Long-Term Interest Rates, International Risk Sharing and Global Macroeconomic Spillovers*

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Abstract

This paper studies the international transmission of monetary policy among advanced economies through long-term interest rates. It presents a micro-founded, two-country model with endogenous portfolio choice amongst country-specific equity, short-term bonds, and long-term bonds. The model provides novel insights about the different roles played by short and long-term bonds in international risk sharing and the global transmission of monetary policy shocks. Short-term bonds predominantly hedge real exchange rate fluctuations that occur immediately after a macroeconomic shock, while long-term bonds mainly hedge expected inflation and expected real exchange rate movements. The model predicts that a surprise tightening of conventional US monetary policy leads to an immediate increase in long-term interest rates in the US and other advanced economies, which align with empirical results from an event study. I extend the empirical results by applying an empirical decomposition of long-term interest rates into interest rate expectations and term premia, using the method of Lloyd (2017a). I find that the spillover effects of US monetary policy are closely associated with changes in expectations: a surprise tightening of US monetary policy immediately increases investors' expectations of future short-term interest rates in the US and other advanced economies. However, term premia fall in response to the same shock, serving to attenuate global spillover effects.

JEL Codes: E43, E52, E58, F31, F32, F41, G12.

Key Words: International Risk Sharing; International Portfolios; Global Spillovers; Term Structure of Interest Rates; Yield Curve.

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1 Introduction

With short-term nominal interest rates at their effective lower bound (ELB) following the 2007-2008 financial crisis, monetary policymakers sought to stimulate economic activity, *inter alia*, by reducing longer-term interest rates with 'unconventional' monetary policies. Although these policies have had domestic effects (see Lloyd, 2017c, and the references within), they have also drawn attention to the global implications of long-term interest rate movements (Fratzscher, Lo Duca, and Straub, 2016). Understanding the role of long-term interest rates in the global transmission of shocks is the primary subject of this paper. Specifically, I ask: to what extent, and through which mechanisms, does conventional US monetary policy spill over to other advanced economies through longer-term interest rates?

This is an important question in light of recent evidence suggesting that the Mundellian trilemma — which states that it is impossible for an open economy to simultaneously have a fixed exchange rate, free international capital movement and independent monetary policy — is, in fact, a dilemma — a choice between independent monetary policy and free capital mobility (Rey, 2014). Advanced economies with floating exchange rates are exposed to US monetary policy through its influence on the 'global financial cycle', which describes the strong correlation between financial market prices and international capital flows (Passari and Rey, 2015). Although recent work has shown US monetary policy to influence the global financial cycle (e.g. Miranda-Agrippino and Rey, 2015; Dedola, Rivolta, and Stracca, 2016; Rey, 2016), further research is required to understand the channels through which US monetary policy exerts international spillover effects. In this paper, I assess the extent to which US monetary policy has global spillover effects through its influence on global bond markets and the term structure of interest rates in other advanced economies.

I draw on a canonical decomposition of longer-term interest rates into expectations of future short-term interest rates and term premia. Movements in long-term interest rates that emanate from changes in expected future short-term interest rates are associated with revisions of investors' expectations of the future monetary policy stance. In contrast, changes in term premia, which reflect the compensation investors demand for taking on risk, are linked to risk-pricing and portfolio rebalancing. This decomposition is salient because the two sub-components have differing policy implications. If US monetary policy predominantly exerts spillover effects through changes in expected future short-term interest rates, monetary policymakers in other advanced economies may attenuate these effects by clearly communicating their future policy intentions through policies such as forward guidance. In contrast, spillover effects that work through term premia motivate a careful focus on international capital flows and risk premia.

I study the international transmission of US monetary policy shocks from both a theoretical and an empirical standpoint. The two-country, two-good, micro-founded model I present has three essential elements.

First, and most importantly, the model allows for endogenous portfolio choice across a range of internationally traded assets: country-specific equity, short-term bonds, and long-term bonds. To incorporate these six assets endogenously, I use the solution method for optimal asset allocation in international macroeconomic models proposed by Devereux and Sutherland (2010, 2011). Unlike existing applications of this solution algorithm, I extend it to investigate multiple bond maturities simultaneously. Within the model, the responses of interest rates to macroeconomic shocks will reflect portfolio adjustment by international investors.

Second, the model assumes that consumers have a greater preference for locally-produced goods, generating consumption home bias. This is consistent with empirical evidence that the majority of consumption consists of locally-produced goods (Kollmann, 2006). Consumption home bias implies that the real exchange rate fluctuates in response to shocks, generating an incentive for investors to take positions that hedge real exchange rate variation.

Third, the model incorporates nominal rigidities, admitting the study of monetary policy. Nominal rigidities are important for generating realistic asset positions within the model. Engel and Matsumoto (2009) show that equity home bias can arise in a two-country model with nominal rigidities because price stickiness generates a negative covariance between relative Home non-financial income (i.e. labour income) and relative Home equity returns.[1] Because of this negative correlation, Home equity provides a good hedge against non-financial income risk.[2]

The model provides two sets of novel contributions. First, because the model includes short *and* long-term bonds, it provides insights about the different roles of the two asset classes in international portfolios. In the model's equilibrium, international asset positions are a function of all sources of risk in the economy. Nevertheless, I find that short-term bond holdings predominantly insure against the immediate response of real exchange rates to macroeconomic shocks, as well as the reaction of monetary policy. For instance, following a negative Home productivity shock, the Home real exchange rate appreciates, reducing the relative return on Foreign short-term bonds in Home consumption units. In this state of nature, Home marginal utility is relatively high, so Home short-term bonds will *ex ante* provide a good hedge against this risk. Long-term bond holdings are sensitive to macroeconomic shocks that change their relative resale value, related to expected inflation and real exchange rate movements in particular. Unlike short-term bonds, Foreign long-term bonds provide a better *ex ante* hedge for negative Home productivity shocks. Following such a shock, heightened and persistent relative Home inflation will increase the relative value of Foreign long-term bonds. As in Coeurdacier and Gourinchas (2016), equity mainly insures against non-financial income risk after controlling for bond returns.

Second, the model provides insights about the international transmission of conventional US monetary policy shocks through the term structure of interest rates that align with empirical ev-

[1] In Engel and Matsumoto (2009), domestic firms who cannot cut prices following a positive Home productivity shock are forced to economise on labour, reducing relative Home non-financial income, while relative Home profits and stock returns increase.

[2] Heathcote and Perri (2013) provide an alternative explanation for equity home bias in a flexible price two-country model which includes productive capital. In their model, equity home bias can arise from the dynamics of investment. For instance, following a positive Home productivity shock, relative Home labour income increases with wages. Yet Home firms invest more, inducing a fall in the relative price of Home capital, reducing relative Home profits and relative Home equity returns. Thus, the models of both Engel and Matsumoto (2009) and Heathcote and Perri (2013) generate a negative covariance between relative earnings and relative stock returns, although the underlying mechanisms differ. In this paper, the mechanism that generates equity home bias resembles Engel and Matsumoto (2009) because I do not include capital in the model.

idence from an event study into the effects of US conventional monetary policy surprises on bond yields in other advanced economies. Within the model, a surprise tightening of US monetary policy generates an immediate increase in bond yields in the US and other advanced economies as a consequence of global portfolio rebalancing, suggesting that movements in interest rates amplify the global spillover effects of US monetary policy.

To extend the event study analysis and shed further light on the global transmission of US monetary policy, I use an empirical decomposition of long-term interest rates into interest rate expectations and term premia, using the method of Lloyd (2017a). I find that the spillover effects of US monetary policy are closely associated with changes in expectations: a surprise tightening of US monetary policy immediately increases investors' expectations of future short-term interest rates in the US and other advanced economies. However, following the same monetary policy surprise, term premia fall, especially at longer horizons, suggesting that portfolio rebalancing by investors serves to attenuate global spillover effects.

The remainder of this paper is structured as follows. After a brief review of the related literature, section 2 presents the stylised facts regarding the size and composition of bilateral international asset positions amongst advanced economies. Importantly, the model is able to account for many of these stylised facts in reasonable regions of the parameter space. The model and its solution algorithm are laid out in section 3. Section 4 presents the model calibration and discusses the role of the different assets in international risk sharing, emphasising the differences between short and long-term bonds. The global spillover effects of US monetary policy and its transmission through longer-term interest rates are discussed from both a theoretical and an empirical standpoint in section 5. Section 6 concludes.

Literature Review There has been a vast literature studying the growth in cross-border asset trade in the last three decades (e.g. Lane and Milesi-Ferretti, 2001, 2007; Coeurdacier and Rey, 2013; Gourinchas and Rey, 2014). Theoretical research has sought to understand the role different assets play in hedging different sources of risk. A long literature studying international risk sharing (e.g. Cole and Obstfeld, 1991; Backus, Kehoe, and Kydland, 1992, 1994; Stockman and Tesar, 1995; Corsetti, Dedola, and Leduc, 2008b) has provided insights about the determinants of the size of international asset positions. Recent computational advances by Devereux and Sutherland (2010, 2011) and Tille and van Wincoop (2010) have enabled a more detailed study of the *composition* of international portfolios, admitting endogenous portfolio choice amongst multiple assets. Building on this, papers have assessed the role played by country-specific equity *and* short-term bonds in international risk sharing (e.g. Devereux and Sutherland, 2008; Coeurdacier, Kollmann, and Martin, 2009, 2010; Coeurdacier and Gourinchas, 2016).[3] This paper extends on this literature by studying the role of country-specific short *and* long-term bonds, as well as country-specific equity, in order to understand the influence of international bond positions on the global financial cycle.

The primary contribution of this paper is to study the mechanisms through which US

[3]Additionally, Heathcote and Perri (2013) study an environment with country-specific equity, and Benigno and Küçük (2012) present a model with country-specific short-term bonds.

monetary policy exerts global spillover effects via long-term interest rates. As such, this paper is related to a literature studying the global financial cycle and the influence of US monetary policy on it (e.g. Rey, 2014, 2016). Passari and Rey (2015) present evidence on the existence of a global financial cycle in gross cross-border flows, asset prices and leverage, motivating research by Miranda-Agrippino and Rey (2015) documenting the effects of US monetary policy on the global financial cycle. Dedola et al. (2016) study the global macroeconomic effects of US monetary policy, emphasising the differences in transmission to advanced and emerging economies. This paper builds on this literature by studying a particular aspect of the global financial cycle for advanced economies, related to international bond portfolios and the term structure of interest rates.

Because the empirical setup is able to distinguish between two sub-components of longer-term interest rates — interest rate expectations and term premia — it can shed light on the differential roles for central bank communication and international portfolio adjustment in global macroeconomic stabilisation. The empirical results presented here rely on the overnight indexed swap (OIS) augmented Gaussian Affine Dynamic Term Structure Model (GADTSM) proposed by Lloyd (2017a), which enables the estimation of interest rate expectations and term premia at a daily frequency. The results in Lloyd (2017a), and existing applications of the OIS-augmented GADTSM (Lloyd, 2017c), pertain to the US only. This is the first paper to apply the OIS-augmented GADTSM to a broader set of countries, and is made possible because OIS rates offer a globally-comparable market-based measure of interest rate expectations in advanced economies (Lloyd, 2017b). Because this paper considers the evolution of bond yields in multiple economies, it goes some way to uncovering information about the interaction between the term structure of interest rates and exchange rates. Stavrakeva and Tang (2016) have recently empirically investigated the comovement of interest rates and exchange rates among advanced economies. They find that the relationship between short-term interest rates and exchange rate changes is primarily driven by expectations of future short-term interest rates, while the comovement of longer-term interest rates and exchange rates is more sensitive to term premia. My empirical results suggest that US monetary policy announcements influence these comovements, as I find that US monetary policy announcements have stronger effects on monetary policy expectations over shorter horizons — out to two years — but larger effects on term premia at longer horizons.

2 Stylised Facts

The theoretical model presented in section 3 has a rich financial market structure, accounting for country-specific equity, and short and long-term bonds. In this section, I present empirical evidence about the size and composition of international portfolios, motivating the need to consider this set of assets within a theoretical framework, as all play a role in international asset portfolios, and providing targets that help guide the model's calibration.

2.1 Size of International Asset Portfolios

Throughout the paper, I focus on a sub-sample of advanced economies with floating exchange rates: Australia, Canada, France, Germany, the UK, and the US. This choice is motivated by a number of factors, primary amongst which is the availability of daily frequency zero-coupon government bond yield data over a sufficiently long sample. This data is necessary in section 5 where I empirically decompose longer-term interest rates into expectations of future interest rates and term premia using the method of Lloyd (2017a). Notwithstanding this, there are economic reasons to consider this sub-sample of countries. First, these countries comprise a large fraction of international asset trade; the combined total international asset position of the six economies averaged 42% of total world international portfolio holdings over the 2001-2014 period.[4] Second, these economies individually comprise a large fraction of world international asset positions, as shown in figure 1. Here, I plot the average size of countries' international asset position as a percentage of total world portfolio investment for the 2001-2014 period for the twenty economies with the largest foreign asset portfolios, ranked in order of size. All six economies included in this study are in the world top twenty, and four of them are in the world top six.[5] Third, these six economies are not 'offshore financial centres'.[6] This is important because the international asset positions attributed to offshore financial centres are not likely to reflect the ultimate country of asset ownership.[7]

I study bilateral financial flows between these advanced economies, with the US acting as the base country in all cases.[8] This choice is motivated by the US's central role in the international financial system. The US dollar is an important funding currency for international banking and is widely used by investment fund managers. Figure 1 goes some way to illustrating the US's important role in the international financial system, showing that it accounted for almost 18% of total world foreign portfolio investment between 2001 and 2014, around 9 percentage points more than the second highest economy, the UK.

Moreover, the US is an important counterparty to cross-border asset holdings for the remaining five countries considered. US investors hold significant quantities of assets issued in Australia, Canada, France, Germany and the UK, as shown in figure 2. Here I present average total US foreign portfolio investment holdings by country of asset issuer as a percentage of US total foreign portfolio investment for the 2001-2014 period, demonstrating how exposed US asset holders are to assets issued in other world economies. The figure plots the top 20 countries ranked by size of holdings, illustrating that US holdings of foreign assets issued in the

[4] This statistic is calculated using annual data from the Coordinated Portfolio Investment Survey (CPIS) by the International Monetary Fund (IMF). See appendix A for more details on this data source.

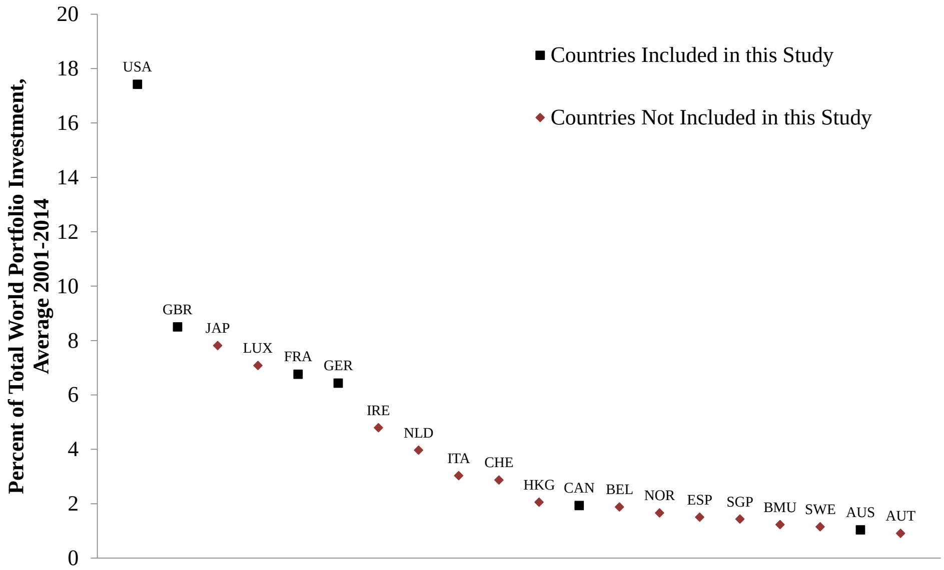
[5] Although Japan individually accounts for the third largest fraction of world asset holdings, I omit this from my study due to its unique economic conditions over the last two decades following the collapse of the Japanese asset price bubble in the 1990s.

[6] I use the IMF classification of offshore financial centres, provided in the following report: `www.imf.org/external/np/pp/eng/2008/050808.pdf`.

[7] Amongst the top twenty economies in figure 1, six are classed as offshore financial centres by the IMF: Bermuda, Hong Kong, Ireland, Luxembourg, Singapore and Switzerland. The remaining countries in figure 1 are omitted from this paper because of a lack of detailed daily frequency zero-coupon government bond yield data.

[8] In the two-country theoretical model presented in section 3, the US is the 'Foreign' country.

Figure 1: Total Foreign Portfolio Investment Holdings as a Percentage of Total World Portfolio Investment, Top 20 World Economies, Average 2001-2014

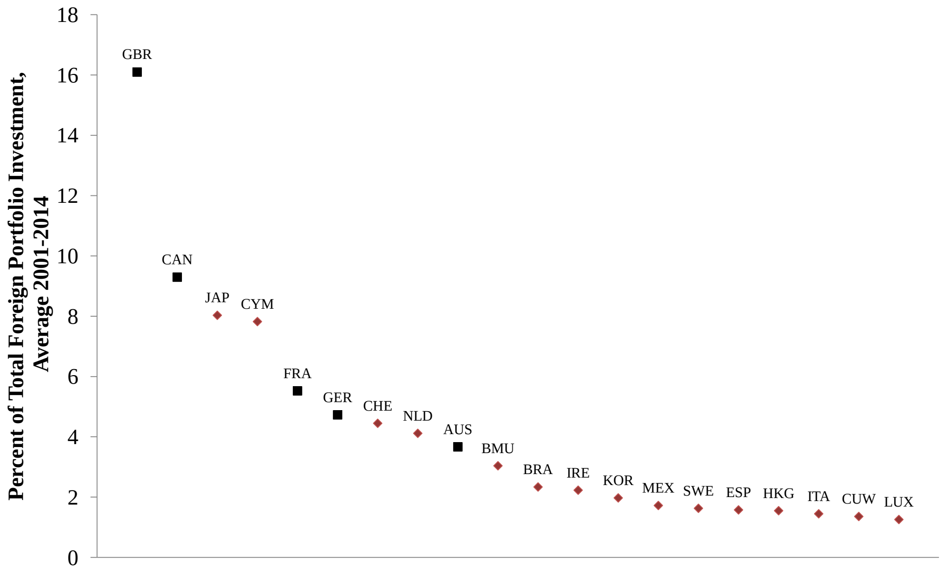


Notes: The average value of total foreign portfolio investment (holdings) for a country as a percentage of total world portfolio investment over the 2001-2014 period (annual data) for the 20 world economies with the largest foreign asset portfolios, ranked in order of size. Economies denoted with black squares are those studied in this paper — United States (USA), United Kingdom (GBR), France (FRA), Germany (GER), Canada (CAN), Australia (AUS). Economies denoted with diamonds are not included in this study, and are comprised of offshore financial centres (as defined by the IMF) — Luxembourg (LUX), Ireland (IRE), Switzerland (CHE), Hong Kong (HKG), Singapore (SGP), Bermuda (BMU) — economies lacking publicly available daily zero-coupon government bond yield data — the Netherlands (NLD), Italy (ITA), Belgium (BEL), Norway (NOR), Spain (ESP), Sweden (SWE), Austria (AUT) — and Japan (JAP), which is omitted from this study due to its unique economic conditions over the last two decades. *Data Source*: Coordinated Portfolio Investment Survey by the IMF and author's own calculations.

UK, Canada, France, Germany and Australia are amongst the top nine countries overall.

Similarly, a large fraction of foreign assets held by Australian, Canadian, French, German and UK investors are US-issued. Figure 3 plots average foreign portfolio investment holdings of Australia, Canada, France, Germany and the UK by country of asset issuer as a percentage of total foreign portfolio investment for 2001-2014, indicating how exposed investors in these countries are to assets issued elsewhere. For three out of the five countries — Australia, Canada and the UK — holdings of US-issued assets comprise the largest fraction of the total foreign asset portfolio. Moreover, their US-issued asset holdings are at least four times larger than holdings of foreign assets from the second-highest country. For these economies, the US is by far the primary counterparty in international asset trade. French and German portfolios are, unsurprisingly, more Eurozone-oriented. US-issued assets comprise the fourth and third largest shares of total international asset positions in these two countries, respectively. Nevertheless, although their foreign asset portfolios are not as concentrated towards a single country, US-

Figure 2: US Foreign Portfolio Investment Holdings by Country of Asset Issuer as a Percentage of Total US Foreign Portfolio Investment, Top 20 World Economies, Average 2001-2014



Notes: The average value of US foreign portfolio investment (holdings) by country of asset issuer as a percentage of total US foreign portfolio investment over the 2001-2014 period (annual data) for the top 20 economies ranked in order of size. Economies denoted with squares are those studied in this paper — United States (USA), United Kingdom (GBR), France (FRA), Germany (GER), Canada (CAN), Australia (AUS). Economies denoted with diamonds are excluded from this study — Japan (JAP), Cayman Islands (CYM), Switzerland (CHE), the Netherlands (NLD), Bermuda (BMU), Brazil (BRA), Ireland (IRE), Republic of Korea (KOR), Mexico (MEX), Sweden (SWE), Spain (ESP), Hong Kong (HKG), Italy (ITA), Curaçao (CUW), Luxembourg (LUX). *Data Source*: Coordinated Portfolio Investment Survey by the IMF and author's own calculations.

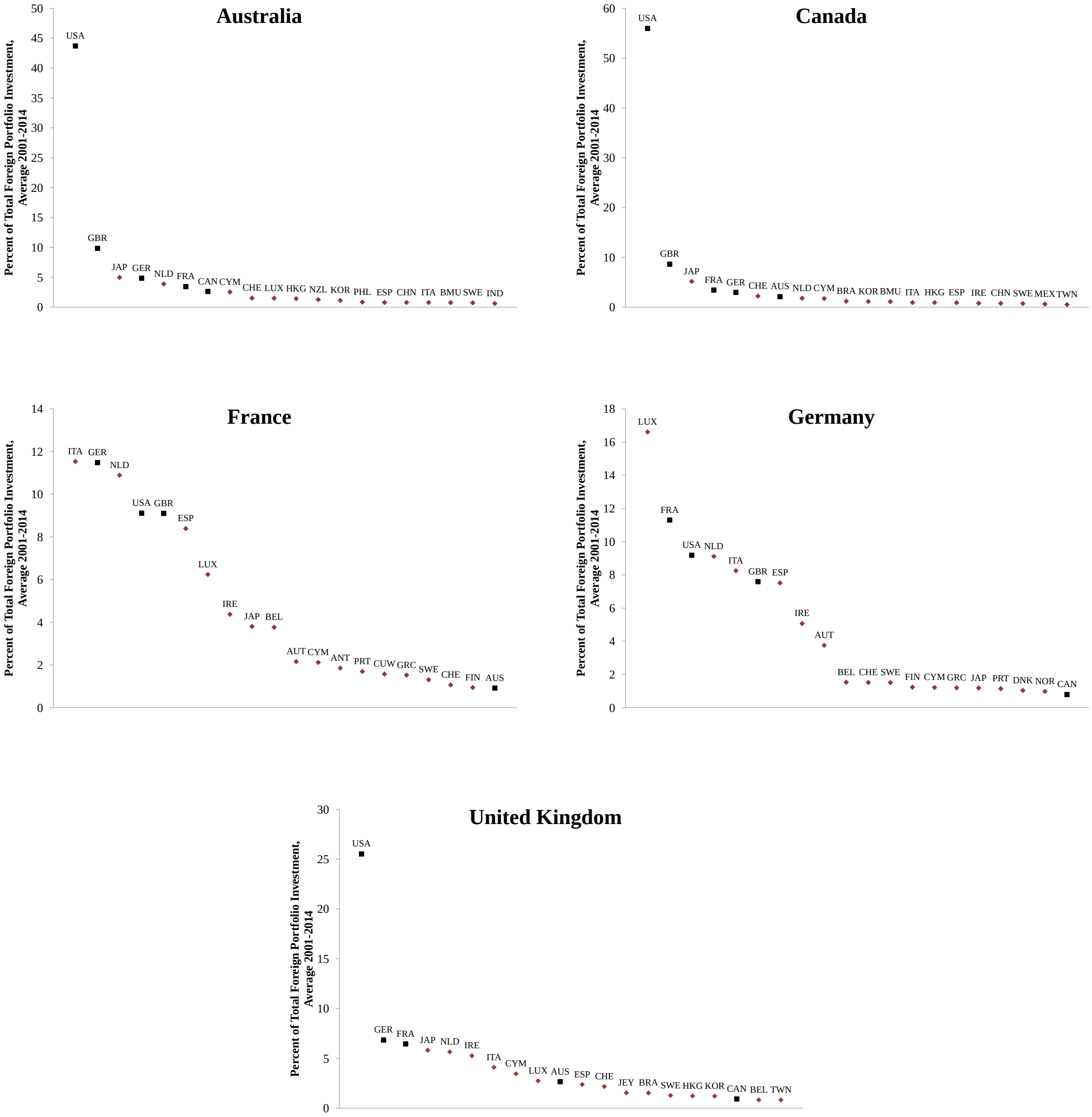
issued assets remain a sizeable fraction of their international portfolio (at least 9%).

