIS contracts written on currencies of the following countries: Australia, Canada, Eurozone, Japan, New Zealand, Sweden, Switzerland, United Kingdom, and United States. For each currency we use one-, three-, six-, nine- and twelve-month tenors. All data comes from Bloomberg. Table 3.1 summarizes specifications of the contracts and data availability. For each currency the table reports the underlying rate of the floating leg;[8] number of business days before the first floating leg indexing, fixing lag, day count convention, and the date since which all tenors are available.[9] Our sample ends in June 2017.

Table 3.1: **OIS contracts summary**

Currency	Underlying rate	Floating indexing start (days)	Fixing lag (days)	Day count	Data since
AUD	AONIA	1	0	Act/365	Oct-2001
CAD	CORRA	0	1	Act/365	May-2002
CHF	TOIS	2	-1	Act/360	Aug-2000
EUR	EONIA	2	0	Act/360	Jan-2000
GBP	SONIA	0	0	Act/365	Dec-2000
JPY	TONA	2	1	Act/365	Mar-2002
NZD	NZIONA	2	0	Act/365	Sep-2002
SEK	STIBOR T/N	2	-1	Act/360	Aug-2004
USD	Effective federal funds rate	2	1	Act/360	Dec-2001

This table summarizes the structure of OIS contracts. For each currency in the first column, column two contains the underlying rate, column three shows number of business days after trade date until the first floating leg indexing happens. Column four contains the fixing lag, meaning that each day of a contract's life its floating leg is indexed by todays' value of the underlying if the fixing lag is zero, by yesterday's value if it is -1, and by tomorrows' value if it is 1. Column five reports day count convention, and column six reports data availability for all tenors considered in this paper (except for the Canadian dollar where the one-year tenor is available from April 2003).

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[8] For Australia and New Zealand the underlying rates are equal to the Interbank Overnight Cash Rate and the Official Cash Rate respectively. Both rates are effectively equivalent to the corresponding central banks' operational targets. AONIA and NZIONA are the names used in the ISDA Definitions.

[9] With a single exception of the Canadian dollar for which the one-year tenor is available from April 2003.

3.2.2 OIS risk premium

In order to be unbiased predictors of the cumulative future underlying rate, the expected return of either OIS counterparty should be zero, that is, OIS should not contain a risk premium. We can test this assumption by calculating the realized return of an OIS fixed rate receiver:

$$rx_{t+m} = W_{m,t} - \prod_{s \in S_{m,t}} (1 + r_s \delta_s), \tag{3.2}$$

and estimating its expected value. Under certain conditions, this expectation can be approximated as the time series average of rx_t. Since neither counterparty pays anything to enter the contract, the realized return is a zero-cost portfolio, so we further refer to this return as the excess return, or risk premium.

Table 3.2 reports the sample estimates of the average excess returns on different OIS, for maturities from one month to one year. For each contract the sample starts as defined in Table 3.1 and ends in June 2017. For each currency (in columns) and for each maturity (in rows) we compute floating leg return according to the contract specification in Table 3.1, and then subtract it from the fixed leg rate. The excess returns are in basis points p.a. The numbers in parentheses show t-statistics, calculated using Newey and West (1987) standard errors with the number of lags determined according to Newey and West (1994).

At the one-month maturity, the return is less than one basis point p.a. on average, with the single exception being the one-month CHF OIS, whose average excess return is 1.53 basis points. The returns are economically insignificant, and the apparent statistical significance of the returns on the one-month AUD swap is misleading: the underlying rate for this OIS is effectively the Cash Rate set by the Reserve Bank of Australia that is held constant for prolonged periods of time, which results in the low variance of the underlying, the low standard error of the mean and consequently the inflated *t*-statistic. For maturities higher than one month, the excess return is most pronounced for the Swiss franc swaps: from 5.88 basis points for the maturity of 3 months to 26.56 basis points for the twelve months maturity. For the US dollar swaps, the excess returns are several times smaller than those documented by Piazzesi and Swanson (2008) for federal funds futures over 1984-2005. For example, they report ”unannualized”[10] excess returns of 2.9, 10.5, and 30.7 basis points for one-, three-, and six-months futures, all statistically significant at 1% level. Standard deviation of OIS excess returns ranges from less than two basis points for Japan to 18.7 basis points for Switzerland at one month maturity and increases with maturity of the swaps for all currencies to as much as 60.4 basis points p.a. for a one-year NZD swap. In general, the distribution of excess

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[10] It is difficult to directly compare excess returns on federal funds futures and OIS beyond the one-month maturity, since payoff of the former for any maturity is determined by annualized effective federal funds rate as reported by the Federal Reserve Bank of New York. A closer counterpart would be one-month OIS with forward start, which lie beyond the scope of this paper.

Table 3.2: **Excess returns of an OIS fixed rate receiver.**

		AUD	CAD	CHF	EUR	GBP	JPY	NZD	SEK	USD
1M	mean	−0.92	−0.07	1.53	0.72	0.83	0.28	0.27	0.54	0.93
	(t)	(−2.44)	(−0.27)	(0.98)	(0.69)	(0.42)	(1.54)	(0.94)	(0.44)	(0.94)
	std.	5.28	5.08	18.70	7.99	12.09	1.92	4.81	10.11	7.44
	5%	−8.85	−6.06	−11.25	−10.07	−15.41	−1.51	−5.07	−8.49	−4.05
	50%	−0.54	−0.07	−0.41	0.29	−0.14	0.06	0.00	0.32	0.03
	95%	5.75	4.45	18.73	13.12	21.68	2.69	7.90	10.78	5.83
3M	mean	−2.55	0.72	5.88	2.83	3.11	0.66	1.52	2.39	3.21
	(t)	(−1.20)	(0.80)	(1.96)	(1.03)	(0.49)	(1.14)	(0.82)	(1.10)	(0.75)
	std.	13.81	7.83	27.86	12.21	18.58	3.30	12.14	16.32	14.51
	5%	−24.04	−10.11	−11.63	−9.83	−10.48	−2.57	−12.68	−11.83	−5.94
	50%	−1.62	−0.28	1.06	0.57	−0.09	0.17	−0.02	0.11	0.45
	95%	13.42	14.03	34.84	23.96	21.18	6.31	20.27	19.95	20.45
6M	mean	−2.75	4.63	13.19	7.18	7.67	1.22	4.65	6.36	7.56
	(t)	(−1.28)	(3.29)	(6.67)	(0.85)	(0.50)	(0.98)	(0.60)	(1.01)	(0.79)
	std.	28.99	17.90	40.94	23.30	33.32	5.47	27.92	28.55	25.17
	5%	−39.09	−16.96	−13.23	−16.96	−12.92	−4.93	−24.70	−19.58	−13.53
	50%	−3.73	0.26	3.67	2.78	0.49	0.26	0.42	1.26	1.60
	95%	26.91	39.80	73.59	44.20	45.89	12.94	43.81	31.88	56.00
9M	mean	−0.79	9.76	20.52	12.91	13.72	2.14	9.41	12.21	12.96
	(t)	(−0.06)	(3.37)	(4.38)	(0.95)	(0.59)	(1.23)	(0.78)	(0.66)	(0.93)
	std.	42.61	27.51	47.12	33.99	46.17	7.53	44.44	41.90	36.06
	5%	−51.14	−21.64	−16.38	−18.72	−20.92	−6.62	−35.97	−27.63	−24.65
	50%	−5.59	3.04	6.62	5.64	3.25	0.57	0.85	3.92	4.25
	95%	49.95	62.13	112.25	63.31	69.76	20.08	86.35	63.02	107.79
1Y	mean	3.19	18.33	26.56	19.87	20.96	3.51	15.60	19.40	19.86
	(t)	(0.17)	(1.69)	(2.82)	(1.10)	(0.75)	(1.32)	(0.51)	(0.73)	(0.96)
	std.	55.17	36.77	49.67	43.28	56.95	9.18	60.43	53.07	48.22
	5%	−57.44	−19.31	−18.81	−21.62	−31.00	−5.06	−47.14	−28.14	−37.51
	50%	−4.79	7.51	11.51	9.72	9.07	1.34	2.52	7.89	7.10
	95%	83.89	90.95	131.89	85.36	107.42	26.54	130.50	100.94	144.65

The table presents descriptive statistics of returns on receiving the fixed and paying the floating leg of an OIS on currency *i* (columns) with maturity *m* (rows), ranging from one month to one year. For each day when the fixed leg rate of an OIS is available, we establish the lifetime of the swap and calculate its future floating leg return, depending on particular contract specifications for each currency (see Table 3.1). We then subtract the realized floating leg return from that of the fixed leg, and report the sample average, standard deviation, median, and 5th and 95th percentiles of the empirical distribution in basis points p.a. The *t*-statistics of means (in parentheses) are calculated using Newey and West (1987) standard errors with the number of lags determined according to Newey and West (1994). The sample start for each currency is reported in Table 3.1. The sample ends in June 2017.

returns tends to be rather tight at low maturities. [11]

Overall, although the excess returns increase on average with maturity they are either economically or statistically insignificant (or both), with an exception of the Swiss franc swaps.

