Oil, Inflation, and Financial Markets

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A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF

Doctor of Philosophy

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Business Administration)

The University of British Columbia

(Vancouver)

July 2016

Abstract

The economy's heavy dependence on fossil energy links oil prices to real economic activities, inflation, and financial markets. This dissertation studies the extent to which fluctuations in oil prices are related to inflation and the prices and expected returns of Treasury bonds.

Chapter 2 shows that the correlation between U.S. core inflation and oil price changes exhibits a time-varying pattern since the 1970s. The significant resurgence of the positive correlation after the 2007 financial crisis is puzzling, given the subdued macroeconomic impact of oil price shocks since the mid-1980s. A two-sector DSGE model illustrates that the relation between the price of oil and core inflation depends on the type of shocks embedded in oil price changes. Oil supply shocks cause the price of oil and core inflation to co-move, whereas the aggregate demand shocks driven by economic growth lead to opposing changes in the price of oil and core inflation. The economic mechanisms uncovered in the model and historical geopolitical events together provide a consistent and logical explanation of the time-varying correlations observed in the data.

Chapter 3 examines the economic impact of oil prices on Treasury bond returns. I find novel evidence that growth rates of crude oil prices can explain contemporaneous excess returns on nominal U.S. Treasury bonds and inflation swaps, and also predict expected future excess returns on inflation swaps. Empirical results suggest that the impact of oil prices on nominal bonds is through the impact on expected inflation. I then build a two-sector New Keynesian model to study theoretical interactions between the economic drivers of oil prices, expected inflation, and bond yields. The model shows that oil supply and demand shocks have opposite impacts on bond yields and expected inflation. The conventional wisdom that high oil prices lead to high expected inflation and nominal yields is true only if high oil prices are driven by a negative shock to the supply of oil. In contrast, when oil prices are driven by a positive shock to productivity growth, high oil prices can lead to low expected inflation and nominal yields.

Preface

This dissertation is original, unpublished, independent work by the author, Haibo Jiang.

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Acknowledgments

I am especially grateful for advice and encouragement from my advisor, Lorenzo Garlappi. I also thank my committee members: Paul Beaudry, Murray Carlson, Jack Favilukis, Carolin Pflueger, and Georgios Skoulakis for their guidance and support. Warm thanks are also due to Adlai Fisher, Ron Giammarino, Hernan Ortiz-Molina, and other finance faculty members and PhD students at UBC Sauder for their valuable comments and help. Special thanks go to Eduardo Schwartz, who sponsored and advised me as a visiting Ph.D. student at UCLA Anderson in 2013. In addition, I thank participants at the Northern Finance Association 2014 and 2015 annual meetings and Brown Bag presentations at the Vancouver School of Economics at UBC and the Sauder School of Business at UBC for helpful suggestions and comments.

My most important debt is to my family, especially my dear wife Xiuli Qi, who continue to support my academic endeavors, with unending patience and unconditional support and love.

Finally, I gratefully acknowledge financial support from the Social Sciences and Humanities Research Council of Canada (SSHRC) CGS Doctoral Fellowship and the Canadian Securities Institute (CSI) PhD Scholarship.

Dedication

To my dear wife, Xiuli Qi

Chapter 1

Introduction

The connection between the price of crude oil and financial markets has attracted considerable attention from investors and policymakers. A series of recent news articles, appeared in the Wall Street Journal and other financial presses, brought public attention to the pronounced reactions of stocks and Treasury bond markets to rises and falls in the price of oil.[1] In addition, U.S. Fed and other central banks also typically pay close attention to oil price movements because oil price changes have a substantial effect on inflation and in particular on energy inflation.

The economy's heavy dependence on fossil energy links oil prices to real economic activities and consequently to the aggregate price level and the financial markets. Petroleum and its derivative products, as the main source of energy supply, are used for transportation and the production of a wide range of goods and services. Global expenditures on petroleum account for about 4.5% of the world GDP. The average U.S. household spends about 4% of pre-tax income on gasoline for day-to-day transportation, and about 40% of industrial energy consumption is accounted for by oil.

When the price of oil fluctuates, it affects households' expenditure on gasoline and firms' energy costs, and, to a large extent, influences aggregate consumption, production, and inflation. Thus oil price fluctuations inevitably have an effect on securities prices and monetary policies. Given the importance of oil to the

[1] Examples of news articles on co-movements between stocks and oil include "Oil and stocks are moving tick for tick" published on January 25, 2016 on CNBC (accessed on May 20, 2016 at http://www.cnbc.com/2016/01/25/oil-and-stocks-are-moving-tick-for-tick.html and "Is the link between stocks and oil breaking up?" published on April 18, 2016 on the Wall Street Journal (accessed on May 20, 2016 at http://blogs.wsj.com/moneybeat/2016/04/18/is-the-link-between-stocks-and-oil-breaking-up/). Examples of news articles on the response of Treasury bonds to oil price fluctuations include "U.S. Government bonds strengthen as oil slips: Yield curve flattest since January 2008" published on January 25, 2016 on the Wall Street Journal (accessed on May 20, 2016 at http://www.wsj.com/articles/u-s-government-bonds-strengthen-as-oil-slips-1453734373) and "US Treasury prices fall as oil buoyed" published on May 16, 2016 on CNBC (accessed on May 20, 2016 at http://www.cnbc.com/2016/05/16/us-treasury-prices-fall-as-oil-buoyed.html).

macroeconomy, it is natural to study the extent to which fluctuations in oil prices are related to inflation and the prices and expected returns of financial securities. Indeed, many studies, starting with Chen, Roll, and Ross (1986), have investigated the role of oil prices in stock returns.[2] However, few papers have studied the impact of oil prices on inflation and bond returns.[3] This is especially surprising since intuition and empirical observations suggest an important link.

The purpose of this dissertation is to fill this gap by studying the relationship between oil prices, inflation, and Treasury bond returns both empirically and theoretically. Specifically, Chapter 2 first documents a puzzling time-varying trend in correlations between U.S. core inflation and one-month lagged oil price changes from 1973 to 2015. The chapter then addresses the question of which economic mechanisms rationalize the observed time-varying correlations. Chapter 3 first addresses the question of whether the price of oil price is a significant explanatory variable and predictor of excess returns on nominal Treasury bonds. Additionally, since oil price variations are widely thought to affect inflation, consumption, and output, I then examine whether oil prices are relevant determinants for expected inflation and real yields on inflation-indexed bonds.

In general, this work is related to an extensive macroeconomic literature that studies the link between oil price shocks and the economy. Hamilton (1983) documents that oil price hikes precede 7 out of 8 postwar U.S. recessions.[4] This seminal paper triggers a series of studies that investigate the mechanisms of transmission from oil price shocks to economic output.