Although the US is an important counterparty for Australia, Canada, France, Germany and the UK, figure 3 shows that a sizable quantity of bilateral portfolio investment occurs between these five countries too, further motivating the selection of these countries.

2.2 Composition of Bilateral Asset Portfolios

Although the size of cross-border financial flows is an important feature of the international financial system, the composition of cross-border flows is the primary focus of this paper. To date, empirical studies of international portfolio composition have focused on foreign currency exposure (Lane and Shambaugh, 2010a,b) and the sectoral breakdown of international asset holdings (Galstyan, Lane, Mehigan, and Mercado, 2016). In this paper, I study the composition of bilateral international asset positions by asset class.

Figure 3: Foreign Portfolio Investment Holdings by Country of Asset Issuer as a Percentage of Total Foreign Portfolio Investment for Australia, Canada, France, Germany and the United Kingdom, Top 20 World Economies, Average 2001-2014



Notes: The average value of Australian, Canadian, French, German and UK foreign portfolio investment (holdings) by country of asset issuer as a percentage of total foreign portfolio investment in each country over the 2001-2014 period (annual data). Each graph plots the top 20 economies ranked in order of size. Economies denoted with squares are those studied in this paper — United States (USA), United Kingdom (GBR), France (FRA), Germany (GER), Canada (CAN), Australia (AUS). Economies denoted with diamonds are excluded from this study — Antilles (ANT), Austria (AUT), Belgium (BEL), Bermuda (BMU), Brazil (BRA), Cayman Islands (CYM), China (CHN), Curacao (CUW), Denmark (DNK), Finland (FIN), Greece (GRC), Hong Kong (HKG), India (IND), Ireland (IRE), Italy (ITA), Japan (JAP), Jersey (JEY), Korea (KOR), Luxembourg (LUX), Mexico (MEX), Netherlands (NLD), New Zealand (NZL), Norway (NOR), Philippines (PHL), Portugal (PRT), Spain (ESP), Sweden (SWE), Switzerland (CHE), Taiwan (TWN). *Data Source*: Coordinated Portfolio Investment Survey by the IMF and author's own calculations.

Data I use data from the US Treasury International Capital (TIC) system, the US government's source on capital flows into and out of the United States.[9] I use the annual holdings data from the TIC system reported by issuers and holders of US and foreign securities. This data is collated from annual surveys at the end of June each year, beginning in 2002, which collect holdings information by individual securities for private investors and are thus considered to be highly accurate.[10] The dataset includes information on the stock of bilateral cross-border asset holdings between US residents (including US-based branches of firms headquartered in other countries) and foreign residents (including offshore branches of US firms). The dataset permits analysis along a variety of dimensions, including currency, type of foreign holder, industry of issuer, and, of particular interest in this study, country of foreign holder, security type and maturity. I exclude holdings of US-issued assets by foreign official institutions (FOIs), because the incentives for private investors for holding US-issued assets may differ from those of FOIs.

I use data on foreign holdings of US-issued equity, short-term debt and long-term debt. Equity is defined to include: common and preferred stock; all types of investment company shares, such as open and closed-end funds, money market mutual funds, and hedge funds; and interest in limited partnerships and other equity interests that may not involve stocks or shares.[11] Debt is defined to include US Treasury debt, US agency debt,[12] and corporate debt.[13]

Within the dataset, long-term debt includes all debt with *original term-to-maturity* in excess of one year, while short-term debt includes all debt with *original term-to-maturity* of one year or less. I use information on the remaining years to maturity of foreign private holdings of US long-term debt reported in the TIC data to redefine the classifications for short and long-term debt. I define long-term debt to include all debt with *remaining time-to-maturity* in excess of one year, while short-term debt includes all debt with *remaining time-to-maturity* of one year or less, to match model definitions in section 3.

Empirical Evidence The US TIC data highlights novel information about the composition of bilateral holdings of US-issued assets. Figure 4 presents the annual time series of holdings of US equity and debt as a percentage of the holding country's nominal GDP.

Figure 4 emphasises three important empirical regularities. First, all five countries hold positive quantities of all classes of US-issued assets; they do not have net short positions in US-issued equity or debt. Second, with the exception of Canada, countries' exposure to US-issued debt is roughly comparable in size to their exposure to US-issued equity. For example, in 2003, UK holdings of US-issued equity and US-issued debt were both 10% of UK GDP. This motivates the need to jointly consider the role of equity *and* bonds in international asset portfolios. Third, the majority of debt holdings are associated with long-term debt, supporting

[9] See appendix A for more details on this data source.

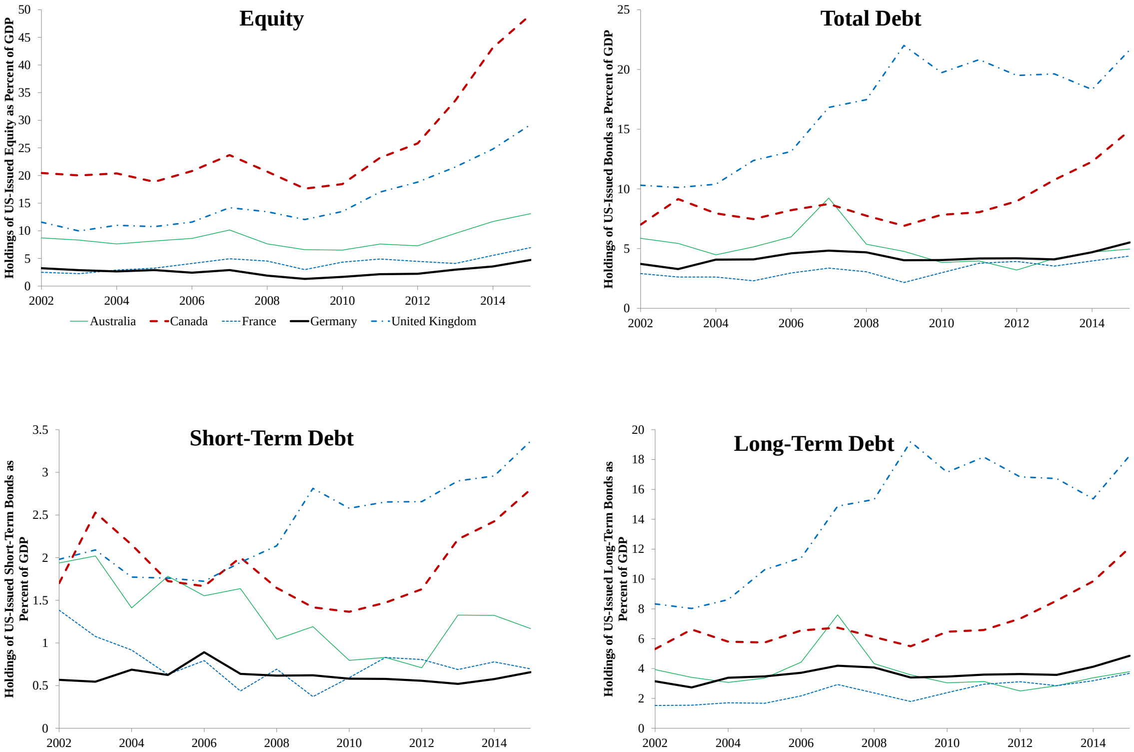
[10] Unlike the survey collection underlying the CPIS by the IMF, reporting for the TIC survey is compulsory, and significant penalties can be imposed for a failure to report.

[11] Because the data is collected on a security-by-security basis, double-counting is eliminated in the TIC system.

[12] Where agencies include US government agencies and corporations, as well as federally sponsored enterprises, such as the Federal National Mortgage Association.

[13] Corporate debt includes all non-Treasury and non-agency debt, such as corporate bonds, certificates of deposit and US municipal debt securities.

Figure 4: Total Private Holdings of US-Issued Assets in Australia, Canada, France, Germany and the UK as a Percentage of Nominal GDP, Annual 2002-2015



Notes: Total private holdings of US-issued assets (equity, debt, short-term debt, and long-term debt respectively) by Australia, Canada, France, Germany and the UK as a percentage of nominal GDP. The data presents stocks of asset holdings as of June 30 in each year, from 2002 to 2015. Equity includes common and preferred stock; all types of investment company shares; interest in limited partnerships and other equity interests that may not involve stocks or shares. Debt includes US Treasury debt, US agency debt, and corporate debt. Long-term debt includes all debt with remaining term-to-maturity in excess of one year, while short-term debt includes all debt with remaining term-to-maturity of one year or less. *Data Sources*: US Treasury International Capital (TIC) system, IMF and author's own calculations.

the separate concern for short and long-term bonds in this paper. Countries' holdings of US-issued short-term debt range from 0.52% to 3.36% of GDP, while holdings of US-issued long-term debt lie between 1.53% and 19.19% of GDP.

Figure 4 also illustrates that there are various dimensions of heterogeneity in the size and composition of US-issued asset holdings across countries. Most strikingly, there is heterogeneity in the size of a foreign countries' exposure to different classes of US-issued assets. During the 2002-2015 period, Canada held the highest stock of US-issued equity of all five countries, with the stock as a percentage of its GDP over four times larger than the corresponding German and French figures in all years. Likewise, UK holdings of US-issued debt as a percentage of its GDP were over double the corresponding figure for Australia throughout the period.

Figure 4 further depicts time variation in bilateral asset holdings. Canadian, German and UK holdings of US-issued equity have increased in every year from 2009, around the time when monetary policy reached its ELB in many advanced economies.[14] The stock of Canadian US-issued equity holdings in 2015 was 49%, almost three times its value in its 2009 trough, 18%. In contrast, UK holdings of US-issued debt, which increased from 10% of UK GDP in 2002 to 22% in 2009, have remained relatively stable since 2009; in 2015, UK holdings of US-issued debt had fallen by just 0.4 percentage points from a peak in 2009. The lower right panel of figure 4 indicates that this variation in UK holdings of US-issued debt emanates from changes in the stock of long-term debt held; short-term debt holdings for all countries have varied within a small band ranging from 0.52% to 3.36% of GDP.

Table 1 presents summary statistics for the time series data in figure 4. The table displays the mean and standard deviation of the stock of US-issued asset holdings by asset class over three time periods: the whole 2002-2015 sample; a pre-ELB 2002-2008 sample; and a post-ELB 2009-2015 sample. The final column denotes the range of the average values across countries, used to guide the model calibration in section 4. Average holdings of US-issued equity range from 2.68% of GDP to 25.42% over the whole 2002-2015 sample period. Over the two sub-periods, only the upper end of this range is significantly affected; the average holdings of US-issued equity ranges from 2.70% of GDP to 20.71% during the 2002-2008 period and from 2.66% to 30.13% during the 2009-2015 period. A similar pattern emerges for the average value of total debt holdings, which range from 3.18% to 16.59% for the 2002-2015 period; in the 2002-2008 and 2009-2015 sub-samples the corresponding ranges are 2.84-12.95% and 3.53-20.23%, respectively. The majority of the change in total debt holdings is associated with long-term debt holdings, which range from 2.42% to 14.21% over the same period, and are 1.99-11.03% and 2.85-17.39% in the 2002-2008 and 2009-2015 sub-samples, respectively. Short-term debt holdings are relatively small — 0.62-2.38% of GDP for the whole sample.

To investigate whether differences between the pre and post-ELB samples are statistically significant, I carry out difference-in-mean significance tests for each country and each series. The significantly different sub-samples are italicised in table 1. For all asset classes, UK holdings of US-issued assets are significantly higher in the second sub-sample. In two cases — for total bonds and long-term bonds — the UK figure defines the maximum in the range. Similarly, French holdings of US-issued long-term debt, which define the minimum in the range, are significantly higher in the second sub-sample. Because there are significant differences across sub-samples for certain asset classes and countries that influence the ranges, I use the 2002-2008 summary statistics as the calibration targets for the theoretical model. For all asset classes — equity, bonds, and short and long-term bonds — the ranges for the 2002-2008 sub-sample are the narrowest of all three sub-samples, so provide the most stringent targets for the model to match.

[14] The growth in the stock of US-issued equity held in Canada, Germany and the UK has exceeded the growth in US equity prices from their trough in February 2009 to 2015.

Table 1: Mean (Standard Deviation) of Foreign Countries' Holdings of US-Issued Assets as a Percentage of Each Country's Nominal GDP by Asset Class, 2002-2015

Country	Australia	Canada	France	Germany	United Kingdom	Range
Equity						
2002-2015	8.68 (1.89)	25.42 (9.70)	4.13 (1.28)	2.68 (0.86)	15.67 (5.88)	2.68-25.42
2002-2008	8.46 (0.86)	20.71 (1.47)	3.49 (1.04)	2.70 (0.43)	*11.79 (1.50)*	2.70-20.71
2009-2015	8.90 (2.62)	30.13 (12.24)	4.76 (1.24)	2.66 (1.19)	*19.56 (6.12)*	2.66-30.13
Total Debt						
2002-2015	5.08 (1.43)	9.00 (2.23)	3.18 (0.66)	4.29 (0.54)	16.59 (4.41)	3.18-16.59
2002-2008	*5.93 (1.54)*	8.04 (0.73)	*2.84 (0.35)*	4.19 (0.56)	*12.95 (3.09)*	2.84-12.95
2009-2015	*4.23 (0.62)*	9.96 (2.85)	*3.53 (0.74)*	4.39 (0.54)	*20.23 (1.31)*	3.53-20.23
Short-Term Debt						
2002-2015	1.34 (0.42)	1.91 (0.45)	0.76 (0.25)	0.62 (0.09)	2.38 (0.53)	0.62-2.38
2002-2008	*1.63 (0.33)*	1.92 (0.33)	0.85 (0.31)	0.65 (0.11)	*1.92 (0.17)*	0.65-1.92
2009-2015	*1.05 (0.26)*	1.90 (0.57)	0.68 (0.16)	0.58 (0.04)	*2.85 (0.27)*	0.58-2.85
Long-Term Debt						
2002-2015	3.74 (1.23)	7.09 (1.89)	2.42 (0.71)	3.67 (0.51)	14.21 (3.97)	2.42-14.21
2002-2008	4.30 (1.54)	*6.12 (0.53)*	*1.99 (0.52)*	3.53 (0.51)	*11.03 (3.05)*	1.99-11.03
2009-2015	3.18 (0.44)	*8.05 (2.29)*	*2.85 (0.61)*	3.81 (0.52)	*17.39 (1.26)*	2.85-17.39

Notes: Mean (standard deviation) of the stock of US-issued equity and debt held in Australia, Canada, France, Germany and the UK (excluding FOI holdings) using annual data over three time periods: the whole 2002-2015 sample; a pre-effective lower bound (ELB) 2002-2008 sub-sample; and a post-ELB 2009-2015 sub-sample. These represent summary statistics for the time series data plotted in figure 4. Italicised entries denote sub-samples that are statistically different from one another using a difference-in-mean hypothesis test and a 5% significance level. *Data Source*: US Treasury International Capital (TIC) system, IMF and author's own calculations.

3 A Model of International Bond Positions

In this section, I present a micro-founded, two-country model of international asset portfolios, which I use to study the role of short and long-term debt in international risk sharing and the global transmission of US monetary policy through longer-term interest rates.

In the model, there are two countries — Home H and Foreign F (the US, denoted with an $*$). Each country is populated by a continuum of infinitely-lived, identical consumers with unit mass. Every period t, each individual in each country consumes a basket of Home and Foreign goods and supplies labour to domestic firms. Firms produce differentiated brands and are monopolistically competitive, facing nominal rigidities à la Calvo (1983). In each country, monetary policymakers set the short-term nominal interest rate according to a Taylor-type rule.

Households have access to six assets: country-specific short-term bonds, long-term bonds, and equity. That is, there are three dimensions to household portfolio choice: (i) country of asset issuance (Home or Foreign); (ii) type of asset (equity or bonds); (iii) maturity of asset (short or long-term bonds). Because of the limited asset availability in comparison to the numerous sources of uncertainty, international financial markets are incomplete.

3.1 Households

A representative Home household maximises discounted expected lifetime utility:

$$U_t = \mathbb{E}_t \sum_{s=0}^{\infty} \delta_{t+s} e^{\zeta_{C,t+s}} \left(\frac{(C_{t+s} - \gamma C_{t+s-1})^{1-\sigma} - 1}{1-\sigma} - e^{\zeta_{L,t+s}} \frac{L_{t+s}^{1+\frac{1}{\nu}}}{1+\frac{1}{\nu}} \right) \tag{1}$$

where $u(C_t) = \frac{(C_t - \gamma C_{t-1})^{1-\sigma} - 1}{1-\sigma}$ is the instantaneous consumption utility function, $\delta_t \in (0,1)$ is the discount factor, C_t is Home consumption, γC_{t-1} is the stock of (external) habits in period t, $\gamma \in [0,1]$ is the persistence of habit formation, $\sigma > 0$ is the coefficient of relative risk aversion, L_t is the labour supply of the Home household, and $\nu > 0$ is the Frisch elasticity of labour supply. $\zeta_{C,t}$ and $\zeta_{L,t}$ are household preference and labour supply shocks respectively. The Home shocks follow independent autoregressive processes of order one:

$$\zeta_{C,t} = \rho_C \zeta_{C,t-1} + \varepsilon_{C,t}, \qquad \varepsilon_{C,t} \sim \mathcal{N}\left(0, \sigma_C^2\right), \qquad \rho_C \in (0,1), \qquad \sigma_C > 0 \tag{2}$$

$$\zeta_{L,t} = \rho_L \zeta_{L,t-1} + \varepsilon_{L,t}, \qquad \varepsilon_{L,t} \sim \mathcal{N}\left(0, \sigma_L^2\right), \qquad \rho_L \in (0,1), \qquad \sigma_L > 0 \tag{3}$$

and similarly in the Foreign country with $\rho_C = \rho_C^*$, $\rho_L = \rho_L^*$, $\sigma_C = \sigma_C^*$ and $\sigma_L = \sigma_L^*$.

The discount factor δ_{t+s} is given by:

$$\delta_{t+s+1} = \delta_{t+s} \beta(C_{t+s}), \quad \delta_t = 1$$

It is well known that in open economy models with incomplete markets, such as this, equilibrium dynamics exhibit non-stationarity. Schmitt-Grohé and Uríbe (2003) outline solutions to this problem for a small-open economy setup, including: endogenising the discount factor, portfolio adjustment costs, or a debt-elastic interest rate. In this paper, I use an endogenous discount factor to induce stationarity, by assuming:[15]

$$\beta(C_t) = \omega C_t^{-\eta}$$

with $\eta \in [0, \sigma)$ and $\omega \overline{C}^{-\eta} \in (0,1)$, where $\overline{C}$ is the steady-state value of consumption, such that $\beta(C_t) \in (0,1)$ and $\beta'(C_t) \leq 0$ for all t. The impact of δ_t on consumption is not internalised by individual decision markers, so that the discount factor depends on the average consumption in an economy, rather than an individual's own consumption.

C_t is the aggregate consumption basket of Home households, comprised of baskets of Home $C_{H,t}$ and Foreign $C_{F,t}$ goods, given by a constant elasticity of substitution (CES) index:

$$C_t \equiv \left[(a_H)^{\frac{1}{\phi}} (C_{H,t})^{\frac{\phi-1}{\phi}} + (1-a_H)^{\frac{1}{\phi}} (C_{F,t})^{\frac{\phi-1}{\phi}} \right]^{\frac{\phi}{\phi-1}} \tag{4}$$

[15]This solution is most readily applied to the model solution algorithm of Devereux and Sutherland (2010, 2011). Moreover, by endogenising the discount factor, I avoid making direct assumptions about the composition of portfolios that I set out to study endogenously in this model.

where $a_H \in [0,1]$ represents the weight of Home goods in the aggregate consumption basket,[16] and $\phi > 0$ denotes the elasticity of substitution between Home and Foreign goods — the 'trade elasticity'. An expenditure minimisation problem for the Home household yields the aggregate Home consumer price index (CPI) corresponding to the basket in (4):

$$P_t = \left[a_H \left(P_{H,t}\right)^{1-\phi} + (1-a_H)\left(P_{F,t}\right)^{1-\phi}\right]^{\frac{1}{1-\phi}} \tag{5}$$

where $P_{H,t}$ and $P_{F,t}$ are the Home country price indices for the baskets of Home and Foreign goods, respectively.

The baskets of Home $C_{H,t}$ and Foreign $C_{F,t}$ goods consumed by the Home households themselves comprise a continuum of differentiated brands, each with unit mass, that are imperfectly substitutable and are aggregated by the following CES indices:

$$C_{H,t} \equiv \left[\int_0^1 C_t(h)^{\frac{\theta-1}{\theta}} \,\mathrm{d}h\right]^{\frac{\theta}{\theta-1}}, \qquad C_{F,t} \equiv \left[\int_0^1 C_t(f)^{\frac{\theta-1}{\theta}} \,\mathrm{d}f\right]^{\frac{\theta}{\theta-1}} \tag{6}$$

where $C_t(h)$ denotes the Home agents' consumption of Home brand h, $C_t(f)$ denotes the Home agents' consumption of foreign brand f, and $\theta > 1$ denotes the elasticity of substitution between varieties — the 'brand elasticity'. The associated price indices, again the result of an expenditure minimisation problem for the Home household, are:

$$P_{H,t} = \left[\int_0^1 P_t(h)^{1-\theta} \,\mathrm{d}h\right]^{\frac{1}{1-\theta}}, \qquad P_{F,t} = \left[\int_0^1 P_t(f)^{1-\theta} \,\mathrm{d}f\right]^{\frac{1}{1-\theta}} \tag{7}$$

where $P_t(h)$ is the Home country price of Home brand h and $P_t(f)$ is the Home country price of Foreign brand f.

Symmetric expressions for the Foreign household are presented in appendix B.1. Unless otherwise stated, the parameterisation across countries is symmetric (e.g. $\sigma = \sigma^*$, $\nu = \nu^*$, $\phi = \phi^*$, $\theta = \theta^*$, $\omega = \omega^*$, $\eta = \eta^*$ and $a_H^* = 1 - a_H$, where a_H^* denotes the weight of Home goods in the Foreign aggregate consumption basket).

3.1.1 Asset Portfolio and Budget Constraint

Agents have access to country-specific equity, short and long-term bonds. All assets are traded on globally integrated financial markets, and are denominated in the currency of the issuing country. Each asset is assumed to be in zero net supply.

Let $B_{jk,t}$ ($B^L_{jk,t}$) denote the stock of real external holdings of short-term (long-term) bonds, issued by country k, held by an agent in country j, carried from period t to $t+1$, defined in units of the Home consumption basket, with $j,k = \{H,F\}$.[17] Similarly, let $S_{jk,t}$ denote the stock of

[16] For $a_H > 1/2$, there is 'home bias' in consumption.

[17] Despite bonds being nominal, I mathematically define the stock of bond holdings in real terms for computational convenience. This definition lends itself to the application of model solution techniques proposed by Devereux and Sutherland (2010, 2011) for international macroeconomic models with portfolios of international assets, as outlined in section 3.6.

real external holdings of country-k equity held by an agent in country j, carried from period t to $t+1$, also defined in terms of the Home consumption basket. Because $B_{HH,t}$, $B^L_{HH,t}$ and $S_{HH,t}$ are defined as the 'external' holdings of Home assets by Home households, then the concurrent Foreign holdings of Home assets are $B_{FH,t} = -B_{HH,t}$, $B^L_{FH,t} = -B^L_{HH,t}$ and $S_{FH,t} = -S_{HH,t}$.

The Home household flow budget constraint, in units of the Home consumption basket, is:

$$\begin{gathered} C_t + B_{HH,t} + e^{-\zeta_{F,t}} B_{HF,t} + B^L_{HH,t} + e^{-\zeta_{F,t}} B^L_{HF,t} + \\ e^{-\zeta_{S,t}} S_{HH,t} + e^{-\zeta_{F,t}} e^{-\zeta_{S^*,t}} S_{HF,t} = w_t L_t + \Pi_t - T_t + B_{HH,t-1} r_t + \\ B_{HF,t-1} r^*_t + B^L_{HH,t-1} r_{L,t} + B^L_{HF,t-1} r^*_{L,t} + S_{HH,t-1} r_{e,t} + S_{HF,t-1} r^*_{e,t} \end{gathered} \tag{8}$$

where w_t denotes the Home real wage, Π_t denotes the real profits of Home firms paid as dividends to the Home households, and T_t denotes real lump-sum taxes levied by the government.[18] r_t (r^*_t) represents the gross real return on Home (Foreign) short-term bonds purchased in period $t-1$; $r_{L,t}$ ($r^*_{L,t}$) is the gross real one-period return on Home (Foreign) long-term bonds purchased in period $t-1$; and $r_{e,t}$ ($r^*_{e,t}$) denotes the gross real return on Home (Foreign) equity purchased in period $t-1$. All gross real returns are defined in units of the Home consumption basket.