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[11] For the Sterling OIS of short maturities the relatively high standard deviation estimate is almost entirely due to the pre-March 14, 2005 period. On this day the Bank of England narrowed the rate corridor on its deposit and lending facilities from +/-100 to +/-25 basis points around the Bank Rate, thus significantly reducing the volatility in the SONIA rate.

3.2.3 OIS underlying rates and central bank policy rates

The underlying rates of OIS contracts on a number of currencies such as the Australian, New Zealand and US dollars coincide with the target rates of the respective central banks. Given the insignificant risk premium documented in the previous section, a natural question arises whether OIS rates can provide an insight into the market expectations of the future course of monetary policy in different countries. Under the "future course of monetary policy" we understand the *target rate compounded overnight* over the lifetime of the swap, akin to the OIS floating leg return, and not the *level of the target rate*.

We start with a simple conjecture: if OIS rates are unbiased predictors of future compound target rates, there should be no difference between indexing the floating leg with the real underlying rate or the central bank target rate. We collect data on target rates for all countries in Table 3.1 except for Japan.[12] The data comes from the central banks' web pages. For each currency, the first three columns in Table 3.3 report the corresponding monetary authority and the target interest rate. In the countries where the central bank targets a range such as the US or Switzerland, we set the corresponding target rate to the band midpoint.

Table 3.3: **Central Banks' Policy Meetings Summary**

Currency	Monetary Authority	Target Rate	Events	Hikes (unscheduled)	Cuts
AUD	Reserve Bank of Australia	Cash Rate	173 (0)	19 (0)	20 (0)
CAD	Bank of Canada	Target for the Overnight Rate	122 (1)	17 (0)	17 (1)
CHF	Swiss National Bank	3-month CHF LIBOR	79 (11)	10 (1)	15 (10)
EUR	European Central Bank	Main Refinancing Operation Rate	225 (1)	17 (0)	22 (1)
GBP	Bank of England	Bank Rate	197 (0)	10 (0)	20 (0)
NZD	Reserve Bank of New Zealand	Official Cash Rate	117 (0)	19 (0)	18 (0)
SEK	Riksbank	Repo Rate	82 (2)	20 (0)	18 (2)
USD	Federal Reserve System	Federal Funds Rate	130 (5)	21 (0)	13 (2)

This table summarizes target rate announcements across currencies. The first three columns report currencies, corresponding monetary authorities and the target rates. The last three columns contain the total number of monetary policy meetings, and the numbers of hikes and cuts, with values inside parentheses showing meetings that occurred outside meeting calendars. For each currency the sample starts once the OIS data is available (see Table 3.1) and ends in June 2017.

Panel A of Table 3.4 reports the excess returns (in basis points p.a.) of receiving the

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[12] We exclude Japan since the Bank of Japan has been using various monetary policy instruments over the past two decades. So for instance, on March 19th 2001 the Bank of Japan changed its operating target from the overnight call rate (MUTAN) to current accounts of Japanese banks at the Bank. The interest rate targeting was restored for the period from March 2006 to April 2013, with average rate being targeted until October 2010, and a band being set thereafter. On April 2013 the Bank of Japan began targeting monetary base. In 2016 the Bank introduced negative interest rates on the current accounts and started to implement the "yield curve control". Also see Kuttner (2014) for a thorough overview of Japan's monetary policy from 1980 to 2012.

fixed and paying the floating leg of an OIS on different currencies (in columns) for maturities ranging from one month to one year (in rows), with the floating leg being indexed by the target rate set by the monetary authority of the corresponding country. The average excess return is computed for each day when the fixed leg rate of an OIS is available, by first, determining the lifetime of the contract according to the contract specification of each currency (see Table 3.1), second, subtracting the realized floating leg return from that of the fixed leg, and third, taking the sample average. Panel B reports the average difference between the excess returns on the OIS with overnight- and the target rate-indexed floating legs, or effectively the difference between the floating leg return indexed by the target and overnight rates. The numbers in parentheses are the *t*-statistics calculated using the HAC estimator of Newey and West (1987) with optimal number of lags according to Newey and West (1994). For each currency the sample starts with availability of the corresponding OIS data as specified in Table 3.1 and ends in June 2017.

For the Australian, Canadian, and US dollars the risk premium estimates of target rate-indexed floating leg OIS deviate from their overnight rate-indexed counterparts by a fraction of a basis point for any maturity, and for the New Zealand dollar[13] the premium is exactly the same. For the euro, British pound, Swedish krona, and Swiss franc the discrepancies between the compound overnight and target rates indexing are more pronounced, but either economically or statistically insignificant, except for the Swiss franc.

What might be the cause of the discrepancies? For the first three of the four latter currencies the target rates are repo rates, whereas the OIS underlying rates are unsecured money market rates, so discrepancies are expected due to the credit and liquidity risks and/or limited access of market participants to the unsecured credit market, accessible by the banks domiciled in the corresponding currency area only, in addition to other institutional characteristics. For example, the negative difference between the target and overnight rates for Swedish krona in Panel B of Table 3.4 means that, on average, the STIBOR compounded over maturities from one month to one year exceeded Riksbank's repo rate by around eight and a half basis points.[14] Similarly, SONIA was below the Bank of England's bank rate by four and a half basis points.[15] For the euro

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[13] We find a single data discrepancy for New Zealand: Bloomberg reports the jump in the underlying rate on April 28th 2004, while the Reserve Bank of New Zealand reports the change in its official cash rate on April 29th. We choose the latter data point over the former.

[14] Although being able to keep the overnight rate stable at the target rate, the Riksbank has no direct way to steer the tomorrow/next rate underlying the SEK OIS. As a result the kronor tomorrow/next market experienced periods of elevated volatility in 2008 and during the phase-out of extraordinary monetary policy measures in 2010 (Riksbank (2014)). Which together with constant spread of 10 basis points over the target rate results in the OIS forecasts being contaminated both with constant and time-varying risk premiums.

[15] The Bank of England's Sterling Monetary Framework explicitly states its objective to keep both unsecured and secured market rates in line with the Bank Rate. BoE (2017) points out that the persistent gap of four to five basis points between SONIA and the Bank Rate over the recent years is likely due to