Recently, several papers document the muted impact of oil price shocks on the U.S. economy and other developed economies. The literature has explored different channels to rationalize this phenomenon. Blanchard and Galí (2010) attribute a reduction in real wage rigidities, along with a reduction in the share of energy in production and a lack of adverse shocks, to the decline in the impact of oil shocks on inflation and economic activity. The channel of the asymmetric impact of oil price shocks on durable goods and non-durable goods, which causes a large reduction in expenditures on durable goods, has been suggested and empirically investigated (Dhawan and Jeske, 2008; Hamilton, 2008; Kilian and Park, 2009). Bernanke, Gertler, and Watson (1997) and Clark and Terry (2010), among others, show that monetary policy dramatically responds to oil price shocks and thus magnifies the impact of oil price shocks on the economy in the

[2] Driesprong, Jacobsen, and Maat (2008), Kilian and Park (2009), Chiang, Hughen, and Sagi (2014), Jiang, Skoulakis, and Xue (2016), among others, find that oil prices impact stock returns.

[3] Exceptions are studies by Kang, Ratti, and Yoon (2014) and Baker and Routledge (2015)

[4] Hamilton (2011) updates the count at 10 out of 11.

1970s and the 1980s, but has become less responsive to oil price shocks since the 2000s. However, Hamilton and Herrera (2004) argue that monetary policy plays a much smaller role.

The impact of oil price shocks on inflation also has been studied in the monetary literature. The literature investigates the passthrough of oil price changes into inflation. The passthrough is usually estimated by the coefficient of the oil price change in a regression of regressing inflation on oil price changes. The influence of the price of oil on inflation has declined from the 1970s to the 2000s. Clarke and Subramanian (2006) show that core inflation in U.S. becomes less responsive to changes in energy prices. A decrease in energy intensity in the economy and in the exchange rate passthrough is attributed to the smaller magnitude of the influence (De Gregorio, Landerretche, Neilson, Broda, and Rigobon, 2007). Clark and Terry (2010) measure the passthrough by allowing time-varying coefficients and volatilities and confirm findings in previous studies.

Alarmingly, oil price fluctuations still have a substantial effect on the economy and the financial markets, as manifested by the most recent news articles on the pronounced reactions of stocks and Treasury bond markets to rises and falls in the price of oil, published in the period in January to May 2016.

The perception of the nature of oil price shocks among economists has evolved. Oil price shocks was thought to be exogenous and was associated with the disruption in supply of oil. Researchers commonly model oil prices as exogenous. However, this assumption is problematic, as pointed out by Rotemberg (2010) and Balke, Brown, and Yücel (2011). Recently, researchers start to realize that not all oil price shocks are the same. Kilian (2009) shows that oil price shocks are mostly driven by aggregate demand shocks instead of oil supply shocks in the period of 1975 to 2007. I take the simple view that oil prices reflect fundamental supply and demand information in the world oil market.

However, empirically identifying the intrinsic shocks embedded in the price of oil is challenging. Kilian (2009) proposes a VAR framework to decompose oil price changes, using data on world oil production and proxy for global real economic activities. Rapaport (2014) and Ready (2014) suggest to use information from the stock market to distinguish supply and demand shocks in the oil market. Rapaport (2014) uses the sign and magnitude of the correlation between daily oil price changes and stock market total returns to identify shocks specific to the oil market and shocks that affect the overall economy. Ready (2014) proposes identifying demand shocks by looking at the correlation between returns to oil firms and innovation in the VIX index.

As pointed out by Sockin and Xiong (2014), a theoretical model can help us better understand the impact of oil price shocks on the economy and the financial markets. The price of oil should be modeled

endogenously, and the demand side of the oil market should be emphasized.

This dissertation highlights three unique features of the oil in the economy. First, an oil sector is explicitly modeled in addition to the standard consumption goods sector. Second, oil is included in a household's utility function, to capture the fact that households spend about 4% of their pre-tax income on gasoline for transportation needs. In addition, household consumption of oil is assumed to be complementary to the consumption of core goods, as in Ready (2015). In particular, oil is complementary to the consumption of some durable goods, such as motor vehicles. Third, oil is also used as an energy input in producing consumption goods, reflecting the fact that 40% of industrial energy comes from oil.

This dissertation is related to a growing literature on studying determinants of nominal and real bond yield curves. Previous papers studying real rates, inflation expectations, and risk premia use latent factor term structure models (Ang, Bekaert, and Wei, 2008; Chernov and Mueller, 2012; Haubrich, Pennacchi, and Ritchken, 2012) and New Keynesian macro models (Kung, 2015; Hsu, Li, and Palomino, 2014). However, oil prices have not been considered in this literature. In chapter 3, the price of oil is treated as an explicit macroeconomic risk factor. In addition, the chapter 3 builds on the New Keynesian model; moreover, it includes an oil sector and incorporates the dual uses of oil to examine macroeconomic linkages among bond yields, inflation expectations, and supply and demand shocks in the oil markets.

My research is also related to several empirical papers that document the connection between oil spot or futures prices and U.S. Treasury bond returns. Kang, Ratti, and Yoon (2014) show that U.S. Treasury bond returns deflated by the U.S. CPI are negatively associated with oil price shocks driven by global aggregate demand for all industrial commodities. Baker and Routledge (2015) document that monthly excess returns on nominal U.S. Treasury bonds are higher when the slope of NYMEX WTI crude oil futures curve is negative. Moreover, few papers study the impact of oil prices on long-term expected inflation, although numerous studies examine the effect of oil prices on contemporaneous core inflation and total inflation, as reviewed in detail in Clark and Terry (2010). Celasun, Mihet, and Ratnovski (2012) find that oil futures price shocks have a statistically significant impact on long-term breakeven inflation. In fact, both real rates and expected inflation are important in understanding nominal bond yields (Duffee, 2014; Pflueger and Viceira, 2015). I am the first to examine not only nominal bond yields as a whole, but also real bond yields and breakeven inflation separately in relation to oil prices.

Last, several recent papers have studied the impact of oil price shocks on equity returns. Driesprong, Jacobsen, and Maat (2008) find that increases in oil prices predict lower future stock returns. Kilian and

Park (2009) show that oil supply and demand shocks jointly explain 22% of the long-run variation in U.S. real stock returns. Chiang, Hughen, and Sagi (2014) demonstrate that oil risk factors explain the returns of non-oil portfolios. These papers highlight important implications of oil price risks for equity returns, but ignore inflation. Unlike these papers, my focus is the impact of oil on inflation and bond yields.