There are three shocks in the Home budget constraint: $\zeta_{F,t}$, $\zeta_{S,t}$ and $\zeta^*_{S,t}$. They influence the relative demand for assets and are uncorrelated with one another. $\zeta_{F,t}$ is an (inverse) cost shock to the ability of households to trade Foreign assets. Itskhoki and Mukhin (2017) label this an 'international asset demand shock',[19] influencing the relative demand for Home versus Foreign assets. The international asset demand shock process is:

$$\zeta_{F,t} = \rho_F \zeta_{F,t-1} + \varepsilon_{F,t}, \qquad \varepsilon_{F,t} \sim \mathcal{N}\left(0, \sigma^2_F\right), \qquad \rho_F \in (0,1), \qquad \sigma_F > 0 \tag{9}$$

$\zeta_{S,t}$ ($\zeta_{S^*,t}$) is a shock to the demand for Home (Foreign) equity. It can be interpreted as a reduced form characterisation of an external finance premium shock, generating exogenous variation in equity returns. The equity demand shock process is:

$$\zeta_{S,t} = \rho_S \zeta_{S,t-1} + \varepsilon_{S,t}, \qquad \varepsilon_{S,t} \sim \mathcal{N}\left(0, \sigma^2_S\right), \qquad \rho_S \in (0,1), \qquad \sigma_S > 0 \tag{10}$$

and similarly for the Foreign equity demand shock, with $\rho_S = \rho^*_S$ and $\sigma_S = \sigma^*_S$.

[18] Here, the Home agent receives all Home profits through dividends in the first instance, while claims to those profits are traded with equity. In a symmetric equilibrium with zero net foreign assets, gross portfolio holdings exactly offset each other in value terms. That is, if $S_{HH,t} < 0$ (implying $S_{FH,t} > 0$ by definition of external asset holdings), then Foreign households hold some non-negative claim to Home profits. As in Devereux and Sutherland (2008), this is simply an accounting convention which simplifies the exposition of the model, but is not critical. Alternatively, one can treat all dividend income as part of equity returns, so that wage earnings represent the Home agents' only non-financial income. In this case, even in a symmetric equilibrium with zero net foreign assets, agents in each economy would have non-zero *net* portfolio positions.

[19] Itskhoki and Mukhin (2017) argue that this shock has a variety of interpretations, which are all isomorphic in reduced form, including that the shock: limits arbitrage in currency markets; represents heterogeneous beliefs in currency markets; or represents financial frictions in currency markets (Gabaix and Maggiori, 2015). In all cases the shock admits deviations from uncovered interest parity (UIP).

3.1.2 Asset Returns and Exchange Rates

Home equity represents a claim on the profits of Home firms. Let $Z_{E,t}$ represent the real price of Home equity at time t in units of the Home consumption basket. Then, the gross real rate of return on Home equity is:

$$r_{e,t} = \frac{\Pi_t + Z_{E,t}}{Z_{E,t-1}}$$

The real price of Foreign equity at time t in units of the Foreign consumption basket is $Z^*_{E,t}$. In units of the Home consumption basket this price is $\mathcal{Q}_t Z^*_{E,t}$, where $\mathcal{Q}_t$ is the real exchange rate defined as:

$$\mathcal{Q}_t = \frac{\mathcal{E}_t P^*_t}{P_t} \tag{11}$$

and $\mathcal{E}_t$ is the nominal exchange rate — the Home country price of one unit of Foreign currency — defined such that an increase in $\mathcal{E}_t$ ($\mathcal{Q}_t$) represents a nominal (real) depreciation of Home currency. The gross real rate of return on Foreign equity in units of the Home consumption basket can be written as:

$$r^*_{e,t} = \frac{\mathcal{Q}_t}{\mathcal{Q}_{t-1}} \frac{\Pi^*_t + Z^*_{E,t}}{Z^*_{E,t-1}}$$

Home nominal short-term bonds represent a claim to one unit of Home currency in the subsequent period. The real price, in units of the Home consumption basket, of a Home short-term nominal bond purchased in period $t-1$ is Z_{t-1}. The real payoff of this bond when carried into period t is $1/P_t$. Thus, the gross real rate of return on the Home nominal bond is $r_t = \frac{1}{P_t Z_{t-1}}$ in units of the Home consumption basket. In units of Home currency, the gross nominal rate of return on the Home nominal bond is $R_{t-1} = r_t \pi_t$, where $\pi_t \equiv P_t/P_{t-1}$ and R_t denotes the nominal short-term interest rate from time t to $t+1$, such that $R_{t-1} = \frac{1}{P_{t-1} Z_{t-1}}$.

Foreign nominal short-term bonds represent a claim to one unit of Foreign currency in the subsequent period. The real price, in units of the Foreign (Home) consumption basket, of a Foreign short-term nominal bond purchased in period $t-1$ is Z^*_{t-1} ($\mathcal{Q}_{t-1} Z^*_{t-1}$). The gross real rate of return on the Foreign nominal bond is $r^*_t = \frac{\mathcal{Q}_t}{\mathcal{Q}_{t-1} P^*_t Z^*_{t-1}}$ in units of the Home consumption basket. In units of Foreign currency, the gross nominal rate of return on the Foreign nominal bond is $R^*_{t-1} = r^*_t \pi_t \frac{\mathcal{E}_{t-1}}{\mathcal{E}_t} = \frac{1}{P^*_{t-1} Z^*_{t-1}}$.

Following Woodford (2001), long-term bonds are modelled as perpetuities. The period-t nominal price of a Home long-term bond, newly-issued in period t, is $P_{L,t}$, in units of the issuing country's currency. Thereafter, the bond pays an exponentially decaying nominal coupon κ^s at time $t+s+1$ for $s = 0, 1, 2, ...$ and $\kappa \in (0, 1]$, also expressed in units of the issuing country's currency.[20] That is, the Home long-term bond pays 1 unit of Home currency in period $t+1$, κ units in $t+2$, κ^2 units in $t+3$, etc. The one-period gross nominal yield to maturity at time t on this bond is $R_{L,t} = \frac{1}{P_{L,t}} + \kappa$.[21] The gross one-period real rate of return $r_{L,t}$ on the

[20] If $\kappa = 1$, the security is a consol.

[21] The price of a nominal bond is equal to the present discounted value of its future payments, so when $\kappa < R_{L,t}$:

$$P_{L,t} = \frac{1}{R_{L,t}} + \frac{\kappa}{R^2_{L,t}} + \frac{\kappa^2}{R^3_{L,t}} + ... = \frac{1}{R_{L,t}} \frac{1}{1 - \frac{\kappa}{R_{L,t}}} = \frac{1}{R_{L,t} - \kappa}$$

long-term Home bond, in units of the Home consumption basket, is related to the nominal yield to maturity through the following expression:[22]

$$r_{L,t} = \frac{1}{\pi_t} \frac{P_{L,t}}{P_{L,t-1}} R_{L,t}$$

The Foreign long-term bond, for which the nominal price $P^*_{L,t}$ and coupon κ^* are expressed in Foreign currency units, has nominal yield to maturity at time t of $R^*_{L,t} = \frac{1}{P^*_{L,t}} + \kappa^*$ in units of Foreign currency. The gross one-period real rate of return, in units of the Home consumption basket, is related to this through the following expression:

$$r^*_{L,t} = \frac{1}{\pi_t} \frac{\mathcal{E}_t}{\mathcal{E}_{t-1}} \frac{P^*_{L,t}}{P^*_{L,t-1}} R^*_{L,t}$$

3.1.3 Household Optimality Conditions

The optimality conditions for the Home households are:

$$w_t = e^{\zeta_{L,t}} C^{\sigma}_{X,t} L_t^{\frac{1}{\nu}} \tag{12}$$

$$1 = \mathbb{E}_t \left[\beta(C_t) e^{\Delta \zeta_{C,t+1}} e^{\zeta_{i,t}} \left(\frac{C_{X,t+1}}{C_{X,t}} \right)^{-\sigma} r_{i,t+1} \right], \qquad \text{where } i = 1, 2, ..., 6 \tag{13}$$

where $C_{X,t} \equiv C_t - \gamma C_{t-1}$, $\zeta_{1,t} \equiv 0$, $\zeta_{2,t} \equiv \zeta_{F,t}$, $\zeta_{3,t} \equiv 0$, $\zeta_{4,t} \equiv \zeta_{F,t}$, $\zeta_{5,t} \equiv \zeta_{S,t}$, $\zeta_{6,t} \equiv \zeta_{F,t} + \zeta_{S^*,t}$, $r_{1,t+1} \equiv r_{t+1}$, $r_{2,t+1} \equiv r^*_{t+1}$, $r_{3,t+1} \equiv r_{L,t+1}$, $r_{4,t+1} \equiv r^*_{L,t+1}$, $r_{5,t+1} \equiv r_{e,t+1}$ and $r_{6,t+1} \equiv r^*_{e,t+1}$.[23] Equation (12) is the Home intratemporal Euler equation associated with optimal labour supply. Equation (13) represents the Home intertemporal Euler equations for the Home and Foreign assets; they comprise the portfolio optimality conditions necessary for the application of the Devereux and Sutherland (2010, 2011) solution method. Equivalent optimality conditions for the Foreign household are presented in appendix B.1.

3.2 Firms

Output in each country is produced by a continuum of monopolistically competitive firms. The production function for a good produced by firm $h \in (0,1)$ in the Home country is:

$$Y_t(h) = e^{a_t} L_t(h)^{1-\alpha} X_t(h)^{\alpha} \tag{14}$$

where $L_t(h)$ is the labour input for firm h, $\alpha \in (0,1)$ is the elasticity of output with respect to intermediate goods $X_t(h)$, which are the same bundle of Home and Foreign goods as in household consumption, with price index P_t in the Home economy.[24] a_t is a stochastic productivity shock

[22] Appendix B.1 provides a derivation of this expression by linking the Home household budget constraint in units of the Home consumption basket (8) to a nominal equivalent, expressed in units of the Home currency.

[23] The numerical labels for $\zeta_{i,t}$ and $r_{i,t}$ are adopted to simplify the algebraic exposition in section 3.6.

[24] The corresponding production function for a Foreign firm $f \in (0,1)$ is $Y^*_t(f) = e^{a^*_t} L^*_t(f)^{1-\alpha} X^*_t(f)^{\alpha}$, where $X^*_t(f)$ represents intermediate goods with price index P^*_t.

with evolution:

$$a_t = \rho_a a_{t-1} + \varepsilon_{a,t}, \qquad \varepsilon_{a,t} \sim \mathcal{N}\left(0, \sigma_a^2\right), \qquad \rho_a \in (0,1), \qquad \sigma_a > 0 \tag{15}$$

and similarly for the Foreign productivity shock, with $\rho_a = \rho_a^*$ and $\sigma_a = \sigma_a^*$. Motivated by evidence in Benigno and Thoenissen (2008), I allow the Home and Foreign productivity shocks to be correlated with one another, but assume they are uncorrelated with all other shocks.

The Home real marginal cost of production is:[25]

$$mc_t = e^{-a_t} \frac{w_t^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^\alpha} \tag{16}$$

Because all firms face the same real marginal costs, optimal Home input demands are:

$$L_t = \frac{(1-\alpha) mc_t Y_t}{w_t} \tag{17}$$

$$X_t = \alpha mc_t Y_t \tag{18}$$

where (17) is labour demand and (18) is intermediate goods demand.

Home firms sell their produce to consumers, firms and government in the Home and Foreign economies. The nominal profits of the Home firm can therefore be written as:

$$P_t \Pi_t = \left(P_{H,t} - P_t mc_t\right) Y_{H,t} + \left(\mathcal{E}_t P_{H,t}^* - P_t mc_t\right) Y_{H,t}^* \tag{19}$$

where $Y_{H,t}$ denotes Home demand for the basket of Home goods and $Y_{H,t}^*$ denotes Foreign demand for the basket of Home goods. Demand for intermediate goods (18), along with the expenditure minimisation problem associated with (4) for the Home household and a similar problem for the Foreign household, implies that these quantities can be written as:

$$Y_{H,t} = a_H \left(\frac{P_{H,t}}{P_t}\right)^{-\phi} \left(C_t + \alpha mc_t Y_t + G_t\right) \tag{20}$$

$$Y_{F,t} = (1-a_H) \left(\frac{P_{F,t}}{P_t}\right)^{-\phi} \left(C_t + \alpha mc_t Y_t + G_t\right) \tag{21}$$

where G_t denotes Home government spending, which is the same bundle of Home and Foreign goods as in Home household consumption (4). Home demand for the basket of Foreign goods $Y_{F,t}$ and Foreign demand for the basket of Foreign goods $Y_{F,t}^*$ are given by:

$$Y_{H,t}^* = a_H^* \left(\frac{P_{H,t}^*}{P_t^*}\right)^{-\phi} \left(C_t^* + \alpha mc_t^* Y_t^* + G_t^*\right) \tag{22}$$

$$Y_{F,t}^* = (1-a_H^*) \left(\frac{P_{F,t}^*}{P_t^*}\right)^{-\phi} \left(C_t^* + \alpha mc_t^* Y_t^* + G_t^*\right) \tag{23}$$

[25] See appendix B.2.1 for a derivation of (16)-(18).

where G_t^* denotes Foreign government spending, which is also the same bundle of Home and Foreign goods as in Foreign household consumption.

3.2.1 Pricing

The monopolistically competitive firms have price-setting power, subject to nominal rigidities à la Calvo (1983), such that, at any time t, firms are unable to change their price with fixed probability $\xi = \xi^* \in [0, 1)$. I assume that firms updating their price do so simultaneously in Home and Foreign markets. Firms face producer currency pricing (PCP), setting all prices in their domestic currency (as in, e.g. Obstfeld and Rogoff, 1995).[26]

Let $\mathcal{P}_t(h)$ denote the price of the Home good in the Home market optimally chosen by firm h who resets its price at time t. $\mathcal{E}_t\mathcal{P}_t^*(h)$ denotes the price set by firm h for the Foreign market, in Home currency terms. Under PCP, $\mathcal{E}_t$ and $\mathcal{P}_t^*(h)$, move inversely — i.e. there is complete exchange rate pass through — and the pricing problem of Home firms is:

$$\max_{\{\mathcal{P}_t(h), \mathcal{E}_t\mathcal{P}_t^*(h)\}} \mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} \left[\frac{(\mathcal{P}_t(h))^{1-\theta}}{(P_{H,t+s})^{-\theta}} Y_{H,t+s} + \frac{(\mathcal{E}_t\mathcal{P}_t^*(h))^{1-\theta}}{(\mathcal{E}_{t+s}P_{H,t+s}^*)^{-\theta}} Y_{H,t+s}^* \right.$$
$$\left. -P_{t+s}mc_{t+s} \left(\frac{\mathcal{P}_t(h)}{P_{H,t+s}} \right)^{-\theta} Y_{H,t+s} - P_{t+s}mc_{t+s} \left(\frac{\mathcal{E}_t\mathcal{P}_t^*(h)}{\mathcal{E}_{t+s}P_{H,t+s}^*} \right)^{-\theta} Y_{H,t+s}^* \right] \tag{24}$$

where $\Omega_{t+s} \equiv \frac{u'(C_{t+s})}{u'(C_t)}$ is the discount factor used to evaluate Home firm profits. The first two terms in square brackets represent Home firm revenues from sales to Home and Foreign, while the final two terms express the costs of producing this output.

The Home firm's problem is solved by the following optimality conditions:

$$\mathcal{P}_t(h) = e^{\mu_t} \frac{\theta}{\theta - 1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} mc_{t+s} P_{t+s} P_{H,t+s}^{\theta} Y_{H,t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} P_{H,t+s}^{\theta} Y_{H,t+s}}$$
$$\mathcal{E}_t\mathcal{P}_t^*(h) = e^{\mu_t} \frac{\theta}{\theta - 1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} mc_{t+s} P_{t+s} (\mathcal{E}_{t+s}P_{H,t+s}^*)^{\theta} Y_{H,t+s}^*}{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} (\mathcal{E}_{t+s}P_{H,t+s}^*)^{\theta} Y_{H,t+s}^*} \tag{25}$$

where μ_t has been added to represent a Home firm markup shock, with evolution:

$$\mu_t = \rho_\mu \mu_{t-1} + \varepsilon_{\mu,t}, \qquad \varepsilon_{\mu,t} \sim \mathcal{N}\left(0, \sigma_\mu^2\right), \qquad \rho_\mu \in (0,1), \qquad \sigma_\mu > 0 \tag{26}$$

Symmetric pricing expressions exist for Foreign firms, with Foreign markup shock μ_t^*, where $\rho_\mu = \rho_\mu^*$ and $\sigma_\mu = \sigma_\mu^*$.

Because all producers that reset their price in period t optimally choose the same price, the

[26] In appendix C, I report results under two alternative pricing models: (i) local currency pricing (LCP) (e.g. Betts and Devereux, 2000), where firms set prices in the currency of the market in which they sell the goods; and (ii) dollar currency pricing (DCP), where both the Home country and the US (the Foreign country) invoice their export prices in dollar terms (i.e. in the foreign currency), motivated by evidence in Gopinath (2015) that the dollar is the dominant currency in world trade.

dynamic evolution of $P_{H,t}$ and $P^*_{F,t}$ can be written as:[27]

$$P_{H,t}^{1-\theta} = \xi P_{H,t-1}^{1-\theta} + (1-\xi)\mathcal{P}_t(h)^{1-\theta} \tag{27}$$

$$\left(P^*_{F,t}\right)^{1-\theta} = \xi\left(P^*_{F,t-1}\right)^{1-\theta} + (1-\xi)\left(\mathcal{P}^*_t(f)\right)^{1-\theta} \tag{28}$$

3.3 Monetary Policy

Monetary policy in the Home and Foreign economies follow Taylor-type rules, with policymakers setting the short-term nominal interest rate in their domestic currency. The interest rate rule for the Home economy is:

$$R_t = R_{t-1}^{\rho_r}\left[\overline{\beta}^{-1}\left(\frac{P_t}{P_{t-1}}\right)^{\phi_\pi}\left(\frac{Y_t}{\overline{Y}}\right)^{\phi_y}\right]^{1-\rho_r} e^{\varepsilon_{mp,t}} \tag{29}$$

where $\rho_r \in [0,1)$ denotes the degree of interest rate smoothing, $\phi_\pi > 1$ and $\phi_y > 0$. $\overline{Y}$ represents steady state output of the Home country. $\varepsilon_{mp,t}$ is a stochastic monetary policy disturbance with distribution: $\varepsilon_{mp,t} \sim \mathcal{N}\left(0, \sigma^2_{mp}\right)$, where $\sigma_{mp} > 0$. For simplicity, there is a symmetric interest rate rule for the Foreign economy, with $\rho_r = \rho^*_r$, $\phi_\pi = \phi^*_\pi$, $\phi_y = \phi^*_y$, $\sigma_{mp} = \sigma^*_{mp}$.

This form of interest rate rule is chosen to replicate the actual practice of central banks, as opposed to an optimal rule from a welfare perspective (e.g. Corsetti et al., 2010, 2016). Specifically, the nominal interest rate is a function of CPI inflation within a country, as has been the case in countries following inflation targeting policies in recent decades.

3.4 Government

Government spending is exogenous and subject to stochastic shocks, evolving according to:

$$G_t = \rho_G G_{t-1} + \varepsilon_{G,t}, \qquad \varepsilon_{G,t} \sim \mathcal{N}\left(0, \sigma^2_G\right), \qquad \rho_G \in (0,1), \qquad \sigma_G > 0 \tag{30}$$

with a symmetric, and independent, expression for Foreign government spending G^*_t, with $\rho_G = \rho^*_G$, $\sigma_G = \sigma^*_G$. All government spending is financed by the lump-sum taxes levied on households T_t, so that the government budget constraint is: $G_t = T_t$.[28]

3.5 Equilibrium

In equilibrium, the product, labour and asset markets must clear.

The Home labour market clears when L_t is consistent with labour supply (12) and labour demand (17), and symmetrically for L^*_t in the Foreign country.

Goods market clearing in Home and Foreign markets requires that aggregate output is equal to the sum of demand from domestic and foreign sources:

$$Y_t = Y_{H,t} + Y^*_{H,t} \tag{31}$$

[27] Appendix B.2.2 presents a derivation.

[28] $G_t < 0$ can be interpreted as a lump-sum transfer to households.

$$Y_t^* = Y_{F,t} + Y_{F,t}^* \tag{32}$$

where $Y_{H,t}$, $Y_{F,t}$, $Y_{H,t}^*$ and $Y_{F,t}^*$ are consistent with (20)-(23).

Asset market clearing requires that all assets are in zero net supply internationally, so:

$$\alpha_{i,t} + \alpha_{i,t}^* = 0, \qquad \text{where } i = 1, 2, ..., 6 \tag{33}$$

where $\alpha_{1,t} \equiv B_{HH,t}$, $\alpha_{2,t} \equiv B_{HF,t}$, $\alpha_{3,t} \equiv B_{HH,t}^L$, $\alpha_{4,t} \equiv B_{HF,t}^L$, $\alpha_{5,t} \equiv S_{HH,t}$, $\alpha_{6,t} \equiv S_{HF,t}$, $\alpha_{1,t}^* \equiv B_{FH,t}$, $\alpha_{2,t}^* \equiv B_{FF,t}$, $\alpha_{3,t}^* \equiv B_{FH,t}^L$, $\alpha_{4,t}^* \equiv B_{FF,t}^L$, $\alpha_{5,t}^* \equiv S_{FH,t}$ and $\alpha_{6,t}^* \equiv S_{FF,t}$.

Finally, the steady state Home household budget constraint (8) can be written as:

$$P_t \sum_{i=1}^{6} \alpha_{i,t} - P_t \sum_{i=1}^{6} \alpha_{i,t-1} r_{i,t} = \mathcal{E}_t P_{H,t}^* Y_{H,t}^* - P_{F,t} Y_{F,t} \tag{34}$$

by setting shocks to their steady state value, and substituting the expressions for Home nominal profits (19), Home labour demand (17), and demand equations (20)-(23) into (19).[29]

3.6 Model Solution

A standard first-order approximation of the model will not yield solutions to the portfolio problem for two reasons. First, the first-order model approximation is not sufficient to determine the optimal portfolio. Second, in the non-stochastic steady state, the equilibrium portfolio is indeterminate.[30] To overcome this, I use the method of Devereux and Sutherland (2011) to solve for the optimal zero-order (or steady state) portfolio holdings, and its extension in Devereux and Sutherland (2010) to solve for the optimal time-varying asset portfolio allocation in response to shocks.[31] Devereux and Sutherland (2011) show that the first of these problems can be overcome by using higher-order approximations of the portfolio problem, and the second can be overcome by treating the approximation point — the steady state portfolio — as unknown.

The solution method for steady state portfolio holdings relies on two observations. First, that the first-order behaviour of macroeconomic variables is independent of time-variation in the portfolio allocation; only the steady state value of the portfolio allocation influences the first-order behaviour of macroeconomic variables. Second, that the steady state value of the portfolio allocation can be attained by combining a second-order approximation of the portfolio equations (13) with a first-order approximation of the non-portfolio equations.

In order to solve for the dynamic behaviour of asset holdings around the steady state portfolio, higher-order approximations are required. Devereux and Sutherland (2010) show that a third-order approximation of the portfolio equations captures the first-order effect of state vari-

[29] Appendix B.3 provides a derivation of this expression.

[30] Devereux and Sutherland (2010) emphasise that these are two distinct problems. The first arises in the approximated model with stochastic shocks because certainty equivalence holds, while the second arises in the non-approximated model without stochastic shocks.

[31] Because this model includes multiple nominal assets, this application of the solution method is most similar to Devereux and Sutherland (2007, 2008). Devereux and Sutherland (2010, 2011) outline the solution method in real models, while Devereux and Sutherland (2007, 2008) apply the method in nominal models.

ables on the second moments of asset returns. Thus, a third-order approximation of the model portfolio equations can be used in conjunction with first and second-order approximations of the non-portfolio equations to solve for dynamic of optimal portfolios.

Hereafter, a bar over a variable indicates its steady state value $\overline{x}$ and a hat indicates the log-deviation from the steady state $\hat{x}_t \equiv \ln(x_t/\overline{x})$, unless otherwise stated.

3.6.1 Portfolio Equations

To apply the Devereux and Sutherland (2010, 2011) solution method, the steady state Home household budget constraint (34) can be rewritten as:

$$P_t NFA_t = P_t \left[NFA_{t-1} r_{1,t} + \sum_{i=2}^{6} \alpha_{i,t-1} \left(r_{i,t} - r_{1,t} \right) \right] + \mathcal{E}_t P^*_{H,t} Y^*_{H,t} - P_{F,t} Y_{F,t} \tag{35}$$

where the net foreign assets of Home agents NFA_t have the following definition using (33):[32]

$$NFA_t \equiv \sum_{i=1}^{6} \alpha_{i,t} \tag{36}$$

At the end of each period, agents from both countries select an asset portfolio to carry into the following period. This is optimally determined by the households' intertemporal Euler equations. Let the Home short-term bond $\alpha_{1,t}$ act as the numéraire asset. The six Home intertemporal Euler equations (13) can be reduced to five portfolio optimality conditions:

$$\mathbb{E}_t \left[C^{-\sigma}_{X,t+1} \widetilde{r}_{1,t+1} \right] = \mathbb{E}_t \left[C^{-\sigma}_{X,t+1} \widetilde{r}_{i,t+1} \right], \quad \text{where } i = 2, 3, ..., 6 \tag{37}$$

where $\widetilde{r}_{i,t+1} \equiv e^{\Delta \zeta_{C,t+1}} e^{\zeta_{i,t}} r_{i,t+1}$ for all $i = 1, 2, ..., 6$. Equivalent Foreign expressions are:

$$\mathbb{E}_t \left[\mathcal{Q}^{-1}_{t+1} \left(C^*_{X,t+1} \right)^{-\sigma} \widetilde{r}_{1,t+1} \right] = \mathbb{E}_t \left[\mathcal{Q}^{-1}_{t+1} \left(C^*_{X,t+1} \right)^{-\sigma} \widetilde{r}_{i,t+1} \right], \quad \text{where } i = 2, 3, ..., 6 \tag{38}$$

The two sets of portfolio optimality conditions, (37) and (38), and the market clearing conditions (33) for $i = 2, 3, ..., 6$, provide fifteen equations which determine $\alpha_{i,t}$, $\alpha^*_{i,t}$ and $r_{x,i,t+1} \equiv r_{i,t+1} - r_{1,t+1}$ for $i = 2, 3, ..., 6$.