Table 3.4: **OIS underlying rates vs. central bank target rates.**

	AUD	CAD	CHF	EUR	GBP	NZD	SEK	USD
Panel A: OIS excess returns, floating leg indexed by target rates (t-statistics)								
1M	−0.95	−0.01	−11.46	−15.61	−3.77	0.28	8.59	0.60
	(−2.52)	(−0.05)	(−4.60)	(−1.33)	(−5.09)	(0.94)	(5.57)	(0.94)
3M	−2.57	0.74	−8.64	−13.56	−1.41	1.52	10.68	2.85
	(−1.21)	(0.81)	(−1.26)	(−1.03)	(−0.41)	(0.82)	(4.26)	(1.67)
6M	−2.77	4.63	−3.80	−9.32	3.25	4.65	14.86	7.16
	(−1.29)	(3.26)	(−1.93)	(−0.59)	(0.29)	(0.60)	(2.24)	(1.09)
9M	−0.81	9.74	2.17	−3.71	9.40	9.41	20.99	12.53
	(−0.06)	(3.34)	(0.63)	(−0.21)	(0.48)	(0.78)	(1.10)	(1.05)
1Y	3.18	18.48	9.00	3.10	16.75	15.60	28.33	19.39
	(0.17)	(1.72)	(0.78)	(0.15)	(0.68)	(0.51)	(1.05)	(1.09)
Panel B: Overnihgt vs. target rate floating leg indexing (t-statistics)								
1M	0.03	−0.05	12.86	16.21	4.61	0.00	−8.05	0.33
	(1.26)	(−0.06)	(2.68)	(0.44)	(1.40)		(−0.78)	(0.04)
3M	0.03	−0.02	14.45	16.27	4.52	0.00	−8.29	0.36
	(1.95)	(−0.03)	(3.63)	(0.15)	(1.01)		(−0.13)	(0.02)
6M	0.02	−0.01	17.07	16.39	4.41	0.00	−8.50	0.39
	(4.98)	(−0.01)	(4.40)	(0.22)	(0.66)		(−0.14)	(0.01)
9M	0.02	0.01	18.35	16.49	4.32	0.00	−8.78	0.43
	(5.12)	(0.01)	(5.03)	(0.22)	(0.96)		(−0.45)	(0.01)
1Y	0.01	−0.16	17.56	16.64	4.21	0.00	−8.94	0.47
	(5.31)	(−0.08)	(4.61)	(0.22)	(1.00)		(−0.62)	(0.01)
Panel C: Regression of overnight on target rates								
α	−0.02	0.47	−4.64	−38.31	−5.18	0.00	1.79	−0.18
(s.e.)	(0.02)	(0.19)	(2.33)	(2.96)	(0.57)		(0.75)	(0.76)
β	1.00	1.00	0.89	1.12	1.01	1.00	1.05	1.00
(s.e.)	(0.00)	(0.00)	(0.02)	(0.01)	(0.00)		(0.01)	(0.00)
$\chi^2(2)$	7.68	7.32	58.60	183.82	98.93		232.24	1.37
(p-value)	(0.02)	(0.03)	(0.00)	(0.00)	(0.00)		(0.00)	(0.50)

Panel A of this table presents the average excess returns, in basis points p.a., of receiving the fixed and paying the floating leg of an OIS on currencies (in columns) for maturities ranging from one month to one year (in rows), with the floating leg being indexed by the target rate set by the monetary authority of the corresponding country. The average excess return is computed for each day when the fixed leg rate of an OIS is available, by first, determining the lifetime of the contract according to the contract specification of each currency (see Table 3.1), second, subtracting the realized floating leg return from the fixed leg return, and third, taking the sample average. Panel B reports the average difference between the excess returns on the OIS with overnight- and target rate-indexed floating legs, or effectively the difference between the floating leg return indexed by the target and overnight rates. Panel C reports the intercept (in basis points p.a.) and slope estimates from the regression of overnight rates on target rates $r_{on,t} = \alpha + \beta r_{tgt,t} + \varepsilon_t$. The last two rows of Panel C report χ^2 statistic and p-value for the joint test of zero intercept and unit slope. The numbers in parentheses are the t-statistics (Panels A and B), standard errors and p-values (Panel C), all calculated using the HAC estimator of Newey and West (1987) with optimal number of lags according to Newey and West (1994). For each currency the sample starts with availability of the corresponding OIS data as specified in Table 3.1 and ends in June 2017.

the positive difference between the average compounded rates is caused by the fact that since 2009 the overnight unsecured rate was stuck at the level of ECB's deposit rate[16] – before that, it closely followed the refinancing rate which we use as the target rate in this study, and was, on average, slightly above the refinancing rate similarly to Sweden.[17,18] The Swiss franc is the notable exception among other currencies. The Swiss National Bank sets a target range for the three month CHF LIBOR without an explicit concern for the overnight money market. Besides the maturity mismatch between the CHF OIS underlying and the central bank's target, SNB explicitly stated its desire to keep the LIBOR rate at the lower bottom of the target range after 2009, thus pushing the unsecured overnight lending rate further downwards, which results in the observed significant positive difference. Nevertheless, the CHF OIS fixed rate predicts the compound future SNB target rate rather accurately slightly underestimating it for lower forecast horizons which is justified by the LIBOR-OIS spread.

To sum up, OIS fixed rates capture the future target rates of the corresponding central banks, being more accurate predictors of the future course of monetary policy when central banks directly target overnight money markets. Yet, as we discuss above, when the target and market rates differ, the institutional characteristics of the monetary policy framework and/or risk premia limit the OIS ability to produce unbiased forecasts of the future compounded target rate. Although the discrepancies between the underlying and target rates are *unconditionally* small in magnitude, do not vary much across swap maturities, and rarely statistically significant, the necessary adjustments should be made in practical applications on country-by-country basis.

Given that the OIS prices themselves bear no significant risk premium, an alternative approach to demonstrate that OIS rates predict future target rates is to show that the underlying rates of the former closely follow the latter. The right hand side of the OIS pricing equation (3.1) implies that if these rates are same, the OIS fixed rates are also unbiased forecasts of the compound target rate, which is the exact case for New Zealand. On the other hand if the underlying rate fluctuates around the target (as in the

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lenders without access to reserves accounts at BoE willing to accept lower rates, and unwillingness of reserves account holders to arbitrage the difference away due to higher leverage to be reported.

[16] Main refinancing operations refer to (reverse) REPO transactions through which the ECB provides the bulk of liquidity to the banks of the Eurosystem. Although the refinancing operations normally have maturity of one week, the main refinancing rate is effectively capped (floored) by the overnight rates on the standing lending (deposit) facilities.

[17] In October 2008 the ECB introduced the fixed-rate full allotment policy effectively providing unlimited amounts of liquidity against eligible collateral at the main refinancing rate, the subsequent expansion of excess reserves, that are remunerated at the rate on the deposit facility, drove the market rates toward the rate on the facility.

[18] In contrast to the ECB, the Riksbank uses the same repo rate not only to provide liquidity to the banking system via repo but also to withdraw it by issuing Riksbank certificates, typically, with maturity of one week. More importantly, in order to stabilize the overnight market rate around the target the Riksbank offers overnight credit or deposits at the repo rate +/- 10 basis points (also known as the fine-tuning transactions) depending on whether the entire system is in deficit or surplus respectively. See Riksbank (2014) for additional institutional details on the monetary policy implementation in Sweden.

US), being the same on average and comoving with the target rate in lockstep – that is, if regression of one rate on another produces zero intercept and unit slope coefficients – the result would depend on the variance of the deviations due to the Jensen's term.

Panel C of Table 3.4 reports the intercept (in basis points p.a.) and slope estimates from regression of overnight on target rates $r_{on,t} = \alpha + \beta r_{tgt,t} + \varepsilon_t$. The last two rows of Panel C report χ^2 statistic and the p-value for the joint test of zero intercept and unit slope. Computation of standard errors and test statistics as well as the sample are the same as in the upper panels of the table.

The regression estimates in the Panel C of Table 3.4 further corroborate the results discussed earlier in this section. The slope estimates are one and the intercept estimates are close to zero for the Australian, Canadian, New Zealand and US dollars. For the British pound and Swedish krona the slopes are close to one and intercepts indicate that the overnight rates are slightly higher and lower than the corresponding targets respectively, though in economic terms the differences are negligible. For the euro the estimates reflect the situation where the overnight rate was stuck at the lower bound set by the ECB's deposit rate since 2009 remaining below the main refinancing rate (negative intercept) and not responding to the cuts in this rate in 2013 and 2014, when the deposit rate was set at zero (estimated slope grater than one). Furthermore, each regression in Panel C produces R^2 of over 99%, meaning that the nonlinearity in the OIS payoff is unlikely to have any sizable impact.

Overall, OIS rates are capable of accurately reflecting the future path of monetary policy measured by the central bank target rates compounded over the OIS lifetimes. Moreover, our inference in this section is likely to be conservative in the sense of over-rejecting the null of zero risk premium: since our returns are overlapping, Hodrick (1992) standard errors would be more restrictive. However, given the small economic magnitude of the risk premium estimates achieving statistical significance, we deem this exercise to be excessive.

3.3 OIS-Implied Rates and Outcomes of Monetary Policy Meetings

Under certain assumptions, it is possible to extract the underlying rate that the OIS market participants expect to prevail after a certain date within the lifetime of a contract. The assumptions have to do with the Jensen's inequality and the relation between the risk-neutral and natural measures. An additional assumption about the relation between the underlying and the target rate changes allows to extract the expected policy rate several days ahead of monetary policy announcements. These OIS-implied expectations have substantial power to predictively classify upcoming announcements into hikes, cuts and no-change decisions, on par with the federal funds futures in the US.