The dissertation is organized as follows. Chapter 2 studies the puzzling time-varying correlations between core inflation and oil price changes. A two sector DSGE model is built to show the distinct impacts of oil supply and demand shocks on oil prices and core inflation. Historical geopolitical events and economic data are then used to reconcile the time-varying correlations. Chapter 3 focuses on the empirical and theoretical relations between oil price, expected inflation, and bond returns. It provides novel empirical evidence of the connection between oil prices, breakeven inflation, and real and nominal Treasury bond returns. A two-sector New Keynesian model illustrates theoretical predictions and replicates several key empirical results. The responses of real yields, breakeven inflation, and nominal yields to increases in oil prices depend on the type of shocks that drive oil prices. Chapter 4 concludes.

Chapter 2

Reconciling the puzzling time-varying correlations between oil price changes and core inflation: The distinct roles of supply and demand shocks

2.1 Introduction

The correlation between oil price changes and inflation has been of great interest to pensioners, pension fund managers, and monetary policymakers. Because oil price changes have a substantial effect on inflation and in particular on energy inflation, U.S. Fed and other central banks typically monitor oil price movements closely. Furthermore, inflation jumps destroy pensioners' purchasing power and increase pension funds' payments and liabilities. The size of the pension entitlements of the private and public pension funds in the U.S. is enormous, around $17.9 trillion dollars as of December 2014.[1] Therefore, understanding the macroeconomic linkage between the price of oil and inflation is very important. The effectiveness of using crude oil futures to hedge inflation critically depends on the correlation between oil price changes and inflation (Gorton and Rouwenhorst, 2006). In addition, oil prices can be used to gauge information regarding inflation (Cheng and Xiong, 2014). The correlation is useful for central banks to filter out the underlying

[1] Data on the pension funds are obtained from the Fed Reserve's websites.

driving forces of inflation.

Core inflation represents the change of the consumer price index (CPI) excluding food and energy. The weight of CPI-core items in the CPI consumer basket is substantial, about 76%.[2] As a result, core inflation is considered as a viable inflation target for monetary policy. Note that total inflation contains energy inflation, which is directly affected by oil price changes. The relationship between core inflation and oil prices is a distinct and clean measure of the inflationary impact of oil price shocks. However, how fluctuations in oil prices are related to core inflation is not straightforward.

A time series of correlations between U.S. core inflation and one-month lagged oil price changes, computed using a five-year rolling estimation window, exhibits an interesting time-varying trend from 1973 to 2015.[3] The correlation declines from 1973 to the mid-1980s, and becomes small and sometimes negative before 2008; but it jumps up to a positive and high level again after 2008, and, interestingly, comes down to a low level from 2014. The decline in the correlation is consistent with the muted impact of oil price shocks on the economy, as documented by Bernanke, Gertler, and Watson (1997), Hamilton (2008), Blanchard and Galí (2010), and Clark and Terry (2010), and others. Surprisingly, the correlation after the 2007 financial crisis reverts to an equivalent level observed in the 1970s. The significant resurgence of the correlation is *puzzling* because it defies easy explanations. For instance, the declining energy intensity in U.S. actually predicts a weaker relationship between oil price changes and core inflation.

The purpose of this chapter is to study the relationship between oil prices and core inflation both empirically and theoretically. Specifically, I first address the question of whether there are structural breaks in correlations between U.S. core inflation and oil price changes. I then examine which economic mechanisms can rationalize the observed puzzling pattern of the time-varying correlations.

The connection between oil prices and inflation is through the indispensable use of oil in the economy. Oil, as the main source of energy supply, is used for transportation and the production of a wide range of goods and services. Statistical data from the U.S. Energy Information Administration show that about 4% of pre-tax income of the average household is spent on gasoline for day-to-day transportation, and about 40% of industrial energy consumption is accounted for by oil in 2013. When the price of oil fluctuates, it affects households' disposable income and firms' energy costs, and, to a large extent, influences consumption, out-

[2]The weights of CPI-energy and CPI-food items are around 8% and 16%, respectively.

[3]One-month lag is used because it takes time for firms to adjust prices and production in response to oil price shocks. The time-varying trend is robust to contemporaneous or lagged correlations, to different lengths of rolling estimation window. The trend is also robust to other measures of the price of oil, such as the real price of oil, the PPI-crude oil price, and the CPI-energy index.

put, and the aggregate price level. Thus oil price fluctuations naturally have an effect on inflation, valuation of financial products that are subject to inflation, and monetary policies.

In my empirical analysis, besides estimating correlations, I also use a generalized Phillips curve model to assess the "passthrough" of oil price changes into core inflation. Chow tests show that two structural breaks in the relationship between oil price changes and core inflation occur in the mid-1980s and during the 2007 financial crisis. The presence of structural breaks indicates that the relationship between core inflation and oil prices is not stable and has fundamentally changed over time.

The perception of the nature of oil price shocks among economists has evolved. Oil price shocks was thought to be exogenous and was associated with the disruption in the supply of oil. Recently, researchers start to realize that not all oil price shocks are the same. Kilian (2009) shows that oil price shocks are mostly driven by aggregate demand shocks instead of oil supply shocks. I take the simple view that oil prices reflect fundamental supply and demand information in the world oil market. Empirically identifying the intrinsic shocks embedded in the price of oil is challenging. Kilian (2009) proposes a VAR framework to decompose oil price changes, using data on world oil production and proxy for global real economic activities. Rapaport (2014) and Ready (2014) suggest to use information from the stock market to distinguish supply and demand shocks in the oil market. As pointed out by Sockin and Xiong (2014), a theoretical model can help us better understand the inflationary impact of oil price shocks.

I use a two-sector general equilibrium model to illustrate the direct and indirect inflationary impact of oil price shocks. The economy consists of an oil sector and a consumption goods sector. Oil is in households' utility function because gasoline is complementary to consumption goods, and oil is in firms' production functions because energy is needed to produce consumption goods. Oil supply shocks are modeled directly by the total factor productivity shock in the oil sector, while oil demand shocks are triggered by the productivity shock in the consumption goods sector, which in turn affects households' demand for gasoline and firms' energy demand.

In the model, when a negative productivity shock hits the oil sector, the oil price increases because of the oil shortage. The marginal cost of producing consumption goods increases because firms have to spend more on energy input. As a result, the price of consumption goods rises. For a negative oil supply shock, both households and consumption goods firms are worse off.

On the other hand, when a positive productivity shock hits the consumption goods sector, the output of consumption goods increases and the price of consumption goods decreases. When households consume

more consumption goods, they demand more for oil, because gasoline is complementary to consumption goods. Increased demand for oil from households pushes up the price of oil, because the supply of oil is inelastic in the short run. For a positive productivity shock in the consumption goods sector, households and firms are better off, even though the oil price is higher.

The economic mechanisms illustrated in the model is then used to rationalize the puzzling pattern of the correlations. Either oil supply disruptions in oil-producing nations or increased demand for oil, especially from fast-growing emerging economies, can drive up the price of oil. But the Consumer Price Index of non-energy goods and services rises when a higher oil price is driven by oil supply shocks, and falls when a higher oil price is driven by aggregate oil demand shocks. The correlation between oil price growth rates and core inflation can be positive or negative, depending on the type of the underlying shocks. As a result, the correlation can be used to identify the types of oil price shocks.