3.6.2 Steady State Portfolio Allocation

Given the scale of this model, I numerically solve for the steady state asset portfolio by applying the Devereux and Sutherland (2011) method, and discuss the findings in section 4. In this subsection I outline the solution method.

[32] For example, net holdings of short-term bonds in the Home country can be rewritten using (33):

$$B_{HF,t} - B_{FH,t} = \alpha_{2,t} - \alpha^*_{1,t} = \alpha_{1,t} + \alpha_{2,t}$$

I approximate the non-portfolio equations around the non-stochastic, zero-growth, zero-inflation steady state of the model. I assume that both countries are symmetric, so countries have zero net external assets in steady state — $\overline{NFA} = 0$, $\overline{\mathcal{Q}} = \overline{\mathcal{E}} = 1$ — and all other macroeconomic variables are equal across countries— e.g. $\overline{Y} = \overline{Y}^*$, $\overline{C}_X = \overline{C}^*_X$ etc.

A second-order approximation of the Home portfolio equations (37), which is required to solve for the steady state optimal asset portfolio allocation, yields:

$$\mathbb{E}_t\left[\hat{\tilde{r}}_{x,i,t+1} + \frac{1}{2}\left(\hat{\tilde{r}}^2_{i,t+1} - \hat{\tilde{r}}^2_{1,t+1}\right) - \sigma\hat{C}_{X,t+1}\hat{\tilde{r}}_{x,i,t+1}\right] = 0 + \mathcal{O}\left(\epsilon^3\right), \qquad \text{where } i = 2, 3, ..., 6$$

where $\hat{\tilde{r}}_{x,i,t+1} \equiv \hat{\tilde{r}}_{i,t+1} - \hat{\tilde{r}}_{1,t+1}$ and $\mathcal{O}\left(\epsilon^3\right)$ is the residual containing all terms of order higher than two. These second-order approximations can be stacked into vector form:

$$\mathbb{E}_t\left[\hat{\tilde{\mathbf{r}}}_{x,t+1} + \frac{1}{2}\hat{\tilde{\mathbf{r}}}^2_{x,t+1} - \sigma\hat{C}_{X,t+1}\hat{\tilde{\mathbf{r}}}_{x,t+1}\right] = 0 + \mathcal{O}\left(\epsilon^3\right) \tag{39}$$

where $\hat{\tilde{\mathbf{r}}}_{x,t+1} \equiv \left[\hat{\tilde{r}}_{x,2,t+1}, \hat{\tilde{r}}_{x,3,t+1}, ..., \hat{\tilde{r}}_{x,6,t+1}\right]'$ and

$$\hat{\tilde{\mathbf{r}}}^2_{x,t+1} \equiv \left[\hat{\tilde{r}}^2_{2,t+1} - \hat{\tilde{r}}^2_{1,t+1}, \hat{\tilde{r}}^2_{3,t+1} - \hat{\tilde{r}}^2_{1,t+1}, ..., \hat{\tilde{r}}^2_{6,t+1} - \hat{\tilde{r}}^2_{1,t+1}\right]'$$

The corresponding expression for the Foreign portfolio conditions (38) is:

$$\mathbb{E}_t\left[\hat{\tilde{\mathbf{r}}}_{x,t+1} + \frac{1}{2}\hat{\tilde{\mathbf{r}}}^2_{x,t+1} - \sigma\hat{C}^*_{X,t+1}\hat{\tilde{\mathbf{r}}}_{x,t+1} - \hat{\mathcal{Q}}_{t+1}\hat{\tilde{\mathbf{r}}}_{x,t+1}\right] = 0 + \mathcal{O}\left(\epsilon^3\right) \tag{40}$$

(39) and (40) can be combined to yield two equilibrium conditions. First, their difference:

$$\mathbb{E}_t\left[\left(\hat{C}_{X,t+1} - \hat{C}^*_{X,t+1} - \hat{\mathcal{Q}}_{t+1}/\sigma\right)\hat{\tilde{\mathbf{r}}}_{x,t+1}\right] = 0 + \mathcal{O}\left(\epsilon^3\right) \tag{41}$$

and second, their sum:

$$\mathbb{E}_t\left[\hat{\tilde{\mathbf{r}}}_{x,t+1}\right] = -\frac{1}{2}\mathbb{E}_t\left[\hat{\tilde{\mathbf{r}}}^2_{x,t+1}\right] + \sigma\frac{1}{2}\mathbb{E}_t\left[\left(\hat{C}_{X,t+1} + \hat{C}^*_{X,t+1} + \hat{\mathcal{Q}}_{t+1}/\sigma\right)\hat{\tilde{\mathbf{r}}}_{x,t+1}\right] + \mathcal{O}\left(\epsilon^3\right) \tag{42}$$

(41) provides a sufficient condition for pinning down steady state values of portfolio holdings. (42) provides corresponding conditions for equilibrium expected excess returns.

Devereux and Sutherland (2011) highlight three key properties of the solution method. First, to evaluate the left-hand side of (41), it is sufficient to derive expressions for the first-order behaviour of consumption and excess returns — i.e. first-order approximations of non-portfolio equations. Second, only the zero-order portfolio allocation affects the first-order accurate behaviour of consumption and excess returns; higher-order aspects of the portfolio decision are irrelevant for the first-order accurate behaviour of non-portfolio variables.[33] Third, to a first-order approximation, the portfolio excess return is a zero mean i.i.d. random variable. This follows from (42) because it only contains second-order terms. This observation simplifies the

[33] This is the case because steady state asset returns are equal.

solution method, as it implies that the steady state portfolio does not affect the eigenvalues of the first-order macroeconomic system.

3.6.3 Portfolio Dynamics

In section 5, I go beyond the steady state portfolio holdings and study the response of interest rates and portfolio positions to macroeconomic shocks. I use the procedure proposed by Devereux and Sutherland (2010) to account for optimal portfolio dynamics.

Devereux and Sutherland (2010) show that, to solve for the dynamic behaviour of asset holdings around the steady state portfolio, it is necessary to carry out a third-order approximation of the portfolio equations. This provides information about how changes in state variables influence the risk characteristics of assets. The third-order approximation of the portfolio equations can be combined with first and second-order approximations of the non-portfolio equations to solve for the optimal portfolio dynamics. Devereux and Sutherland (2010) derive analytical expressions for the optimal portfolio dynamics within their model. However, because of the scale of this model, I derive the portfolio dynamics numerically by applying their algorithm.

4 International Risk Sharing

In this section, I present the model calibration, describe its ability to replicate the stylised facts presented in section 2, and discuss the mechanisms underlying international risk sharing.

4.1 Benchmark Calibration

This quarterly frequency benchmark model calibration is listed in table 2.

Structural Parameters The steady state value of the discount factor $\overline{\beta}$ is chosen to yield a steady state annualised (real and nominal) rate of return of approximately 4%. The Uzawa convergence parameter η is set such that the speed of convergence to the nonstochastic steady state is small. The constant term in the endogenised discount factor ω (ω^*) is implicitly defined given $\overline{\beta}$, $\overline{C}$ and η.

The coefficient of relative risk aversion σ is set to 2 as in existing studies into international capital flows (e.g. Corsetti et al., 2008b). The calibration for habit persistence γ is motivated by Smets and Wouters (2007). The Frisch elasticity of labour supply ν is chosen to match the figure reported in Chetty, Guren, Manoli, and Weber (2011) for the intensive margin.

The relative weight on Home tradables in total tradables consumption a_H is chosen such that imports are 5% of aggregate output in steady state. Corsetti et al. (2008b) choose this figure as it corresponds to the average ratio of US imports from Europe, Canada and Japan to US GDP between 1960 and 2002. The elasticity of substitution between varieties of tradable goods θ — the brand elasticity — is chosen to yield a steady state monopoly markup of 15%, as in Corsetti et al. (2008a).

Table 2: Benchmark Parameter Values

Parameter	Description	Value
	Structural Parameters	
$\overline{\beta} = \omega \overline{C}^{-\eta}$	Steady State Discount Factor	0.99
η	Uzawa Convergence Parameter	0.01
σ	Coefficient of Relative Risk Aversion	2
γ	Persistence of Habit Stock	0.65
ν	Frisch Labour Supply Elasticity	0.5
a_H	Share of Home Goods in Consumption Basket	0.72
θ	Brand Elasticity	7.7
κ (κ^*)	Home (Foreign) Nominal Coupon on Long-Term Bond	0.9595
$1 - \alpha$	Labour Share in Production of Final Goods	0.61
ξ	Fraction of Prices not Reset Each Period	0.3023
ρ_r	Degree of Monetary Policy Smoothing	0.91
ϕ_π	Taylor Rule Reaction to CPI Inflation	1.58
ϕ_y	Taylor Rule Reaction to Output Deviations from Steady State	0.14
ϕ	Trade Elasticity	0.78
	Shock Process Parameters	
ρ_C	Persistence of Preference Shock	0.74
σ_C	Standard Deviation of Preference Shock	0.0040
ρ_L	Persistence of Labour Supply Shock	0.88
σ_L	Standard Deviation of Labour Supply Shock	0.0042
ρ_a	Persistence of Productivity Shock	0.95
σ_a	Standard Deviation of Productivity Shock	0.0134
$\mathrm{Cov}(a, a^*)$	Covariance of Home and Foreign Productivity Shocks	0.000081
ρ_F	Persistence of International Asset Demand Shock	0.97
σ_F	Standard Deviation of International Asset Demand Shock	0.0005
ρ_S	Persistence of Equity Demand Shock	0
σ_S	Standard Deviation of Equity Demand Shock	0.0049
ρ_μ	Persistence of Markup Shock	0
σ_μ	Standard Deviation of Markup Shock	0.0015
σ_{mp}	Standard Deviation of Monetary Policy Shock	0.0013
ρ_G	Persistence of Government Spending Shock	0.9
σ_G	Standard Deviation of Government Spending Shock	0.0030

Note: Parameter calibration for the model presented in section 3. The model is calibrated at a quarterly frequency.

The long-term bond parameters, κ and κ^*, denote the nominal coupon in units of the issuing country's currency. Woodford (2001) shows that these perpetuities have duration $\left(1-\overline{\beta}\kappa\right)^{-1}$ when prices are stable. The parameters are chosen to imply a duration of 5 years, approximately in line with estimates of the duration of outstanding privately-held debt reported in Hilscher, Raviv, and Reis (2014).

The labour share in the production of final tradable goods $1-\alpha$ is set to match Stockman and Tesar (1995), who calculate that labour comprises 61% of the production share of tradable goods. The Calvo-pricing parameter ξ is chosen to imply an average period between price changes of 4.3 months, as estimated by Bils and Klenow (2004). The Taylor rule coefficients, ρ_r, ϕ_π and ϕ_y, are set using estimates in Clarida, Galí, and Gertler (2000).

The final structural parameter, the trade elasticity ϕ, is subject to empirical and theoretical disagreement surrounding its value. Theoretically, Corsetti et al. (2008b) show that both low and high trade elasticities can be consistent with the Backus and Smith (1993) puzzle within a two-country, micro-founded model. Within their model, Corsetti et al. (2008b) find that a low trade elasticity magnifies the consumption risk arising from productivity shocks through terms of trade and real exchange rate volatility. Nevertheless, similar results are obtained with a high trade elasticity when productivity shocks are highly persistent. Empirically, there is a division between macro and micro-estimates of the trade elasticity. Macro-estimates tend to be low; Corsetti et al. (2008b) use the method of moments and estimate the trade elasticity to be around 0.5. Micro-estimates tend to be high; Feenstra, Luck, Obstfeld, and Russ (2014) estimate the trade elasticity to be around 1.5. In the next subsection, I demonstrate that the model most closely matches the stylised facts when the trade elasticity is set to 0.78, closer to the value estimated by Corsetti et al. (2008b).

Shock Process Parameters The parameterisation of the productivity shock a_t mirrors Benigno and Thoenissen (2008), accounting for cross-country correlation. Benigno and Thoenissen (2008) use annual data, so the parameterisation for this model adjusts for this by using quarterly frequency equivalents from Küçük and Sutherland (2015).

The calibration of preference, labour supply, markup, monetary policy and government shock parameters is based on estimates by Smets and Wouters (2005, 2007). The benchmark calibration of the international asset demand shock is due to Itskhoki and Mukhin (2017).

4.2 Matching the Stylised Facts

In this sub-section, I discuss the model's ability to match the stylised facts regarding the size and composition of international asset positions summarised in table 1. I use the range of average values for the 2002-2008 sub-sample as the target for the model.

I first define the model quantities that I compare to the empirical benchmarks. All quantities are expressed as a fraction of Home country (steady state) GDP, $\overline{Y}$. Total (net) holdings of

Home and US-issued assets in the Home country, t_{HH} and t_{HF} respectively, are defined as:

$$t_{Hk} = \frac{\overline{B}_{Hk} + \overline{B}^L_{Hk} + \overline{S}_{Hk}}{\overline{Y}}, \quad \text{for } k = H, F$$

These summarise the home country's total exposure to all Home and US assets respectively.[34] In order to be consistent with the empirical evidence, $t_{HF} \in (0.0554, 0.3366)$.

Home holdings of Home and US-issued equity are given by:

$$s_{HH} = 1 + \frac{\overline{S}_{HH}}{\overline{Y}} \quad \text{and} \quad s_{HF} = \frac{\overline{S}_{HF}}{\overline{Y}}$$

respectively.[35] To match the empirical evidence, $s_{HF} \in (0.0270, 0.2071)$. Home holdings of Home and US-issued debt, b_{HH} and b_{HF} respectively, are defined as:

$$b_{Hk} = \frac{\overline{B}_{Hk} + \overline{B}^L_{Hk}}{\overline{Y}}, \quad \text{for } k = H, F$$

which includes both short and long-term bond holdings. To be consistent with the target, $b_{HF} \in (0.0284, 0.1295)$. To further decompose external debt holdings, I define Home holdings of Home and US-issued short and long-term bonds as:

$$b^S_{Hk} = \frac{\overline{B}_{Hk}}{\overline{Y}} \quad \text{and} \quad b^L_{Hk} = \frac{\overline{B}^L_{Hk}}{\overline{Y}}, \quad \text{for } k = H, F$$

respectively. To be consistent with the empirical evidence, $b^S_{HF} \in (0.0065, 0.0192)$ and $b^L_{HF} \in (0.0199, 0.1103)$.

In addition to the stylised facts in section 2, there are empirical regularities pertaining to international asset portfolios which the model should also replicate.

First, the equity home bias puzzle describes the fact that external holdings of Foreign equity are lower than predicted by economic theory (French and Poterba, 1991). Agents tend to hold a disproportionately high percentage of domestic equity. To study the model's performance in this respect, I define the home share of Home equity holdings in the Home country equity portfolio $\widetilde{s}_{HH}$ as:

$$\widetilde{s}_{HH} = \frac{1 + \overline{S}_{HH}}{1 + \overline{S}_{HH} + \overline{S}_{HF}}$$

which has this form because residents initially own 100% of domestic equity before international financial markets open. For the model to account for equity home bias, $\widetilde{s}_{HH} \in (0.5, 1)$.

Second, countries have negative external asset positions; they sell domestic equity and bonds abroad. Within the model, this requires that the Home external position in Home assets is negative: $b_{HH} < 0$, $b^S_{HH} < 0$, and $b^L_{HH} < 0$.

Table 3 presents the steady state portfolio quantities for Home investors under the model's

[34] As the steady state is defined where $\overline{NFA} = 0$, the sum of t_{HH} and t_{HF} is zero for all values of ϕ.

[35] Home holdings of Home equity have this form because it is assumed that countries initially own 100% of their equity before international financial markets open, as they receive dividends from the home firm in (8).

baseline calibration from 2.[36] The PCP model closely matches the stylised facts at the baseline trade elasticity ϕ parameterisation of 0.78. At this value, the model can quantitatively match: total Home holdings of US assets t_{HF}; equity home bias $\widetilde{s}_{HH}$; Home holdings of US equity s_{HF}; Home holdings of Home debt b_{HH}; Home holdings of Foreign debt b_{HF}; Home holdings of Home short-term debt b^S_{HH}; and Home holdings of home long-term debt b^L_{HH}. Although the PCP model does not quantitatively match the Home holdings of US-issued short and long-term bonds, b^S_{HF} and b^L_{HF} respectively, the model is still qualitatively correct; Home households hold positive quantities of US-issued short and long-term bonds in the model's steady state.

Because the trade elasticity ϕ is the parameter in the model with the greatest uncertainty surrounding its value, I also assess the model's ability to match the empirical evidence for different values of ϕ. To do this, I calculate steady state portfolio positions within the model for different values of ϕ ranging from 0.01 to 2.50, in increments of 0.005. This range bounds both the macro (Corsetti et al., 2008b) and micro (Feenstra et al., 2014) estimates presented in the previous sub-section. All other parameters are set to the values defined in table 2. Table 4 presents the ranges of values of ϕ for which the model can account for each of the stylised facts, implying that it most closely fits the empirical evidence around the baseline calibration.

4.3 Determinants of International Asset Positions

In the remainder of this section, I analyse the sources of macroeconomic risk that affect the composition of international asset positions the model, by reporting how steady state asset holdings vary with the volatility of different sources of risk and model parameters. Figure 5 plots steady state asset portfolios as a function of the productivity shock volatility σ_a.[37] The grey bands depict the range consistent with the empirical evidence regarding international portfolios from table 1. The vertical dashed lines are positioned at the baseline value for σ_a.

Although Home agents' steady state holdings of Foreign short-term bonds are positive in the baseline parameterisation, they decrease in the volatility of the productivity shocks, and become negative at sufficiently high values of σ_a. In contrast, Home agents' steady state holdings of Foreign long-term bonds increase with σ_a, but only turn positive when the productivity shock standard deviation is sufficiently high. Additionally, the Home share of Home equity increases with the standard deviation of the productivity shock, while Home holdings of Foreign equity decrease, with both quantities remaining positive for all values of σ_a.

What can explain the relationships between steady state asset holdings and the volatility of productivity shocks? Consider a negative Home productivity shock ($\varepsilon_{a,t} < 0$), which may become increasingly severe as the volatility of productivity shocks increases. Following the shock, relative (habit-adjusted) consumption $C_{X,t}/C^*_{X,t}$ decreases. That is, the marginal utility of Home agents relative to Foreign agents increases. In this state of the world, Home agents would prefer assets that pay out relatively more highly.

This shock has competing effects on the relative returns on Home and Foreign short-term

[36] In appendix C.1, I compare the model's fit under different price-setting regimes.
[37] Shock volatilities are kept the same in the two countries at all times.

Table 3: Steady State Portfolio Quantities for Home Investors Under the Model's Baseline Calibration

Holdings	Data	PCP
Total US Assets, t_{HF}	5.54-33.66%	**5.68%**
Equity Home Bias, $\widetilde{s}_{HH}$	50-100%	**97.09%**
US Equity, s_{HF}	2.70-20.71%	**2.77%**
Home Debt, b_{HH}	<0%	$-$**3.71%**
US Debt , b_{HF}	2.84-12.95%	**2.90%**
Home Short-Term Debt, b^S_{HH}	<0%	$-$**2.79%**
US Short-Term Debt, b^S_{HF}	0.65-1.92%	*1.97%*
Home Long-Term Debt, b^L_{HH}	<0%	$-$**0.93%**
US Long-Term Debt, b^L_{HF}	1.99-11.03%	*0.93%*

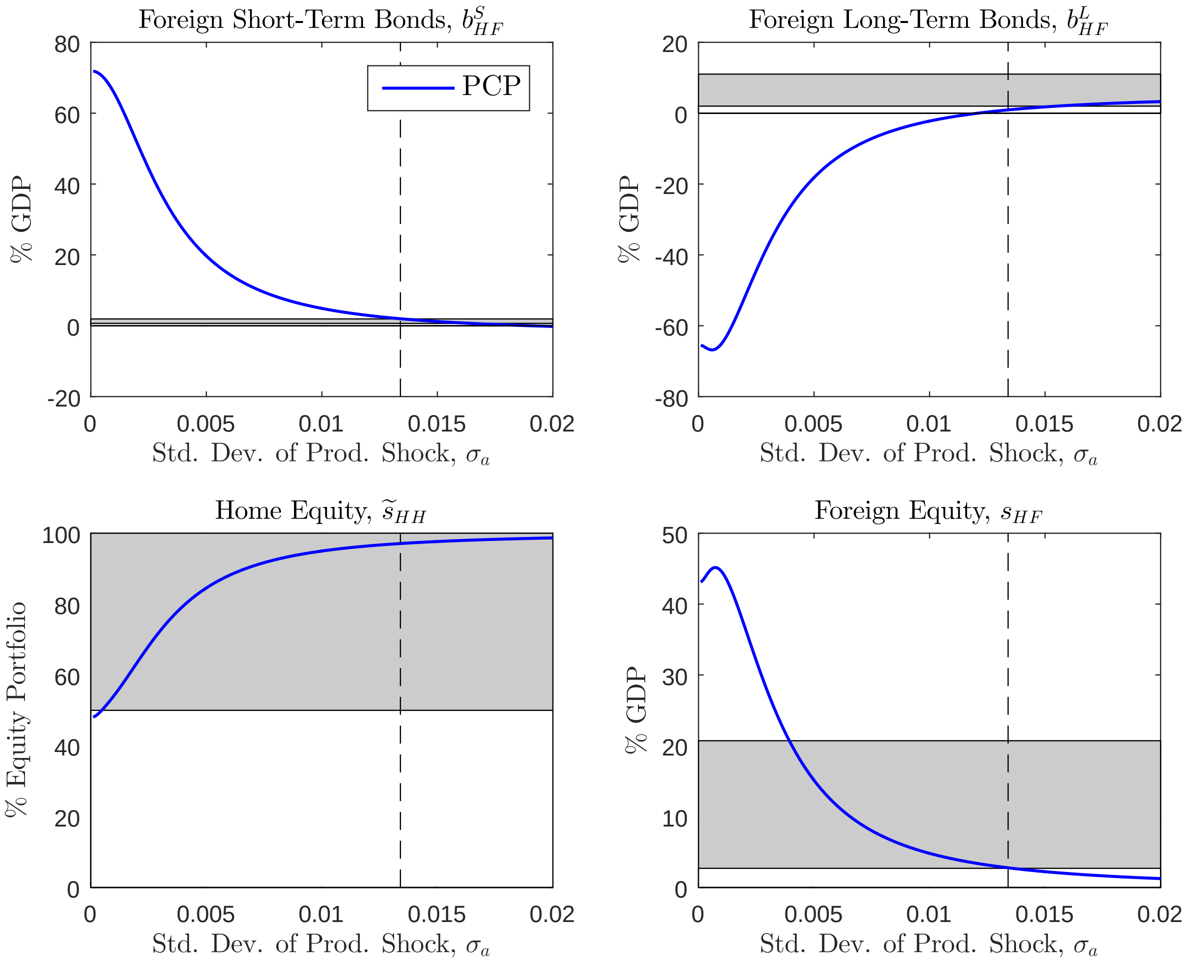
Notes: Steady state portfolio quantities under the baseline model calibration with $\phi = 0.78$. Emboldened values denote quantities that quantitatively match the empirical evidence. Italicised values denote quantities that qualitatively match the empirical evidence. Values that are neither emboldened nor italicised do match the empirical evidence qualitatively or quantitatively.

Table 4: Ranges of Values of the Trade Elasticity ϕ within which Steady State Portfolio Quantities for Home Investors are Consistent with Empirical Evidence

Holdings	PCP
Total US Assets, t_{HF}	0.690-0.785
Equity Home Bias, $\widetilde{s}_{HH}$	0.185-0.205, 0.640-0.790
US Equity, s_{HF}	0.725-0.785
Home Debt, b_{HH}	0.005-0.880
US Debt, b_{HF}	0.325-0.380, 0.775-1.295
Home Short-Term Debt, b^S_{HH}	0.005-0.790
US Short-Term Debt, b^S_{HF}	0.780-0.785
Home Long-Term Debt, b^L_{HH}	0.775-2.500
US Long-Term Debt, b^L_{HF}	0.780-0.805

Notes: Ranges of values of the trade elasticity ϕ within which the steady state portfolio quantities of the model, presented in section 3, are consistent with the empirical evidence presented in section 2.2. I solve the model for values of ϕ ranging from 0.005 to 2.500, in increments of 0.005.