3.3.1 Recovering expected target rate changes

Consider the risk-neutral pricing formula in equation (3.1) and let the fixing rate of the floating leg be possibly subject to change on a predetermined day $s^* \in S_{m,t}$. We will refer to s^* as the "event" or "announcement".[19] That said, equation (3.1) can be restated as the product of the accrued floating rates before and after s^*:

$$W_{m,t} = \mathrm{E}_t \left[\prod_{s<s^*} (1 + r_s \delta_s) \prod_{s \geq s^*} (1 + r_s \delta_s) \right], \tag{3.3}$$

The following assumption will allow to isolate the post-event part of the floating leg rate by swapping (no pun implied) the expectation and product operators.

Assumption 1. *The Jensen's inequality holds as equality with accuracy sufficient for the practical purposes.*

In this case, we can express equation (3.3) as follows:

$$W_{m,t} = \prod_{s<s^*} (1 + \underbrace{\mathrm{E}_t \left[r_s \right]}_{\bar{r}_t} \delta_s) \prod_{s \geq s^*} (1 + \underbrace{\mathrm{E}_t \left[r_s \right]}_{\bar{r}_t^*} \delta_s), \tag{3.4}$$

where $\bar{r}_t$, $\bar{r}_t^*$ is the short-hand notation for expected pre- and post-announcement rates. The next assumption will allow to retain the post-announcement expected rate as the only unknown variable in (3.4).

Assumption 2. *The expected pre-announcement OIS underlying rate is known.*

A straightforward way to estimate $\bar{r}_t$ is to take the sample average of the OIS underlying rate since the last announcement. If the rate is credibly kept constant by the central bank such as in New Zealand or tends to fluctuate around a constant value from one announcement to another such as in the US, Assumption 2 holds. Now, equation (3.4) can be solved numerically for the post-announcement expected rate $\bar{r}_t^*$. Another assumption is needed to equate this risk-neutral expectation to the expectation under the natural measure.

Assumption 3. *The expectation of the underlying rate taken under the risk-neutral measure coincides with that taken under the natural measure.*

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[19] Most often, the OIS fixing rate changes in response to a target rate change several days after the announcement, because of a delay in the target rate becoming effective, quote and/or fixing lags. For example, a new target rate communicated by the Fed on Wednesday becomes effective on Thursday and is likely to affect the Thursday's effective federal funds rate (EFFR), but because of a 1-day fixing lag, the first time the new rate enters the calculations is Friday. This is known in advance to investors, and, while we honor it in the empirical part, here we neglect it for notational simplicity.

Now, the solution to equation (3.4) is the "real world" expectation of the OIS underlying rate after the upcoming announcement. The final assumption is needed to connect the OIS underlying rates to the central bank target rates.

Assumption 4. *The expected post-announcement OIS underlying rate differs from the expected pre-announcement rate by the expected target rate change.*

$$\bar{r}_t^* = \bar{r}_t + E_t\left[\Delta r_{\text{tgt}}\right], \tag{3.5}$$

where r_{tgt} *is the central bank target rate.*

In other words, the differences in the expected levels of the pre- and post-announcement OIS underlying rates must equal the expected target rate changes.

Under these assumptions, the difference between the OIS-implied rate and the expected pre-announcement rate equals the market expectation of the target rate change. Several days before each announcement, we recover the implied rate and calculate the bespoke difference:

$$\mathrm{E}_t\left[\Delta r_{\text{tgt}}\right] = \bar{r}_t^* - \bar{r}_t. \tag{3.6}$$

3.3.2 Assumptions close-up

Assumption 1 allows us to equate the expectation of the product of (gross) daily interest rates and the product of their expectations. To be able to say anything about its restrictiveness, we run a simulation exercise. In particular, we calculate the following difference, which can be recognized as the Jensen's term:

$$\mathrm{E}\left[\prod_{t=1}^{30}(1 + r_t/360)\right] - \prod_{t=1}^{30}(1 + \mathrm{E}\left[r_t/360\right]), \tag{3.7}$$

where r_t is conditionally Normally distributed and has the autocorrelation of 0.95, a value often estimated in the data:

$$r_t|\mathcal{F}_{t-1} \sim \mathcal{N}(\mu, \sigma),$$
$$\rho[r_t, r_{t-1}] = 0.95.$$

We let $\mu \in (0, 900)$ basis points p.a. and $\sigma \in (10, 100)$ basis points p.a., which subsumes the actually observed range of rate values in our sample. We proxy the left expectation in equation (3.7) by means of the sample average over 1000 simulations. In the extreme case of a 100 basis points standard deviation in the daily short rate and a mean value of 900 basis points, the Jensen's term is as small as 0.003 basis points p.a. in magnitude and hence can safely be ignored in the applications.

Assumption 3 is essentially equivalent to absence of risk premium in OIS rates. In Section 3.2.2 we demonstrated that the risk premium in the swaps is either economically or statistically insignificant (or both) for all currencies except for the Swiss franc.

Assumption 4 says that the two rates – the OIS underlying and the central bank target – are expected to move one-for-one. In the previous section we reported that the two rates closely correspond to each other in levels and move in lockstep for all currencies except for the euro and Swiss franc. However, we emphasize here that the two rates should jump by an equal amount on the announcement day without systematic errors. We test it by comparing the difference in the average post- and pre-announcement rates to the announced target rate change.

We project the underlying rate changes onto the target rate changes. Denote $\Delta\bar{r}_a = \bar{r}_a^* - \bar{r}_a$, as the change in average OIS underlying rate prevailing after ($\bar{r}_a^*$) and before ($\bar{r}_a$) the target rate announcement a, and $\Delta r_{\text{tgt},a}$ as the announced change in the target rate. If the OIS underlying rates indeed reflect the target rate, then the intercept in the regression below should be zero and the slope coefficient should be one:

$$\Delta\bar{r}_a = \alpha + \beta\Delta r_{\text{tgt},a} + \varepsilon_a,\ a \in A, \tag{3.8}$$

where A is the set of all announcements of a central bank. In other words, the underlying and target rates should move in lockstep and there should be no systematic errors. For example, if the OIS-underlying rate consistently changes less than one for with the target rate ($\beta < 1$), then the OIS-implied future rate forecasts will be biased downwards.

By the end of 2000 all major central banks adopted announcements of target interest rates on pre-scheduled dates. We collect the monetary policy announcements data for all countries in Table 3.1 except for Japan. The data comes from the web pages of the central banks. The last three columns of Table 3.3 report the total number of announcements, target rate hikes and cuts respectively. The numbers in parentheses are unscheduled policy meetings which occurred outside the pre-specified calendars. The sample for each country begins with availability of the corresponding OIS data (the last column in Table 3.1) and ends in June 2017.

One additional piece of information required to test the equivalence of changes in the OIS underlying and target rates is the effective date of the target rate change. In the following countries the target rate change becomes effective on the day of the announcement: Australia (before 2008), Canada, New Zealand, Switzerland. For Australia (after 2008), the United Kingdom and the United States, the change in the target rate comes into effect on the day following the meetings. In the Eurozone and Sweden the effective date is announced at the meeting, and is usually in a week from the announcement date.

Table 3.5 reports the estimates of regression 3.8 for target rate announcements of central banks represented by currency codes in columns. The χ^2 statistics is for the joint hypothesis of zero intercept and unit slope. The intercept is in basis points p.a. The numbers in parentheses report standard errors for coefficient estimates and p-value of the joint hypothesis, both derived using HAC estimator of Newey and West (1987) with optimal number of lags according to Newey and West (1994). For each currency sample starts with availability of the corresponding OIS data as specified in Table 3.1 and ens in June 2017.