With the benefit of hindsight, I use historical geopolitical events and economic data to reconcile the time-varying trend of the historical correlation between core inflation and oil price changes. Oil supply shocks due to geopolitical events in the period of 1973 to the mid-1980s have been widely documented, such as the Arab embargo from December 1973 to March 1974, the Iranian revolution from May 1979 to July 1979, and the Iran-Iraq war from November 1980 to February 1981. The price of crude oil increased more than 45% in each aforementioned historical event. Negative oil supply shocks were the main driver of the rising price of oil during this period. U.S. core inflation reached its historic highest level during this period. Large and positive correlations are observed, which is consistent with the passthrough of the supply-driven price of oil.

Correlations declined in the mid-1980s. This decline may be attributed to other channels, suggested by previous studies, such as the reduced share of energy in production, the deregulation of the energy sector, a less accommodative monetary policy of shocks, the lack of adverse shocks, less rigid real wages, and foreign exchange rates.

From the mid-1980s to 2008, correlations are were small, fluctuating around zero, because oil supply and demand shocks co-exist. There were mild oil supply shocks resulting from unrest in Venezuela, Gulf War I, and Gulf War II from August 1990 to October 1990. In the same period, there was increased demand for oil, especially from fast-growing emerging economies such as China and India. The IMF reports that the global real GDP grew more than 4.7% over the period of 2004-2007.[4] In addition, the negative correlation

[4]The data source is IMF World Economic Outlook Database.

observed in the period of 2004 to 2008 supports the view that the persistent rise in oil prices before 2008 was driven by the increased oil demand from emerging economies. This provides an alternative explanation of the oil price hike other than the bubble view associated with the financialization of commodity futures markets.

Since the 2007 financial crisis, the correlations jumped to the positive and high level that was observed in the 1970s. Both positive oil supply shocks and weak oil demand shocks are responsible for the resurgence of the correlations. The rapid development of shale oil in U.S. led to a positive shock to oil supply. After the 2007 financial crisis, many economies around the globe entered recessions. As illustrated in the model, both positive oil supply and weak oil demand result in a stronger co-movement between oil price changes and core inflation. Last, the decline of correlations from 2014 is consistent with the burst of shale oil boom.

This chapter makes three contributions to the literature. First, this chapter documents a new time-varying pattern of the correlation between core inflation and changes in the price of oil. The resurgence of the correlations after the 2007 financial crisis is puzzling, in contrast to the economy's declining energy intensity. Second, the puzzling pattern is reconciled by the distinct inflationary impact of oil supply shocks and demand shocks. The correlation between oil price fluctuations and core inflation is time-varying and depends on the type of shocks in the oil market. This finding has useful implications for using oil futures to hedge inflation. Third, the sign of the correlation between core inflation and oil price changes indicates whether the intrinsic shocks embedded in the price of oil are supply shocks or aggregate demand shocks. This chapter provides a new method for identifying the type of oil price shocks.

The chapter is organized as follows. The next section reviews related literature. Section 2.3 describes data and presents empirical facts. A two sector DSGE model is presented in Section 2.4. Section 2.5 analyzes model implications on inflation and the price of oil. Historical geopolitical events and economic data are used to reconcile the time-varying correlations in Section 2.6. Section 2.7 concludes.

2.2 Related literature

This chapter is related to the new strand of literature that uncovers underlying economic shocks from the price of oil. Researchers commonly model oil prices as exogenous. However, this assumption is problematic, as pointed out by Rotemberg (2010) and Balke, Brown, and Yücel (2011). The price of crude oil is determined by the global supply and demand for oil, so oil price shocks are not exogenous shocks; rather, they reflect underlying fundamental shocks in the world economy.

However, empirically identifying intrinsic shocks underlying variations in the price of oil is challenging. Kilian (2009) uses a structural VAR framework to estimate demand and supply shocks in the global crude oil market by decomposing shocks to the real price of oil into oil supply shocks, aggregate demand shocks, and oil-specific demand shocks. He shows that from 1975 to 2007, major forces driving oil price shocks were global aggregate demand shocks and precautionary demand shocks for crude oil. He suggests that the price of oil should be modeled endogenously and that models of the endogenous price of oil should emphasize the demand side of the oil market. Rapaport (2014) uses the sign and magnitude of the correlation between daily oil price changes and stock market total returns to identify shocks specific to the oil market and shocks that affect the overall economy. Ready (2014) proposes identifying demand shocks by looking at the correlation between returns to oil firms and innovation in the VIX index. This chapter suggests a new way to distinguish oil price shocks by examining the correlation between core inflation and oil price changes.

This chapter is also related to the empirical literature that investigates the passthrough of oil prices into inflation. The passthrough is usually estimated by the coefficient of the oil price change in a regression of regressing inflation on oil price changes. The influence of the price of oil on inflation has declined from the 1970s to the 2000s. Clarke and Subramanian (2006) show that core inflation in U.S. becomes less responsive to changes in energy prices. A decrease in energy intensity in the economy and in the exchange rate passthrough is attributed to the smaller magnitude of the influence (De Gregorio, Landerretche, Neilson, Broda, and Rigobon, 2007). Clark and Terry (2010) measure the passthrough by allowing time-varying coefficients and volatilities and confirm findings in previous studies. Using a correlation measure to estimate the interdependence between core inflation and the price of oil, this chapter provides an alternative explanation of such a decline, investigating beyond the declined "passthrough".

In general, this work is related to an extensive macroeconomic literature that studies the link between oil price shocks and the economy. Hamilton (1983) documents that oil price hikes precede 7 out of 8 postwar U.S. recessions, triggering a series of papers that investigate the mechanisms of transmission from oil price shocks to economic output. Hamilton (2011) updates the count at 10 out of 11. Unlike oil price shocks in 1970s, recent shocks from 2004 to 2007 are correlated with healthy global growth.

To explain the muted impact of oil price shocks on the U.S. economy and other developed economies, the literature has explored different channels. Blanchard and Galí (2010) attribute a reduction in real wage rigidities, along with a reduction in the share of energy in production and a lack of adverse shocks, to the decline in the impact of oil shocks on inflation and economic activity. The channel of the asymmetric impact

of oil price shocks on durable goods and non-durable goods, which causes a large reduction in expenditures on durable goods, has been suggested and empirically investigated (Dhawan and Jeske, 2008; Hamilton, 2008; Kilian and Park, 2009). Bernanke, Gertler, and Watson (1997) and Clark and Terry (2010), among others, show that monetary policy dramatically responds to oil price shocks and thus magnifies the impact of oil price shocks on the economy in the 1970s and the 1980s, but has become less responsive to oil price shocks since the 2000s. Hamilton and Herrera (2004) argue that monetary policy plays a much smaller role. My model differs from this line of research in that a separate oil sector is explicitly modeled and there is a feedback effect from the consumption goods sector to the oil sector.

