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Oil Price Shocks and Bond Risk Premia: Evidence from a Panel of 15 Countries¹

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Abstract

We study the effect of oil price shocks on bond risk premia. Based on Baumeister and Hamilton (2019), we identify the different sources of oil price shocks using a structural vector autoregressive (SVAR) model of the global market for crude oil. These structural factors are then used as unspanned factors in an affine term structure model based on the representation of (Joslin et al., 2014). This is done for a total of 15 countries. Unspanned factors are responsible for most of the variability in bond risk premia for short holding periods, while spanned factors dominate the variance decomposition for longer holding periods. In both cases, global oil supply and global economic activity are clearly the most important unspanned shocks. A historical decomposition around the outbreak of the COVID-19 crisis shows the clear influence of global economic activity shocks during the months of February and March 2020, increasing bond risk premia significantly.

Keywords: oil prices shocks, affine term structure models, bond risk premia

JEL: C11, E43, E44, Q43

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1. Introduction

Crude oil is probably the most important commodity for the global economy. Its impact on aggregate economic activity was first pointed out by Hamilton (1983). Since then, a number of studies has analyzed its effect on various macroeconomic and financial market variables.²

Due to the size of the global bond market³, and the importance of the term structure of interest rates for investors and central bankers, among others,⁴ this paper assesses the contribution of the different sources of oil price shocks to movements in bond risk premia.

For fixed income investors, bond risk premia (expected excess returns) indicate the reward risk averse agents require to hold riskier long-maturity bonds for a short period of time rather than riskless bonds for the same time period. For central bankers, in turn, bond premia are key drivers of the transmission mechanism linking changes in short-term rates (a central bank's primary monetary policy instrument) with changes in the entire yield curve. This is particularly the case for its long end, which has an important effect, for example, on aggregate demand. In both cases, it is thus crucial to understand the primary sources of fluctuations in yield risk premia.

In this respect, we base our study on two well-established results in the literature. First, the rejection of the expectations hypothesis of interest rates. According to this theory, bond risk premia are constant (weak form) or zero (strong form).⁵ In our setting, bond premia are time varying and a function of two types of risk factors (described below). Second, the empirical evidence linking macroeconomic variables to the term structure of interest rates. Some studies show that macroeconomic variables account for a large part of the

²For example, see the studies related to economic activity, Azad and Serletis (2022), inflation and interest rates, Cologni and Manera (2008), unemployment, Kocaaslan (2019), economic activity and exchange rates, Śmiech et al. (2021), the stock market, Park and Ratti (2008) and Clements et al. (2019), and the yield curve, Ioannidis and Ka (2018) and Cepni et al. (2022).

³According to Cepni et al. (2022), the global bond market exceeds USD100 trillion, in comparison to USD65 trillion for the global equity market.

⁴See Piazzesi (2010) for a description of the agents interested in the yield curve dynamics.

⁵Studies rejecting the expectations hypothesis include Fama and Bliss (1987), Stambaugh (1988), Campbell and Shiller (1991), Bekaert and Hodrick (2001), Cochrane and Piazzesi (2005), and Sarno et al. (2007).

variation in bond yields.⁶ Others find that macro variables are able to predict bond-holding period returns.⁷ We use a set of structural shocks to the global oil market as our macroeconomic variables.

Beyond these premises, the approach adopted in this paper involves two important methodological issues. First, the correct identification strategy of the underlying sources driving oil price shocks. We discuss briefly two possibilities and the ongoing debate in the literature.⁸ Second, the appropriate model for the yield curve. The debate here is centered around the spanning hypothesis implied by a generation of yield curve models.

Regarding the identification strategy of the structural shocks, the first method is due to the seminal contribution of Kilian (2009).⁹ He applies a Cholesky identification strategy to a structural model of the global crude oil market. His three-equation system includes measures of global crude oil production, global real economic activity, and the real price of oil. This identification scheme has strong implications for the estimation of some of the structural parameters. For example, it implies that global oil supply has no contemporaneous response to the price of oil. On the other hand, it imposes no restrictions regarding the response of global oil demand to changes in the oil price.

According to Baumeister and Hamilton (2019), this approach can be viewed as a special case of Bayesian inference with very strong prior beliefs. Using our illustration above, it implies that the econometrician knows with certainty that oil supply has no immediate response to changes in the oil price. But it also means that the econometrician has absolutely no useful information regarding the response of oil demand to the price of oil. This is what they call the “all or nothing” characteristic of the prior information used in structural models.

⁶See Ang and Piazzesi (2003), Dewachter et al. (2006), Hördahl et al. (2006), Bekaert et al. (2010), and Bikbov and Chernov (2010), among others.

⁷For example, Cooper and Priestley (2009), Ludvigson and Ng (2009), and Bikbov and Chernov (2010). Interestingly, Sarno et al. (2016) show that even a model that jointly fits bond yields and bond excess returns cannot outperform the expectations hypothesis out-of-sample in terms of economic value.

⁸Ready (2018) proposes an alternative method of classifying changes in oil prices as demand or supply driven at daily frequency. This technique has been applied, for example, by Demirer et al. (2020) and Umar et al. (2022).

⁹This method is applied by Lee et al. (2017), Ioannidis and Ka (2018), and Filippidis et al. (2020), among others.

Baumeister and Hamilton (2019), therefore, propose a method of identification that tries to find a middle ground between those extremes. The authors suggest the use of a Bayesian approach, allowing the econometrician to express the degree of uncertainty regarding each of the structural parameters.¹⁰

One common message between Kilian (2009) and Baumeister and Hamilton (2019) is the fact that different structural shocks to the oil market have different impacts on the real price of oil. Nevertheless, these authors disagree on the relative importance of such shocks. For example, Kilian finds that oil supply disruptions have a small and transitory increase in the price of oil. The results from Baumeister and Hamilton, however, give more importance to this type of shock when they consider the historical movements in the oil price.

In this paper, we adopt the identification methodology of Baumeister and Hamilton (2019) applied to a structural system composed of: *(i)* a global oil supply curve; *(ii)* an equation describing the global economic activity; *(iii)* an oil-specific global demand equation; and *(iv)* an equation describing global inventory demand. Their methodology avoids the hard restrictions on the set of parameter estimates mentioned before and gives more flexibility in the use of prior information regarding each structural parameter. We believe this might lead to a better estimation of the bond risk premium dynamics.

The second methodological issue relates to the specification of the appropriate model for the term structure of interest rates. Such model should satisfy a number of requirements, i.e. it should: *(i)* explain both the cross-section and the time series dimension of the yield curve; *(ii)* guarantee the absence of arbitrage opportunities; *(iii)* be econometrically and numerically tractable; and *(iv)* allow for considerable flexibility in the data generating process of the state variables. The class of affine term structure models satisfies all these requirements.¹¹ Ideally, however, such models should also be able to identify the economic forces behind yield curve movements. An important contribution in this direction is given by Ang and Piazzesi (2003).

A number of models followed the same direction incorporating macroe-

¹⁰The debate about these two methods of identification is expressed in Baumeister and Hamilton (2020), Kilian (2022), and Kilian and Zhou (2019).

¹¹The framework for (latent) affine term structure models is set out in Duffie and Kan (1996).

conomic and financial variables as possible drivers of bond yields.¹² Most of these models, though, implicitly assume that such risk factors can be expressed as a linear combination of, i.e. are spanned by, bond yields. This is the so-called spanning hypothesis. It also implies that the current yield curve contains all the relevant information necessary to predict future interest rates.

In an important contribution, however, Joslin et al. (2014) reject the spanning hypothesis. They regress bond returns on various macroeconomic variables controlling for information in the yield curve. They find that macro variables contain additional predictive power to forecast bond returns. Based on these results, these authors introduce macroeconomic variables as unspanned factors in otherwise standard affine models. They adopt the representation proposed by Joslin et al. (2011), which uses a small number of observable yield portfolios (spanned factors) to model the cross-section of the yield curve. In this way, although unspanned factors do not impact directly on bond yields, they may still have predictive content for bond excess returns beyond the information contained in bond yields.

That appeared to be an optimal solution, allowing one to keep the desirable features of affine yield models with the necessary flexibility to model the dynamics of risk premia. A candidate for a consensus model seemed in sight. Bauer and Hamilton (2018), nevertheless, contest this result. They propose a number of robust tests and challenge the previous rejection of the spanning hypothesis. Bauer and Rudebusch (2017) also support the original spanned models. They show that simply by incorporating small yield measurement errors one could (inappropriately) conclude in favor of the presence of unspanned macroeconomic information in the data.

Finally, a recent study by Bekaert et al. (2021) brings once more evidence against the spanning hypothesis, keeping the debate alive. They show that macroeconomic factors are significant predictors of bond excess returns, even after controlling for yield curve factors. Furthermore, these results are obtained using the robust tests proposed by Bauer and Hamilton (2018).

In this study, we follow Joslin et al. (2014) and adopt the class of macro-finance term structure models (MTSMs) with both spanned and unspanned factors. Our unspanned factors are obtained from the structural vector au-

¹²See Gürkaynak and Wright (2012) for a review of such models, and Dewachter and Iania (2011) for a model with financial variables as risk factors.

toregressive (SVAR) model of the global market for oil of Baumeister and Hamilton (2019). The spanned factors are represented by the level, slope, and curvature of the yield curve.¹³

We apply our framework to monthly data for 15 countries with different profiles. This allows us to evaluate how the response of bond risk premia depends on: (i) the type of shock hitting the global economy (demand or supply, mainly); (ii) the country’s economic situation (developing or developed); (iii) the country’s position in the oil market (net oil-exporter or net oil-importer); and (iv) the maturity of the bond. We include a wide range of maturities, from three months to 10 years, and, depending on the country, we cover a period spanning from March 2007 to February 2024 -the shortest sample - and from June 1977 to February 2024 - the longest sample.

We contribute to the literature in two dimensions. Our first contribution is methodological. As just mentioned, we combine the methodology of Baumeister and Hamilton (2019), which allows us to identify the sources of oil price shocks, with the yield curve representation proposed by Joslin et al. (2014), which allows us to use the oil factors as unspanned factors in the term structure model. Our second contribution is empirical. We analyze the effect of each oil factor on the risk premia of bonds from 15 countries, with different positions in the oil market and levels of development, and with a wide range of maturities.

Our model specification is able to fit the yield curve for the 15 countries rather well. Since we use three spanned factors, and based on the seminal work of Litterman and Scheinkman (1991), this is actually not surprising.¹⁴ More importantly, the fit of the realized excess returns is also satisfactory.

Regarding the unspanned factors, we obtain the expected response of bond risk premia to global economic shocks and oil supply shocks in most of the cases. Nevertheless, Russia stands out as having a different response to these shocks in comparison with the other oil-exporting countries. Interestingly, we find that unspanned factors explain most of the variability in bond risk premia for short holding periods, while spanned factors dominate the variance decomposition for longer holding periods. In both cases, global oil supply and global economic activity are clearly the most important un-

¹³In this respect, we differ from Joslin et al. (2011), who propose the use of the first three principal components of the yield data as the spanned factors.

¹⁴Litterman and Scheinkman (1991) show that three factors (labelled level, slope, and curvature) are able to capture most of the variation in US bond yields.

spanned shocks. Finally, a historical decomposition around the outbreak of the COVID-19 crisis shows the impact of global economic activity shocks during the months of February and March 2020, increasing bond risk premia significantly.

The remainder of the paper is organized as follows. Section 2 describes the model specification, including the standard term structure setting, the structure model for the global oil market, and the representation making use of both spanned and unspanned factors. Section 3 presents the estimation procedure and the data for the 15 countries in our sample. Section 4 presents the results of the paper and is divided in two parts. The first part presents a model evaluation while the second part analyzes the relative importance of each structural shock for the dynamics of bond risk premia of the different groups of countries. This is done by means of impulse response functions (IRFs), variance decompositions, and a historical decomposition. Concluding remarks are presented in Section 5.

2. The model

As mentioned before, our modelling specification has two key ingredients: (i) the SVAR model, which allows the identification of four global oil price factors, in the spirit of Baumeister and Hamilton (2019); and (ii) the term structure specification, modelling bond prices, which is based on the class of MTSMs with both spanned and unspanned factors, as in Joslin et al. (2014).

For each country, the cross-section of yields is an affine function of a set of spanned risk factors. These factors are labelled *spanned* since they are represented by a linear combination of bond yields – the so-called yield portfolios. The factor loadings on each bond is obtained from no-arbitrage restrictions (see Ang and Piazzesi (2003), among others). The dynamics of the yield portfolios (under the historical measure), however, is represented by means of a SVAR model, including both the yield curve portfolios (spanned factors) and the four global oil price factors (unspanned factors).

Although the model is estimated separately for each country, the global unspanned factors are the same in all cases (the common factors among the 15 countries). Based on the affine yield curve representation and the SVAR dynamics, we assess the relative contribution of each macroeconomic variable (global oil factor) in the yield curve dynamics of each country.

2.1. The basic affine term structure setting

To fix notation, we denote by $y_t^{(n)}$ the zero-coupon yield of the n -period bond of a certain country. We call Y_t the vector collecting the yields for N maturities at time t . We employ a Gaussian affine no-arbitrage setting to price the government bonds, which is equivalent to expressing Y_t as an affine function of the risk factors $\mathbf{Z}_t$, identified in Section 2.2.