For each currency the slope coefficients are statistically indistinguishable from one, meaning that, on average, the underlying rates move in lockstep with target rates. Furthermore, the joint hypothesis of zero slope and unit intercept can not be rejected at any conventional significance level for all currencies except for the Australian dollar, which is also the single currency with statistically significant intercept of two hundredth of a basis point. As we mentioned earlier, there is almost no inter-event variability in the AUD OIS underlying over the course of the sample. However, the underlying is the Reserve Bank of Australia's estimate of the overnight unsecured interbank rate in the domestic market and deviated by one to four basis points from the official target rate, with the bulk of deviations concentrated before 2003, which together with virtually no discrepancy between the underlying and the target in the following years leads to the inflated statistical significance.

Table 3.5: **Projection of overnight rate changes on policy rate changes.**

	AUD	CAD	CHF	EUR	GBP	NZD	SEK	USD
α	0.02	0.05	−0.49	−0.28	0.36	0.00	0.16	−0.09
(s.e.)	(0.01)	(0.09)	(1.01)	(0.45)	(0.45)		(0.45)	(0.70)
β	1.00	0.99	0.87	0.93	1.13	1.00	1.10	0.84
(s.e.)	(0.00)	(0.01)	(0.07)	(0.12)	(0.08)		(0.08)	(0.09)
$\chi^2(2)$	11.57	1.34	4.18	0.95	2.70		1.52	3.88
(p-value)	(0.00)	(0.51)	(0.12)	(0.62)	(0.26)		(0.47)	(0.14)

This table presents the intercept and slope estimates for the following regression:

$$\Delta\bar{r}_a = \alpha + \beta\Delta r_{\mathrm{tgt},a} + \varepsilon_a,\ a \in A,$$

where $\Delta\bar{r}_a$ is the change in the average OIS underlying rate prevailing after and before announcement a, $\Delta r_{\mathrm{tgt},a}$ is the respective target rate change, and A is the set of monetary policy meetings of a central bank. The regression is estimated by each central bank in the sample (represented by currencies in columns). The χ^2 statistics is for the joint hypothesis of zero intercept and unit slope. The intercept is in basis points p.a. The numbers in parentheses report standard errors for coefficient estimates and p-value of the joint hypothesis, both derived using the HAC estimator of Newey and West (1987) with optimal number of lags according to Newey and West (1994). For each currency the sample starts with availability of the corresponding OIS data as specified in Table 3.1 and ends in June 2017.

To obtain a deeper insight into the relation between the underlying rate changes and the target rate changes, in Figure 3.1 we plot the distribution of the former conditional on the latter for each currency. The target and underlying rate changes (in basis points p.a.) are along horizontal and vertical axes respectively, the average rates are computed over the inter-announcements periods. For each target rate change bracket we draw a box plot, with the box covering middle 50% of the empirical distribution, whiskers covering additional 1.5 interquartile ranges in both directions, and outliers beyond the whiskers drawn as dots. The red diamonds represent the perfect fit, as if intercept and slope were equal to zero and one for every target rate change within a bracket and the underlying moved in lockstep with the target rate. The sample is the same as in Table 3.5.

Figure 3.1 shows that the post-announcement OIS underlying rates changes are indeed concentrated around the target rate changes. For a one-to-one relation, the distribution collapses to the single point of mass coinciding with the red diamonds in the subfigures, as in the case of New Zealand and Australia. The mean underlying rate change, depicted by the solid line within the body of each box, is most close to the announced target rate change in the majority of cases, with several large deviation for a handful cuts in Switzerland.

Figure 3.1 also highlights that the deviations from the equivalence between the OIS underlying and target rate changes (in terms of unit slope point estimates) are driven by a few extreme events. For example, in the US the cut of 87.5 basis points on December 16 2008[20] is arguably the main source of the slope point estimate deviating from one, ignoring this announcement alone results in the slope estimate of 0.95. Similarly, the 50 basis point target rate hike in the Eurozone on June 6, 2000 and 100 basis point cut on November 20, 2008 in Switzerland are responsible for the deviations of the slope estimates for these countries. The same reasoning also applies to the United Kingdom, where the 150 basis point cut was announced on November 6, 2008. In Sweden the deviation is solely due to the underlying's overreaction to 50 basis points target rate cuts. Three out of five 50 basis points happened during the acute stage of the 2007-2009 financial crisis. On each of the six meetings from October 8, 2008 to Jule 2, 2009, the Riksbank announced reduction in its target rate slashing it from 4.75% to 0.25%. More importantly, at its monetary policy announcements, the Bank publishes the projected path of the policy rate, which was substantially revised downwards at each announcement during this period.[21] For the Australian, Canadian and New Zealand dollar OIS, the underlying and target rates are virtually the same.

Overall, we find empirical evidence supporting the assumptions stated at the begin-