2.3 Empirical facts

Two approaches to measuring the relationship between core inflation and oil price changes are considered. First, I present the correlation between historical core inflation and one-month lagged oil price growth rates. Second, I use a generalized Phillips curve model to assess the "passthrough" of oil prices into core inflation. In addition, I conduct Chow tests of structural breaks in the impact of oil price changes on core inflation.

2.3.1 Data and summary statistics

I use the consumer price index to measure inflation. I obtain four series of monthly CPI for All Urban Consumers (seasonally adjusted): all items, food, energy, and all items less food and energy from the website of the Bureau of Labor Statistics (BLS). I use CPI for all items, and CPI for all items less food and energy to estimate total inflation and core inflation.[5] CPI excluding volatile food and energy items is called core CPI, which measures more persistent underlying inflation. Ajello, Benzoni, and Chyruk (2012) document that average weights of CPI-energy, CPI-food, and CPI-core in the CPI consumer basket are 8%, 18%, and 74% (8%, 15%, and 77%), respectively, for the sample period of 1962Q1–2011Q4 (1985Q1–2011Q4).

The nominal price of oil is based on the refiner acquisition cost of imported crude oil, provided by the U.S. Department of Energy since 1974.[6] I extend these growth rates back to February 1973, using the dataset provided by Kilian (2009).[7] Data on global oil production are obtained from the U.S. Energy

[5] Alternatively, total inflation and core inflation could be measured by the Personal Consumption Expenditure (PCE) data from the Bureau of Economic Analysis (BEA). Ajello, Benzoni, and Chyruk (2012) also document that average weights on PCE-energy, PCE-food, and PCE-core are 6%, 12%, and 82% (5%, 9%, and 86%) for the sample period of 1962Q1–2011Q4 (1985Q1–2011Q4).

[6] The producer price index (PPI) (WPU0561) for crude oil is another proxy for the nominal price of oil used by other papers. As expected, growth rates of the price of oil based on these two proxies are highly correlated.

[7] Data are obtained from the AEA website at http://www.aeaweb.org/aer/data/june09/20070211_data.zip.

Information Administration. I use monthly data of world crude oil production for the period of January 1973 to December 2015. The unit of monthly oil production is one thousand barrels per day, which is the daily average of production over a month. The full sample period is from January 1973 to December 2015. The starting date of the sample period is constrained by the data availability for crude oil prices.

Table 2.1 presents summary statistics of four series of inflation and the rates of oil price changes. The inflation of three sub-indices has distinct characteristics. The core inflation series is very persistent and less volatile, while the energy inflation series is less persistent and very volatile. The volatility of oil price changes is 3 times larger than that of CPI-energy inflation and around 28 times that of core inflation. Comparing three subsample periods, the average growth rate of the price of oil from March 1973 to July 1987 (i.e., the pre-Greenspan period) is larger than those of two late subsample periods, and the kurtosis is about at least 3 times larger than those in the later period, meaning that more extreme oil price changes happened in the 1970s and early 1980s.

Figure 2.1 plots the historical real price of crude oil and core CPI inflation from February 1973 to December 2015. Core inflation is in the range of 3% to 13% from 1974 to 1983, and becomes smaller and less volatile starting from 1984. This stabilization of inflation is called the "great moderation." The real price of crude oil is much more volatile than core CPI inflation. Oil price hikes took place in a sequence of geopolitical events: the Arab embargo from December 1973 to March 1974, the Iranian revolution from May 1979 to July 1979, the Iran-Iraq war from November 1980 to February 1981, Gulf War I from August 1990 to October 1990, unrest in Venezuela and Gulf War II from November 2002 to March 2003.

The steady rise of the price of oil from 2004 to 2008 is an unprecedented phenomenon. Hamilton (2013) argues that global economic growth from 2004 to 2007, over 4.7% of annual real GDP growth as estimated by the IMF, is responsible for the accompanying increase in the price of oil. In particular, a group of newly industrialized economies, such as China and Indina, represent 69% of the increase in global oil consumption. Since 2008 the oil price has sharply declined and rapidly recovered.

Figure 2.2 shows the historical world oil production along with the price of oil from 1973 to 2015. Starting in the 1980s, global oil production exhibits an upward trend, but the oil supply flattens out beginning in 2005. This stagnant oil supply impedes downward pressures on the price of oil.

2.3.2 The puzzling time-varying correlations between core inflation and oil price changes

I use correlations to estimate the empirical interdependence between core inflation and changes in the price of oil. As it takes time for firms to adjust prices in response to oil price shocks, I measure the correlation between core inflation and one-month lagged oil price changes.

Figure 2.3 plots the correlation between core inflation and one-month lagged rates of oil price changes, computed using a five-year rolling estimation window, over the sample period from March 1973 to December 2015. The correlation (the solid line) is historically large and positive before 1983, becomes small and even becomes negative for a substantial period from the early 1980s to 2007, and finally rises after 2008. The solid line exhibits a time-varying pattern. The jump of the correlations happens in the fourth quarter of 2008. The magnitude of the correlation after the jump is close to that observed before the mid-1980s.

In addition, I estimate correlations in three sub-sample periods: February 1973 to July 1987 (the Pre-Greenspan period), August 1987 to September 2007 (the Great Moderation period), and October 2007 to December 2015 (the Post-Crisis period), which are plotted as dotted lines in Figure 2.3. Three correlations are 0.17 (significant at the 5% significance level), -0.09 (insignificant), and 0.16 (insignificant), respectively.

I follow Fisher (1921) to test for the difference between two independent correlations.[8] The z-tests of the differences between correlations of the Pre-Greenspan period and Post-Crisis period versus that of the Great Moderation period are 2.56 and 2.03, respectively. Both differences are significant at the 5% significance level.

Last, the time-varying trend is robust to various measures of the price of oil, such as the real price of oil, the PPI-crude petroleum index, and the CPI-energy index.