We impose that (i) the one-period zero-coupon rate, $y_t^{(1)}$, is an affine function of $\mathbf{Z}_t$; and (ii) the risk factors have affine Gaussian dynamics under both the risk-neutral and historical probability measures, $\mathbb{Q}$ and $\mathbb{P}$, respectively:

$$y_t^{(1)} = \rho_0 + \boldsymbol{\rho}'_1 \mathbf{Z}_t, \quad (1)$$

$$\mathbf{Z}_t = \boldsymbol{\mu}^i + \boldsymbol{\Phi}^i \mathbf{Z}_{t-1} + \boldsymbol{\Sigma} \boldsymbol{\varepsilon}_t^i, \quad \boldsymbol{\varepsilon}_t^i \sim \mathcal{N}(\mathbf{0}, \mathbf{I}) \text{ and } i = \mathbb{Q}, \mathbb{P}, \quad (2)$$

where ρ_0 , $\boldsymbol{\rho}_1$, $\boldsymbol{\mu}^{\mathbb{Q}}$, $\boldsymbol{\mu}^{\mathbb{P}}$, $\boldsymbol{\Phi}^{\mathbb{Q}}$, $\boldsymbol{\Phi}^{\mathbb{P}}$, and $\boldsymbol{\Sigma}$ are model parameters, while $\mathbf{I}$ is an identity matrix of conformable dimension. The parameters of equation (2) under $\mathbb{Q}$ determine the pricing of the cross-section of yields, while the parameters under $\mathbb{P}$ are key for the risk premium dynamics. The link between the two probability measures is obtained (i) by assuming essentially affine market prices of risk, $\boldsymbol{\Lambda}_t$, and (ii) by expressing the stochastic discount factor, M_t , as an exponentially affine function of $y_t^{(1)}$, $\boldsymbol{\Lambda}_t$ and the system's shocks, $\boldsymbol{\varepsilon}_t^{\mathbb{P}}$, weighted by $\boldsymbol{\Sigma}$:

$$\boldsymbol{\Lambda}_t = \boldsymbol{\Sigma}^{-1} (\boldsymbol{\lambda}_0 + \boldsymbol{\lambda}_1 \mathbf{Z}_t), \quad \boldsymbol{\mu}^{\mathbb{Q}} = \boldsymbol{\mu}^{\mathbb{P}} - \boldsymbol{\lambda}_0, \quad \boldsymbol{\Phi}^{\mathbb{Q}} = \boldsymbol{\Phi}^{\mathbb{P}} - \boldsymbol{\lambda}_1, \quad (3)$$

$$M_t = \exp(-y_t^{(1)} - \frac{1}{2} \boldsymbol{\Lambda}_t' \boldsymbol{\Lambda}_t - \boldsymbol{\Lambda}_t' \boldsymbol{\Sigma} \boldsymbol{\varepsilon}_t^{\mathbb{P}}). \quad (4)$$

Under these assumptions, it is possible to express $y_t^{(n)}$ as an affine function of the risk factors, $\mathbf{Z}_t$:

$$y_t^{(n)} = a_n + \mathbf{b}_n' \mathbf{Z}_t, \quad (5)$$

whereby the weights of (5) derive from standard Riccati equations (see Ang and Piazzesi (2003)). Specifically, $a_n = -n^{-1} a_n$ and $\mathbf{b}_n = -n^{-1} \mathbf{b}_n$

$$a_n = a_{n-1} + b_{n-1}\boldsymbol{\mu}^{\mathbb{Q}} + \frac{1}{2}(b_{n-1})'\boldsymbol{\Sigma}\boldsymbol{\Sigma}'b_{n-1} - \rho_0, \quad (6)$$

$$b_n = (\boldsymbol{\Phi}^{\mathbb{Q}})'b_{n-1} - \boldsymbol{\rho}_1. \quad (7)$$

The next two sections define (i) equation (2) under both measures and (ii) identify the restrictions governing the change of measure and hence the risk premium dynamics.

2.2. Oil shocks and yield curve factors

We follow Baumeister and Hamilton (2019) and identify four structural shocks to the global oil market – shocks to oil supply, economic activity, oil-specific demand, and inventory demand – via a SVAR model with four variables: (i) the monthly growth rate of oil production, q_t ; (ii) a measure of real economic activity, g_t ; (iii) the real price of oil, p_t ; and (iv) the change in world crude oil inventories as a fraction of previous month's world production, $\Delta i_t = \Delta I_t / Q_{t-1}$, where Q_{t-1} is the oil production at $t-1$ and ΔI_t is the monthly change in global inventories. Staking the four variables in the vector $\mathbf{m}_t = [q_t, g_t, p_t, \Delta i_t]'$ and denoting its lagged values in the 12 preceding months by $\mathbf{m}_{1:12}^L = [\mathbf{m}_{t-1}', \dots, \mathbf{m}_{t-12}']'$, we can express the structural model for the global oil market as follows:¹⁵

$$q_t = a_q + \alpha_{qp}p_t + \mathbf{b}_1'\mathbf{m}_{1:12}^L + \varepsilon_{1t}^{\mathbb{P}}, \quad (8)$$

$$g_t = a_g + \alpha_{gp}p_t + \mathbf{b}_2'\mathbf{m}_{1:12}^L + \varepsilon_{2t}^{\mathbb{P}}, \quad (9)$$

$$q_t - \chi^{-1}\Delta i_t = a_d + \alpha_{dg}g_t + \alpha_{dp}p_t + \mathbf{b}_3'\mathbf{m}_{1:12}^L + \varepsilon_{3t}^{\mathbb{P}}, \quad (10)$$

$$\Delta i_t = a_i + \alpha_{ip}p_t + \alpha_{iq}q_t + \mathbf{b}_4'\mathbf{m}_{1:12}^L + \varepsilon_{4t}^{\mathbb{P}}. \quad (11)$$

Equation (8) represents the oil supply curve, whereby oil production (q_t) depends on the real oil price (p_t) and on the lagged (12 months) values of all variables, $\mathbf{m}_{1:12}^L$. Equation (9) models world economic activity in function of the current real price of oil and the lagged values of $\mathbf{m}_t$. Equation (10) models the growth of world's oil consumption demand (net of the relative changes in

¹⁵We use 12 lags for the macroeconomic variables in the structural system as in Baumeister and Hamilton (2019) and Ioannidis and Ka (2018).

oil inventories) as a function of real oil prices, world economic activity, and $\mathbf{m}_{1:12}^L$. Finally, Equation (11) models the relative growth in oil inventories in function of oil production, real oil price, and the lagged values of all variables. As in Baumeister and Hamilton (2019), the parameter χ is the fraction that the OECD oil inventories represent out of the total inventories in the world.

We assume that yield curve movements for a certain country can be summarized by linear combinations of three yield curve portfolios (factors), $\mathcal{L}_t$, $\mathcal{S}_t$, and $\mathcal{C}_t$, which are referred to as level, slope, and curvature, respectively, and represented by $\mathcal{F}_t = (\mathcal{L}_t, \mathcal{S}_t, \mathcal{C}_t)'$. These factors are computed as follows. For each point in time, the level factor is the average of the yields for all the maturities available. The slope factor is computed as the 10-year bond yield minus the three-month bond yield. Finally, the curvature factor is equal to the 10-year bond yield plus the three-month bond yield minus two times the five-year bond yield.¹⁶ These three yield curve factors evolve according to the following system:

$$\mathcal{L}_t = a_c + \alpha_{co}\mathbf{m}_t + \mathbf{b}'_c\mathcal{F}_{t-1} + \mathbf{b}'_5\mathbf{m}_{1:12}^L + \varepsilon_{ct}^{\mathbb{P}}, \quad (12)$$

$$\mathcal{S}_t = a_s + \alpha_{so}\mathbf{m}_t + \alpha_{sc}\mathcal{L}_t + \mathbf{b}'_s\mathcal{F}_{t-1} + \mathbf{b}'_6\mathbf{m}_{1:12}^L + \varepsilon_{st}^{\mathbb{P}}, \quad (13)$$

$$\mathcal{C}_t = a_c + \alpha_{co}\mathbf{m}_t + \alpha_{cc}\mathcal{L}_t + \alpha_{cs}\mathcal{S}_t + \mathbf{b}'_c\mathcal{F}_{t-1} + \mathbf{b}'_7\mathbf{m}_{1:12}^L + \varepsilon_{ct}^{\mathbb{P}}. \quad (14)$$

As it is standard in the term structure literature, equations (12) to (14) impose that the level factor is the most exogenous yield curve factor, followed by the slope and curvature factors. Comparing equations (12) to (14) with equations (8) to (11), two points stand out. First, oil factors are not influenced by term structure factors and shocks. This is equivalent to saying that country-specific nominal interest rates do not have a real impact on oil demand and supply beyond the impact on the global series summarized by Baumeister and Hamilton (2019). Second, oil factors can influence term structure movements, and hence its shape, contemporaneously via α_{co} , α_{so} , and α_{co} , and with a lag via $\mathbf{b}_5$, $\mathbf{b}_6$, and $\mathbf{b}_7$.

Equations (8) to (14) can be expressed more compactly by grouping the parameters governing the contemporaneous (lagged) interaction between oil factors, between yield curve factors, and between oil factors and yield curve factors into $\mathbf{A}^m$ ($\mathbf{B}^m$), $\mathbf{A}^{\mathcal{F}}$ ($\mathbf{B}^{\mathcal{F}}$), and $\mathbf{A}^{m\mathcal{F}}$ ($\mathbf{B}^{m\mathcal{F}}$) and the intercepts in the

¹⁶See Bekaert et al. (2010) for similar definitions.

equations of the oil (yield curve) factors in $\mathbf{a}^m$ ($\mathbf{a}^{\mathcal{F}}$):

$$\begin{bmatrix} \mathbf{m}_t \\ \mathcal{F}_t \end{bmatrix} = \begin{bmatrix} \mathbf{a}^m \\ \mathbf{a}^{\mathcal{F}} \end{bmatrix} + \begin{bmatrix} \mathbf{A}^m & \mathbf{0} \\ \mathbf{A}^{m\mathcal{F}} & \mathbf{A}^{\mathcal{F}} \end{bmatrix} \begin{bmatrix} \mathbf{m}_t \\ \mathcal{F}_t \end{bmatrix} + \begin{bmatrix} \mathbf{B}^m & \mathbf{0} \\ \mathbf{B}^{m\mathcal{F}} & \mathbf{B}^{\mathcal{F}} \end{bmatrix} \begin{bmatrix} \mathbf{m}_{1:12}^L \\ \mathcal{F}_{t-1} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\varepsilon}_t^{\mathbb{P},m} \\ \boldsymbol{\varepsilon}_t^{\mathbb{P},\mathcal{F}} \end{bmatrix}. \quad (15)$$

Equation (15)¹⁷ can be written in a standard compact dynamic structural form by defining $\mathbf{Z}_t = [\mathbf{m}'_t, \mathcal{F}'_t]'$, $\mathbf{Z}_{1:12}^L = [\mathbf{m}_{1:12}^{L'}, \mathcal{F}'_{t-1}]'$, and stacking the $\mathbf{a}$'s, $\mathbf{A}$'s, $\mathbf{B}$'s, and $\boldsymbol{\varepsilon}_t^{\mathbb{P}}$'s in $\mathbf{a}$, $\mathbf{A}$, $\mathbf{B}$, and $\boldsymbol{\varepsilon}_t^{\mathbb{P}}$, respectively:

$$(\mathbf{I} - \mathbf{A})\mathbf{Z}_t = \mathbf{a} + \mathbf{B}\mathbf{Z}_{1:12}^L + \boldsymbol{\varepsilon}_t^{\mathbb{P}}, \quad (16)$$

which can also be written as in equation (2):

$$\mathbf{Z}_t = \boldsymbol{\mu}^{\mathbb{P}} + \boldsymbol{\Phi}^{\mathbb{P}}\mathbf{Z}_{1:12}^L + \boldsymbol{\Sigma}\boldsymbol{\varepsilon}_t^{\mathbb{P}}, \quad (17)$$

with $\boldsymbol{\mu}^{\mathbb{P}} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{a}$, $\boldsymbol{\Phi}^{\mathbb{P}} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{B}$ and $\boldsymbol{\Sigma} = (\mathbf{I} - \mathbf{A})^{-1}$.

2.3. Canonical representation

We adopt the normalization of Joslin et al. (2011), which dramatically reduces the number of parameters of equation (2) under $\mathbb{Q}$ via two sets of restrictions. First, it imposes the so-called spanning restrictions, which means that under the risk-neutral measure $\mathbb{Q}$ only a few linear combinations of the yields in Y_t , i.e. $\mathcal{F}_t$, span the cross-section of Y_t over time:

$$\mathbb{E}_t^{\mathbb{Q}}[y_{t+j}^{(n)} | Z_t] = \mathbb{E}_t^{\mathbb{Q}}[y_{t+j}^{(n)} | \mathcal{F}_t]. \quad (18)$$

To satisfy condition (18), we impose that, under the risk-neutral dynam-

¹⁷We have adapted the estimation procedure to account for the Covid-19 period. Specifically, we follow Lenza and Primiceri (2022) and scale up the (diagonal) covariance matrix of the structural shocks for the global oil market, $\boldsymbol{\varepsilon}_t^{\mathbb{P},m}$, by s_t . s_t is a factor that is assumed to be: (i) equal to 1 before the pandemic, a period denoted by t^* ; (ii) equal to s_0 at t^* ; (iii) equal to s_1 at $t^* + 1$, (iii) equal to s_2 at $t^* + 2$; and (iv) equal to $1 + (s_2 - 1)\rho^{j-2}$ at $t^* + j$ for $j > 2$. Following Lenza and Primiceri (2022), we set t^* to March 2020 and for ρ we impose a penalty function based on a similar Beta distribution, i.e. with mode and standard deviation equal to 0.8 and 0.2, respectively.

ics, equations (1) and (2) depend only on $\mathcal{F}_t$:

$$y_t^{(1)} = \rho_0 + (\boldsymbol{\rho}_1^{\mathcal{F}})' \mathcal{F}_t, \quad (19)$$

$$\mathcal{F}_t = \boldsymbol{\mu}^{\mathbb{Q}, \mathcal{F}} + \boldsymbol{\Phi}^{\mathbb{Q}, \mathcal{F}} \mathcal{F}_{t-1} + \boldsymbol{\Sigma}^{\mathcal{F}} \boldsymbol{\varepsilon}_t^{\mathbb{Q}, \mathcal{F}}, \quad \boldsymbol{\varepsilon}_t^{\mathbb{Q}, \mathcal{F}} \sim \mathcal{N}(\mathbf{0}, \mathbf{I}), \quad (20)$$

where the 3×1 vectors $\boldsymbol{\rho}_1^{\mathcal{F}}$ and $\boldsymbol{\mu}^{\mathbb{Q}, \mathcal{F}}$ and the 3×3 matrices $\boldsymbol{\Phi}^{\mathbb{Q}, \mathcal{F}}$ and $\boldsymbol{\Sigma}^{\mathcal{F}}$ are the non-zero components of $\boldsymbol{\rho}_1'$, $\boldsymbol{\mu}^{\mathbb{Q}}$, $\boldsymbol{\Phi}^{\mathbb{Q}}$ and $\boldsymbol{\Sigma}$ in equation (2) corresponding to $\mathcal{F}_t$. From equations (19) and (20), it follows that Y_t is an affine function of $\mathcal{F}_t$, hence equation (5) simplifies to:

$$y_t^{(n)} = a_n^{\mathcal{F}} + \mathbf{b}_n^{\mathcal{F}} \mathcal{F}_t, \quad (21)$$

where the loadings are obtained similarly as in equations (6) and (7), namely, $a_n^{\mathcal{F}} = -n^{-1} a_n^{\mathcal{F}}$ and $\mathbf{b}_n^{\mathcal{F}} = -n^{-1} \mathbf{b}_n^{\mathcal{F}}$ with:

$$a_n^{\mathcal{F}} = a_{n-1}^{\mathcal{F}} + b_{n-1}^{\mathcal{F}} \boldsymbol{\mu}^{\mathbb{Q}, \mathcal{F}} + \frac{1}{2} (b_{n-1}^{\mathcal{F}})' \boldsymbol{\Sigma}^{\mathcal{F}} (\boldsymbol{\Sigma}^{\mathcal{F}})' b_{n-1}^{\mathcal{F}} - \rho_0, \quad (22)$$

$$b_n^{\mathcal{F}} = (\boldsymbol{\Phi}^{\mathbb{Q}, \mathcal{F}})' b_{n-1}^{\mathcal{F}} - \boldsymbol{\rho}_1^{\mathcal{F}}. \quad (23)$$

Inspecting equations (19), (20), and (21), we notice that the spanning condition (18) is trivially satisfied as, under $\mathbb{Q}$, Y_t depends only on $\mathcal{F}_t$, which in turn depends only on its lagged values.