Figure 5: International Asset Portfolios in the PCP Model's Steady State and the Volatility of Productivity Shocks σ_a



Note: Home holdings of Foreign assets (b^S_{HF},b^L_{HF},s_{HF}), and Home share of Home equity $\widetilde{s}_{HH}$, in the steady state of the PCP model plotted against the volatility of productivity shocks σ_a. The volatility is the same for home and foreign economies, and is plotted at increments of 0.0001 from $\sigma_a = 0.0001$ to $\sigma_a = 0.02$. The values of all other parameters are defined in table 2. The grey shaded area denotes the area consistent with the empirical evidence presented in section 2.2. The vertical dashed line is positioned at $\sigma_a = 0.0134$.

bonds. Because the shock increases the relative price level P_t/P_t^*, as Home goods become relatively more scarce, it erodes the relative real return on Home bonds. However, the real exchange rate $\mathcal{Q}_t$ will also immediately appreciate, reducing the return on Foreign short-term bonds in units of the Home consumption basket. For Home agents' steady state holdings of short-term bonds to be positive in the the baseline calibration, the former of these effects must dominate. However, the latter effect explains why Home holdings of Foreign short-term bonds turn negative at sufficiently high values for σ_a. The immediate exchange rate appreciation that a negative Home productivity shock induces will, *ceteris paribus*, increase the relative return on Home short-term bonds at precisely the time when relative Home (habit-adjusted) consumption is low, such that Foreign short-term bonds will not provide a good hedge for productivity shocks.

When σ_a is sufficiently high in comparison to other macroeconomic shocks, Foreign long-term bonds provide a good hedge for productivity shocks. The same negative Home productivity shock will generate a persistent increase in relative Home inflation $\hat{\pi}_t - \hat{\pi}^*_t$, which is expected to erode the value of Home long-term bonds relative to Foreign long-term bonds over their lifetime. Consequently, the value of Home long-term bonds $P_{L,t}$ will fall after a negative Home productivity shock and Home investors will view Foreign long-term bonds as a better hedge for productivity shocks *ex ante*, because their relative resale price is high at precisely the time when relative (habit-adjusted) consumption is low. Therefore, steady state holdings of Foreign long-term bonds by Home households are increasing in the volatility of productivity shocks.

The relationship between equity holdings and the volatility of the productivity shock can be explained by the reaction of relative non-financial income $w_t L_t / w^*_t L^*_t$ to productivity shocks, as in Coeurdacier and Gourinchas (2016). The mechanism in this model relies on price stickiness, mirroring Engel and Matsumoto (2009). Consider a positive Home productivity shock. Firms who are able to reset their price in the period of the shock will cut it, reducing relative Home inflation $\hat{\pi}_t - \hat{\pi}^*_t$. However, Home firms who are unable to reset their price will be forced to economise on labour to reduce costs. For this reason, relative labour earnings in the Home economy $w_t L_t / w^*_t L^*_t$ will fall. To hedge this change in their non-financial income, investors will seek assets that pay relatively highly in this state of nature. Home equity provides a hedge for this, conditional on bond returns hedging the change in relative (habit-adjusted) consumption, because the reduction in Home labour costs will increase the relative profitability of home firms. Engel and Matsumoto (2009) discuss how this mechanism can generate equity home bias within their model; the same reasoning can be applied here.

Importantly, because the model is symmetric, the above reasoning is invariant to the consideration of Foreign shocks. For instance, a positive Foreign productivity shock will reduce relative Home (habit-adjusted) consumption $C_{X,t}/C^*_{X,t}$ and increase relative Home labour income $w_t L_t / w^*_t L^*_t$. Home households will seek bonds that pay out highly in this state of nature to hedge changes in relative (habit-adjusted) consumption, but will prefer equity that pays out relatively more when relative labour income is low. Foreign long-term bonds continue to provide a good hedge for the former risk, while Home short-term bonds will not. The positive foreign productivity shock will reduce prices abroad, increasing P_t/P^*_t. The immediate Home real exchange rate $\mathcal{Q}_t$ appreciation will reduce the return on Foreign short-term bonds in units of the Home consumption basket, while the persistent increase in relative Home inflation $\hat{\pi}_t - \hat{\pi}^*_t$ will erode the relative value of Home long-term bonds. Because of this, investors will use Foreign long-term bonds to insure against this shock *ex ante*, while holding fewer Foreign short-term bonds in the model's steady state. Home equity continues to provide a good hedge for fluctuations in non-financial income, because relative labour income and relative firm profitability are inversely correlated.

5 Global Transmission Through Long-Term Interest Rates

In this section, I use the model presented in section 3 to study the global spillover effects of US monetary policy. Although recent work has shown that US monetary policy exerts an influence on the global financial cycle (e.g. Miranda-Agrippino and Rey, 2015; Dedola et al., 2016; Rey, 2016), this paper extends on this literature by isolating a specific transmission channel through longer-term interest rates and international bond market flows.

5.1 Model Predictions

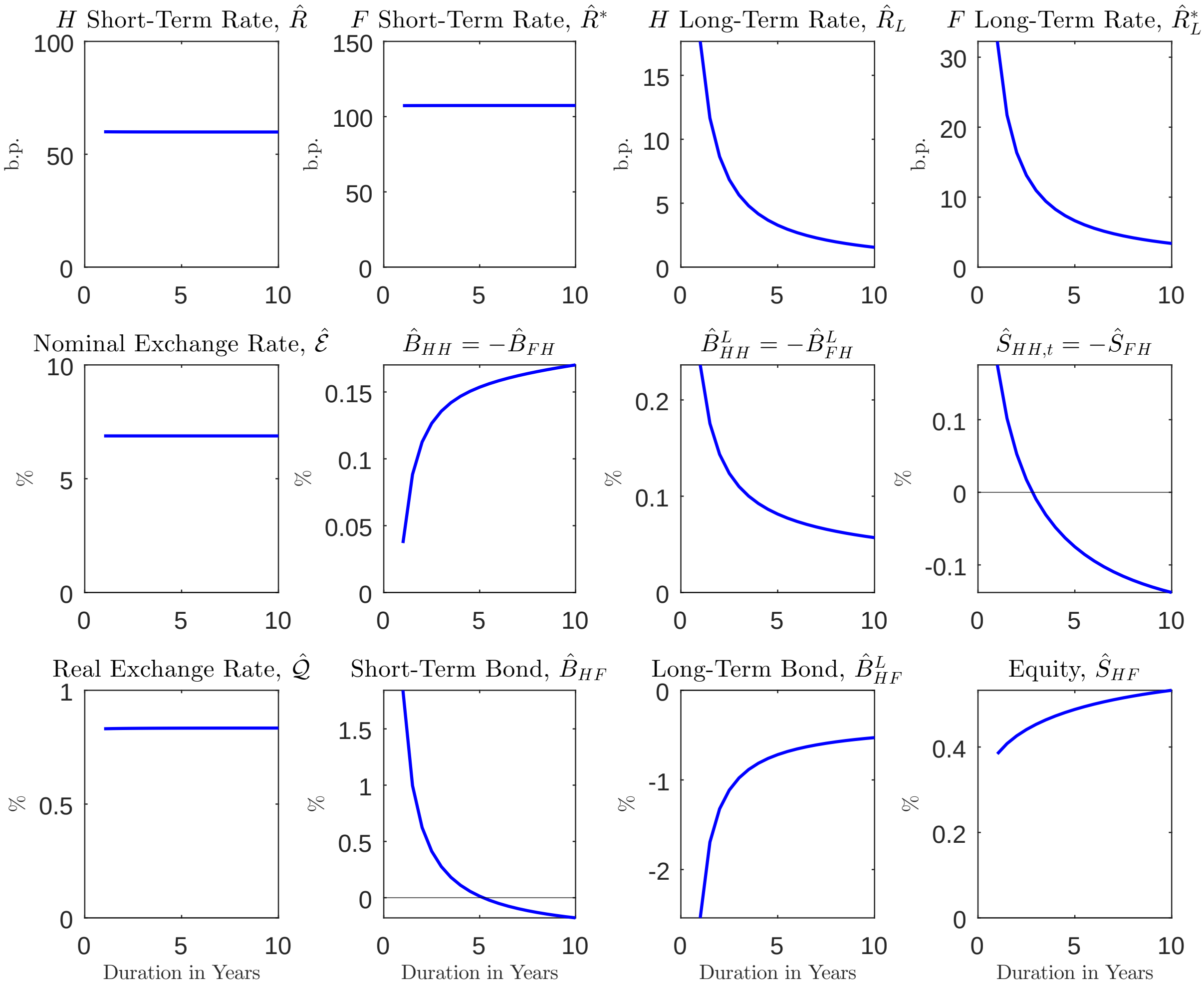
I use the model to investigate the impact responses of interest rates to a US (i.e. Foreign) monetary policy shock $\varepsilon^*_{mp,t}$. Although the bond duration in the baseline calibration is five years, I study the response of the whole term structure of interest rates. Within the model, this is possible because long-term bonds are defined as perpetuities with exponentially declining coupon payments κ. I present impact responses for values of κ set so that the long-term bond duration ranges from one year ($L = 4$ quarters) to ten years ($L = 40$ quarters), with all other parameters maintained at their baseline values.

Figure 6 plots the model-implied impact responses of interest rates, asset positions and the exchange rate to a surprise US monetary policy tightening of approximately 100 basis points. The horizontal axis denotes the long-term bond duration in years. It demonstrates that a surprise increase in the US monetary policy rate unambiguously increases US long-term interest rates at all durations. It also illustrates that the US policy rate change has global effects. First, in accordance with conventional wisdom, the Home currency depreciates on impact, in nominal and real terms. This is independent of the long-term bond duration. Second, Home long-term interest rates respond to the US monetary policy shock, increasing for each duration; the global transmission of US monetary policy through longer-term interest rates serves to amplify comovements between advanced economies.

What generates these spillover effects via longer-term interest rates? Following a tightening of US monetary policy, the Home exchange rate will depreciate. This will generate imported inflation in the Home country, as the Home currency price of US imports increases, necessitating a tightening of Home monetary policy in the future. In turn, this raises expectations of future Home short-term interest rates, placing upward pressure on Home long-term interest rates. However, because Home monetary policy is expected to tighten in the future, the Home real exchange rate, which depreciates immediately after the US monetary tightening, will be expected to appreciate in the future as the world economy returns to its steady state. Because Home investors expect this real exchange rate appreciation, which will reduce the relative return on US long-term bonds in Home consumption units, they will rebalance their portfolio towards Home long-term bonds. That is, the Home advanced economy does not suffer from a capital outflow through the bond market.[38] This portfolio rebalancing will bid down Home longer-term interest rates, serving to offset the increase in Home longer-term interest rates due to increased interest rate expectations to some extent. Bond portfolio rebalancing in advanced economies serves to attenuate some of the spillover effects of US monetary policy that transmit through longer-term interest rates.

[38] Dedola et al. (2016) reach a similar conclusion for advanced economies. Within an empirical vector autoregression study, these authors find that advanced economies do not see capital outflow following a US monetary policy tightening, although emerging market economies do.

Figure 6: PCP Model-Implied Impact Response of Interest Rates, the Exchange Rate and International Portfolios to a Surprise US (Foreign F) Monetary Policy Tightening of Approximately 100 Basis Points



Note: Impact response of Home (Foreign) short-term interest rates $\hat{R}_t^{(*)}$, long-term interest rates $\hat{R}_{L,t}^{(*)}$, international asset holdings, and the nominal and real exchange rate ($\hat{\mathcal{E}}_t$ and $\hat{\mathcal{Q}}_t$) to a surprise tightening, of approximately 100 basis points (b.p.), in US monetary policy $\varepsilon^*_{mp,t}$. $\hat{B}_{Hk,t}$ ($\hat{B}^L_{Hk,t}$) denotes the impact response of home holdings of home (when $k = H$) and foreign (when $k = F$) short-term (long-term) bonds. $\hat{S}_{HH,t}$ ($\hat{S}_{HF,t}$) denotes the impact response of home holdings of home (foreign) equity. The impact responses are plotted for variants of the model with different long-term bond durations, ranging from $L = 4$ (one year) to $L = 40$ (ten years) where κ is altered to match the required long-term bond duration. The values of all other parameters are defined in table 2. 'PCP' denotes producer currency pricing. All interest rate responses are annualised.

5.2 Empirical Comparison

I compare the model's predictions to empirical evidence by carrying out an event study into the impact responses of longer-term interest rates in Australia, Canada, France, Germany and the UK to US monetary policy surprises. I use daily frequency interest rate data, and isolate US monetary policy surprises using intraday data, to estimate the following regression:

$$\Delta y^{(k)}_{L,t-1,t} = \alpha_L + \beta_L mp_t + u_{L,t} \tag{43}$$

where $\Delta y^{(k)}_{L,t-1,t}$ is the change in the country-k L-quarter (net) interest rate from day $t-1$ to t, mp_t denotes the surprise change in US monetary policy on day t, and $u_{L,t}$ is a disturbance term. α_L represents the average daily change in the L-quarter interest rate on days without monetary policy surprises, and β_L represents the impact response of the interest rate to a surprise 100 basis point tightening of US monetary policy, equivalent to the impact responses in figure 6.

5.2.1 Data

I estimate (43) using daily frequency zero-coupon government bond yields as the dependent variable. The duration and maturity of zero-coupon bonds are identical, permitting comparison with the model impact responses. Specifically, I use the following maturity yields: 1 year, 18 months, 2 years, 30 months, 3 years, 42 months, 4 years, 54 months, 5, 7 and 10 years. The sample of countries is the same as in section 2, with the US acting as the base country from where the monetary policy shock emanates.[39]

I measure US monetary policy surprises using intraday movements in the current calendar month federal funds futures (FFFs) rates in a thirty-minute window around Federal Open Market Committee (FOMC) announcements, compiled by Gürkaynak et al. (2005). FFFs contracts have a variety of maturities extending to the first 36 months into the future (including the current calendar month). The contracts pay out at maturity based on the average effective federal funds rate realised in the calendar month specified in the contract. FFFs rates have regularly been used to measure investors' expectations of future short-term interest rates, and empirical evidence suggests that shorter-horizon FFFs provide accurate measures of interest rate expectations (see Lloyd, 2017b, and the references within). Changes in the current month FFFs rate, adjusted for the timing of the announcement within the month, can be associated with revisions in expectations of the effective federal funds rate for the remainder of the month and measure the surprise component of the FOMC decision (Kuttner, 2001).

I estimate (43) using data from January 2002 to December 2015 for all six countries (118 announcement days). I choose this start date for reasons stated in section 5.3. The sample ends in December 2015 because the monetary policy surprise series concludes in this month.

Because the daily zero-coupon bond yields are quoted at the closing time of relevant markets, I adjust the data for the event study. For instance, by the time an FOMC announcement

[39] Because of data availability, I use fewer maturities for the French results: 1, 2, 3, 5, 7 and 10 years. A complete description of data sources is in appendix A.

occurs at 2.15pm in the US, the Australian, French, German and UK markets will have closed. Therefore, the relevant daily change in yields in these jurisdictions comes on the calendar date after the US announcement.

5.2.2 Event Study

Figure 7 presents the impact response of bond yields to a surprise 100 basis point US monetary policy tightening. The black dots represent the estimated $\hat{\beta}_L$ coefficients and the thin dashed lines correspond to 95% confidence intervals using heteroskedasticity and autocorrelation robust **?** standard errors. For comparison, the thin blue line denotes the impact responses of equivalent interest rates to an equal-sized shock plotted in figure 6.

The bottom-right panel of figure 7 illustrates that, following a 100 basis point surprise tightening of US monetary policy, US longer-term interest rates significantly increase at all maturities. The magnitude of the increase is monotonically decreasing with the maturity, with the 1-year yield responding most strongly.

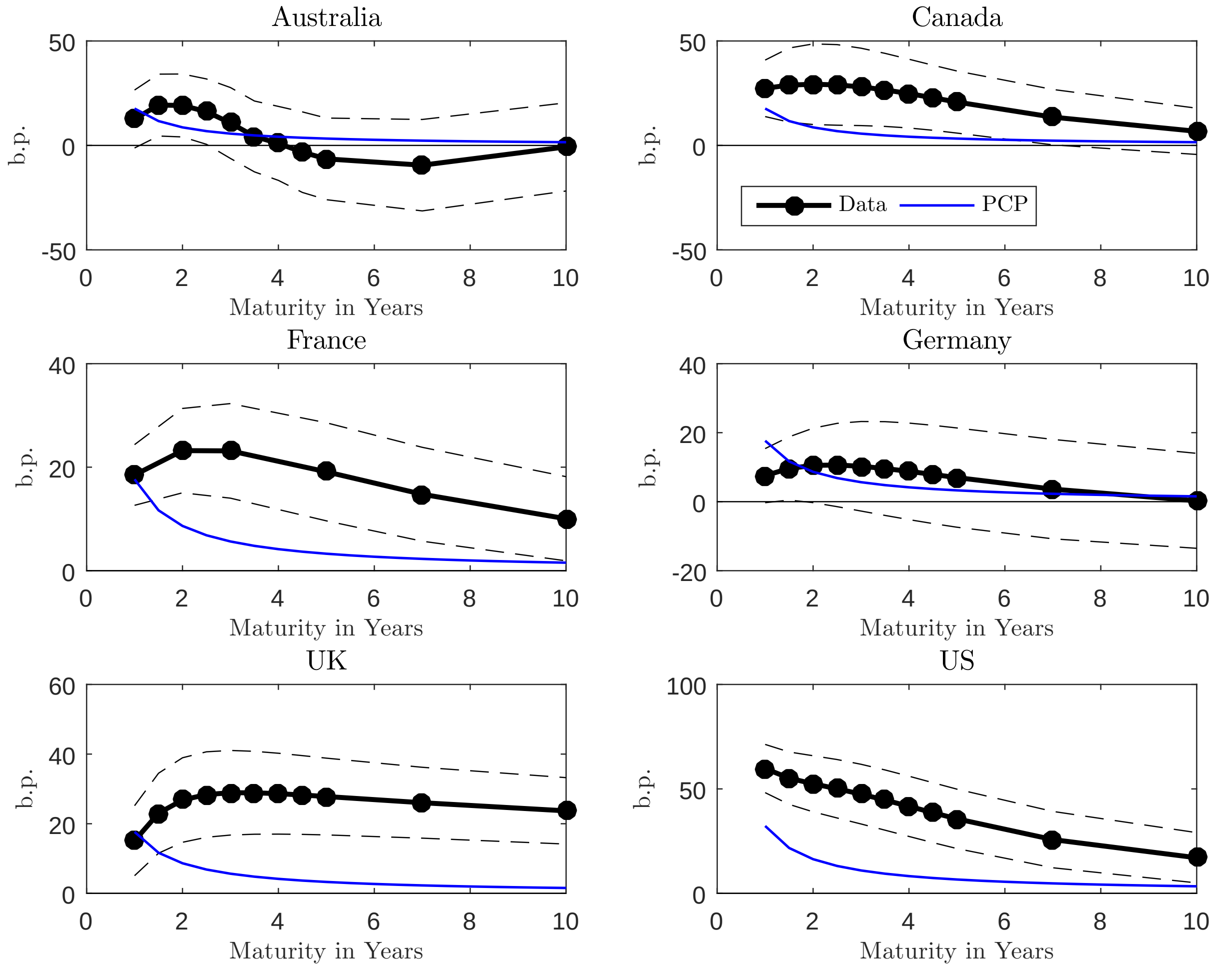
The remaining panels of figure 7 indicate that many longer-term interest rates in other advanced economies increase around a surprise US monetary policy tightening. In France and the UK, interest rates significantly increase at all horizons on FOMC announcement days. In the UK, the 3-year yield is most responsive, increasing by 28.9 basis points around a 100 basis point surprise US tightening. Canadian bond yields are also sensitive to US monetary policy surprises, significantly increasing at all horizons out to 7 years. The 2-year Canadian yield is the most responsive of all plotted in figure 7, increasing by 29.3 basis points around a 100 basis point surprise US tightening. Point estimates of the responsiveness of German bond yields are positive at all horizons, albeit only statistically significant out to 2 years. Interestingly, the response of German bond yields is about half that of French yields. Australian bond yields react most uniquely to a surprise tightening of US monetary policy. The estimated coefficients are positive for the 1 to 4-year maturities, but turn negative — albeit statistically insignificant — at longer maturities.

Visually, the response of the German yield curve most closely matches the predictions of the PCP model. The model-implied quantities lie within the estimated confidence intervals at all maturities beyond 1-year. In Canada, the model-implied predictions lie within the estimated confidence intervals at maturities below 2 years and in excess of 5 years, while in France and the UK, the model-implied quantities lie below the estimated confidence intervals at maturities of 2 years or more. Taken together, the model-implied responses are qualitatively similar to those implied by the data in Canada, France, Germany and the UK, but indicate that the international spillover effects of US monetary policy through longer-term interest rates may be stronger than implied by the model.

5.3 Long-Term Interest Rate Decomposition

To understand why the global macroeconomic spillover effects of US monetary policy through longer-term interest rates is stronger than implied by the model, I use a canonical decompo-

Figure 7: Impact Response of Bond Yields to a Surprise US Monetary Policy Tightening of 100 Basis Points Compared to PCP Model-Implied Impact Response



Note: The black dots denote the impact response of (annualised) longer-term interest rates of different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated β_L coefficients in equation (43). The horizontal axis denotes the maturity in years. Interest rates are zero-coupon government bond yields. The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rate in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005). The dashed lines represent the 95% confidence intervals around the estimated coefficients, constructed using robust standard errors. The estimates are constructed using data from January 2002 to December 2015. The thin blue line denotes the corresponding impact responses of the equivalent interest rates to an equal-sized shock from the PCP model laid out in section 3.

sition of longer-term interest rates into a risk-neutral expected future short-term interest rate component and a term premium:[40]

$$y_{L,t} = \underbrace{\mathbb{E}_t \left[\frac{1}{L} \sum_{l=0}^{L-1} y_{1,t+l} \right]}_{\equiv exp_{L,t}} + tp_{L,t} \tag{44}$$

where $y_{L,t}$ is the yield on an L-period government bond at time t,[41] $y_{1,t}$ is the one-period (net) interest rate, and $tp_{L,t}$ is the term premium on the L-period rate. The first term on the right-hand side of (44), $exp_{L,t}$, defines the average of expected future short-term interest rates between period t and the bond's maturity.

This decomposition lends itself to the study of international spillovers of monetary policy for a number of reasons. First, the decomposition is of direct relevance to policy as the two sub-components have differing policy implications. The first term, $exp_{L,t}$, relates to expectations about the future monetary policy stance in an economy. If, following a US monetary policy announcement, long-term interest rate movements in other advanced economies are associated with changes in interest rate expectations, then monetary policymakers in other advanced economies may attenuate these spillover effects by clearly communicating to investors through policies such as forward guidance. The second term, $tp_{L,t}$, can be linked to the pricing of risk and portfolio rebalancing by international investors, as the term premium reflects the compensation that investors receive for holding long-term bonds over-and-above what they expect to receive by rolling-over short-term contracts over the same period instead. Insofar as investors view different asset classes and maturities as imperfect substitutes, the price of an asset will rise and its term premium fall when demand for that asset increases. If US policy influences longer-term interest rates in other advanced economies through term premia, then this motivates a need for policymakers to keep a watchful eye on international capital flows and the pricing of risk.

Second, the decomposition in (44) can be estimated empirically, using a no-arbitrage Gaussian affine dynamic term structure model (GADTSM) (e.g. Lloyd, 2017a).

I use daily frequency estimates of expectations and term premia to extend the event study from the previous subsection by estimating the following regressions:

$$\Delta exp^{(k)}_{L,t-1,t} = \alpha_{L,e} + \beta_{L,e} mp_t + u_{L,e,t} \tag{45}$$

$$\Delta tp^{(k)}_{L,t-1,t} = \alpha_{L,tp} + \beta_{L,tp} mp_t + u_{L,tp,t} \tag{46}$$

where $exp^{(k)}_{L,t-1,t}$ is the change in the average expectation of the short-term interest rate over the next L quarters in country k from day $t-1$ to t, and $\Delta tp^{(k)}_{L,t-1,t}$ is the daily change in the L-quarter term premium. These regressions extend upon the results in section 5.2 by focusing on policy-relevant mechanisms through which US monetary policy can exert international spillover

[40] Where the term premium is defined broadly to encompass compensation for interest rate risk, inflation risk, liquidity premia, counterparty risk etc.

[41] In comparison to the gross long-term interest rate defined within the theoretical model, $R_{L,t} \equiv 1 + y_{L,t}$.

effects through longer-term interest rates.

5.3.1 Estimating the Decomposition

I estimate interest rate expectations and term premia by applying the OIS-augmented no-arbitrage GADTSM proposed by Lloyd (2017a).

In its simplest form, a GADTSM takes a panel of bond yield $y_{L,t}$ data as an input to estimate two quantities, fitted yields $\widehat{y}_{L,t}$ and risk-neutral yields $\widehat{exp}_{L,t}$.[42] However, as is widely recognised within the literature, this 'unaugmented' GADTSM[43] suffers from an identification problem that results in estimates of interest rate expectations that are spuriously stable (e.g. Kim and Orphanides, 2012). Central to the identification problem is an informational insufficiency. Unaugmented GADTSMs use a single input to estimate two quantities. The input, bond yield data, provides information of direct relevance to the estimation of fitted yields, but not the interest rate expectations. As a symptom of the identification problem, a 'finite-sample' bias will arise when there is insufficient information and a limited number of interest rate cycles in the observed yield data.[44] Finite-sample bias will result in estimates of expected future short-term interest rates that are spuriously stable and, because bond yields are highly persistent, the bias can be severe. Moreover, the severity of the bias is increasing in the persistence of actual yield data. For daily frequency yields, which I use for an event study analysis of the global spillover effects of US monetary policy announcements, the bias is particularly pertinent.