2.3.3 Structural changes

Alternatively, I conduct Chow tests of structural change for the coefficients of lagged oil price changes in the following regression. I integrate the Chow test into a generalized Phillips curve model specified as

[8] Howell (2012) provides details and textbook examples of this method on pages 284-5. Because the sampling distribution of a correlation (denoted by r) is not approximately normal, the first step is to transfer r to a new variable $r' = 0.5ln(|1+r|/|1-r|)$. The converted variable r' is approximately normally distributed with the standard error $s_{r'} = 1/\sqrt{T-3}$, where T is the number of observations. The z-test is estimated by $z = (r'_1 - r'_2)/\sqrt{1/(T_1-3)+1/(T_2-3)}$, where T_1 and T_2 are the number of observations of two correlations r_1 and r_2, respectively.

follows:

$$\pi_t^C = \beta_0 + \beta_1 \pi_{t-1}^C + \beta_2 (y_t - \bar{y}_t) + \beta_3 (y_{t-1} - \bar{y}_{t-1}) + \beta_4 \Delta p_t^o + \beta_5 \Delta p_{t-1}^o + \beta_6 D_{breakdate} + \beta_7 D_{breakdate} * \Delta p_{t-1}^o + \varepsilon_t. \tag{2.1}$$

In the above regression equation, π^C is the monthly core inflation rate. y is the monthly log industrial production index, and $\bar{y}$ is the Hodrick-Prescott filtered trend of y. Δp^o is the log growth of the monthly nominal price of oil. $D_{breakdate}$ is a dummy variable that takes a value of 0 before the known break date and 1 thereafter. The coefficient β_7 of the interaction term between the dummy and the lagged oil price change measures the difference of the impact of the lagged oil price change on core inflation before and after the known break date.

The results of Chow tests are presented in Table 2.2. Columns 1 and 2 show the existence of structural changes of the coefficients after July 1987 and after September 2007. The coefficients of the interactive variable are significantly negative after July 1987, and are significantly positive after September 2007. I also conduct Chow tests on two different break dates: December 1983, when the U.S. inflation came down from its historic highest level, and September 2008, when crude oil prices started to drop after reaching a historic peak and Lehman Brothers filed for bankruptcy. Results in columns 3 and 4 show that the changes of coefficients are significant as well for these two different break dates.

All these tests indicate that the relationship between core inflation and oil price changes in the 1970s to early 1980s and after the 2007 financial crisis is different from that in the Great Moderation period. There are structural breaks in their relationship.

However, how fluctuations in oil prices are related to core inflation is not straightforward. As not all oil price shocks are the same (Kilian, 2009), I take the simple view that oil prices reflect fundamental supply and demand information in the world oil market. As discussed in previous sections, empirically identifying the intrinsic shocks embedded in the price of oil is challenging. I build a theoretical model to better understand the inflationary impact of oil price shocks.

2.4 A two-sector general equilibrium model

I use a simple model to illustrate the basic intuition behind the economic mechanism that generates similar oil price shocks but has a distinct impact on inflation and economic fluctuations. The model features a competitive, frictionless economy, in which oil and final goods are produced by an oil sector and a final

goods sector, respectively. Oil is in the household's utility function, as oil is considered complementary to the consumption of other goods, and oil is used as input in the production of the final goods. Prices in the model are endogenous and flexible. The supply shock in the oil market is modeled by the total factor productivity shock in the oil sector. The demand shock in the oil market comes from aggregate demand for oil from the household and the final goods producer, both of which are driven by the total factor productivity shock in the final goods sector.

I consider a closed economy, i.e., the global economy, because the oil market is a global market. Although the model is very simple, it captures the key feature of the oil consumption in the economy. In addition, supply and demand shocks are separately modeled. The production of oil and consumption goods is greatly simplified, abstracting from many rich features in the oil market and the real economy. Overall, the two-sector general equilibrium model has the minimum number of elements but possesses all necessary features to address the different impact of oil supply and demand shocks on oil prices and core inflation.

2.4.1 Households

An infinitely-lived representative household maximizes the expected utility

$$E_0 \sum_{t=0}^{\infty} \beta^t [\xi (C_t)^{1-\gamma} + (1-\xi)(O_t^H)^{1-\gamma}]^{1/(1-\gamma)},\ 0 < \beta < 1,\ 0 < \xi < 1,\ \gamma > 0, \tag{2.2}$$

where β is the time discount factor, C_t the consumption of the final goods, and O_t^H is the consumption of oil. The weight on oil in the utility function is measured by $1-\xi$. The elasticity of substitution is equal to $1/\gamma$.[9]

The household owns the capital used in the oil firm and in the final goods firm and receives rental income. In addition, the household can trade one-period riskless bonds available in zero net supply. The budget constraint is expressed as

$$P_t^C C_t + P_t^O O_t^H + B_t \leq R_{t-1} B_{t-1} + R_t^C K_t^C + R_t^O K_t^O, \tag{2.3}$$

where B_t is the number of shares of bonds, R_t^C is the rental rate of the capital of the final goods firm K_t^C, and R_t^O is the rental rate of the capital of the oil firm K_t^O. The one-period riskless bond costs one dollar in current period t and pays R_t next period, which is the gross nominal interest rate. In addition, the one-period

[9] When $\gamma = 1$, one period felicity is given by the Cobb-Douglas form $(C_t)^{\xi}(O_t^H)^{1-\xi}$.

riskless bond price serves as the numéraire in the model. P_t^C and P_t^O are prices of the final goods and oil, respectively.

2.4.2 Oil sector

The oil is produced by a representative oil firm. The oil production function takes a simple form

$$Y_t^O = Z_t^O K_t^O = Z_t^O, \tag{2.4}$$

where Z_t^O is the total factor productivity (TFP) in the oil sector and K_t^O is the capital and is normalized to 1: $K_t^O \equiv 1$. I assume that $z_t^o \equiv logZ_t^O$ follows an AR(1) process

$$z_t^o = \rho_o z_{t-1}^o + \varepsilon_t^o, \tag{2.5}$$

where $\varepsilon_t^o \sim N(0, \sigma_o^2)$. The oil is sold at the price of P_t^O, which is, in equilibrium, determined by the supply and demand for oil from both households and the final goods firm.

Given the prices P_t^O and R_t^O , the oil firm maximizes its profit

$$\max_{K_t^O} \{Z_t^O K_t^O P_t^O - R_t^O K_t^O\}. \tag{2.6}$$

2.4.3 Final consumption goods sector

A representative final goods firm uses capital and oil to produce the final goods. The production function is given by

$$Y_t^C = Z_t^C (K_t^C)^\alpha (O_t^I)^{1-\alpha} = Z_t^C (O_t^I)^{1-\alpha}, \tag{2.7}$$

where Z_t^C is the total-factor productivity (TFP), O_t^I is the amount of oil, and K_t^C is the capital and normalized to 1: $K_t^C \equiv 1$. The share of oil in the production is measured by $1-\alpha$. Similarly, $z_t^c \equiv logZ_t^C$ is assumed to follow an AR(1) process

$$z_t^c = \rho_c z_{t-1}^c + \varepsilon_t^c, \tag{2.8}$$

where $\varepsilon_t^c \sim N(0, \sigma_c^2)$. In addition ε_t^c is assumed to be independent of ε_t^o.