The spanning assumption results in the following set of zero restrictions on the prices of risk and stochastic discount factor, cfr. equations (3) and (4):

$$\boldsymbol{\Lambda}_t^{\mathcal{F}} = (\boldsymbol{\Sigma}^{\mathcal{F}})^{-1} (\boldsymbol{\lambda}_0^{\mathcal{F}} + \boldsymbol{\lambda}_1^{\mathcal{F}} \mathbf{Z}_t), \quad (24)$$

$$\boldsymbol{\lambda}_0^{\mathcal{F}} = \mathbf{D}_{\mathcal{F}} \boldsymbol{\mu}^{\mathbb{P}} - \boldsymbol{\mu}^{\mathbb{Q}, \mathcal{F}}, \quad (25)$$

$$\boldsymbol{\lambda}_1^{\mathcal{F}} = \mathbf{D}_{\mathcal{F}} \boldsymbol{\Phi}^{\mathbb{P}} - [\mathcal{O} \boldsymbol{\Phi}^{\mathbb{Q}, \mathcal{F}}], \quad (26)$$

$$M_t = \exp(-y_t^{(1)} - \frac{1}{2} (\boldsymbol{\Lambda}_t^{\mathcal{F}})' \boldsymbol{\Lambda}_t^{\mathcal{F}} - (\boldsymbol{\Lambda}_t^{\mathcal{F}})' \boldsymbol{\Sigma}^{\mathcal{F}} \boldsymbol{\varepsilon}_t^{\mathbb{P}, \mathcal{F}}). \quad (27)$$

with $\mathcal{O}$ a zero matrix of conformable dimension and $\mathbf{D}_{\mathcal{F}} = [\mathcal{O} \mathbf{I}_{3 \times 3}]$ a matrix selecting the last three rows of $\boldsymbol{\mu}^{\mathbb{P}}$ and $\boldsymbol{\Phi}^{\mathbb{P}}$, i.e. the parts related to $\mathcal{F}_t$.

In a nutshell, as the cross-section of bond rates is summarized by $\mathcal{F}_t$, only

shocks to those principal components are priced; see equation (27). However, via equation (24), unspanned factors play a role in the pricing of those shocks, which are weighted by the 3×1 prices of risk vector $\mathbf{\Lambda}_t^{\mathcal{F}}$, that in turn is linked to all the variables of the dynamic system (17) via the matrix $\mathbf{\lambda}_1^{\mathcal{F}}$ of equation (24).

To identify the risk-neutral parameters, we follow Joslin et al. (2011) and impose a second set of identifying restrictions on the $\mathbb{Q}$ -dynamics, so that the real-world dynamics can be estimated without restrictions. We assume $N = 3$ latent factors $\mathcal{Q}_t$ and impose the following restrictions on their $\mathbb{Q}$ -dynamics:

$$y_t^{(1)} = \iota \mathcal{Q}_t, \quad \mu^{\mathcal{Q}} = \begin{bmatrix} \kappa^{\mathcal{Q}} \\ 0 \\ 0 \end{bmatrix}, \quad \Phi^{\mathcal{Q}} = \begin{bmatrix} \lambda_1^{\mathcal{Q}} & & \\ & \lambda_2^{\mathcal{Q}} & \\ & & \lambda_3^{\mathcal{Q}} \end{bmatrix}, \quad (28)$$

where ι is 1×3 vector of ones and the $\lambda^{\mathcal{Q}}$ s are assumed to be less than one in absolute value. Subsequently, we obtain the term structure loadings related to $\mathcal{Q}_t$, $A_{\mathcal{Q}}$ and $B_{\mathcal{Q}}$, and use the definition of $\mathcal{F}_t = W^{\mathcal{F}} Y_t$ to obtain the loadings for $\mathcal{F}_t$ in function of the parameters in (28):

$$Y_t = (I - B_{\mathcal{Q}}(W^{\mathcal{F}} B_{\mathcal{Q}})^{-1} W^{\mathcal{F}}) A_{\mathcal{Q}} + B_{\mathcal{Q}}(W^{\mathcal{F}} B_{\mathcal{Q}})^{-1} \mathcal{F}_t, \quad (29)$$

where $A_{\mathcal{Q}}$ and $B_{\mathcal{Q}}$ are the affine yield loadings on $\mathcal{Q}_t$ and $W^{\mathcal{F}} = [w'_l, w'_s, w'_c]'$.

3. Econometric framework

3.1. Estimation

We estimate the model using a penalized likelihood approach, a widely-used methodology in high-dimensional statistics, see Hastie et al. (2001), among others. The three-equation system from which we derive the likelihood function is the following:

$$\mathbf{Z}_t = \mu^{\mathbb{P}} + \Phi^{\mathbb{P}} \mathbf{Z}_{1:12}^L + \Sigma \epsilon_t^{\mathbb{P}}, \quad (30)$$

$$Y_t = A^{\mathcal{F}}(\Theta^{\mathcal{Q}}, \Sigma^{\mathcal{F}}) + B^{\mathcal{F}}(\Theta^{\mathcal{Q}}, \Sigma^{\mathcal{F}}) \mathcal{F}_t + \xi_t, \quad (31)$$

where equation (31) is a compact form of equation (29), with ϵ_t being i.i.d. Gaussian fitting errors and $\Theta^{\mathcal{Q}} = \{\lambda_1^{\mathcal{Q}}, \lambda_2^{\mathcal{Q}}, \lambda_3^{\mathcal{Q}}, \kappa^{\mathcal{Q}}\}$ the risk-neutral param-

eters. The penalized log-likelihood is composed of two groups, l_t^Z and l_t^Y :

$$l_t \propto \underbrace{-\ln|\mathbf{E}_2| - \tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P}'} \mathbf{E}_2^{-1} \tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P}}}_{\text{Eq.(30)}} + \underbrace{p(\boldsymbol{\Phi}^{\mathbb{P}}) + p(\boldsymbol{\Sigma})}_{\text{Penalties}} + \underbrace{-\ln|\boldsymbol{\Xi}| - \tilde{\boldsymbol{\xi}}_t' \boldsymbol{\Xi}^{-1} \tilde{\boldsymbol{\xi}}_t}_{\text{Eq.(31)}}. \quad (32)$$

In the first group, $\tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P}}$ indicates the fitting errors from equation (30), $\mathbf{E}_2 = \boldsymbol{\Sigma} \boldsymbol{\Sigma}'$, and the two penalties parts (i) identify oil shocks as in Baumeister and Hamilton (2019) and (ii) shrink to zero higher-lag parameters. In the second group, $\tilde{\boldsymbol{\xi}}_t$ are the fitting errors from equation (31) and $\boldsymbol{\Xi}$ is a diagonal matrix containing the variances of $\tilde{\boldsymbol{\xi}}_t$. As indicated by equations (30) and (31), the likelihood of the macro and yield factors hinges upon the historical parameters while the fitting of the yield curve is related to the risk-neutral parameters. The only parameters that belong to both likelihoods is $\boldsymbol{\Sigma}^{\mathcal{F}}$.

Since l_t^Z is independent of $\boldsymbol{\Theta}^{\mathbb{Q}}$, we split the maximization of equation (32) in two steps. In the first step, we fit equation (30), which we write in an expanded version to elicit the components of the likelihood and the penalty functions:

$$\begin{bmatrix} \mathbf{m}_t \\ \mathcal{F}_t \end{bmatrix} = \begin{bmatrix} \boldsymbol{\mu}^m \\ \boldsymbol{\mu}^{\mathcal{F}} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\Phi}^m & \mathbf{0} \\ \boldsymbol{\Phi}^{m,\mathcal{F}} & \boldsymbol{\Phi}^{\mathcal{F}} \end{bmatrix} \begin{bmatrix} \mathbf{m}_{1:12}^L \\ \mathcal{F}_{t-1} \end{bmatrix} + \begin{bmatrix} \boldsymbol{\Sigma}^m & \mathbf{0} \\ \boldsymbol{\Sigma}^{m,\mathcal{F}} & \boldsymbol{\Sigma}^{\mathcal{F}} \end{bmatrix} \begin{bmatrix} \boldsymbol{\varepsilon}_t^{\mathbb{P},m} \\ \boldsymbol{\varepsilon}_t^{\mathbb{P},\mathcal{F}} \end{bmatrix}. \quad (33)$$

Noticeably, equation (33) highlights that the oil block's equation related to $\mathbf{m}_t$ is independent of the country-specific yield curve factors.¹⁸ This observation, combined with the fact that all series are observed, allows us to estimate $\boldsymbol{\mu}^m$, $\boldsymbol{\Phi}^m$, and $\boldsymbol{\Sigma}^m$ separately from $\boldsymbol{\mu}^{\mathcal{F}}$, $\boldsymbol{\Phi}^{m,\mathcal{F}}$, $\boldsymbol{\Phi}^{\mathcal{F}}$, $\boldsymbol{\Sigma}^{m,\mathcal{F}}$, and $\boldsymbol{\Sigma}^{\mathcal{F}}$:

$$l_t^Z \propto \underbrace{-\ln|\mathbf{E}^m| - \tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P},m'} \mathbf{E}^{m-1} \tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P},m}}_{\text{Eq.(33): fitting of } \mathbf{m}_t} + \underbrace{p(\boldsymbol{\Sigma}^m)}_{\text{Oil shocks identification}} + \underbrace{-\ln|\mathbf{E}^{\mathcal{F}}| - \tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P},\mathcal{F}'} \mathbf{E}^{\mathcal{F}-1} \tilde{\boldsymbol{\varepsilon}}_t^{\mathbb{P},\mathcal{F}}}_{\text{Eq.(33): fitting of } \mathcal{F}_t} + \underbrace{p(\boldsymbol{\Phi}^{m,\mathcal{F}})}_{\text{Penalization for lags in oil factors}}. \quad (34)$$

¹⁸As the oil block is independent of (each) country-specific yield curve factor, we have used the entire sample of Baumeister and Hamilton (2019).

The functional form of the penalization terms related to $p(\Sigma^m)$ is derived as follows. First, we denote by $\tilde{\mathbf{A}}^m$ the part of $\mathbf{I} - \mathbf{A}$ related to the oil variables in equation (17), implying that

$$\Sigma^m = \frac{1}{\det \tilde{\mathbf{A}}^m} \text{adj}(\mathbf{A}^m).$$

Subsequently, following Baumeister and Hamilton (2019), we parameterize $\tilde{\mathbf{A}}^m$ as

$$\tilde{\mathbf{A}}^m = \begin{bmatrix} 1 & 0 & -\alpha_{qp} & 0 \\ 0 & 1 & -\alpha_{gp} & 0 \\ 0 & -\alpha_{dg} & -\alpha_{dp} & -\chi^{-1} \\ -\alpha_{iq} & 0 & -\alpha_{ip} & 1 \end{bmatrix}, \quad (35)$$

with the penalty function for each parameter given by

$$p(\alpha_j) \propto -4 \ln \left[1 + \frac{(\bar{\alpha}_j - \mu_j)^2}{9\sigma_j^2} \right] \quad \{\bar{\alpha}_j, \mu_j, \sigma_j\} = \begin{cases} \{\alpha_{qp}^+, .1, .2\} \\ \{\alpha_{gp}^-, -.05, .1\} \\ \{\alpha_{qg}^+, .7, .2\} \\ \{\alpha_{dp}^-, -.1, .2\} \\ \{\alpha_{iq}, 0, .5\} \\ \{\alpha_{ip}, 0, .5\} \end{cases} \quad (36)$$

Finally, for the $\det \tilde{\mathbf{A}}^m$ and χ we have imposed penalties in line with Baumeister and Hamilton (2019), i.e. an asymmetric t distribution to ensure that $\det \tilde{\mathbf{A}}^m > 0$ and a Beta distribution to ensure that $\chi \in (0, 1)$, respectively.

3.2. Data

Our analysis covers 15 countries, selected based on data availability and the size of the country (in terms of GDP). We divide the countries into three groups: (i) net oil exporters, i.e. Brazil, Canada, Mexico, Norway, and Russia; (ii) developing countries which are net oil importers, i.e. China, India, Indonesia, South-Africa, and Turkey; and (iii) developed countries which are net oil importers, i.e. Germany, Japan, South-Korea, UK, and USA.¹⁹

¹⁹A classification based on the country's net trade position in crude oil is provided by the International Energy Agency (IEA), <https://www.iea.org>.

For all countries - except the US, UK, and Canada- yield curve data are retrieved from Bloomberg.²⁰ The US yield curve is from Liu and Wu (2021) while the Canadian and UK rates are from the respective central banks. We use end-of-the-month zero-coupon yields with maturities of 3, 6, 12, 24, 36, 48, 60, 84, 96, 108, and 120 months (a total of 11 maturities).²¹

Oil-related data are from Baumeister and Hamilton (2019) and are available at their websites. Monthly global crude oil production comes from the weekly Oil and Gas Journal for the period January 1958 to December 1972, and from the U.S. Energy Information Administration’s (EIA) Monthly Energy Review for the period January 1973 to Feb 2024.