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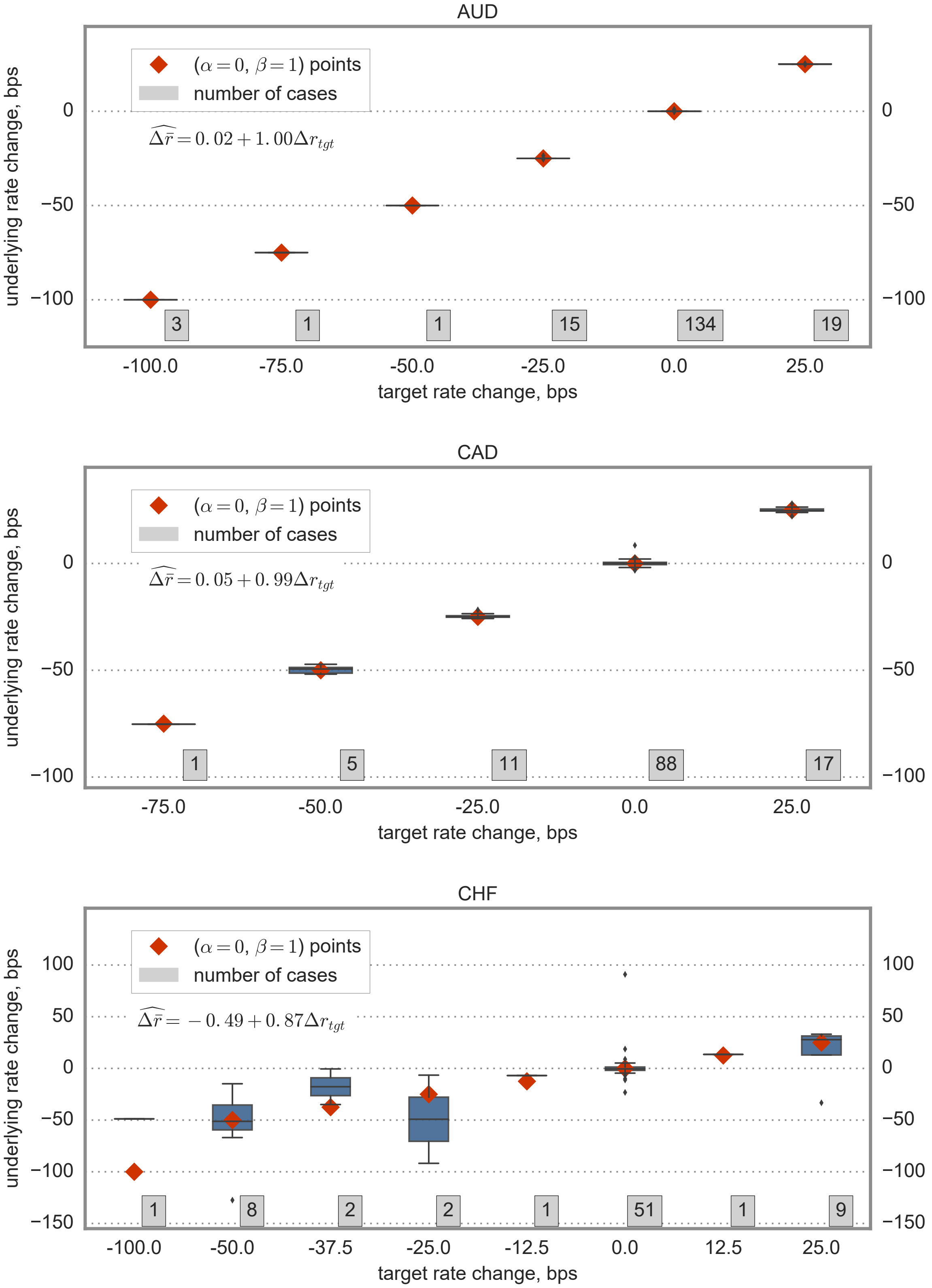
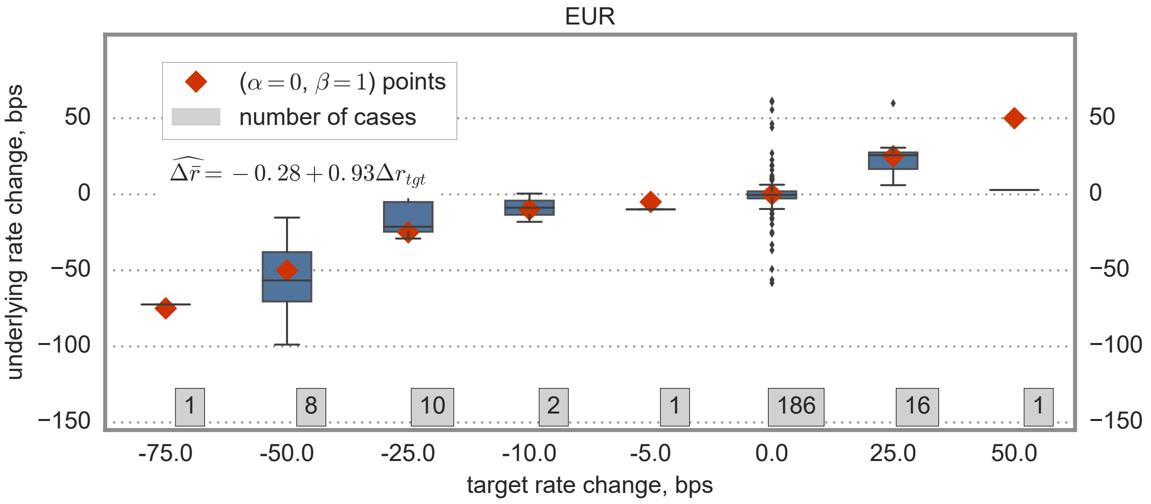
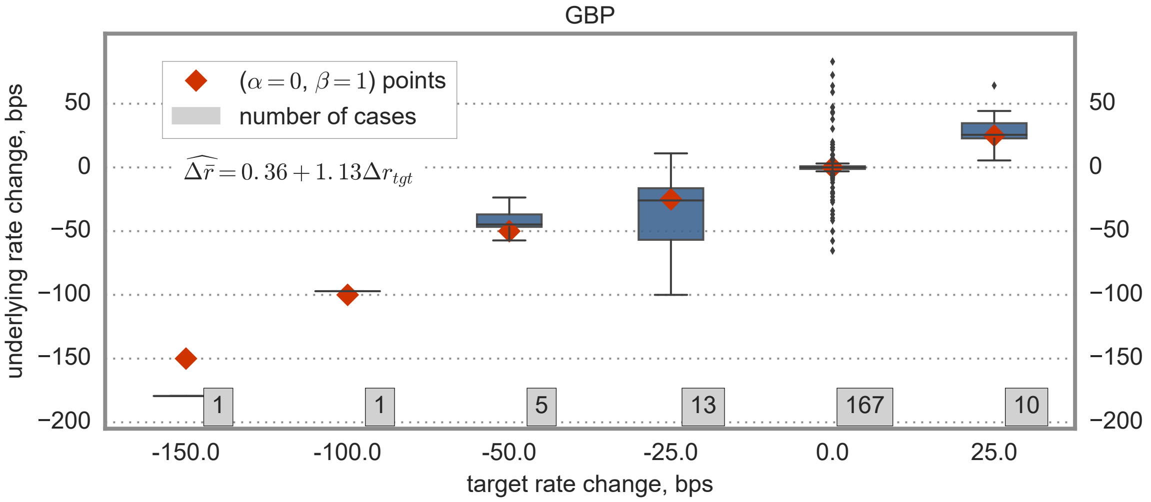
[20] On this day the Fed set the target range for the federal funds rate from zero to 25 basis points, before this date it targeted the level of the rate.

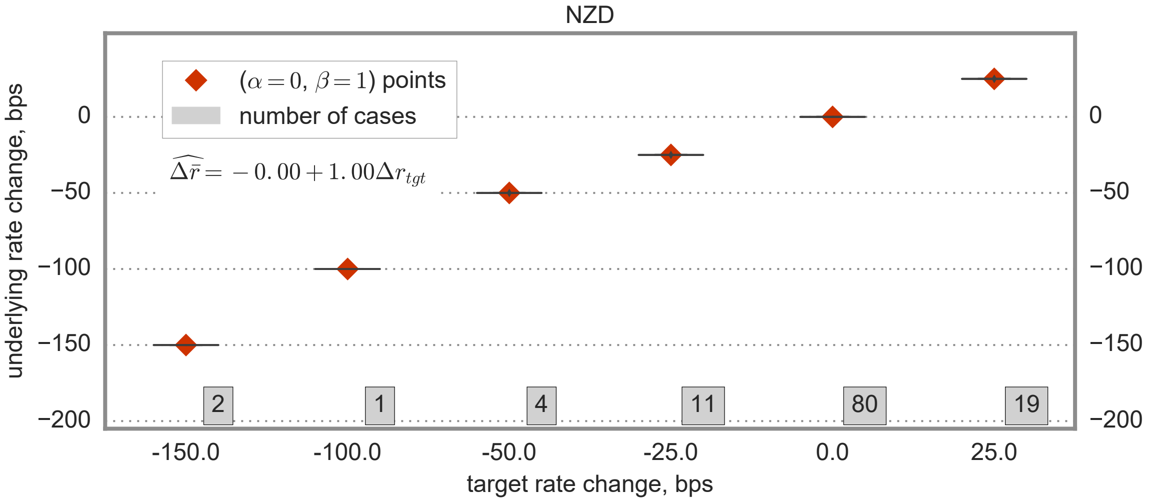
[21] Similarly, the 50 basis point cut announced on July 3, 2014 was accompanied with a significant downside revision of the projected target and followed by subsequent reductions in the target rate. The Riksbank is also quite explicit in communicating its view of the future target rate to the public: for instance in the release accompanying the October 22, 2008 cut, the Bank communicated that the rate "will need to be cut further by 0.5 percentage points" over the coming half a year.

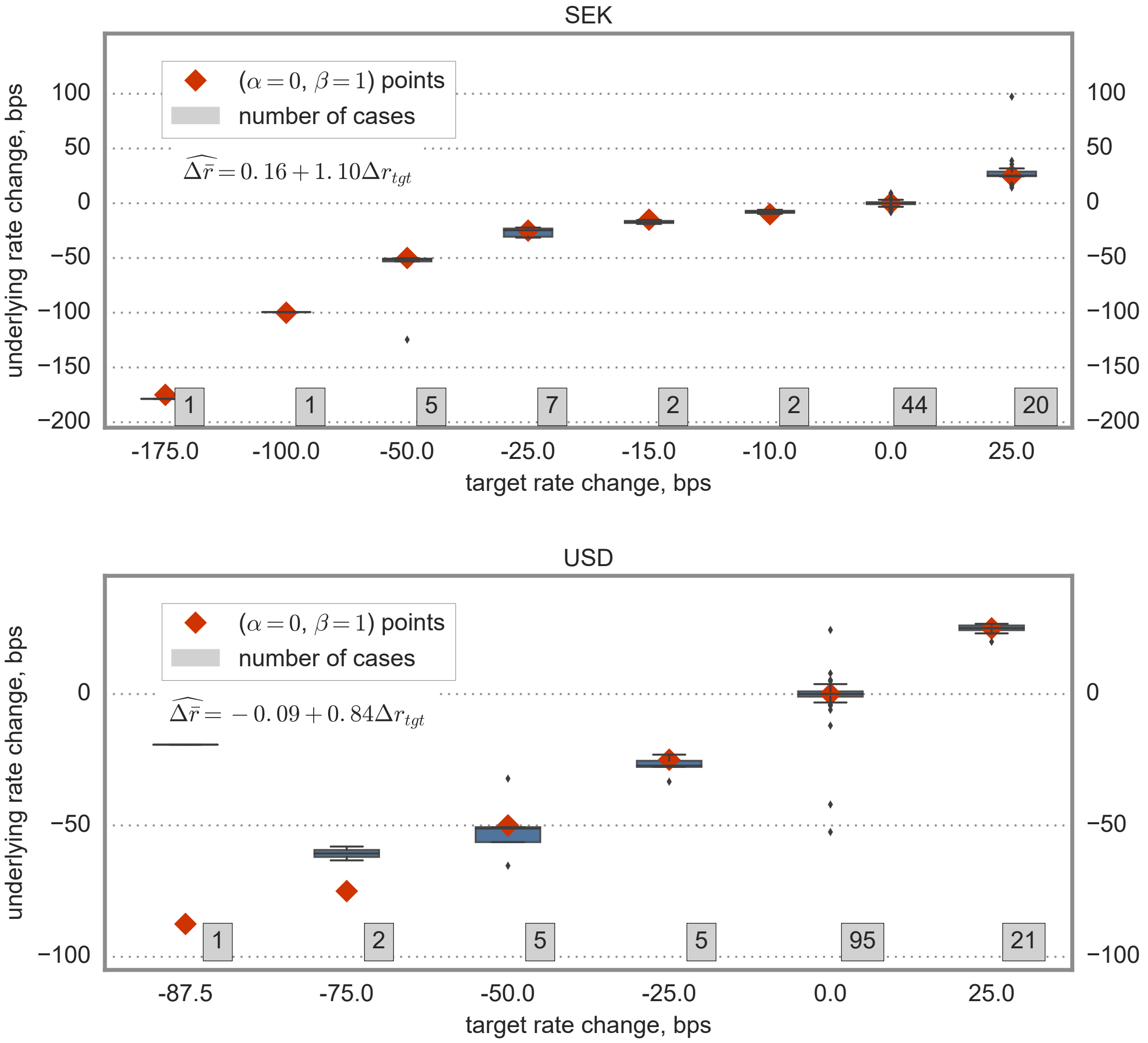
Figure 3.1: **Changes in the OIS underlying rates vs. target rate changes.**