Each period, the final goods firm maximizes its profit

$$\max_{K_t^C, O_t^I} \{Z_t^C (K_t^C)^{\alpha} (O_t^I)^{1-\alpha} P_t^C - K_t^C R_t^C - O_t^I P_t^O\}, \tag{2.9}$$

subject to (2.7), taking the price and the rental rate as given.

2.4.4 Central bank

To complete the model, a central bank follows a Taylor rule to set the nominal interest rate as follows

$$i_t = logR_t = \rho + \phi_\pi \pi_t^c,\ \phi_\pi > 1, \tag{2.10}$$

where $\rho = -log\beta$ and $\pi_t^c = log(P_t^C / P_{t-1}^C)$ is the inflation rate of the final goods price.

As there is no friction in this simple model, the monetary policy does not affect real variables. However, nominal variables, such as prices and inflation, are not independent of the Taylor rule.

2.4.5 Equilibrium

The optimal conditions of the household's and two firms' maximization problems are given in Appendix A. In the model, two total factor productivity shocks are exogenous, and capital in both firms is normalized to 1. All other real and nominal variables are endogenous.

2.5 Oil price and core inflation

Instead of going through analytical solutions for the oil price and the final goods price, I use supply-demand diagrams in the oil market and the final goods market to illustrate the transmission of two productivity shocks to two prices. I then discuss the co-movement between the price of oil price and the price of the consumption goods, which is corresponding to the price index of core inflation in the model.

2.5.1 Supply-demand diagrams

In the diagram for the oil market, the oil supply curve is a vertical line because the production of oil is determined by the fixed level of the oil capital and by the exogenous productivity level. Demand for oil is the sum of the demand from households and the demand from the final goods firm. The oil demand curve is a downward sloping. In the diagram for the consumption goods market, the supply curve of the final goods

is upward sloping, and the demand curve of the final goods is downward sloping.

Figure 2.4 shows how a negative productivity shock in the oil firm affects the supply and demand of oil and the final goods and their prices. The output of oil decreases when a negative productivity shock hits the oil sector. The vertical supply curve of oil is shifted to the left. Everything else being equal, the negative oil supply shock results in a higher oil price. Because the final goods firm needs the oil to produce the final goods, the higher oil price means a higher marginal production cost for the final goods. The final goods firm will produce less and supply fewer final goods. The supply curve of the final goods is shifted to the left, so the final goods price also goes up.

Thus, a negative productivity shock in the oil firm leads to higher prices for both oil and the final goods. Oil price shocks originating from the supply side of oil lead to a positive correlation between the prices of the consumption goods and oil.

Figure 2.5 shows that a positive productivity shock in the final goods sector leads to a lower price of the final goods but a higher price of oil. When productivity in the final goods firm increases, the marginal production cost decreases even if I assume that the final goods firm does not change its demand for energy. The final goods firm produces and supplies more of the final goods, so the supply curve of the final goods is shifted to the right. Everything else being equal, the final goods are sold at lower prices. Households increase their consumption of the final goods, given that the final goods are cheaper. Because of the income effect and the complementarity of oil to the final goods (i.e., $1/\gamma < 1$ in the utility function), households want to increase their consumption of oil.

The change of the aggregate demand for oil needs further analysis, because the oil demand by the final goods firm could be lower. Assume that the final goods firm initially does not change its demand for oil. As analyzed above, the oil demand by households increases, so the aggregate oil demand increases. Given that the supply of oil does not change, the demand curve of oil is shifted to the right, resulting in a higher oil price. Facing the increased costs of oil, the final goods firm decreases its demand for oil. Continuing this analysis, the oil price is adjusted high enough to clear the oil market, and the final goods price is adjusted low enough to clear the final goods market.

When the positive productivity shock hits the final goods market, the lower price of the final goods and the higher price of oil are observed. But the higher oil price this time comes from the demand side of the oil market. Most important, the transmission mechanism from a positive innovation in productivity to the economy induces a negative correlation between core inflation and the oil price.

2.5.2 Positive and negative correlations

To sum up, the rise of the oil price can occur because of either a negative productivity shock in the oil firm or a positive productivity shock in the final goods firm. However, the price of the final goods goes up for a negative Z_t^O shock but goes down for a positive Z_t^C shock. As no food is considered in this model, the change of the final goods price represents core inflation. Thus, the correlation between core inflation and an oil price change could be positive or negative depending on the underlying shocks that drive the oil price. A mixture of two types of TFP shocks can generate a very rich set of scenarios.

Theoretically, positive or negative correlations, and small or large correlations, are all possible, depending on which mechanism dominates the other. I examine the usefulness of the two mechanisms to help explain the time-varying trend discussed below.

Next, the economic mechanisms are examined by using historical geopolitical events and economic data to explain the time-varying trend and structural breaks of the relationship between oil price changes and core inflation.

2.6 Historical events, oil supply and demand shocks, and correlations

With the benefit of hindsight, I use historical geopolitical events and economic data to distinguish oil supply shocks from global demand shocks in subsample periods. Table 2.3 lists oil-related geopolitical and economic events from 1973 to 2015. I further utilize the identified types of oil shocks to reconcile the puzzling time-varying pattern of correlations between U.S. core inflation and oil price changes.

Oil supply shocks due to geopolitical events in the period of 1973 to the mid-1980s have been widely documented, including the Arab embargo from December 1973 to March 1974, the Iranian revolution from May 1979 to July 1979, and the Iran-Iraq war from November 1980 to February 1981. The price of crude oil increased by more than 45% upon each of the aforementioned three historical events. Negative oil supply shocks were the main driver of the rising price of oil in this period. U.S. core inflation reached its historic highest level during this period. Thus, a large and positive correlation of 0.17 is observed in the period of March 1973 to July 1987, which is consistent with the proposed mechanism.

Note that the correlation declines from the mid-1980s onward. It is argued that the decline may be attributed to other factors, suggested by previous studies, such as a reduced share of energy in production, deregulation of the energy sector, a less accommodative monetary policy of shocks, a lack of adverse shocks,

less rigid real wages, and foreign exchange rates.

For instance, Figure 2.6 shows that energy intensity, measured by the total primary energy consumption per dollar of GDP, halves from 1980 to 2010. As the share of petroleum in the overall economy declines, the price of crude oil has less influence on inflation. A smaller energy share in aggregate production helps explain lower correlations between inflation and oil prices from the 1970s to 2007, but it contradicts the rise of these correlations after the 2007 financial crisis, because the energy share does not increase after 2007.

Over the course of the mid-1980s to 2003, Gulf War I from August 1990 to October 1990, the mild oil supply shocks of Venezuelan unrest, and Gulf War II from November 2002 to March 2003 all took place. A handful of small oil supply shocks happened. Correspondingly, correlations were also small, fluctuating around zero as the supply and demand channels co-existed.