The measure of global economic activity is the industrial production index for OECD countries and six major non-member economies (Brazil, China, India, Indonesia, the Russian Federation and South Africa), all retrieved from the OECD.

The nominal price of oil (spot) for West Texas Intermediate (WTI) is retrieved from the Federal Reserve Economic Data (FRED) database maintained by the Federal Reserve Bank of St. Louis²² and is deflated by the U.S. consumer price index²³, also obtained from the FRED database.

Finally, monthly U.S. crude oil stocks in millions of barrels are available from the EIA. The estimate for global stocks is obtained by multiplying the U.S. crude oil inventories by a ratio which the numerator is the OECD inventories of crude petroleum and petroleum products and the denominator is the U.S. inventories of petroleum and petroleum products.

4. Results

The results are presented in two parts. Section 4.1 presents the overall model validation. We start by commenting on the performance of the model with respect to the fit of the yield curve for the 15 countries analyzed. We then analyze whether the model-implied risk premia are able to explain the realized excess returns. Section 4.2 presents the main results of the paper.

²⁰In Bloomberg Russian data ends in February 2022. From March 2022, we have complemented Bloomberg the Russian Central Bank’s zero curves.

²¹Table A.1 shows the period used for each country.

²²FRED mnemonic: OILPRICE.

²³FRED mnemonic: CPIAUCSL (consumer price index for all urban consumers: all items, index 1982-1984 = 100).

We analyze the effect of each macroeconomic shock on the bond risk premia of each country. This is done with the use of IRFs, variance decompositions, and a historical decomposition.

4.1. Model validation

4.1.1. Fit of the term structure

Since we analyze 15 countries and include 11 maturities for each country, we fit a total of 165 bonds. For all countries, the model is able to fit the term structure rather well. The average standard deviation of the fitting errors among the 165 cases equals 11 basis points.²⁴ The maximum standard deviation of the fitting errors is equal to 64 basis points for the Russian 84-month bond.

This result is not surprising since we include three spanned factors in our yield curve model. There is a vast literature starting with Litterman and Scheinkman (1991) showing that three factors are sufficient to capture most of the variation in US bond yields.²⁵ The crucial issue is how well our model is able to fit realized excess returns. We turn to this question in the next item.

4.1.2. Realized versus expected excess return

Although we use bonds with maturities ranging from 3 months to 10 years, we illustrate the relation between model-implied risk premia and realized excess returns for bonds with maturities of 2 and 10 years. We show results for holding periods of three and 12 months. This can be seen in Figures A.1 to A.6.

Above each graph in these figures, we also report the correlation between the series. The best results are obtained for the group of oil-exporting countries. The correlation between the series is the highest for 10-year bonds with a holding period of 12 months (average correlation among the five oil-exporting countries of 56%). The average correlation among the 60 cases presented (15 countries, 2 maturities, and 2 holding periods) is equal to 43%. When examining 12-month holding periods—a duration commonly referenced in the literature—we can contextualize our findings within the scope of existing studies. Predominantly, the literature employs predictive

²⁴These results are in line with the ones reported by Piazzesi (2010) and are available upon request.

²⁵See also de Jong (2000) and a number of studies that followed.

regressions, correlating realized returns with various control variables. Our results can be readily compared to these studies, as the model-implied risk premia can be interpreted as fitted values from restricted regressions, where the linear coefficients are determined by no-arbitrage constraints. For the US, using different types of control variables, similar levels of correlations (R^2) have been reported in the studies by Ludvigson and Ng (2009), Cochrane and Piazzesi (2005), Cochrane and Piazzesi (2009), and Bauer and Hamilton (2018), among others. For the developing countries - UK and Germany, in particular- Dahlquist and Hasseltoft (2013) found average levels²⁶ of R^2 of around 21% and 15%, which are broadly in line with the correlations reported in our plots. Turning to developing countries, Zhang et al. (2022) report the model-implied predictive R^2 and, hence, comparable to our setting. They obtain R^2 ranging from 20% for two-year bonds to 22% for five-year contracts, which are broadly in line with our findings. Our model-implied R^2 are 36% for the two-year contract and 25% for the ten-year contract.

4.2. Effect of oil shocks on bond risk premia

4.2.1. Impulse response functions

We analyze the dynamics of bond risk premia by means of IRFs. This allows us to visualize the response of the risk premium to a one-standard deviation shock to each variable in our structural model (8)-(11). We focus, however, on the first three shocks of our system, i.e. global oil supply, global economic activity, and global oil demand shocks. Our results are in line with Baumeister and Hamilton (2019), who report that changes in global inventory demand play a minor role in oil price movements.

We divide the 15 countries in our sample in three groups: (i) net oil-exporting; (ii) net oil-importing developing, and (iii) net oil-importing developed countries.²⁷ Cepni et al. (2022), for example, show how the yield curve of oil-exporting and oil-importing countries respond differently to oil price shocks. For each group of countries, we show IRFs for a holding period of three and 12 months.

The IRFs are presented in Figures A.7 to A.12 and show the response of the risk premium for a horizon up to 12 months after the shock. Each graph shows two lines. Although we use bonds with maturities ranging from

²⁶Across different maturities and predictive models.

²⁷A classification based on the country's net trade position in crude oil is provided by the International Energy Agency (IEA), <https://www.iea.org>.

3 months to 10 years, we illustrate the dynamics of the IRFs for bonds with maturities of 2 and 10 years. The lines, therefore, represent the median response of each bond risk premium to a specific structural shock. Finally, the color of the markers in each line represents the statistical significance of each point: white (less than 67%); grey (between 67% and 95%); and black (above 95%).

Before we interpret the results of each structural shock separately, we make a number of general observations. First, except for shocks to the global economic activity, we expect a different reaction of bond risk premia to the other two structural shocks depending on the country's position on the oil market (net oil-exporter or net oil-importer) and on the pass-through to inflation. Second, as expected, we observe that the risk premia on 10-year bonds are more responsive to all structural shocks than those for 2-year bonds. Third, in 83% of the cases (75 out of the 90 graphs we present), we observe a statistically significant reaction of the risk premium at the 5% level for at least one of the two bonds and at some forecasting horizon (between 0 and 12 months).

Global oil supply shock: We follow Baumeister and Hamilton (2019) and impose a negative oil supply shock. We expect supply shocks to move oil production and prices in opposite directions. Therefore, we expect a negative oil supply shock to have an instantaneous negative impact on oil production and a positive impact on oil prices. This would benefit oil-exporting countries due to the increase in export revenues and possibly decrease the risk premium on its bonds. We expect the contrary to happen in oil-importing countries.

Korhonen and Ledyeva (2010), however, point to the presence of indirect effects. Since a jump in oil prices slows down economic growth, oil-importing countries import less from oil-exporting countries. Therefore, the gain in growth for an oil-exporting country is not as large as one could expect. For net oil-exporting countries (Fig. A.7 and A.8, first column of graphs), global oil supply shocks induce a mixed response of bond risk premia depending on the forecasting horizon and maturity of the bond. The overall picture, however, is of an increase in risk premia, running counter to what one would expect. This could be a negative reaction to a possible increase in inflation or the consequence of the mentioned indirect effects.

Russia seems to be a special case. Although the effect on risk premia is positive up to three months, it is mainly negative (as expected) after that

period. This is in line with the results of Korhonen and Ledyeva (2010) who find that Russia benefits from positive oil price shocks through an increase in GDP.

For net oil-importing developing countries (Fig. A.9 and A.10), most of the statistically significant reactions of the risk premia are positive (as expected). Indonesia is an exception with most of the effect on risk premia being negative. China and Turkey also present a negative reaction of bond risk premia up to a three-month horizon.

One possible explanation for a negative response of bond risk premia to negative supply shocks could be the fact that the resulting increase in oil prices are associated with a reduction in short-term interest rates, i.e. a loosening in the monetary policy to counteract the negative impact on economic growth. Such reaction is documented by Ioannidis and Ka (2018) for a group of industrialized countries. They show that oil supply disruptions have a short-lived impact on the slope factor (decrease in the short-term interest rate). This is also observed by Cepni et al. (2022).

Finally, in the case of net oil-importing developed countries, for both holding periods (short and long, Fig. A.11 and A.12, respectively), the reaction of the risk premium is in most cases positive (as expected). This is especially the case for Germany and the UK for a twelve-month holding period. Altogether, the results are in line with Baumeister et al. (2010) who observe very different effects across countries of oil supply shocks.

Global economic activity shock: As mentioned before, we expect a decrease in bond risk premia for all countries after a positive shock in the global economic activity. For net oil-exporting countries (Fig. A.7 and A.8, middle column of graphs), this is mostly what we find. For all countries, with the exception of Russia, we observe statistically significant negative risk premia on impact and after a few months. The statistically significant increase in risk premia in the case of Russia is hard to explain.

For net oil-importing developing countries (Fig. A.9 and A.10), responses to global economic activity shocks are in most cases not significant. We only observe the expected significant negative response of risk premia on impact for India and China. Turkey presents positive and significant risk premia on impact, which is hard to rationalize.

Finally, for net oil-importing developed economies (Fig. A.11 and A.12), we observe the expected negative risk premia on impact and after a few

months in all cases following an increase in global economic activity. For Japan and South Korea, the effect on risk premia becomes positive after a few months, although not statistically significant.

Global oil demand shock: In the case of net oil-exporting countries (Fig. A.7 and A.8, right column of graphs), we expect a decrease in bond risk premia following an increase in global oil demand. On impact and a few months thereafter, this reaction is significant and as expected for Brazil and Mexico. It has the wrong sign for Norway after two months and for the three-month holding period and it is mostly not significant for Canada and Russia.

For net oil-importing developing countries (Fig. A.9 and A.10), we expect an increase in bond risk premia following a positive global oil demand shock. The overall evidence is mixed. China presents mostly a positive reaction (as expected) of bond risk premia for both holding periods. In Turkey, nevertheless, the reaction of bond risk premia is mostly negative, in contrast to what we would expect. India also presents a statistically significant negative reaction on impact and after a six-month horizon.

Finally, for net oil-importing developed economies, we also expect an increase in bond risk premia following a positive shock in global oil demand. Most of the reaction is either not significant or has the wrong sign (Fig. A.11 and A.12). Only Japan presents a significant expected positive reaction on impact for a three-month horizon. Germany presents mostly a negative reaction to bond risk premia.

In summary: Regarding oil supply shocks, oil-exporting countries exhibit mainly the wrong effect on bond risk premia, with the exception of Russia. Oil-importing countries present a mixed reaction. The countries that stand out with the expected reaction are India, South Africa, and China (this one for the twelve-month horizon) among the developing countries, and Germany and the UK among the developed countries.

With respect to global economic activity shocks, overall we find a negative reaction of bond risk premia, as we would expect for all countries. Oil-exporting countries exhibit the expected reaction of bond risk premia (i.e. decrease), with the exception of Russia. Oil-importing developing countries present mixed results, with few cases being significant and with the expected sign. Oil-importing developed countries present the expected negative reac-

tion of bond premia, this time with the exception of Japan with a positive reaction a few months after the shock.

Finally, for global oil demand shocks, in the case of oil-exporting countries we get the expected negative reaction on impact in two out of the five cases. For both oil-importing developing and developed countries, bond premia reaction is mostly not significant or has the sign, with a few exceptions.

4.2.2. Variance decompositions

We now assess the contribution of each shock to the dynamics of bond risk premia making use of variance decompositions. The results are shown in Figures A.13 and A.14 for a holding period of three and 12 months, respectively. In each of these figures, there are three columns of graphs. The left column includes net oil-exporting countries (Brazil, Canada, Mexico, Norway, and Russia), the middle column net oil-importing developing countries (China, India, Indonesia, South Africa, and Turkey), and the right column net oil-importing developed countries (Germany, Japan, South Korea, UK, and USA). For each country, we present three groups of bars. Each group refers to a bond with a different maturity. The left group (first three bars) represents the variance decomposition for three-month bonds, the middle group two-year bonds, and the right group 10-year bonds. Finally, each group of bars shows the variance decomposition for three different forecasting horizons (three months, one year, and two years), shown on the horizontal axis. The contribution of each shock to each bond risk premium is shown on the vertical axis.

As a consequence, for the three-month holding period (Fig. A.13), we illustrate a total of 135 cases (15 countries, 3 bonds, and 3 forecasting horizons). For the twelve-month holding period, however, we show a total of only 90 cases (15 countries, 2 bonds, and 3 forecasting horizons). We cannot include the analysis for three-month bonds since its maturity (3 months) is shorter than the holding period (12 months).

Spanned versus unspanned factors: We start by analyzing the overall contribution of spanned (level, slope, and curvature) versus unspanned (global oil supply, global economic activity, global oil demand, and oil inventory) shocks. For this, we take an average of the contribution of each shock for each group of countries over the different bond maturities and forecasting horizons.

For a relatively short holding period (three months, Fig. A.13), unspanned factors explain the bulk of the variability in bond risk premia. These factors are responsible, on average, for 66% of the forecast variance, while spanned factors account for the remaining 34%. For a longer holding period (twelve months, Fig. A.14), these proportions are reversed. Unspanned factors explain 34% of such variability, while spanned factors account for 66% of the variance decomposition.

Among the unspanned factors, and for both holding periods (three and twelve months), it is striking the importance of global oil supply and global economic activity (global demand) shocks in comparison with global oil demand and inventory shocks. For the three-month holding period, those two shocks account for 72% of the variance explained by unspanned factors. This amounts to 47% of the total forecast variance. For the twelve-month holding period, this contribution reduces to 63%, or 34% of the total forecast variance.

Among the spanned factors, for a short holding period, the three types of shocks (level, slope, and curvature) have almost equal contribution to the variability in bond premia. For a longer holding period, the first two shocks (level and slope) are responsible for 75% of the variability attributable to spanned factors.

Effect on different groups of countries: When we focus on the different groups of countries, we observe that the contribution of unspanned versus spanned shocks to the total variability of bond premia is approximately the same for the three groups (respectively, 66% and 34% for a short holding period and 34% and 66% for a longer holding period).