EUR
(α = 0, β = 1) points
number of cases
$\widehat{\Delta\bar{r}} = -0.28 + 0.93\Delta r_{tgt}$
underlying rate change, bps
50
0
−50
−100
−150
1
8
10
2
1
186
16
1
-75.0
-50.0
-25.0
-10.0
-5.0
0.0
25.0
50.0
target rate change, bps


GBP
(α = 0, β = 1) points
number of cases
$\widehat{\Delta\bar{r}} = 0.36 + 1.13\Delta r_{tgt}$
underlying rate change, bps
50
0
−50
−100
−150
−200
1
1
5
13
167
10
-150.0
-100.0
-50.0
-25.0
0.0
25.0
target rate change, bps


NZD
(α = 0, β = 1) points
number of cases
$\widehat{\Delta\bar{r}} = -0.00 + 1.00\Delta r_{tgt}$
underlying rate change, bps
0
−50
−100
−150
−200
2
1
4
11
80
19
-150.0
-100.0
-50.0
-25.0
0.0
25.0
target rate change, bps



These figures present response of the OIS underlying rates to changes in the target rates of the respective central banks, conditional on the magnitude of the latter. The target rate changes are along the horizontal axis, and the changes between pre- and post-announcement averages of the OIS underlying rate are along the vertical axis. The average rates are computed over the whole period between events. All rate changes are in basis points. Each box covers the middle 50% of the distribution (between the first and the third quartiles of the dataset) while the whiskers cover additional 1.5 interquartile ranges in both directions. The outliers beyond the whiskers are shown as dots. The red diamonds represent the points of perfect fit, as if the underlying and target rates would comove perfectly. The number of observations of a certain target rate change is framed in a dark gray box in the bottom of each plot. For each currency the sample starts with availability of the corresponding OIS data as specified in Table 3.1 and ends in June 2017.

ning of this section, so the OIS-implied future rates are likely to reflect the future policy rates. Next we proceed to inferring the expected direction of upcoming target rate changes from the quantity in equation (3.6).

3.3.3 Classifying upcoming target rate decisions

Intuitively, one would expect a rate hike if the implied post-meeting OIS underlying rate exceeds the current level, a rate cut in the opposite case, and no announced change if the rates are equal. In reality, the third case almost never happens, as the implied future rates exceed or undershoot the current underlying rate levels because of noise or risk premium in the market quotes of OIS, estimation errors, failure of Assumptions 1 through 4 and other random and non-random factors. Also, target rate changes have historically been observed over a very limited set of values, most often equaled 25 basis points, and never gone below 10 basis points. That said, instead of deeming any positive (negative) difference to be a hike (cut), we choose a threshold which the difference should exceed (fall short of) to be classified as a target rate change. Following the vast statistics literature on such classification problems, we call the sign of target rate changes *response*, hikes, cuts and no-changes *classes*, and the difference between the implied and the current underlying rate *marker*. The classification rule is stated as follows:

$$\widehat{a_t} = \begin{cases} -1, & \text{if } \Delta_t \leq h^-, \\ 0, & \text{if } h^- < \Delta_t < h^+, \\ +1, & \text{if } \Delta_t \geq h^+, \end{cases}$$

where $\widehat{a_t}$ is the time t estimate of the response, and $\Delta_t = \mathrm{E}_t\left[\Delta r_{\text{tgt}}\right]$ as in equation (3.6) is the marker.

The values of h^- and h^+ are arbitrary classification thresholds. For each pair thereof, it is possible to compare the predicted target rate decisions to the actually observed ones, which is best illustrated in form of a confusion matrix such as the one in Figure 3.2.

In the two examples presented therein, we choose two different pairs of thresholds (±25 and ±10 in Panel 3.2a and Panel 3.2b respectively) to show how this choice determines the power to discriminate between different types of announcements five days in advance. In theory, for any series of recovered implied rates, there exists an infinite number of such confusion matrices, one for each possible pair of thresholds, although many of them look alike. A natural question to ask is whether one series, e.g. the rates implied in the prices of federal funds futures, results in a better marker than another, e.g. the OIS-implied rates.

To answer this question, we calculate the volume-under-the-surface (VUS) measure of classifying power, which is a three-class extension of the area-under-the-curve approach to choosing the best threshold-based classifier. As discussed in detail by Mossman (1999) and Dreiseitl et al. (2000), this measure is equal to the probability that a randomly drawn triplet of observations, one from each class, is sorted in the correct order (that is, the marker value corresponding to the actually observed cut is less than that corresponding to the no-change, and both are less than that corresponding to the hike). A non-parametric unbiased estimator of VUS is as follows:

$$VUS = \frac{1}{n_h n_c n_z} \sum_{p=1}^{n_h} \sum_{q=1}^{n_c} \sum_{m=1}^{n_z} I(x_{h,p} x_{c,q} x_{z,m}), \tag{3.9}$$

where h, c, z stand for rate hikes, cuts and no-change decisions respectively; n_h, n_c and n_z are the number of rate hikes, cuts and no-changes respectively; $x_{i,j}$ denotes j^{th} marker value from class i; $I(\cdot)$ is a function that takes value 1 if its three arguments are correctly ordered. VUS equals 1 if the classifier is perfect, i.e. if it is possible to select a pair of thresholds (h^+, h^-) such that the measurements are perfectly separated into classes, and equal to $1/6$ if the classification is done randomly, e.g. if the marker values are i.i.d. distributed across classes.

Table 3.6 presents the VUS estimates for classifiers constructed as in equation (3.6) for a number of currencies.