In response to this identification problem, Lloyd (2017a) proposes OIS-augmentation. An OIS contract is an over-the-counter traded derivative in which two counterparties exchange fixed and floating interest rate payments based on a notional principal. The floating interest rate on OIS contracts is closely tied to the monetary policy stance in an economy. The floating reference rate on US contracts is the effective federal funds rate, while in the UK and the Eurozone, the floating reference rates are SONIA and EONIA respectively. Lloyd (2017b) argues that OIS contracts include numerous features that make them excellent candidate measures of investors' interest rate expectations and documents that OIS rates, with maturities of up to 24 months, tend to exhibit statistically insignificant *ex post* excess returns in the US, UK, Japan and the Eurozone. Lloyd (2017a) demonstrates that the OIS-augmented model provides estimates of US interest rate expectations that closely correspond to those implied by FFFs rates and survey expectations at a range of horizons, outperforming existing GADTSMs, including the unaugmented model as well as alternative solutions to the identification problem, namely bias correction (Bauer, Rudebusch, and Wu, 2012) and survey-augmentation (Kim and Orphanides, 2012). In this paper, I estimate the OIS-augmented GADTSM for Australia, Canada, France, Germany, the UK and the US. This is the first paper to present estimates of the OIS-augmented model for countries other than the US.

To estimate the OIS-augmented GADTSM, I use the same daily frequency government bond yield data as in section 5.2. For GADTSM-estimation, I also use 3 and 6-month interest

[42]The term premium $\widehat{tp}_{L,t}$ equals the fitted yield minus the corresponding-maturity risk-neutral yield.
[43]The model is 'unaugmented' because it takes bond yields as the sole input to the estimation algorithm.
[44]Samples spanning 5-15 years may contain too few interest rate cycles (Kim and Orphanides, 2012, p. 242).

rates.[45] In addition, I use daily frequency 3, 6, 12 and 24-month OIS rates, where available. The choice of maturities is motivated by evidence in Lloyd (2017a,b) suggesting that OIS rates with maturities out to two years accurately reflect investors' expectations of future short-term interest rates. However, because of data availability, I only use the 3, 6 and 12-month OIS rates for the Australian and Canadian decompositions. The sample runs from January 2, 2002 to December 31, 2015, starting in 2002 because OIS rate data is not available from 1999 in most countries, with many series beginning in 2001 or 2002.

5.3.2 Estimates of Interest Rate Expectations and Term Premia

Figure 8 presents the results from the US OIS-augmented GADTSM at the 2-year horizon. As a benchmark for comparison, I also plot the unaugmented GADTSM estimated using the algorithm Joslin, Singleton, and Zhu (2011). The illustration corroborates a number of important findings in Lloyd (2017a). First, OIS-augmentation does not compromise the overall fit of the model with respect to actual bond yields. The top panel of figure 8 plots the actual 2-year yield against the fitted yields from the unaugmented and OIS-augmented models. The series co-move extremely closely. This is unsurprising, because the identification problem in GADTSMs relates to the estimation of risk-neutral yields. Bond yield data alone is sufficient for the accurate fitting of actual bond yields.

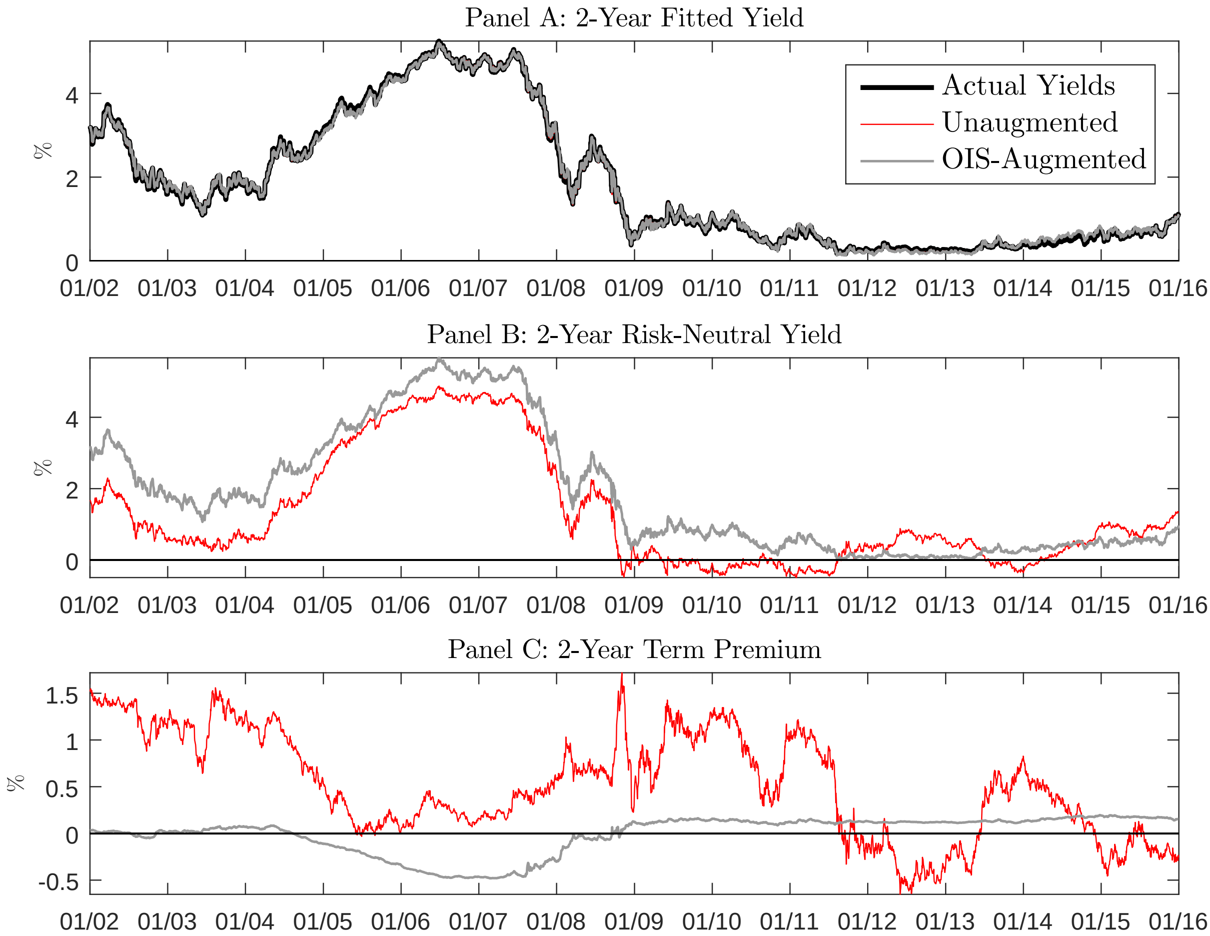
Panels B and C of figure 8 illustrate that OIS-augmentation influences estimates of risk-neutral yields and term premia over the whole sample. Notable differences in the risk-neutral yields from the two GADTSMs exist from the late-2008 onwards, the period within which US monetary policy was at its ELB. Casual observation suggests that the estimates of the risk-neutral yield from the OIS-augmented model are more reasonable than those from the unaugmented model. The 2-year risk-neutral yield from the OIS-augmented model remains above 0% for this whole period, while estimates from the unaugmented model are persistently negative for much of this period, counter-factually implying that investors' expectations of future short-term interest rates were negative.

To study these differences more closely, I compare the risk-neutral yields from the GADTSMs to survey expectations of future interest rates. The risk-neutral yields from the preferred model should closely align with corresponding-horizon survey expectations. Formally, I compare the estimated 3 and 6-month, and 1-year risk-neutral yields to corresponding-maturity interest rate expectations from surveys. I calculate approximate future short-term interest rate expectations using data from the quarterly *Survey of Professional Forecasters* at the Federal Reserve Bank of Philadelphia. As in Lloyd (2017a,c), where I perform a similar exercise, I construct the approximations from a weighted geometric average of the median expectation of the 3-month T-Bill rate in the current quarter, and the first, second, third and fourth quarters ahead.[46] To compare the estimated risk-neutral yields and survey expectations, I present the root mean square error (RMSE) of the differences between risk-neutral yields and corresponding-horizon

[45] See appendix A for further information on data sources.

[46] Complete descriptions of how these approximations are calculated are presented in appendices in Lloyd (2017a,c).

Figure 8: Estimated US Yield Curve Decomposition, January 1999 to December 2015



Note: In panel A, I plot the actual 2-year bond yield and the fitted 2-year bond yields from two GADTSMs. In panels B and C, I plot the estimated 2-year risk-neutral yields and term premia from the GADTSMs. The 'unaugmented' GADTSM is estimated using the algorithm of Joslin et al. (2011) and the OIS-augmented GADTSM is estimated using the algorithm of Lloyd (2017a). The models are estimated with three pricing factors, using daily data from January 2, 2002 to December 31, 2015. All figures are in annualised percentage points. The horizontal axis date labels are in MM/YY format.

survey expectations on survey submission deadline dates.

Table 5 presents the numerical results of this comparison. Immediately, the results indicate that the OIS-augmented GADTSM unambiguously provides the best fit for survey expectations over the 1999-2015 period. This is true at all three horizons, corroborating with Lloyd (2017a,c).

A similar pattern emerges from the GADTSMs estimation in the remaining five countries. Further estimation results for these countries are discussed in appendix D.

5.3.3 Event Study Results

Endowed with daily frequency estimates of interest rate expectations and term premia for each of the six countries, I estimate (45) and (46). I plot the impact responses of bond yield components for maturities of 1 year or more. In appendix E, I report two robustness exercises. In the first, I

Table 5: GADTSM-Implied Expectations: Root Mean Square Error (RMSE) of the In-Sample Risk-Neutral Yields *vis-à-vis* 3, 6 and 12-month Survey Expectations

GADTSM	3-Month Expectations	6-Month Expectations	12-Month Expectations
Unaugmented	0.2232	0.2833	0.4725
OIS-Augmented	**0.1823**	**0.1695**	**0.1850**

Notes: RMSE of the risk-neutral yields from two GADTSMs in comparison to approximated survey expectations. The 'unaugmented' GADTSM is estimated using the algorithm of Joslin et al. (2011) and the OIS-augmented GADTSM is estimated using the algorithm of Lloyd (2017a). The models are estimated with three pricing factors, using daily data from January 2, 2002 to December 31, 2015. All figures are in annualised percentage points. The construction of the survey expectation approximations, using data from the Survey of Professional Forecasters from the Federal Reserve Bank of Philadelphia, is described in appendices to Lloyd (2017a,c). The lowest RMSE model at each maturity has been emboldened for ease of reading.

account for the possibility that US 'unconventional' monetary policies, enacted since late-2008, may influence the conclusions made here about conventional monetary policy. I find that the transmission of US monetary policy to other advanced economies through the term structure of interest rates in 2002-2008 was not significantly different from 2002-2015. In the second, I demonstrate that the results are robust when an unaugmented GADTSM is used.

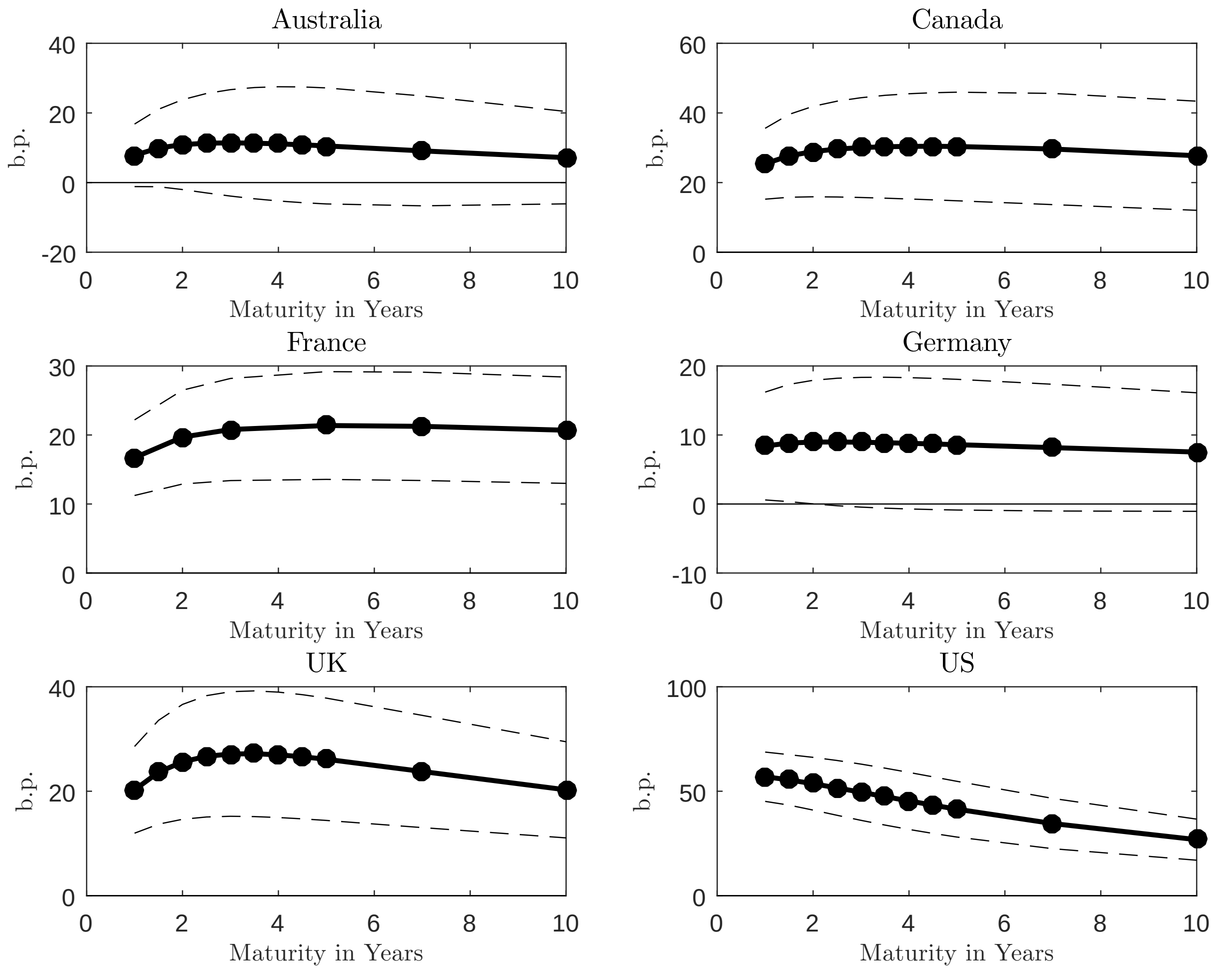
Figure 9 presents estimates of the responsiveness of interest rate expectations to a surprise 100 basis point tightening of US monetary policy from (45). The bottom-right panel of figure 9 illustrates that this significantly increases US interest rate expectations at all horizons.

The remaining panels illustrate the response of the term structure of interest rate expectations in the other five advanced economies. In Canada, France, and the UK, a surprise tightening of US monetary policy is associated with an immediate and significant, increase in interest rate expectations at all horizons, consistent with investors forming expectations that other advanced economies will tighten monetary policy following a US monetary policy tightening. Moreover, in these countries, the impact response of the term structure of interest rate expectations is hump-shaped. Interest rate expectations are most responsive in these economies at the 3.5 to 5-year horizons. This suggests that international spillover effects of US monetary policy through interest rate expectations are pertinent at a wide range of horizons, extending beyond the near-term. In Australia and Germany, the estimated responses of interest rate expectations are also positive at all horizons, albeit statistically insignificant at most tenors.[47] At long horizons especially, the impact responses of interest rate expectations tend to be greater than the responses of corresponding-maturity bond yields, indicating that spillovers through this channel can explain the differences between empirical and model-implied responses in figure 7.

Figure 10 presents the impact responses of term premia to a surprise tightening of US

[47] In figure 9, the response of German interest rate expectations is about half that of French interest rate expectations. This occurs because German and French yield curve decompositions are estimated independently. An alternative approach to estimating Eurozone decompositions, which accounts for commonality of monetary policy rates, involves using estimating interest rate expectations with bond yields from one country (i.e. Germany) and calculating term premia for the other using (44). If this method is applied, the impact response of French interest rate expectations would be the same as German expectations in figure 9, while the impact response of French term premia would be higher at all maturities than in figure 10.

Figure 9: Impact Response of Interest Rate Expectations to a Surprise US Monetary Policy Tightening of 100 Basis Points



Note: The black line denotes the impact response of interest rate expectations of different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated $\beta_{L,e}$ coefficients in equation (45). The horizontal axis denotes the maturity of the interest rate expectations in years. The interest rate expectations are estimated using the OIS-augmented GADTSM of Lloyd (2017a). The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rates in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005). The dashed lines represent the 95% confidence intervals around the estimated coefficients, constructed using robust standard errors. The estimates are constructed using data from January 2002 to December 2015.

monetary policy. The bottom-right panel of the figure depicts the response of US term premia to a US monetary policy tightening. At all horizons, US term premia fall significantly following a surprise tightening of US monetary policy. The largest fall in US term premia occurs at the 4-year horizon; following a surprise 100 basis point tightening of US monetary policy the premium at this tenor declines by 7.57 basis points.

The remaining panels of figure 10 plot the responsiveness of the term structure of term premia in Australia, Canada, France, Germany and the UK to a surprise US monetary policy tightening. In Australia, Canada, France and Germany, the longer-horizon term premia fall significantly in response to a surprise tightening of US monetary policy.[48] Moreover, the responses tend to increase in magnitude at longer horizons, suggesting that the international spillover effects of US monetary policy through term premia are most pertinent at longer-term horizons.

Taken together, the results in figures 9 and 10 indicate that US monetary policy announcements do have spillover effects to other advanced economies that propagate through longer-term interest rates. Moreover, the decomposition of longer-term interest rates in (44) sheds further light on these spillovers. Two implications are noteworthy. First, movements in interest rates in many advanced economies on FOMC announcement dates are strongly positively associated with changes in interest rate expectations at horizons beyond the near-term. This suggests the monetary policymakers in advanced economies may be able to attenuate some of the spillover effects of US monetary policy by clearly communicating expectations of future short-term interest rates through policies such as forward guidance at a range of horizons. Second, at longer horizons, FOMC announcements are associated with reductions in term premia in other advanced economies that serve to attenuate some of the spillover effects of US monetary policy, and are consistent with the portfolio rebalancing of investors seen in the model in figure 6, where investors rebalance their portfolio towards Home long-term bonds because they expect future real exchange rate appreciation.

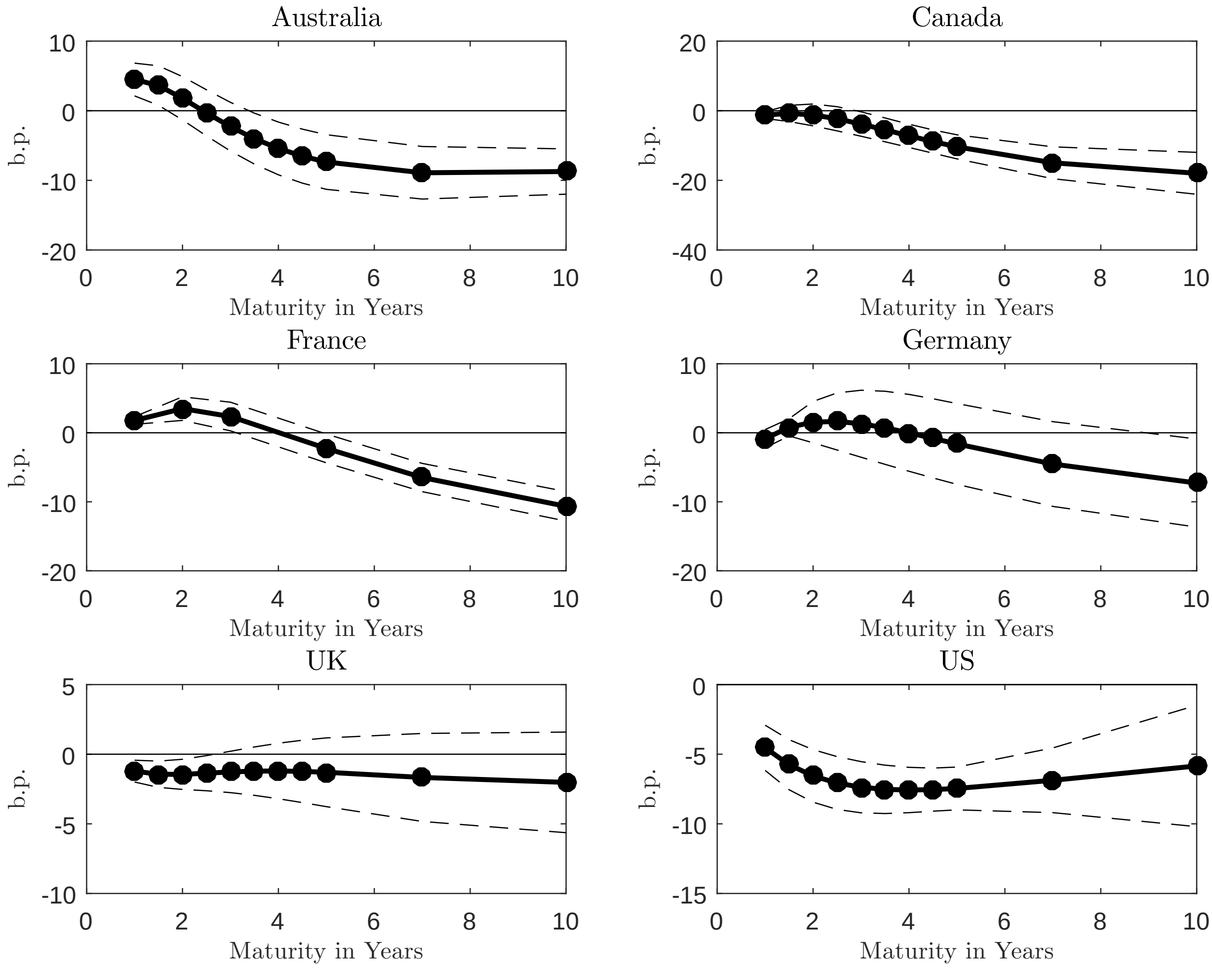
This conclusion echoes a finding of Stavrakeva and Tang (2016) who assess quarterly frequency correlations between longer-term interest rates and exchange rates amongst advanced economies. They find that correlations between shorter-term interest rates and exchange rates are predominantly driven by interest rate expectations, and correlations between longer-term interest rates and exchange rates by term premia. Insofar as US monetary policy surprises influence exchange rates, the empirical results in this paper suggest that US monetary policy shocks may be one of the drivers of the correlations found in Stavrakeva and Tang (2016).

6 Conclusion

In this paper, I study the mechanisms through which international macroeconomic spillovers between advanced economies propagate through longer-term interest rates. I present a microfounded, two-country model with endogenous portfolio choice amongst country-specific equity, short and long-term bonds. The model provides novel insights about the different roles played by

[48]In the UK, the point estimates for the response of term premia are negative at all horizons, albeit statistically insignificant from the 3-year maturity onwards.

Figure 10: Impact Response of Term Premia to a Surprise US Monetary Policy Tightening of 100 Basis Points



Note: The black line denotes the impact response of term premia at different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated $\beta_{L,tp}$ coefficients in equation (46). The horizontal axis denotes the maturity of the term premia in years. The term premia are estimated using the OIS-augmented GADTSM of Lloyd (2017a). The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rates in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005). The dashed lines represent the 95% confidence intervals around the estimated coefficients, constructed using robust standard errors. The estimates are constructed using data from January 2002 to December 2015.

short and long-term bonds in international risk sharing and the global transmission of monetary policy shocks. Within the model, short-term bonds are predominantly used to hedge real exchange rate fluctuations that occur immediately after a macroeconomic shock, while long-term bonds mainly hedge expected inflation and real exchange rate movements.

I assess the model's predictions regarding the international transmission of US conventional monetary policy shocks through longer-term interest rates. Within the model, a surprise tightening of US monetary policy generates immediate increases in longer-term interest rates in the US and other advanced economies, that qualitatively align with estimates from an event study, indicating that US monetary policy has powerful global spillover effects through longer-term interest rates.

I extend the empirical analysis by estimating a decomposition of longer-term interest rates into interest rate expectations and term premia. I find that US monetary policy shocks exert powerful spillover effects through interest rate expectations. Surprise US monetary policy tightening tends to immediately increase investors' expectations of future short-term interest rates in other advanced economies at a range of horizons beyond the near-term. In contrast, following the same surprise, term premia in other advanced economies tend to fall, especially at longer horizons, attenuating the global spillover effects of monetary policy.