Nevertheless, bond risk premia of different groups of countries are affected the most by different types of shocks. As expected, for net oil-exporting countries, global economic activity (global demand) shocks dominate the variance decomposition. It explains 27% of the total variability in bond risk premia for a three-month holding period. It also accounts for 42% and 44% of the variance attributable to unspanned shocks when we consider a holding period of three and twelve months, respectively. Supply shocks come in second place, with the equivalent figures equal to 32% and 24%, respectively.

Also not surprisingly, in the case of net oil-importing developing countries, global oil supply shocks dominate the forecast variance. It explains around 27% of the total forecast variance for a short holding period. In turn, it is

responsible for 41% and 28% of the variability assigned to unspanned factors, respectively for a short and long holding period.

For net oil-importing developed countries, bond risk premia are mainly affected by global demand (economic activity) shocks. For a short holding period, this type of shock is responsible for 33% of the variability in bond risk premia. This translates into a contribution of 49% and 35% of the variability attributable to unspanned factors for a short and long holding period, respectively.

With respect to spanned shocks, in most cases, level and slope factors have a bigger impact on bond risk premia. Only for net oil-exporting countries, curvature shocks play a prominent role.

In summary: Unspanned factors dominate the variance decomposition for a short holding period (three months), predominantly due to global oil supply and global economic activity (global demand) shocks. For a longer holding period (twelve months), although spanned factors explain most of the variability in bond risk premia, global oil supply and global demand shocks still play a significant role.

4.2.3. Historical decomposition

As an illustration of the contribution over time of each structural shock, we perform a historical decomposition of bond risk premia over the initial period of the COVID-19 crisis, from November 2019 to May 2020. The graphs are presented in Figures A.15 to A.17 for net oil-exporting, net oil-importing developing, and net oil-exporting developed countries, respectively. We focus on bonds with maturities of two years (first two lines of graphs from the top) and 10 years (last two lines of graphs) and analyze the effect on bond premia for a holding period of three months (first and third lines of graphs) and 12 months (second and fourth lines of graphs).

In each graph, we show the following. The bars show the contribution of each unspanned shock (global oil supply, global economic activity, global oil demand shocks, and global inventory shocks). Since each shock might have a positive or negative contribution, we show the sum of these shocks in the short-dashed line with dots. The solid line represents the total model-implied risk premium. The difference between the solid line and the short-dashed line represents the contribution of the shocks due to the spanned factors (level, slope and curvature). Note that for each graph we show the evolution of the risk premium starting from zero at the beginning of the period analyzed

(November 2019), and expressed in percentage points. Each point on the horizontal axis thereafter represents one of the six following months until May 2020.

The period analyzed is characterized by a drop of around 70% in the crude oil price. In general, we expect oil price decreases to be detrimental to net oil-exporting countries with an increase in bond risk premia. In turn, it should benefit net oil-importing countries with a decrease in bond premia. On the other hand, as mentioned before, a negative shock in the global economic activity, as the one experienced as a result of the COVID-19 pandemic, should lead to an increase in bond risk premia of all countries, both net oil exporting and importing.

General remarks: Considering Figures A.15 to A.17, we present a total of 60 graphs (15 countries, 2 bonds, and 2 holding periods). A number of observations can be made: *(i)* As expected, in almost all cases, we observe an increase in total bond risk premia (solid line) during the months of February to May of 2020, a clear consequence of the global negative economic activity shock which occurred during this period. In many countries, the months of February and March of 2020 mark the beginning of the recession caused by the COVID-19 pandemic; *(ii)* Overall, and also as expected, negative global economic shocks contribute the most to the increase in bond risk premia; *(iii)* In most cases, bond premia only started to increase in February 2020 (fourth bar on the horizontal axis). In a number of countries, bond premia actually decrease during the months of December 2019 and January 2020. *(iv)* The increase in risk premia of long-term bonds (10 years) is significantly higher than that of shorter-term bonds (two years). This was also observed in our analysis of impulse responses (Section 4.2.1).

Country-specific remarks: For oil-exporting countries (Fig. A.15), only in the case of Russia we observe a pronounced decrease in total bond premia (solid line), especially for long-term bonds. For Brazil, Canada, and Mexico, we also see a notable influence of negative global oil demand shocks during the months of April and May of 2020 (last two bars in the horizontal axis), raising bond risk premia.

For oil-importing developing countries (Fig. A.16), we also observe the impact of negative global economic activity shocks, raising bond risk premia from February to May of 2020 (last four bars in the horizontal axis). This

is very clear in the case of India and for two-year bonds (for both 3- and 12-month holding periods, first two graphs from the top). In some cases, we can also see the impact of negative global oil supply shocks increasing bond risk premia. This is noticeable for China in the case of 10-year bonds with a 3-month holding period (third graph from the top). Indonesia and Turkey, in particular, show a significant decrease in total bond premia (solid line) during most of the period analyzed.

For oil-importing developed countries (Fig. A.17), we see a similar picture. A significant increase in bond premia during the months of February and March 2020, being global economic activity shocks responsible for most of this dynamics.

5. Conclusions

We present a methodology to analyze the effect of oil price shocks on bond risk premia. The approach combines the strategy proposed by Baumeister and Hamilton (2019) to identify the different sources of oil price shocks with an affine yield curve model including both spanned and unspanned factors, as in Joslin et al. (2014). The structural factors modelling the global market for crude oil are used as the unspanned factors in the yield curve model. The spanned factors are the usual level, slope and curvature factors.

The model is applied to a total of 15 countries divided in three groups: (i) net oil-exporting; (ii) net oil-importing developing; and (iii) net oil-importing developed countries. We cover different periods for each country. The shortest period starts in March 2007 and ends in February 2024. The analysis includes bond data with maturities ranging from three months to 10 years.

As expected, our specification fits the yield curve of all countries rather well. More importantly, our model-implied bond risk premia also explain the realized excess returns satisfactorily. Analyzing the IRFs, we obtain the expected negative response of bond risk premia to global economic shocks in about 75% of the cases. The response to global oil supply shocks is also as expected in more than 50% of the cases. Among the oil-exporting countries, Russia stands out as having a different response than the other countries with respect to global oil supply and economic activity shocks.

Analyzing the IRFs, we obtain the expected negative response of bond risk premia to global economic shocks in about 75% of the cases. The response to global oil supply shocks is also as expected in more than 50% of

the cases. Among the oil-exporting countries, Russia stands out as having a different response than the other countries with respect to global oil supply and economic activity shocks.

Interestingly, while unspanned factors explain most of the variability in bond risk premia for a short holding period (three months), spanned factors dominate the variance decomposition for a longer holding period (twelve months). In both cases, global oil supply and global economic activity are clearly the most important unspanned shocks.

Finally, a historical decomposition of the initial COVID-19 crisis shows the clear influence of global economic activity shocks, increasing bond risk premia significantly especially during the months of February and March 2020.

Appendix A. Appendix

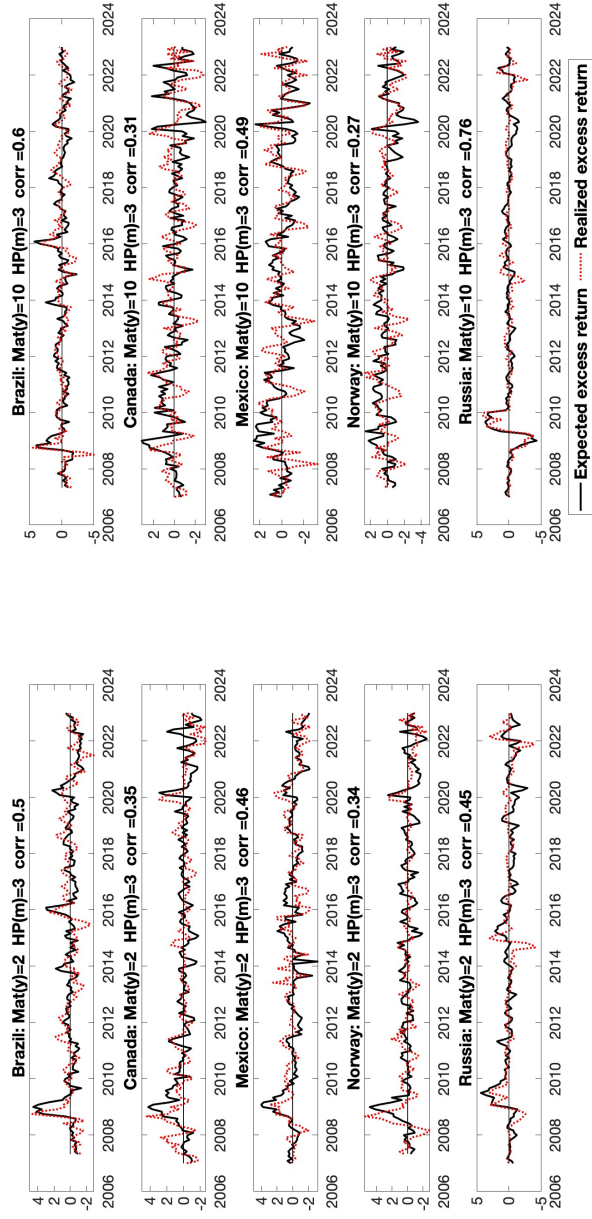
Table A.1: Date range for each country

	Start date	End date	Source
<i>Exporting countries</i>			
Brazil	Mar-2007	Feb-2024	Bloomberg
Canada	Jan-1986	Feb-2024	Bank of Canada
Mexico	Aug-2003	Feb-2024	Bloomberg
Norway	Dec-1994	Feb-2024	Bloomberg
Russia	Jan-2007	Feb-2024	Bloomberg
<i>Importing developing countries</i>			
China	Apr-2004	Feb-2024	Bloomberg
India	Nov-1998	Feb-2024	Bloomberg
Indonesia	May-2003	Feb-2024	Bloomberg
South Africa	Jan-1995	Feb-2024	Bloomberg
Turkey	Dec-2002	Feb-2024	Bloomberg
<i>Importing developed countries</i>			
Germany	Dec-1994	Feb-2024	Bloomberg
Japan	Apr-1991	Feb-2024	Bloomberg
South Korea	Sep-1999	Feb-2024	Bloomberg
UK	Jun-1977	Feb-2024	Bank of England
US	Jun-1977	Feb-2024	Liu and Wu (2021)*

Note: From Feb 2022 the zero coupon data for Russia is taken from the Russian Central Bank.

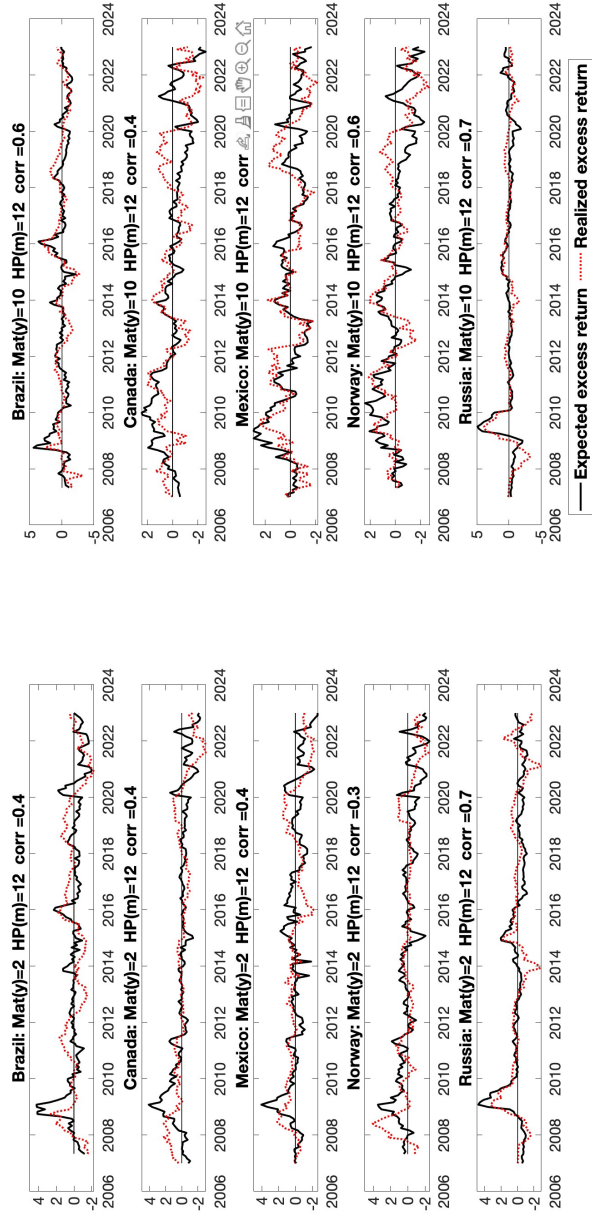
* We thank the authors for making the data going until Dec-2023 available on their website. The data for Jan/Feb-2024 were obtained from Bloomberg.

Figure A.1: Realized vs. expected excess returns - Oil-exporting countries - Oil-exporting countries, 3-month holding period



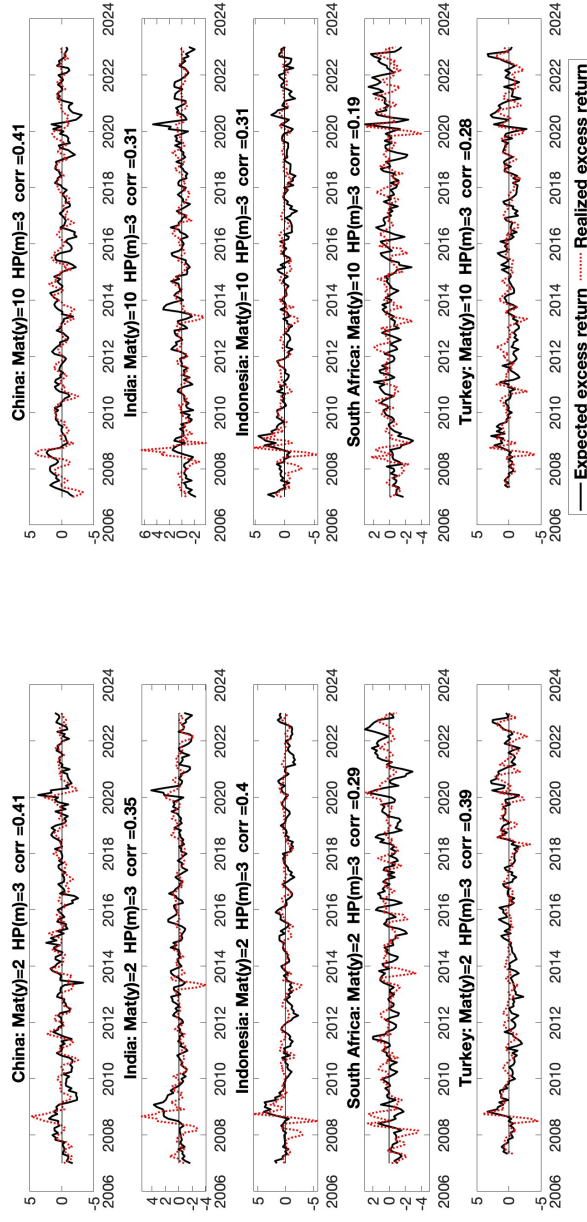
Note: The figure shows the realized (red lines) and expected excess returns (black lines) on 2-year bonds (left column of graphs) and 10-year bonds (right column of graphs) for oil-exporting countries with a holding period of three months.