Table 3.6: **Forecasting power of OIS and federal funds futures.**

lag	AUD	CAD	CHF	EUR	GBP	NZD	SEK	USD	USD (FFF)
1	0.9726	0.9816	0.8071	0.8138	0.8764	0.9812	0.8479	0.9932	0.9447
2	0.9686	0.9063	0.7950	0.9291	0.8317	0.9879	0.9032	0.9980	0.9694
3	0.9643	0.9207	0.7763	0.9232	0.7912	0.9864	0.8476	1.0000	0.9890
4	0.9666	0.9195	0.7822	0.9087	0.6474	0.9795	0.8190	0.9990	0.9960
5	0.9442	0.9698	0.7566	0.8842	0.6274	0.9863	0.8090	0.9990	0.9970
6	0.9501	0.9633	0.7515	0.8449	0.6246	0.9809	0.8001	0.9978	0.9924
7	0.9387	0.9383	0.7420	0.8219	0.5778	0.9804	0.8043	1.0000	0.9918
8	0.9419	0.8828	0.6601	0.7787	0.6202	0.9848	0.7440	1.0000	0.9839
9	0.9383	0.8849	0.7127	0.7342	0.6299	0.9804	0.7266	0.9957	0.9783
10	0.9309	0.8232	0.7018	0.7928	0.6909	0.9729	0.7156	0.9753	0.9283

This table presents the volume-under-surface (VUS) values of classifiers based on the OIS-implied rates, by prediction lag (in days). On each day before an announcement, we recover the OIS underlying rate expected to prevail after it, proxy the rate expected to prevail before it as the sample average of the rates since the last announcement and calculate the difference between the two. The time-series of such differences becomes the marker for the upcoming target rate changes, and the VUS estimates thereof are obtained on the full sample of hikes, cuts and no-change decisions using eq. (3.9). The last column reports the VUS values of the classifier based on the federal funds futures-implied rates. Sample size start is different for each contract, as described in Table 3.1, the end is in June 2017.

Not surprisingly, prediction accuracy deteriorates as we move farther from announcements, although the drop is barely evident for the announcements in the countries where the best classification power is achieved: Australia, New Zealand and the US.

In the US, investors could have been able to tell upcoming hikes from cuts and no-changes almost every time since 2001. Interestingly, even in Switzerland, where the central bank target a rate most different from the OIS underlying rate, classification power is high at 0.81 immediately before announcements.

To compare the OIS-based marker to a literature staple, in the last column of the Table we show the VUS estimates of the marker constructed from the federal funds futures-implied rates. We use the standard methodology of recovering the implied rates (see Kuttner (2001) for a reference) and proxy the expected target rate change as in equation (3.6). Interestingly, OIS provide better material for predicting the course of monetary policy in the US: at every lag the OIS-implied rates dominate their federal funds futures-implied counterparts in terms of the VUS value.

Table 3.7 shows the outcome of the similar exercise with the LIBOR-implied rates. We collect the one-month LIBOR quotes from Bloomberg[22] and compute the LIBOR-implied in the same way, we compute the OIS-implied rates.

With the LIBOR rates the forecasting power in terms of VUS decreases dramatically for all currencies and forecast horizons: a randomly selected triplet of hike, cut and no change in the US target rate is correctly predicted in 43 percent of cases five days in advance of the FOMC announcements, comparing to 99.9 and 99.7 percent when using the OIS- and the federal funds futures-implied rates respectively. At the five day forecast horizon the prediction accuracy in the United Kingdom is only 15.8 percent, which is worse than a random guess – in that case one would expect to correctly classify one sixth of all triplets.

3.4 Conclusions

We study the information content of OIS rates and find them to be unbiased predictors of future compound short rates across developed countries. We document that for the overwhelming majority of currencies the prices of OIS do not bear significant risk premium. We further demonstrate that the OIS underlying rates accurately reflect the corresponding target rates set by central banks, thus providing empirical evidence favoring OIS rates as unbiased forecasts of the future target rates compounded over lifetime of the contract.

We critically assess the assumptions needed to extract the expected future policy rates from the OIS prices, finding support for their validity in the data. We find that the OIS-implied future policy rates can accurately predict the outcomes of monetary policy

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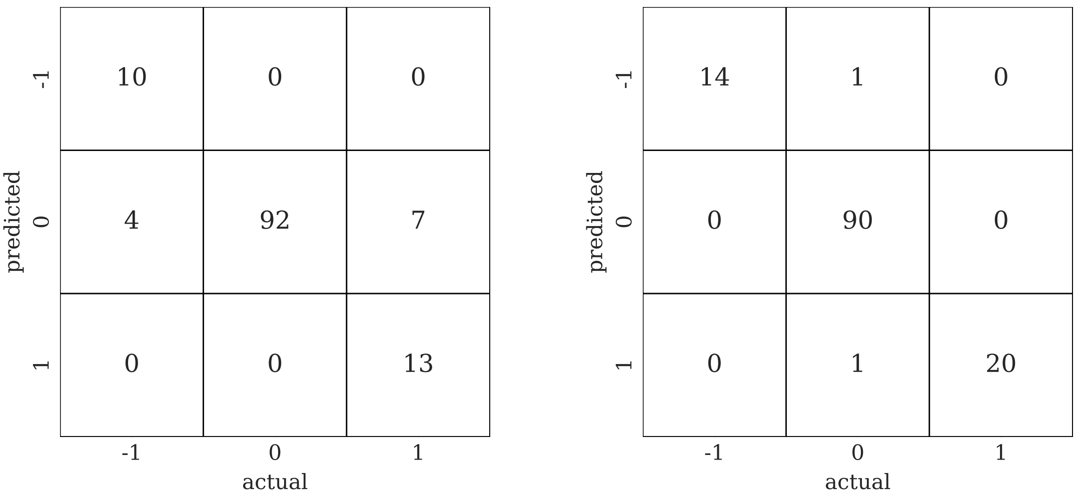
[22] After 2013 when LIBOR ceased to exist in a number of countries, we use one-month Bank Bill Swap Rate for Australia, Canadian Dollar Offered Rate for Canada, Bank Bill yields for New Zealand, and Stockholm Interbank Offered Rate for Sweden as substitutes.

Figure 3.2: **Two confusion matrices in forecasting the sign of FOMC announcements.**



(a) $h^- = h^+ = 25$ bps

predicted \ actual	-1	0	1
-1	10	0	0
0	4	92	7
1	0	0	13

(b) $h^- = h^+ = 10$ bps

predicted \ actual	-1	0	1
-1	14	1	0
0	0	90	0
1	0	1	20

Panel 3.2a (Panel 3.2b) in this figure shows the confusion matrix of the target rate change direction classifier five days ahead of announcements, with thresholds set to ±25 (±10) basis points. Entry (x, y) (x denotes rows) in the matrices shows the number of announcements of type y that were classified as type x, such as the columns sum up to the total number of announcements of each type.

Table 3.7: **Forecasting power of LIBOR rates.**

lag	AUD	CAD	CHF	EUR	GBP	NZD	SEK	USD
1	0.4980	0.3292	0.5124	0.4116	0.3089	0.5356	0.3676	0.5013
2	0.4338	0.3207	0.4526	0.4027	0.3025	0.5636	0.3581	0.4906
3	0.4054	0.3017	0.5030	0.3970	0.1896	0.5540	0.3456	0.4494
4	0.3892	0.2593	0.5124	0.3959	0.1737	0.5125	0.3234	0.4341
5	0.3702	0.2309	0.5124	0.3784	0.1576	0.4510	0.3396	0.4304
6	0.3411	0.2033	0.5308	0.3611	0.1827	0.3800	0.3330	0.3607
7	0.3149	0.1782	0.5291	0.3471	0.1945	0.3256	0.3170	0.3571
8	0.2853	0.1677	0.5047	0.3175	0.2265	0.2532	0.2961	0.3695
9	0.2717	0.1684	0.4748	0.3066	0.2296	0.2072	0.2621	0.3564
10	0.2850	0.1824	0.4171	0.2760	0.2577	0.1890	0.2392	0.3647

This table presents the volume-under-surface (*VUS*) values of classifiers based on the LIBOR-implied rates, by prediction lag (in days). At each prediction lag before an announcement, we recover the implied overnight rate expected to prevail after it, proxy the rate expected to prevail before it as the 5-day rolling average of the previous rates and calculate the difference between the two. The time-series of such differences becomes the marker for the upcoming target rate changes, and the VUS estimates thereof are obtained on the full sample of hikes, cuts and no-change decisions using eq. (3.9). Sample size start is different for each contract, as described in Table 3.1, the end is in June 2017.

meetings across the major economies.

Our findings have important implications for gauging financial markets' expectations of future policy rates. Specifically, we advocate OIS as a novel tool for evaluating the future path of monetary policy that can be used by academics, practitioners, and regulators. More importantly, we demonstrate robustness of this tool by bringing international dimension to the monetary policy prediction exercise.

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- XXVI Finance Forum Best Paper on Fixed Income for the research paper ’Monetary Policy and Currency Returns: the Foresight Saga’ (shared with Igor Pozdeev)
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