These findings have important implications for monetary policymakers in advanced economies and contribute to the growing literature on the global financial cycle (Rey, 2014; Miranda-Agrippino and Rey, 2015; Passari and Rey, 2015; Rey, 2016). Monetary policymakers may be able to contain spillover effects through interest rate expectations by clearly communicating their intentions for future policy through policies such as forward guidance at a range of horizons. Nevertheless, the reaction of term premia help to attenuate the spillover effects of US monetary policy to other advanced economies. These movements warrant careful consideration of international capital flows and the pricing of risk, as they indicate that global portfolio rebalancing can help to circumvent the Mundellian trilemma.

Appendix

A Data Sources

A.1 International Asset Portfolio Data

Coordinated Portfolio Investor Survey (CPIS) This is collated by the International Monetary Fund (IMF) and is available here: `cpis.imf.org`. The CPIS is a voluntary data collection exercise, in which participating economies provide data on its total holdings of portfolio investment securities. The survey quotes international asset holdings on December 31 for the 2001-2012 period. From 2013 onwards, the survey has been carried out twice a year: on June 30 and December 31. I use the annual December surveys only, from 2001 to 2014.

US Treasury International Capital (TIC) System The TIC reporting system the US government's source of data on capital flows into and out of the United States. The data is collected by the US Treasury and the Federal Reserve Bank of New York, and is accessible here: `www.treasury.gov/resource-center/data-chart-center/tic/Pages/index.aspx`. In section 2.2, I use annual holdings data from the TIC system. This data is collated from surveys of issuers and holders of US and foreign securities held at the end of June each year. The first annual survey was conducted in 2002, and I use the survey data from 2002 to 2015 in section 2.2. Prior to 2002, similar surveys were carried out, albeit less frequently. I use the data to study asset holdings by country of foreign holder, security type and maturity.

Two features of the TIC system data enhance its accuracy *vis-à-vis* the CPIS data. First, TIC surveys acquire information at the level of individual securities. Second, reporting for the TIC surveys is compulsory, and significant penalties can be imposed for failure to report.

A.2 Interest Rate and Exchange Rate Data

In this sub-section, I detail the data used to estimate the OIS-augmented GADTSM (Lloyd, 2017a) for Australia, Canada, France, Germany, the UK and the US. For each country, I estimate the OIS-augmented GADTSM using daily frequency data from January 2, 2002 to December 31, 2015. Unless otherwise stated, I use zero-coupon government bond yields of the following maturities: 3 and 6 months, 1 year, 18 months, 2 years, 30 months, 3 years, 42 months, 4 years, 48 months, 5, 7 and 10 years. All OIS rate data is from *Bloomberg*. Where there are differences between the bond yield sample period and OIS rate availability, I make use of the Kalman filter-based algorithm of Lloyd (2017a) to deal with missing observations in the GADTSM.

Australia Zero-coupon government bond yields from the Reserve Bank of Australia, available here: `www.rba.gov.au/statistics/historical-data.html`. Daily frequency OIS rate series start in January 2002 for the 1, 2, 3, 4, 5, 6, 9 and 12-month maturities; 7, 8, 10 and 11-month OIS rate data is available from May 2002; 18 and 24-month OIS rate data is available from

June 2003; and 36-month data begins in April 2004. Because of the OIS rate availability, I use 3, 6 and 12-month OIS rates for the Australian GADTSM only.

Canada I use zero-coupon government bond yields from the Bank of Canada, available here: `www.bankofcanada.ca/rates/interest-rates/bond-yield-curves/`. Daily frequency OIS rate series start in May 2002 for the 1, 2, 3, 4, 5, 6 and 9-month maturities. Although 1-year OIS rates are available from June to October 2003, they are not available for all business days until October 2007. 7, 8, 10, 11, 18 and 24-month OIS rates are only available from October 2007, while 3, 4 and 5-year OIS rates are first available from January 2011. Because of OIS rate availability, I use 3, 6 and 9-month OIS rates for the Canadian GADTSM only.

France I combine 3 and 6-month Treasury bill rates from *Datastream* and 1, 2, 3, 5, 7 and 10-year zero-coupon government bond yields from *Bloomberg*. I convert the T-Bill rates from their discount basis to the yield basis. The availability of Eurozone OIS rates is detailed in the appendix of Lloyd (2017b). I estimate the French GADTSM using 3, 6, 12 and 24-month Eurozone OIS rates.

Germany I estimate the OIS-augmented GADTSM for Germany using zero-coupon government bond yields from the Bundesbank, available here: `bundesbank.de/Navigation/EN/Statistics/Time_series_databases/Datenkorb/datenkorb_node.html?mode=its`. The availability of Eurozone OIS rates is detailed in the appendix of Lloyd (2017b). I estimate the German GADTSM using 3, 6, 12 and 24-month Eurozone OIS rates.

United Kingdom I use zero-coupon government bond yields from the Bank of England, available here: `www.bankofengland.co.uk/statistics/pages/yieldcurve/default.aspx`. These yield curves are constructed by applying the method of Anderson and Sleath (2001). The published zero-coupon bond yields do not always include yields for maturities below one year, depending on the maturity of the shortest UK government bond available on a given date. As in Malik and Meldrum (2014), I fill in the gaps by linearly interpolating between Bank Rate (the UK monetary policy rate, which is taken to have zero-period maturity) and the shortest available maturity bond yield. The availability of UK OIS rates is detailed in the appendix of Lloyd (2017b). I estimate the UK GADTSM using 3, 6, 12 and 24-month UK OIS rates.

United States I combine 3 and 6-month T-Bill rates from *Federal Reserve Statistical Release H.15* and zero-coupon government bond yields constructed by applying the method of Gürkaynak, Sack, and Wright (2007), as in Lloyd (2017a). I convert the T-Bill rates from their discount basis to the yield basis. The availability of US OIS rates is detailed in the appendix of Lloyd (2017b). I estimate the US GADTSM using 3, 6, 12 and 24-month UK OIS rates, as in Lloyd (2017a).

B Model Derivation

This appendix provides mathematical derivations for expressions in section 3.

B.1 Households

The Home household problem maximises its discounted expected lifetime utility (1) subject to (8), the Home household budget constraint in units of the Home consumption basket. The associated optimality conditions are given by (12)-(13), where $r_t = R_{t-1}/\pi_t$, $r^*_t = \mathcal{Q}_t/(\mathcal{Q}_{t-1}P^*_t Z^*_{t-1})$, $r_{L,t} = (R_{L,t}P_{L,t})/(\pi_t P_{L,t-1})$ and $r^*_{L,t} = (R^*_{L,t}\mathcal{E}_t P^*_{L,t})/(\pi_t \mathcal{E}_{t-1} P^*_{L,t-1})$.

The Home household budget constraint can be expressed in nominal terms:

$$
\begin{aligned}
&P_t C_t + \check{B}_{HH,t} + e^{-\zeta_{F,t}}\mathcal{E}_t \check{B}_{HF,t} + P_{L,t}\check{B}^L_{HH,t} + e^{-\zeta_{F,t}}\mathcal{E}_t P^*_{L,t}\check{B}^L_{HF,t} + e^{-\zeta_{S,t}}\check{S}_{HH,t} + \\
&e^{-\zeta^*_{S,t}}e^{-\zeta_{F,t}}\mathcal{E}_t\check{S}_{HF,t} = P_t w_t L_t + P_t\Pi_t - P_t T_t + \check{B}_{HH,t-1}R_{t-1} + \check{B}_{HF,t-1}\mathcal{E}_t R^*_{t-1} + \\
&\check{B}^L_{HH,t-1}(1+\kappa P_{L,t}) + \check{B}^L_{HF,t-1}\mathcal{E}_t(1+\kappa P^*_{L,t}) + \check{S}_{HH,t-1}\frac{P_t}{P_{t-1}}r_{e,t} + \check{S}_{HF,t-1}\frac{P_t\mathcal{E}_{t-1}}{P_{t-1}}r^*_{e,t}
\end{aligned}
$$

where $\check{B}_{jk,t}$, $\check{B}^L_{jk,t}$ and $\check{S}_{jk,t}$ denote country-j holdings of country-k short-term bonds, long-term bonds and equity, respectively, in units of issuing country's currency. To attain the Home household budget constraint in units of the Home consumption basket (8) from this, divide through by P_t, define

$$
\begin{aligned}
B_{HH,t} = \frac{\check{B}_{HH,t}}{P_t},\quad B_{HF,t} = \frac{\mathcal{E}_t\check{B}_{HF,t}}{P_t},\quad B^L_{HH,t} = \frac{P_{L,t}\check{B}^L_{HH,t}}{P_t},\\
B^L_{HF,t} = \frac{\mathcal{E}_t P^*_{L,t}\check{B}^L_{HF,t}}{P_t},\quad S_{HH,t} = \frac{\check{S}_{HH,t}}{P_t},\quad S_{HF,t} = \frac{\mathcal{E}_t\check{S}_{HF,t}}{P_t}
\end{aligned}
$$

and use the definitions of r_t, r^*_t, $r_{L,t}$, $r^*_{L,t}$, $r_{e,t}$ and $r^*_{e,t}$ provided in section 3.1.2.

The Foreign household problem maximises its discounted expected lifetime utility subject to the Foreign household budget constraint, expressed in units of the Foreign consumption basket:

$$
\begin{aligned}
C^*_t + \mathcal{Q}_t^{-1}&\left(B_{FH,t} + e^{-\zeta_{F,t}}B_{FF,t} + B^L_{FH,t} + e^{-\zeta_{F,t}}B^L_{FF,t} + e^{-\zeta_{S,t}}S_{FH,t} + e^{-\zeta_{F,t}}e^{-\zeta_{S^*,t}}S_{FF,t}\right)\\
&= w^*_t L^*_t + \Pi^*_t - T^*_t + \mathcal{Q}_t^{-1}\left(B_{FH,t-1}r_t + B_{FF,t-1}r^*_t + B^L_{FH,t-1}r_{L,t} + \right.\\
&\qquad \left. B^L_{FF,t-1}r^*_{L,t} + S_{FH,t-1}r_{e,t} + S_{FF,t-1}r^*_{e,t}\right)
\end{aligned}
$$

The associated optimality conditions are:

$$
w^*_t = e^{\zeta^*_{L,t}}\left(C^*_{X,t}\right)^{\sigma}\left(L^*_t\right)^{\frac{1}{\nu}} \tag{47}
$$

$$
1 = \mathbb{E}_t\left[\beta\left(C^*_t\right)e^{\Delta\zeta^*_{C,t+1}}e^{\zeta_{i,t}}\left(\frac{C^*_{X,t+1}}{C^*_{X,t}}\right)^{-\sigma}\frac{\mathcal{Q}_t}{\mathcal{Q}_{t+1}}r_{i,t+1}\right] \quad \text{where } i = 1, 2, ..., 6 \tag{48}
$$

where $C^*_{X,t} \equiv C^*_t - \gamma C^*_{t-1}$, $\zeta_{1,t} \equiv 0$, $\zeta_{2,t} \equiv \zeta_{F,t}$, $\zeta_{3,t} \equiv 0$, $\zeta_{4,t} \equiv \zeta_{F,t}$, $\zeta_{5,t} \equiv \zeta_{S,t}$, $\zeta_{6,t} \equiv \zeta_{F,t} + \zeta_{S^*,t}$, $r_{1,t+1} \equiv r_{t+1}$, $r_{2,t+1} \equiv r^*_{t+1}$, $r_{3,t+1} \equiv r_{L,t+1}$, $r_{4,t+1} \equiv r^*_{L,t+1}$, $r_{5,t+1} \equiv r_{e,t}$, and $r_{6,t+1} \equiv r^*_{e,t}$.

B.1.1 Within-Period Consumption

An expenditure minimisation problem for Home households with (4), and similarly for Foreign households, provides Home consumer demand for Home goods $C_{H,t}$, Home consumer demand for Foreign goods $C_{F,t}$, Foreign consumer demand for Home goods $C^*_{H,t}$, and Foreign consumer demand for Foreign goods $C^*_{F,t}$:

$$C_{H,t} = a_H \left(\frac{P_{H,t}}{P_t}\right)^{-\phi} C_t, \quad C_{F,t} = (1-a_H)\left(\frac{P_{F,t}}{P_t}\right)^{-\phi} C_t$$
$$C^*_{H,t} = a^*_H \left(\frac{P^*_{H,t}}{P^*_t}\right)^{-\phi} C^*_t, \quad C^*_{F,t} = (1-a^*_H)\left(\frac{P^*_{F,t}}{P^*_t}\right)^{-\phi} C^*_t$$

These expenditure minimisation problems also yield Home and Foreign consumer price indices:

$$P_t = \left[a_H P_{H,t}^{1-\phi} + (1-a_H) P_{F,t}^{1-\phi}\right]^{\frac{1}{1-\phi}}, \quad P^*_t = \left[a^*_H \left(P^*_{H,t}\right)^{1-\phi} + (1-a^*_H)\left(P^*_{F,t}\right)^{1-\phi}\right]^{\frac{1}{1-\phi}}$$

B.2 Firms

Output in each country is produced by a continuum of monopolistically competitive firms. The production function for a good produced by firm $h \in (0,1)$ in the Home country is (14).

B.2.1 Marginal Cost of Production

The Home firm chooses factor inputs to minimise real total costs tc_t:

$$\min_{\{L_t(h), X_t(h)\}} tc_t(h) = w_t L_t(h) + X_t(h)$$

subject to their production function (14). This yields the following optimal factor demands:

$$L_t(h) = Y_t(h) e^{-a_t} \left(\frac{1}{w_t}\frac{1-\alpha}{\alpha}\right)^{\alpha}, \quad X_t(h) = Y_t(h) e^{-a_t}\left(w_t \frac{\alpha}{1-\alpha}\right)^{1-\alpha}$$

With these factor demands, real total costs for firm h are:

$$tc_t(h) = Y_t(h) e^{-a_t} \frac{w_t^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}}$$

so the real marginal cost function for the Home firm is:

$$mc_t = e^{-a_t}\frac{w_t^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}}$$

which is the same for all Home firms, because each firm faces the same aggregate productivity shock and real wage. A similar expression exists for Foreign firms:

$$mc^*_t = e^{-a^*_t}\frac{(w^*_t)^{1-\alpha}}{(1-\alpha)^{1-\alpha}\alpha^{\alpha}} \tag{49}$$

The optimal input demand functions for the Home firms, written in terms of the real marginal cost, are (17) and (18). Similar expressions are attained for the Foreign firm:

$$L_t^* = \frac{(1-\alpha)mc_t^* Y_t^*}{w_t^*} \tag{50}$$

$$X_t^* = \alpha mc_t^* Y_t^* \tag{51}$$

B.2.2 Pricing: Producer Currency Pricing (PCP)

Under PCP, the Home firm's pricing problem is given by (24), with associated optimality conditions (25).

The Home good price index is given by:

$$P_{H,t} = \left[\int_0^1 P_t(h)^{1-\theta}\,\mathrm{d}h\right]^{\frac{1}{1-\theta}}$$

This comprises surviving contracts and newly set prices. Given that in each period a price contract has a probability $1-\xi$ of ending, the probability that a contract signed in period $t-s$ survives until period t and ends in that period is $(1-\xi)\xi^s$. Therefore:

$$P_{H,t} = \left[\int_0^1 \sum_{s=0}^{\infty}(1-\xi)\xi^s \mathcal{P}_{t-s}(h)^{1-\theta}\,\mathrm{d}h\right]^{\frac{1}{1-\theta}}$$

so with PCP, the price indices evolve according to (27) and (28).

B.3 Equilibrium

Here, I derive (34). First, set all shocks to zero in (8) and impose the government budget constraint, $T_t = G_t \equiv 0$:

$$C_t + B_{HH,t} + B_{HF,t} + B^L_{HH,t} + B^L_{HF,t} + S_{HH,t} + S_{HF,t} =$$
$$w_t L_t + \Pi_t + B_{HH,t-1}r_t + B_{HF,t-1}r_t^* + B^L_{HH,t-1}r_{L,t} + B^L_{HF,t-1}r^*_{L,t} + S_{HH,t-1}r_{e,t} + S_{HF,t-1}r^*_{e,t}$$

Then, substitute for real profits Π_t using (19):

$$P_tC_t + P_t(B_{HH,t} + B_{HF,t} + B^L_{HH,t} + B^L_{HF,t} + S_{HH,t} + S_{HF,t}) =$$
$$P_t w_t L_t + P_{H,t}Y_{H,t} + \mathcal{E}_t P^*_{H,t}Y^*_{H,t} - P_t mc_t(Y_{H,t} + Y^*_{H,t}) +$$
$$P_t(B_{HH,t-1}r_t + B_{HF,t-1}r_t^* + B^L_{HH,t-1}r_{L,t} + B^L_{HF,t-1}r^*_{L,t} + S_{HH,t-1}r_{e,t} + S_{HF,t-1}r^*_{e,t})$$

which can be rewritten as:

$$P_tC_t + P_t\sum_{i=1}^{6}\alpha_{i,t} = P_t(1-\alpha)mc_tY_t + P_{H,t}Y_{H,t} + \mathcal{E}_tP^*_{H,t}Y^*_{H,t} - P_tmc_tY_t + P_t\sum_{i=1}^{6}\alpha_{i,t-1}r_{i,t}$$

using (17) and (31), where $\alpha_{i,t}$ and $r_{i,t}$ are defined in the main body of the text. Rearranging:

$$P_t(C_t + \alpha mc_t Y_t) - P_{H,t}Y_{H,t} + P_t \sum_{i=1}^{6} \alpha_{i,t} - P_t \sum_{i=1}^{6} \alpha_{i,t-1} r_{i,t} = \mathcal{E}_t P^*_{H,t} Y^*_{H,t}$$

Using (20) and (21), in a symmetric steady state:

$$P_t \sum_{i=1}^{6} \alpha_{i,t} - P_t \sum_{i=1}^{6} \alpha_{i,t-1} r_{i,t} = \mathcal{E}_t P^*_{H,t} Y^*_{H,t} - P_{F,t} Y_{F,t}$$

returning (34).

C Alternative Price-Setting Regimes

In this appendix, I present two alternative price-setting regimes to PCP: local currency pricing (LCP) (Betts and Devereux, 2000), where firms set prices in the currency of the market in which they sell the goods; and dollar currency pricing (DCP) (Gopinath, 2015), where both the home country and the US (the foreign country) invoice their export prices in dollar terms.

Local Currency Pricing As with PCP, let $\mathcal{P}_t(h)$ denote the price of the Home good in the Home market optimally chosen by firm h who can reset their price at time t. However, unlike under PCP, the Home firm h sets its Foreign price in Foreign currency terms $\mathcal{P}_t^*(h)$ under LCP. The pricing problem for Home firms under LCP can be written as:

$$\max_{\{\mathcal{P}_t(h),\mathcal{P}_t^*(h)\}} \mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} \Bigg[\frac{(\mathcal{P}_t(h))^{1-\theta}}{(P_{H,t+s})^{-\theta}} Y_{H,t+s} + \mathcal{E}_{t+s} \frac{(\mathcal{P}_t^*(h))^{1-\theta}}{(P_{H,t+s}^*)^{-\theta}} Y_{H,t+s}^* \\ - P_{t+s} mc_{t+s} \left(\frac{\mathcal{P}_t(h)}{P_{H,t+s}} \right)^{-\theta} Y_{H,t+s} - P_{t+s} mc_{t+s} \left(\frac{\mathcal{P}_t^*(h)}{P_{H,t+s}^*} \right)^{-\theta} Y_{H,t+s}^* \Bigg]$$

The Home firms' optimality conditions are:

$$\begin{aligned} \mathcal{P}_t(h) &= e^{\mu_t} \frac{\theta}{\theta-1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} mc_{t+s} P_{t+s} P_{H,t+s}^{\theta} Y_{H,t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} P_{H,t+s}^{\theta} Y_{H,t+s}} \\ \mathcal{P}_t^*(h) &= e^{\mu_t} \frac{\theta}{\theta-1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} mc_{t+s} P_{t+s} (P_{H,t+s}^*)^{\theta} Y_{H,t+s}^*}{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s \xi^s \Omega_{t+s} \mathcal{E}_{t+s} (P_{H,t+s}^*)^{\theta} Y_{H,t+s}^*} \end{aligned} \tag{52}$$

where the markup shock μ_t is defined in (26).

The Foreign optimality conditions are:

$$\begin{aligned} \mathcal{P}_t(f) &= e^{\mu_t^*} \frac{\theta}{\theta-1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s^* \xi^s \Omega_{t+s}^* mc_{t+s}^* P_{t+s}^* P_{F,t+s}^{\theta} Y_{F,t+s}}{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s^* \xi^s \Omega_{t+s}^* \mathcal{E}_{t+s}^{-1} P_{F,t+s}^{\theta} Y_{F,t+s}} \\ \mathcal{P}_t^*(f) &= e^{\mu_t^*} \frac{\theta}{\theta-1} \frac{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s^* \xi^s \Omega_{t+s}^* mc_{t+s}^* P_{t+s}^* (P_{F,t+s}^*)^{\theta} Y_{F,t+s}^*}{\mathbb{E}_t \sum_{s=0}^{\infty} \delta_s^* \xi^s \Omega_{t+s}^* (P_{F,t+s}^*)^{\theta} Y_{F,t+s}^*} \end{aligned} \tag{53}$$

where $\Omega_{t+s}^* \equiv \frac{u'(C_{t+s}^*)}{u'(C_t^*)}$ is the discount factor used to evaluate Foreign firm profits.

Because Home and Foreign prices are set independently, the law of one price is violated with any movement of the exchange rate under LCP. Since all producers that reset their price in period t will choose the same price level, there are now four equations that describe the dynamic evolution of the price indices $P_{H,t}$, $P_{H,t}^*$, $P_{F,t}$ and $P_{F,t}^*$:

$$P_{H,t}^{1-\theta} = \xi P_{H,t-1}^{1-\theta} + (1-\xi)\mathcal{P}_t(h)^{1-\theta} \tag{54}$$

$$(P_{H,t}^*)^{1-\theta} = \xi (P_{H,t-1}^*)^{1-\theta} + (1-\xi)\mathcal{P}_t^*(h)^{1-\theta} \tag{55}$$

$$P_{F,t}^{1-\theta} = \xi P_{F,t-1}^{1-\theta} + (1-\xi)\mathcal{P}_t(f)^{1-\theta} \tag{56}$$

$$(P^*_{F,t})^{1-\theta} = \xi(P^*_{F,t-1})^{1-\theta} + (1-\xi)\mathcal{P}^*_t(f)^{1-\theta} \tag{57}$$

Dollar Currency Pricing Gopinath (2015) documents that an overwhelming share of international trade is invoiced in very few currencies, with the dollar the dominant currency. Motivated by this, I investigate the effect of DCP on international risk sharing and the international transmission of shocks.

To implement DCP, firms in the Home country act isomorphically to LCP; they set the domestic prices in the Home currency and their export prices in the Foreign currency — here, the US dollar. In contrast, Foreign firms engage in PCP; they set both domestic and export prices in the Foreign currency.

C.1 Matching the Stylised Facts Under Different Price-Setting Regimes

Table 6 illustrates that the model differs in its ability to match the empirical evidence under different price-setting regimes. Here, I present the steady state portfolio quantities for Home investors under the model's baseline calibration presented in table 2. The PCP model most closely matches the stylised fasts at the baseline trade elasticity ϕ parameterisation of 0.78. Under LCP and DCP, the model quantitatively replicates equity home bias $\widetilde{s}_{HH}$, Home holdings of US-issued equity s_{HF}, and Home holdings of Home-issued short-term debt b^S_{HH}. Both LCP and DCP models are unable to qualitatively match empirical evidence related to holdings of long-term debt and total debt.

Table 7 presents the ranges of value of ϕ within which the steady state portfolio quantities for Home investors are consistent with the empirical evidence.

Table 6: Steady State Portfolio Quantities for Home Investors Under the Model's Baseline Calibration

HOLDINGS	DATA	PCP	LCP	DCP
Total US Assets, t_{HF}	5.54-33.66%	**5.68%**	-2.81%	*1.96%*
Equity Home Bias, $\widetilde{s}_{HH}$	50-100%	**97.09%**	**93.29%**	**95.14%**
US Equity, s_{HF}	2.70-20.71%	**2.77%**	**6.46%**	**4.66%**
Home Debt, b_{HH}	<0%	$\mathbf{-3.71\%}$	7.60%	1.32%
US Debt , b_{HF}	2.84-12.95%	**2.90%**	-9.26%	-2.70
Home Short-Term Debt, b^S_{HH}	<0%	$\mathbf{-2.79\%}$	$\mathbf{-4.80\%}$	$\mathbf{-4.45\%}$
US Short-Term Debt, b^S_{HF}	0.28-1.25%	*1.97%*	*3.12%*	*3.08%*
Home Long-Term Debt, b^L_{HH}	<0%	$\mathbf{-0.93\%}$	12.40%	5.77%
US Long-Term Debt, b^L_{HF}	2.20-12.17%	*0.93%*	-12.39%	-5.78%

Notes: Steady state portfolio quantities under the baseline model calibration, including $\phi = 0.78$. Emboldened values denote quantities that quantitatively match the empirical evidence. Italicised values denote quantities that qualitatively match the empirical evidence. Values that are neither emboldened not italicised do match the empirical evidence qualitatively or quantitatively.