Figure A.2: Realized vs. expected excess returns - Oil-exporting countries, 12-month holding period



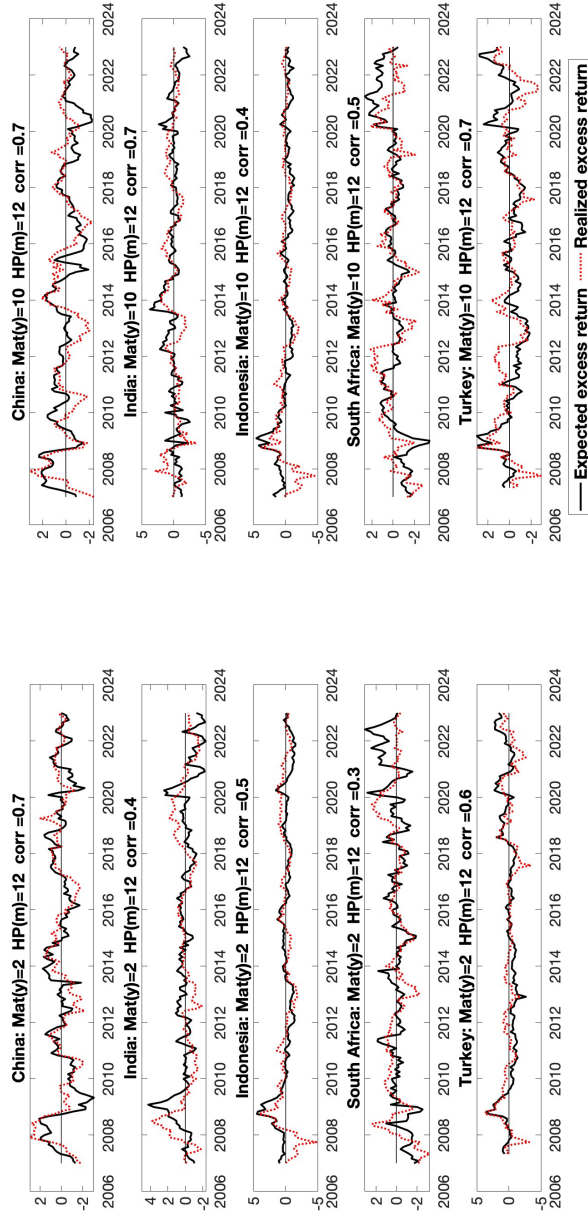
Note: The figure shows the realized (red lines) and expected excess returns (black lines) on 2-year bonds (left column of graphs) and 10-year bonds (right column of graphs) for oil-exporting countries with a holding period of twelve months.

Figure A.3: Realized vs. expected excess returns - Oil-importing developing countries, 3-month holding period



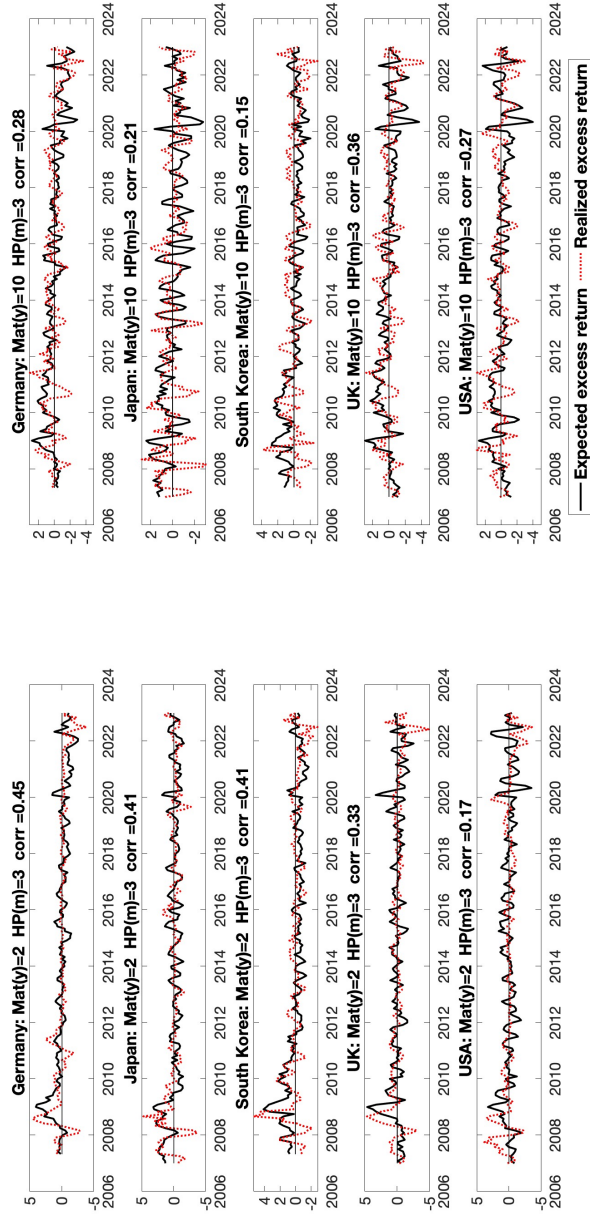
Note: The figure shows the realized (red lines) and expected excess returns (black lines) on 2-year bonds (left column of graphs) and 10-year bonds (right column of graphs) for oil-importing developing countries with a holding period of three months.

Figure A.4: Realized vs. expected excess returns - Oil-importing developing countries, 12-month holding period



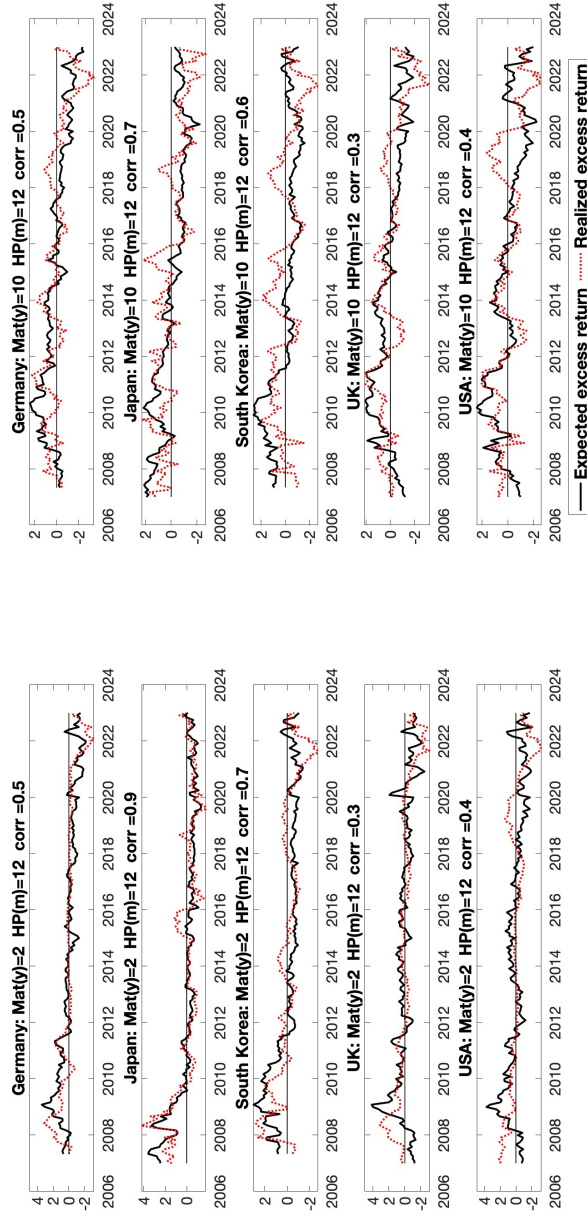
Note: The figure shows the realized (red lines) and expected excess returns (black lines) on 2-year bonds (left column of graphs) and 10-year bonds (right column of graphs) for oil-importing developing countries with a holding period of twelve months.

Figure A.5: Realized vs. expected excess returns - Oil-importing developed countries, 3-month holding period



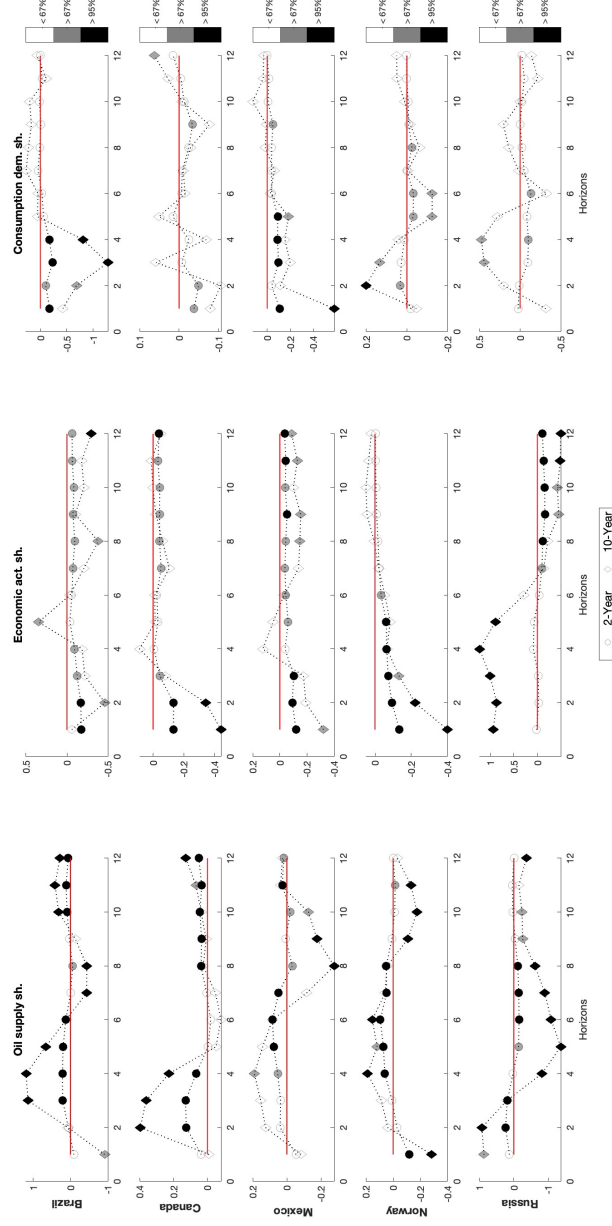
Note: The figure shows the realized (red lines) and expected excess returns (black lines) on 2-year bonds (left column of graphs) and 10-year bonds (right column of graphs) for oil-importing developed countries with a holding period of three months.

Figure A.6: Realized vs. expected excess returns - Oil-importing developed countries, 12-month holding period



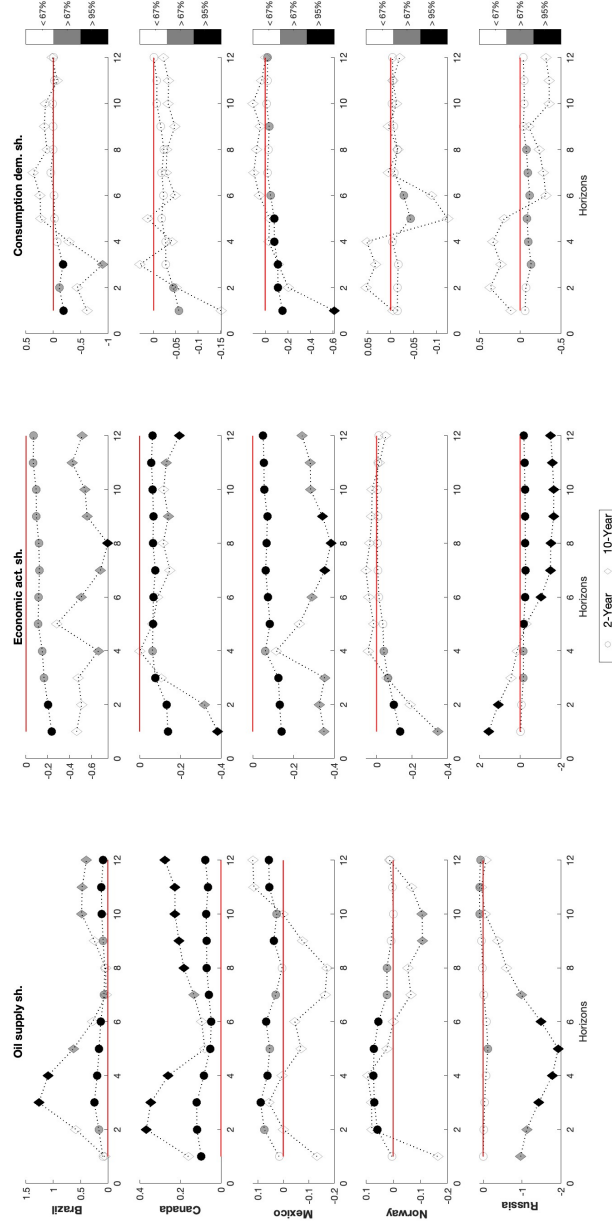
Note: The figure shows the realized (red lines) and expected excess returns (black lines) on 2-year bonds (left column of graphs) and 10-year bonds (right column of graphs) for oil-importing developed countries with a holding period of twelve months.