Table 7: Ranges of Values of the Trade Elasticity ϕ within which Steady State Portfolio Quantities for Home Investors are Consistent with Empirical Evidence

HOLDINGS	PCP	LCP	DCP
Total US Assets, t_{HF}	0.690-0.785	0.660-0.755	0.675-0.770
Equity Home Bias, $\widetilde{s}_{HH}$	0.185-0.205, 0.640-0.790	0.185-0.200, 0.650-0.805	0.185-0.200, 0.645-0.795
US Equity, s_{HF}	0.725-0.785	0.735-0.795	0.730-0.790
Home Debt, b_{HH}	0.005-0.880	0.005-0.195, 0.205-0.485	0.005-0.740
US Debt, b_{HF}	0.325-0.380, 0.775-1.295	0.275-0.290, 1.045-1.345	0.295-0.320, 0.940-1.320
Home Short-Term Debt, b^S_{HH}	0.005-0.790	0.005-0.790	0.010-0.790
US Short-Term Debt, b^S_{HF}	0.780-0.785	0.780-0.790	0.780-0.790
Home Long-Term Debt, b^L_{HH}	0.775-2.500	0.205-0.215, 0.805-2.500	0.790-2.500
US Long-Term Debt, b^L_{HF}	0.780-0.805	0.810-0.835	0.795-0.820

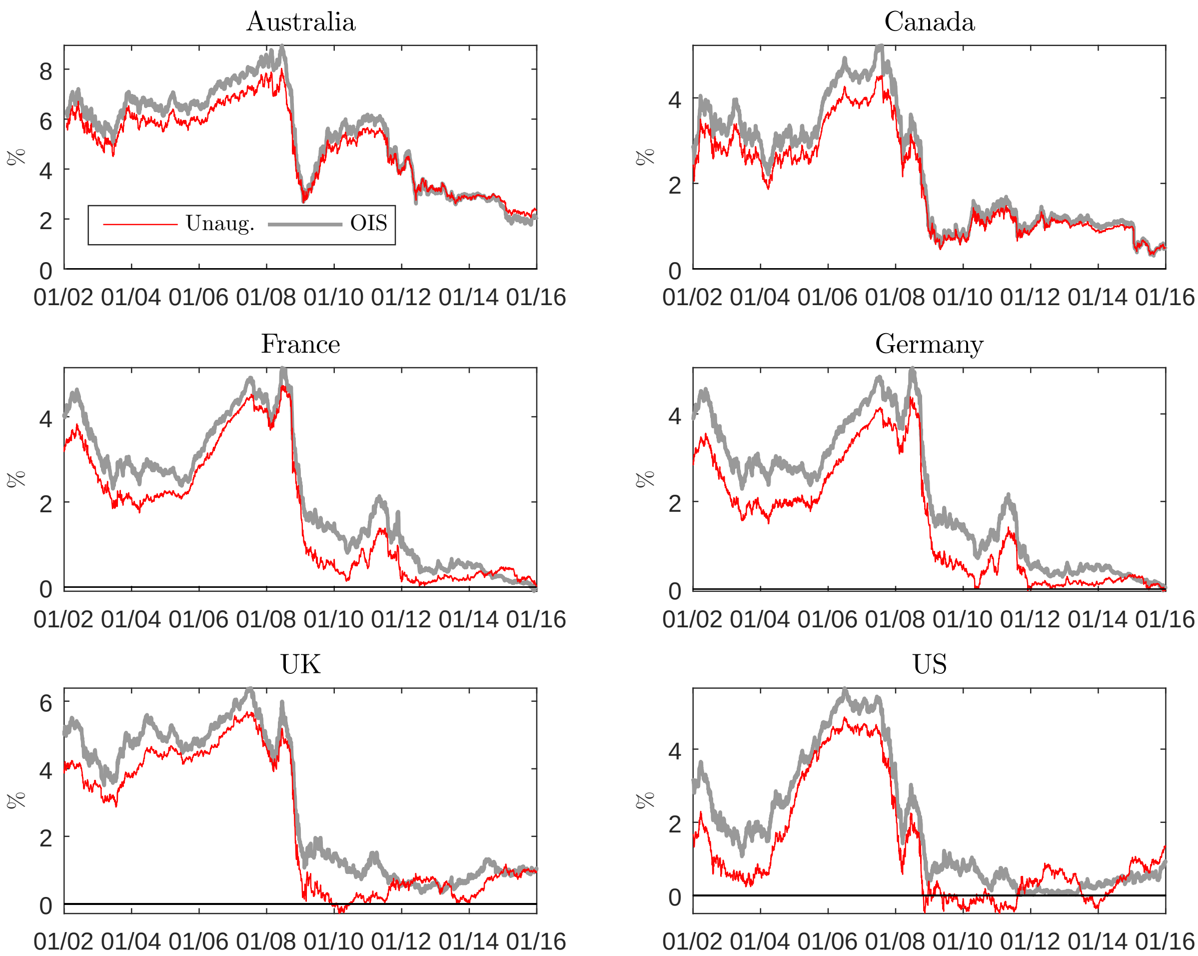
Notes: Ranges of values of the trade elasticity ϕ within which the steady state portfolio quantities of the model, presented in section 3, are consistent with the empirical evidence presented in section 2.2. I solve the model for values of ϕ ranging from 0.005 to 2.500, in increments of 0.005.

D Estimates of the OIS-Augmented GADTSM

In this appendix, I present additional information regarding the estimates of the OIS-augmented GADTSM (Lloyd, 2017a) for Australia, Canada, France, Germany, the UK and the US. This is the first paper to apply the proposal of Lloyd (2017a) to countries other than the US and UK. The results further support the conclusions in Lloyd (2017a).

Figure 11 presents the 2-year risk-neutral interest rate expectations from the unaugmented and OIS-augmented models. Although the risk-neutral yields from the two models follow broadly similar patterns, risk-neutral yields from the unaugmented model are more often negative.

Figure 11: 2-Year Risk-Neutral Yield from the Unaugmented and OIS-Augmented GADTSMs, January 2002 to December 2015



Note: 2-year risk-neutral yields from two GADTSMs: (i) unaugmented GADTSM, estimated using the algorithm of Joslin et al. (2011); and (ii) the OIS-augmented GADTSM, estimated using the algorithm of Lloyd (2017a). The models are estimated with three pricing factors, using daily data from January 2, 2002 to December 31, 2015. All figures are in annualised percentage points.

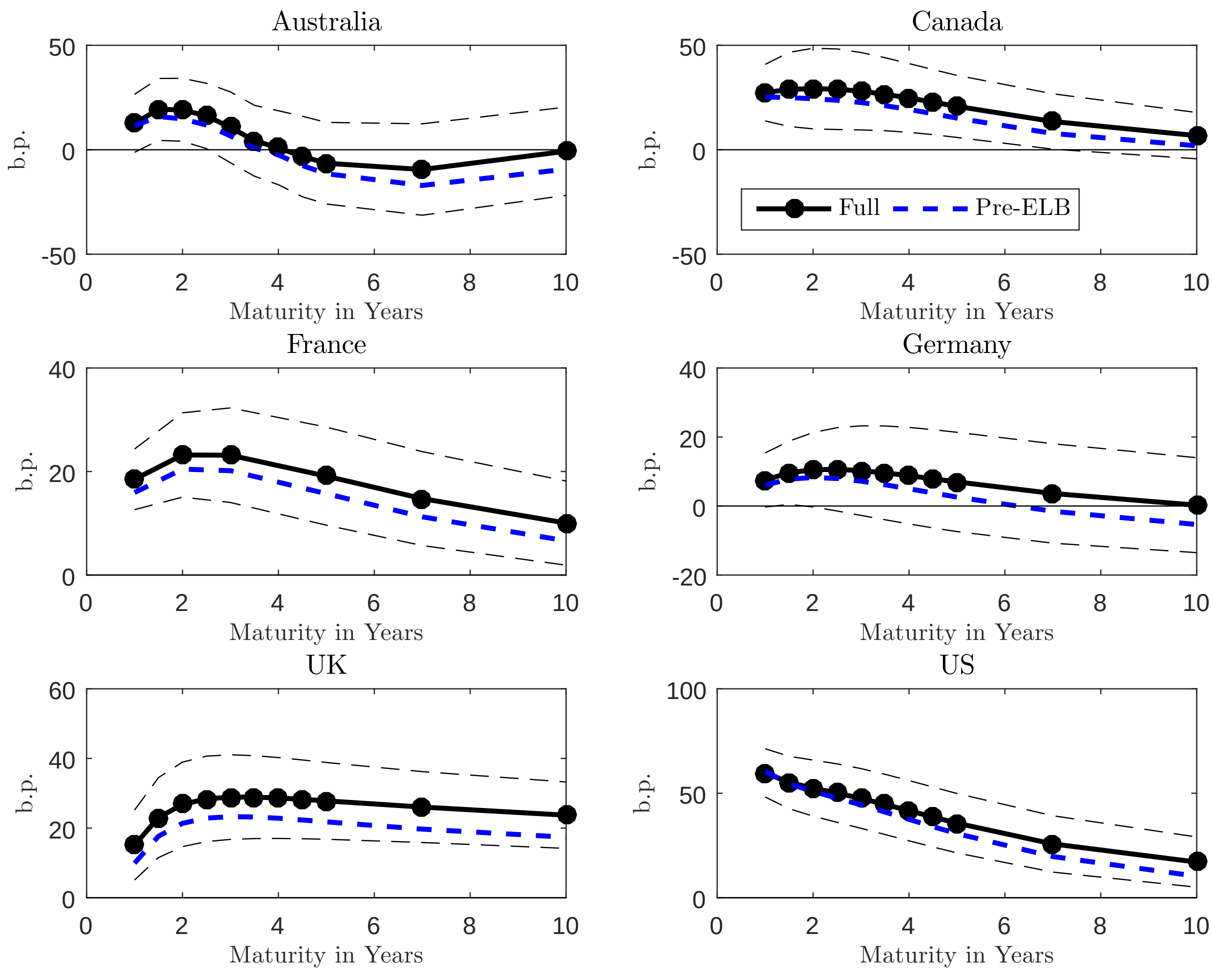
E Event Study Robustness Analysis

In this appendix, I present additional estimates of the event study regression (43) to demonstrate the robustness of the results.

Figures 12-14 present the coefficients from (43) estimated using a shorter sub-sample of US monetary policy announcements pertaining to the pre-ELB period. Specifically, the sample runs from January 2002 to November 2008, the month prior to when the US federal funds rate target reached its ELB. In figures 13 and 14, I use interest rate expectations and term premia from the OIS-augmented model (Lloyd, 2017a). All three figures illustrate that the estimated coefficients using the pre-ELB sample lie within the confidence intervals for the estimated coefficients from the whole sample. Moreover, the estimated coefficients from the pre-ELB sample are close to the point estimates from the whole sample.

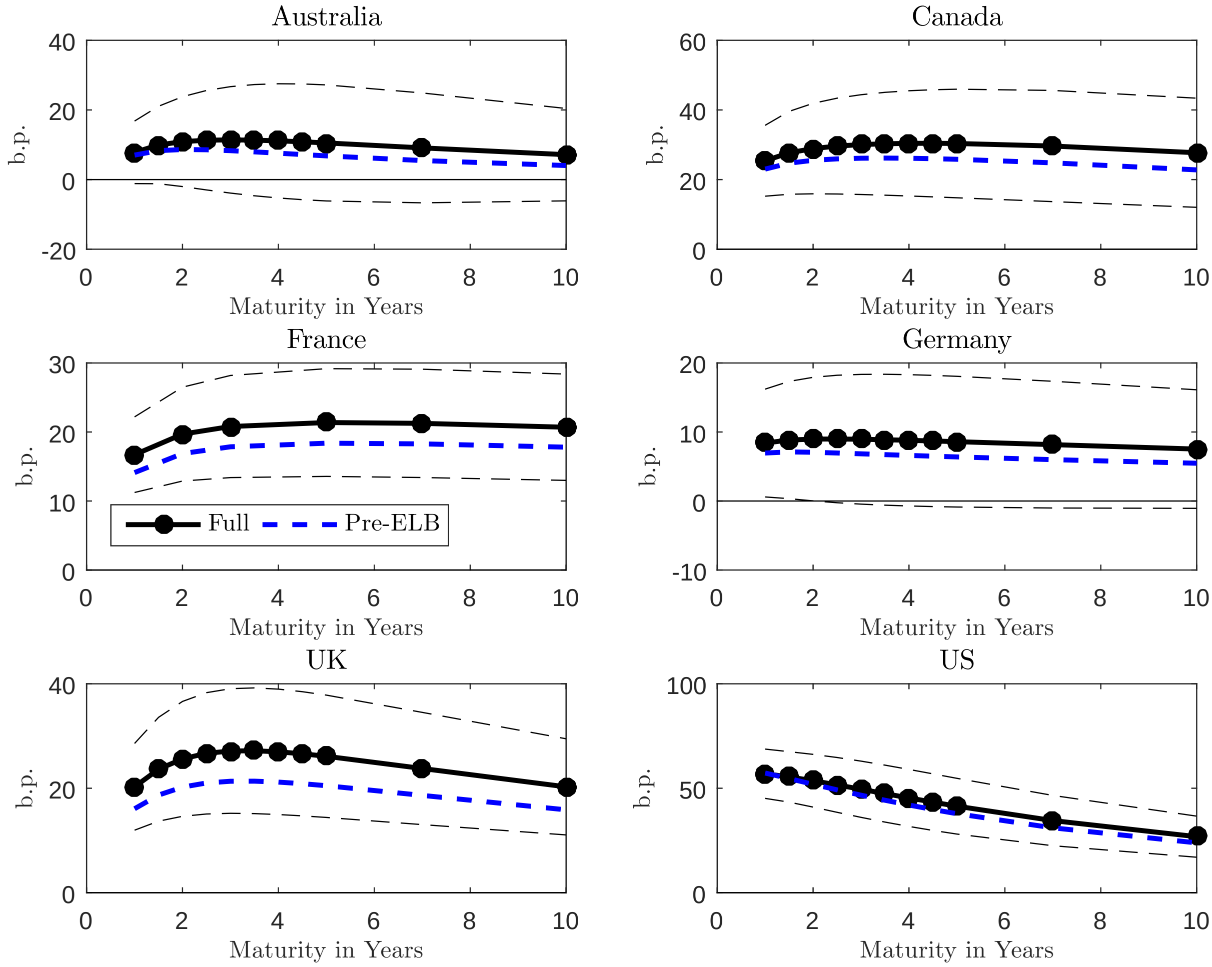
Figure 15 compares the estimated coefficients from OIS-augmented GADTSM and an unaugmented model, estimated using the Joslin et al. (2011) algorithm. Interest rate expectations are the dependent variable. The figure illustrates that the estimated coefficients from the two models are similar. In all countries, except the UK, the estimated coefficients from the unaugmented model lie within the confidence bands for the OIS-augmented model at all maturities. In the UK, the estimated coefficients from the unaugmented model are smaller than those from the OIS-augmented model, albeit of the same sign.

Figure 12: Impact Response of Bond Yields to a Surprise US Monetary Policy Tightening of 100 Basis Points for the Whole Sample and a Pre-ELB Sample



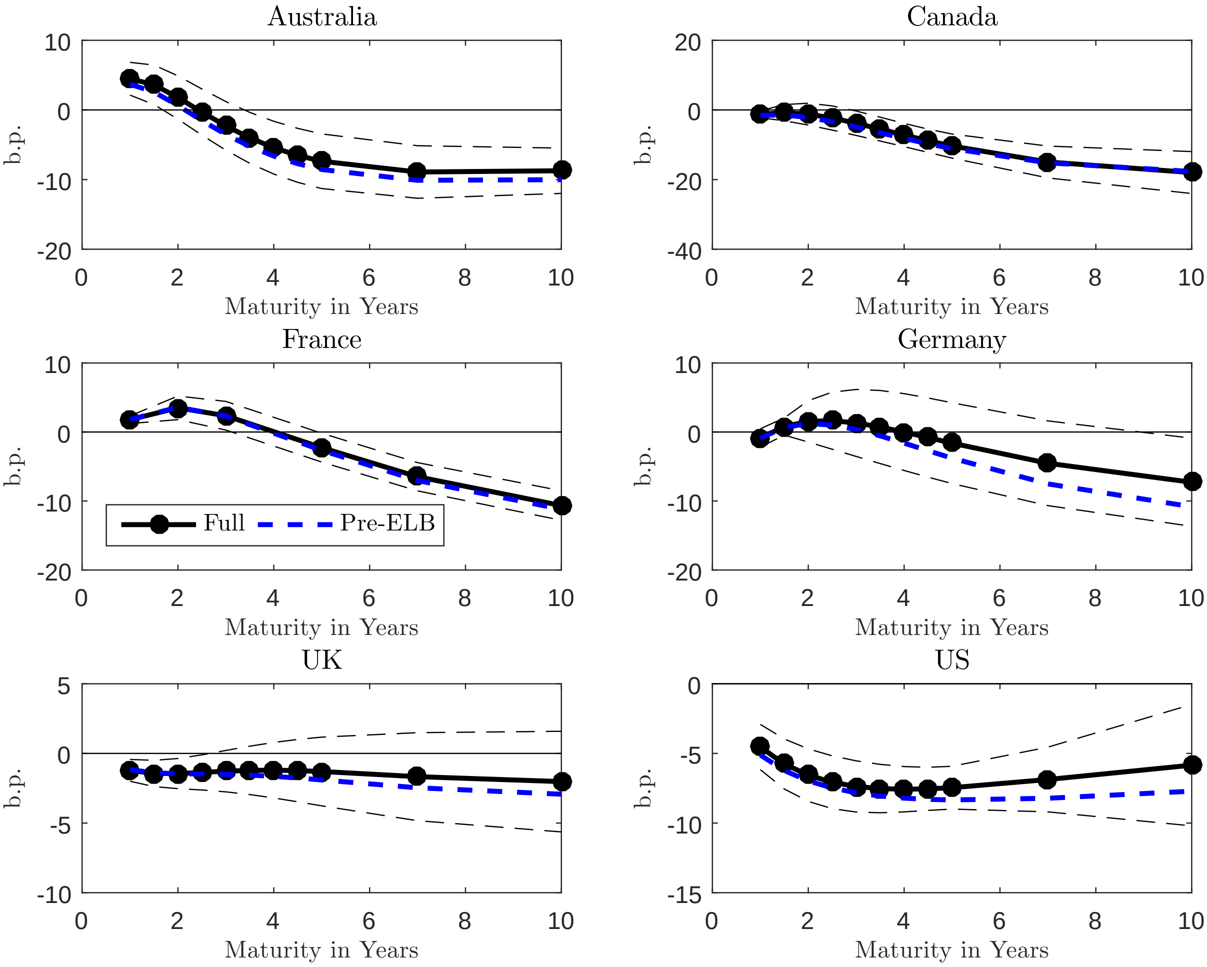
Note: The black line denotes the impact response of (annualised) longer-term interest rates of different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated β_L coefficients in equation (43) for the full 2002-2015 sample ('Full'). The thin dashed black lines represent the 95% confidence interval around these estimated coefficients, constructed using robust standard errors. The thick dashed blue line denotes the corresponding estimates from a pre-ELB sample, running from January 2002 to November 2008 ('Pre-ELB'). The horizontal axis denotes the maturity of the interest rate in years. Interest rates are zero-coupon government bond yields. The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rates in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005).

Figure 13: Impact Response of Interest Rate Expectations to a Surprise US Monetary Policy Tightening of 100 Basis Points for the Whole Sample and a Pre-ELB Sample



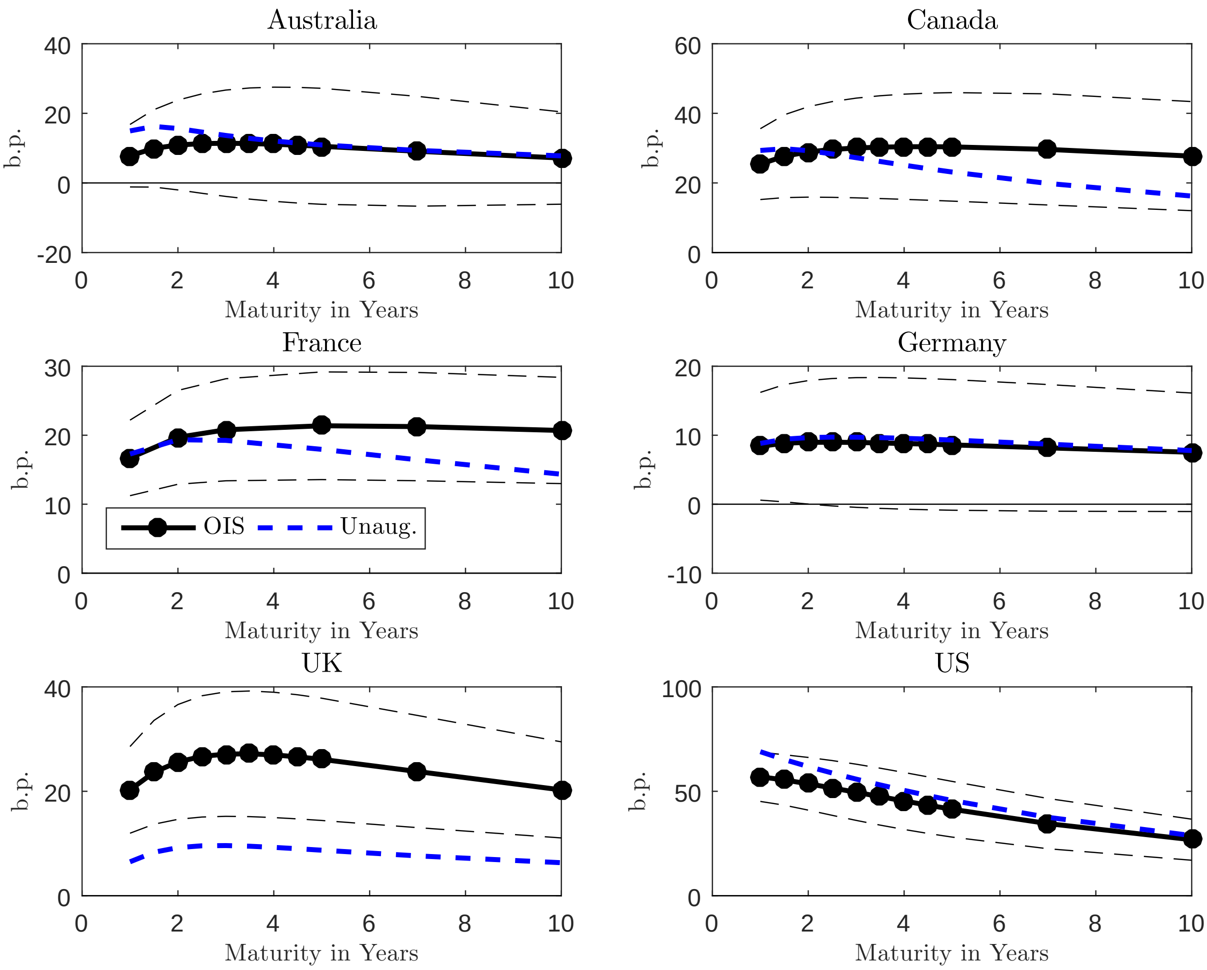
Note: The black line denotes the impact response of interest rate expectations of different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated $\beta_{L,e}$ coefficients in equation (45) for the full 2002-2015 sample ('Full'). The thin dashed black lines represent the 95% confidence interval around these estimated coefficients, constructed using robust standard errors. The thick dashed blue line denotes the corresponding estimates from a pre-ELB sample, running from January 2002 to November 2008 ('Pre-ELB'). The horizontal axis denotes the maturity of the interest rate in years. Interest rates are zero-coupon government bond yields. The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rates in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005).

Figure 14: Impact Response of Term Premia to a Surprise US Monetary Policy Tightening of 100 Basis Points for the Whole Sample and a Pre-ELB Sample



Note: The black line denotes the impact response of term premia at different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated $\beta_{L,tp}$ coefficients in equation (46) for the full 2002-2015 sample ('Full'). The thin dashed black lines represent the 95% confidence interval around these estimated coefficients, constructed using robust standard errors. The thick dashed blue line denotes the corresponding estimates from a pre-ELB sample, running from January 2002 to November 2008 ('Pre-ELB'). The horizontal axis denotes the maturity of the interest rate in years. Interest rates are zero-coupon government bond yields. The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rates in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005).

Figure 15: Impact Response of Interest Rate Expectations to a Surprise US Monetary Policy Tightening of 100 Basis Points using the OIS-Augmented GADTSM and the Unaugmented GADTSM



Note: The black line denotes the impact response of interest rate expectations of different maturities in Australia, Canada, France, Germany, the UK and the US to a surprise US monetary tightening of 100 basis points, corresponding to the estimated $\beta_{L,e}$ coefficients in equation (45). The horizontal axis denotes the maturity of the interest rate expectations in years. The interest rate expectations are estimated using the OIS-augmented GADTSM of Lloyd (2017a) ('OIS'). The monetary policy surprise is measured using the intraday movement in the current month federal funds futures rates in a thirty minute window around an FOMC announcement (Gürkaynak et al., 2005). The thin dashed black lines represent the 95% confidence intervals around the estimated coefficients, constructed using robust standard errors. The estimates are constructed using data from January 2002 to December 2015. The thick dashed blue line denotes the corresponding estimates using the interest rate expectations estimates from the unaugmented GADTSM (Joslin et al., 2011) ('Unaug.').

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