Figure A.7: Impulse responses for the risk premium (3-month holding period): Oil-exporting countries



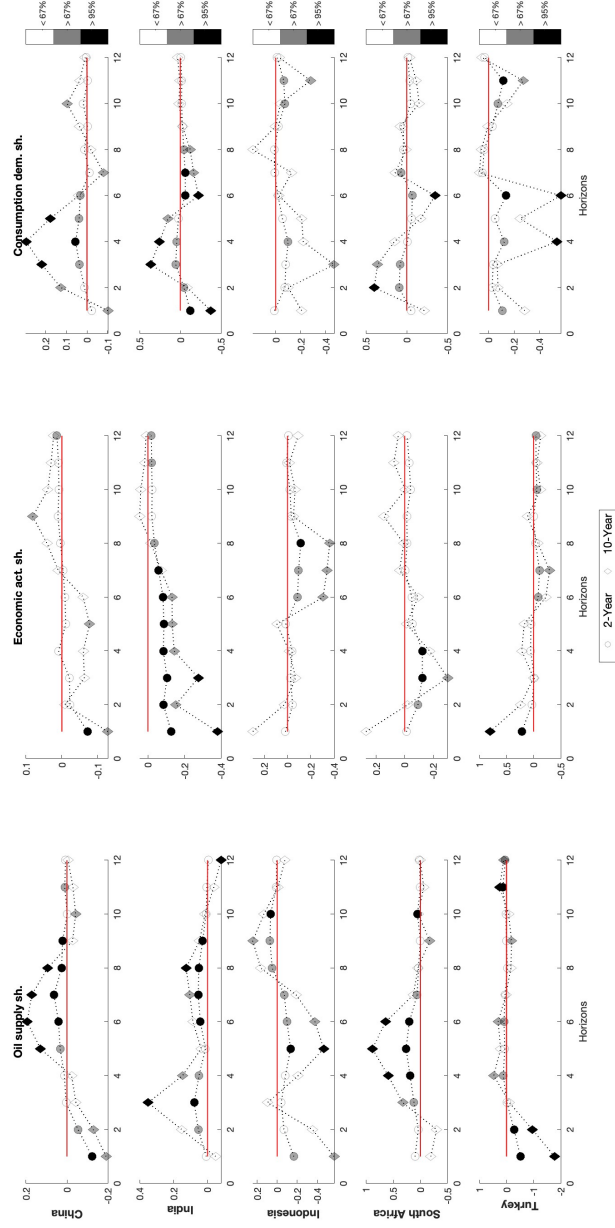
Note: The figure shows the impulse responses of the risk premium (expected excess return) of 2-year bonds (lines with circles) and 10-year bonds (lines with diamonds) for a 3-month holding period on one standard deviation oil supply shock on the left, one standard deviation economic activity shock in the center and one standard deviation consumption demand shock on the right. The darkness of circles and diamonds shows the significance of the shocks: black represents more than 95% significance, grey is more than 67% and white is less than 67% significance. In the figure, the results are for oil-exporting countries (Brazil, Canada, Mexico, Norway and Russia)

Figure A.8: Impulse responses for the risk premium (12-month holding period): Oil-exporting countries



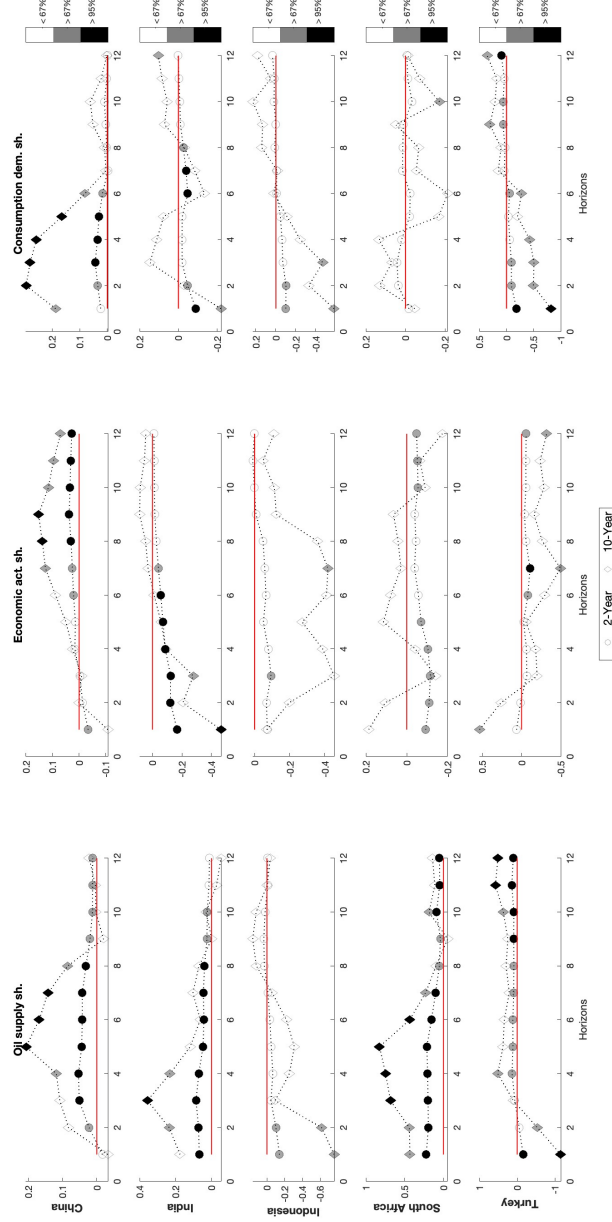
Note: The figure shows the impulse responses of the risk premium (expected excess return) of 2-year bonds (lines with circles) and 10-year bonds (lines with diamonds) for a 12-month holding period on one standard deviation oil supply shock on the left, one standard deviation economic activity shock in the center and one standard deviation consumption demand shock on the right. The darkness of circles and diamonds shows the significance of the shocks: black represents more than 95% significance, grey is more than 67% and white is less than 67% significance. In the figure, the results are for oil-exporting countries (Brazil, Canada, Mexico, Norway and Russia)

Figure A.9: Impulse responses for the risk premium (3-month holding period): Oil-importing developing countries



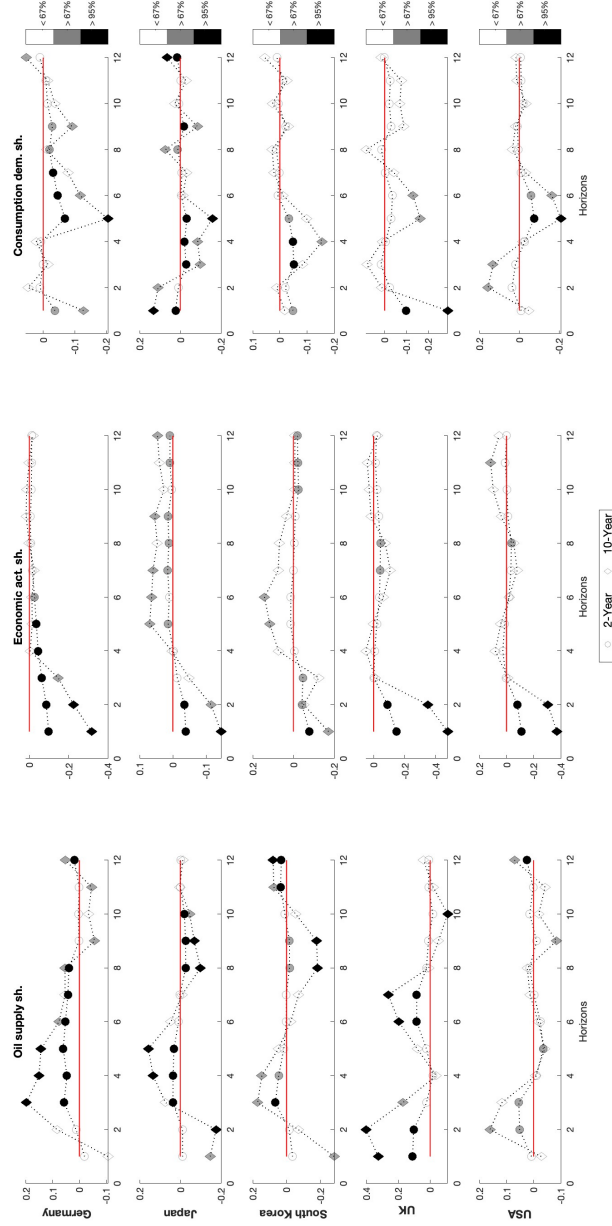
Note: The figure shows the impulse responses of the risk premium (expected excess return) of 2-year bonds (lines with circles) and 10-year bonds (lines with diamonds) for a 3-month holding period on one standard deviation oil supply shock on the left, one standard deviation economic activity shock in the center and one standard deviation consumption demand shock on the right. The darkness of circles and diamonds shows the significance of the shocks: black represents more than 95% significance, grey is more than 67% and white is less than 67% significance. In the figure, the results are for oil-importing developing countries (China, India, Indonesia, South Africa and Turkey)

Figure A.10: Impulse responses for the risk premium (12-month holding period): Oil-importing developing countries



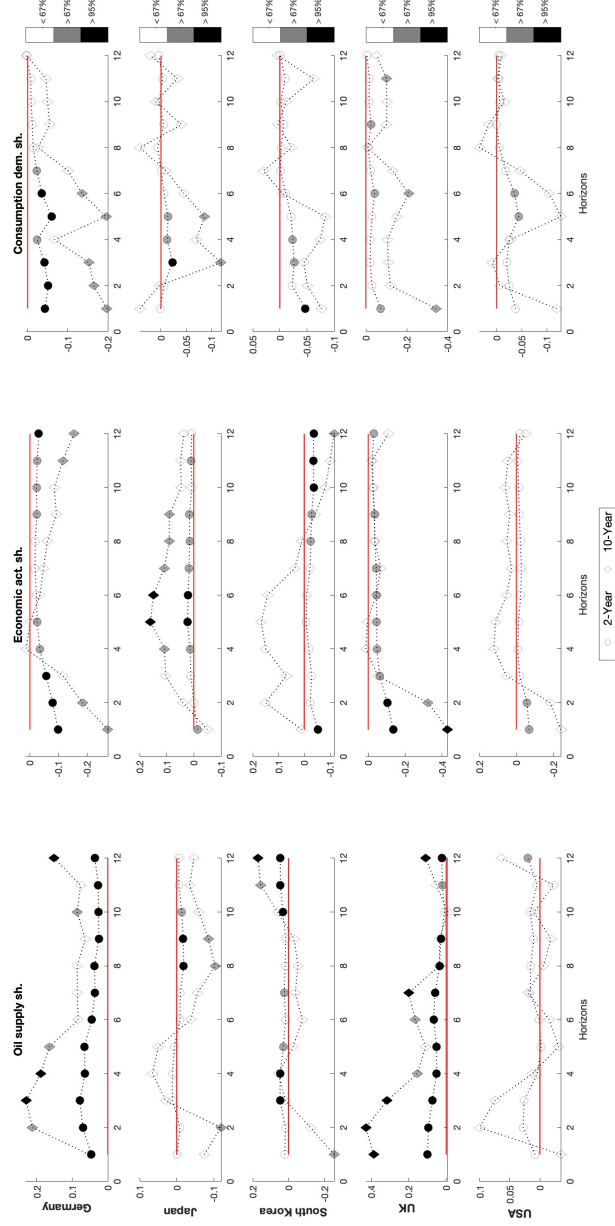
Note: The figure shows the impulse responses of the risk premium (expected excess return) of 2-year bonds (lines with circles) and 10-year bonds (lines with diamonds) for a 12-month holding period on one standard deviation oil supply shock on the left, one standard deviation economic activity shock in the center and one standard deviation consumption demand shock on the right. The darkness of circles and diamonds shows the significance of the shocks: black represents more than 95% significance, grey is more than 67% and white is less than 67% significance. In the figure, the results are for oil-importing developing countries (China, India, Indonesia, South Africa and Turkey)

Figure A.11: Impulse responses for the risk premium (3-month holding period): Oil-importing developed countries



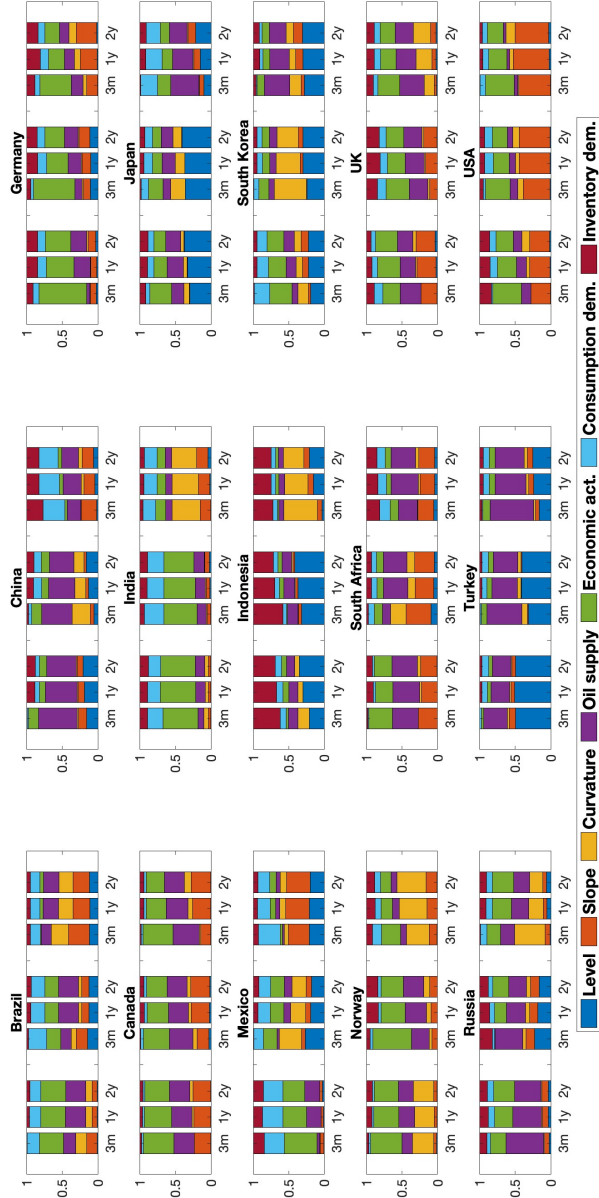
Note: The figure shows the impulse responses of the risk premium (expected excess return) of 2-year bonds (lines with circles) and 10-year bonds (lines with diamonds) for a 3-month holding period on one standard deviation oil supply shock on the left, one standard deviation economic activity shock in the center and one standard deviation consumption demand shock on the right. The darkness of circles and diamonds shows the significance of the shocks: black represents more than 95% significance, grey is more than 67% and white is less than 67% significance. In the figure, the results are for oil-importing developed countries (Germany, Japan, South Korea, UK and US)

Figure A.12: Impulse responses for the risk premium (12-month holding period): Oil-importing developed countries



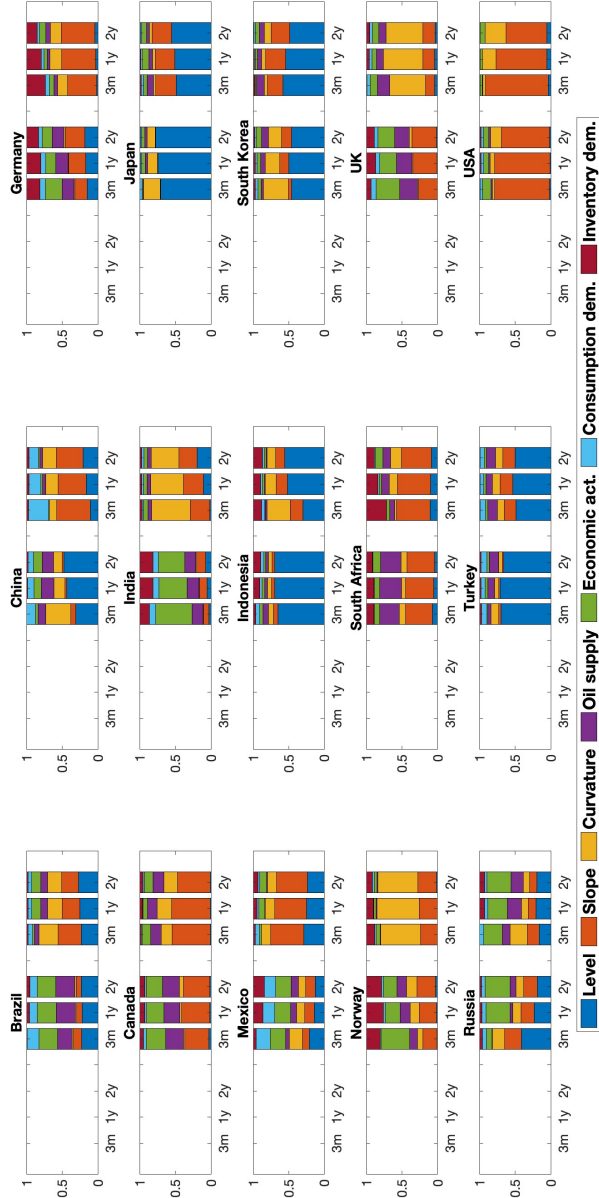
Note: The figure shows the impulse responses of the risk premium (expected excess return) of 2-year bonds (lines with circles) and 10-year bonds (lines with diamonds) for a 12-month holding period on one standard deviation oil supply shock on the left, one standard deviation economic activity shock in the center and one standard deviation consumption demand shock on the right. The darkness of circles and diamonds shows the significance of the shocks: black represents more than 95% significance, grey is more than 67% and white is less than 67% significance. In the figure, the results are for oil-importing developed countries (Germany, Japan, South Korea, UK and US)

Figure A.13: Variance decomposition - 3-month holding period



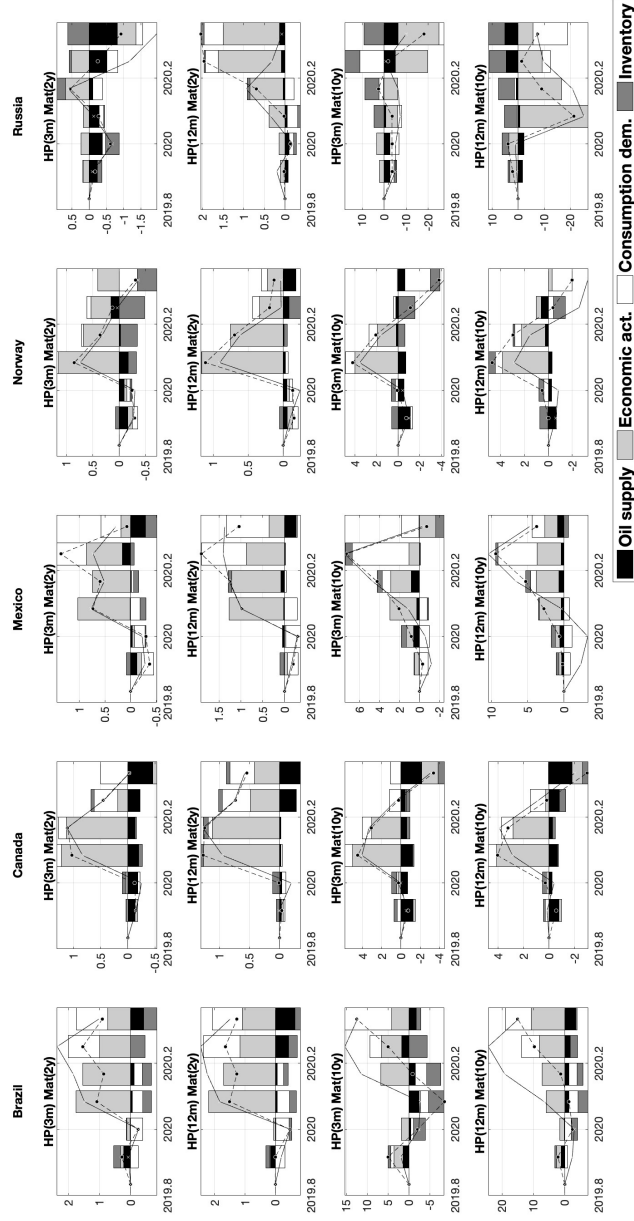
Note: The figure shows the variance decomposition of bond risk premia for a three-month holding period. Each graph shows the forecasting horizon on the horizontal axis (three months, one year, and two years) and the variance contribution on the vertical axis. There are three columns of graphs. The left column includes net oil-exporting countries, the middle column net oil-importing developing countries, and the right column net oil-importing developed countries. For each country, we present three groups of bars. Each group refers to a bond with a different maturity. The left group (first three bars) represents the variance decomposition for three-month bonds, the middle group two-year bonds, and the right group 10-year bonds.

Figure A.14: Variance decomposition - 12-month holding period



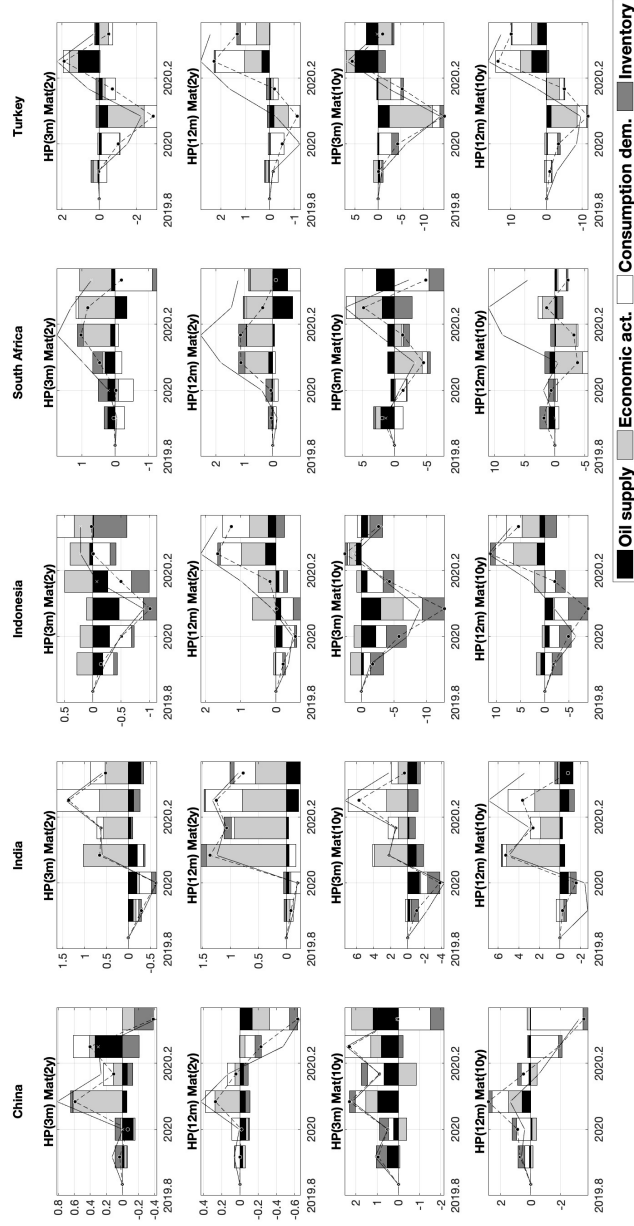
Note: The figure shows the variance decomposition of bond risk premia for a twelve-month holding period. Each graph shows the forecasting horizon on the horizontal axis (three months, one year, and two years) and the variance contribution on the vertical axis. There are three columns of graphs. The left column includes net oil-exporting countries, the middle column net oil-importing developing countries, and the right column net oil-importing developed countries. For each country, we present three groups of bars. Each group refers to a bond with a different maturity. The left group (first three bars) represents the variance decomposition for three-month bonds, the middle group two-year bonds, and the right group 10-year bonds.

Figure A.15: Historical Decomposition: Net oil-exporting countries



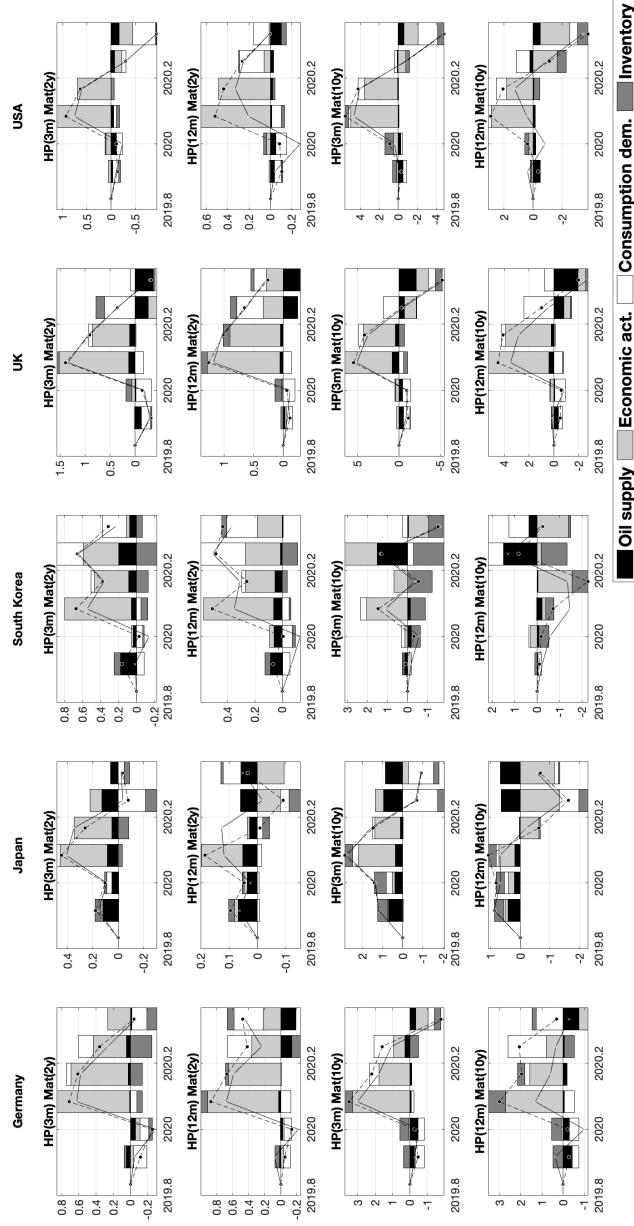
Note: The figure shows the historical decomposition of the bond risk premia of net oil-exporting countries for the period between November 2019 and May 2020. The decomposition is done for bonds with maturities of two years (first two lines of graphs) and 10 years (last two lines of graphs) and for a holding period of three months (first and third line of graphs) and 12 months (second and fourth line of graphs). The bars show the contribution of each unspanned shock (global oil supply, global economic activity, global oil demand shocks, and global inventory shocks). The short-dashed line with dots shows the sum of these shocks. The solid line represents the total model-implied risk premium. The difference between the solid line and the short-dashed line represents the contribution of the shocks due to the spanned factors (level, slope and curvature). Each graph shows the evolution of the risk premium starting from zero at the beginning of the period analyzed and expressed in percentage points.

Figure A.16: Historical Decomposition: Net oil-importing developing countries



Note: The figure shows the historical decomposition of the bond risk premia of net oil-importing developing countries for the period between November 2019 and May 2020. The decomposition is done for bonds with maturities of two years (first two lines of graphs) and 10 years (last two lines of graphs) and for a holding period of three months (first and third line of graphs) and 12 months (second and fourth line of graphs). The bars show the contribution of each unspanned shock (global oil supply, global economic activity, global oil demand shocks, and global inventory shocks). The short-dashed line with dots shows the sum of these shocks. The solid line represents the total model-implied risk premium. The difference between the solid line and the short-dashed line represents the contribution of the shocks due to the spanned factors (level, slope and curvature). Each graph shows the evolution of the risk premium starting from zero at the beginning of the period analyzed and expressed in percentage points.

Figure A.17: Historical Decomposition: Net oil-importing developed countries



Note: The figure shows the historical decomposition of the bond risk premia of net oil-importing developed countries for the period between November 2019 and May 2020. The decomposition is done for bonds with maturities of two years (first two lines of graphs) and 10 years (last two lines of graphs) and for a holding period of three months (first and third line of graphs) and 12 months (second and fourth line of graphs). The bars show the contribution of each unspanned shock (global oil supply, global economic activity, global oil demand shocks, and global inventory shocks). The short-dashed line with dots shows the sum of these shocks. The solid line represents the total model-implied risk premium. The difference between the solid line and the short-dashed line represents the contribution of the shocks due to the spanned factors (level, slope and curvature). Each graph shows the evolution of the risk premium starting from zero at the beginning of the period analyzed and expressed in percentage points.

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