The IMF reports that global real GDP grew by more than 4.7% over the period of 2004-2007.[10] Fast-growing emerging economies, such as China and India, increased demand for oil. For instance, the share of world total petroleum consumption consumed by China and India has persistently risen from 5% to 15% from 1990 to 2013. This rise can be interpreted as the dominance of the aggregate demand channel. Correlations are negative over this period, although mostly not significantly different from zero.

It is worth noting that the financialization of commodity markets also occurred in the period of 2004 to 2008. The large inflow of investments to commodity futures markets triggered a heated debate about whether commodity prices are distorted by the financialization. In particular, it is argued that speculation in futures markets led to a bubble in oil prices in 2007 and 2008. Although there is some evidence to support this bubble view, Fattouh, Kilian, and Mahadeva (2012), among many others, defend a fundamental view that economic fundamentals, such as disruption to oil supply and increased global demand for oil, are responsible for the persistent run-up in oil prices. Interestingly, the empirical correlation between core inflation and oil price changes in this period may shed some light on this debate. If the persistent rise in oil prices before 2008 was due to speculation in crude oil futures, it would lead to higher energy costs for consumers and producers, i.e., like the scenario of a disruption in oil supply; consequently, as analyzed in the model, the correlation between core inflation and oil prices should be positive and increasing. However, the observed correlation is negative, which is inconsistent with the bubble view but in favor of the fundamental view. Admittedly, as pointed out by Cheng and Xiong (2014), the two different views are not necessarily

[10]The data source is IMF World Economic Outlook Database, which is accessible at http://www.imf.org/external/pubs/ft/weo/2014/01/weodata/index.aspx.

exclusive.

After the 2007 financial crisis, economies across the world have fallen into recessions, followed by recoveries. A lack of strong economic growth is apparent. Meanwhile, the U.S. domestic oil supply grew rapidly as the fracking technology improved and have been widely adopted. Because both positive supply shocks and weaker demand shocks increase correlations in the model, these two facts together can explain the positive correlations between core inflation and oil price changes after the 2007 financial crisis. The resurgence of positive correlations cannot be explained by channels suggested in the literature, such as the reduced share of energy in the economy.

Last, it is noticeable that the correlations decrease to small values from 2014. The decline in correlations is consistent with the beginning of the burst of shale oil boom and the steady economic growth in U.S. and other major economies.

In summary, the aforementioned historical events provide a consistent and logical explanation of the time-varying correlations observed in the data. The above analysis supports the implications of the two-sector general equilibrium model.

2.7 Conclusion

This chapter studies the macroeconomic linkage between the price of oil and core inflation, which sheds light on identifying intrinsic shocks in oil price shocks. I document that the correlation between U.S. core inflation and changes in the price of oil exhibits a time-varying pattern from 1973 to 2015: being large and positive before the mid-1980s, declining and then sometimes being negative for a substantial period of time from the mid-1980s to 2008, rising after 2008, and finally declining from 2014. Empirical results confirm the presence of two structural breaks in correlations in the mid-1980s and during the 2007 financial crisis.

I build a two-sector general equilibrium model to study the underlying economic mechanism and to further rationalize these facts. Theoretical analysis shows that the relation between the price of oil and inflation risk depends on the type of shocks embedded in oil price changes. Oil supply shocks cause the price of oil and core inflation to co-move, whereas the aggregate demand shocks in the consumption goods sector lead to an opposing movement of the price of oil and core inflation. The implications of the model are supported by the analysis of using historical events to explain the time-varying correlation observed in the data.

The implications from this chapter are practical for central banks and pension fund managers. The

sign of correlation indicates whether the intrinsic shocks embedded in the price of oil are supply shocks or aggregate demand shocks. This structural analysis provides a new method for identifying the type of oil price shocks. In addition, the understanding of time-varying correlation based on the supply and demand shocks in the oil market can help investors to more effectively hedge inflation, and it can help central banks to better gauge information regarding inflation from oil price shocks.

Table 2.1: Summary statistics of inflation series and oil price changes

This table reports summary statistics for the inflation series on CPI, CPI-core, CPI-food, and CPI-energy, and oil price changes. The full sample period is from March 1973 to December 2015. Inflation rates are annualized percent change. Oil price changes are expressed as annualized percent growth. The last two columns are corresponding correlations with contemporaneous and 1-month lagged oil price changes, respectively. *, **, and *** denote significance of correlations at the 10%, 5%, and 1% level, respectively.

Panel A: Full sample period: 1973.3 - 2015.12

	Central Moments						Autocorrelation		Correlation	
	Mean	SD	Skew.	Kurt.	Min	Max	AC(1)	AC(2)	Cont.	Lagged
CPI	4.01	4.14	0.14	6.91	-21.25	21.72	0.64	0.47	0.44***	0.43***
CPI-core	3.97	3.10	1.60	5.97	-2.96	17.03	0.77	0.75	0.07*	0.08*
CPI-food	3.97	5.13	3.79	35.92	-11.58	61.98	0.36	0.28	0.11**	0.13***
CPI-energy	4.85	28.40	-0.91	13.44	-216.29	161.53	0.42	0.01	0.60***	0.60***
Oil price changes	4.52	90.93	-0.26	9.35	-439.88	541.11	0.48	0.14	–	–

Panel B: Subsample period: 1973.3 - 1987.7

	Central Moments						Autocorrelation		Correlation	
	Mean	SD	Skew.	Kurt.	Min	Max	AC(1)	AC(2)	Cont.	Lagged
CPI	6.78	4.43	0.22	3.29	-6.56	21.72	0.64	0.58	0.42***	0.43***
CPI-core	6.76	3.63	0.60	3.43	-2.96	17.03	0.64	0.59	0.12	0.17**
CPI-food	6.39	7.45	2.78	19.88	-11.58	61.98	0.28	0.21	0.21***	0.20***
CPI-energy	8.17	19.28	-0.74	7.13	-83.22	59.08	0.68	0.37	0.61***	0.65***
Oil price changes	9.65	71.79	1.46	27.10	-383.53	541.11	0.54	0.21	–	–

Panel C: Subsample period: 1987.8 - 2007.9

	Central Moments						Autocorrelation		Correlation	
	Mean	SD	Skew.	Kurt.	Min	Max	AC(1)	AC(2)	Cont.	Lagged
CPI	3.01	2.58	0.34	7.12	-6.03	16.52	0.29	-0.11	0.39***	0.45***
CPI-core	2.89	1.42	0.58	3.49	0.00	7.79	0.42	0.42	-0.06	-0.09
CPI-food	2.94	2.74	0.60	5.02	-5.23	15.97	0.20	0.03	0.03	0.11
CPI-energy	4.59	27.95	0.59	7.73	-86.84	161.53	0.28	-0.22	0.46***	0.56***
Oil price changes	6.56	92.45	0.27	4.98	-237.22	459.66	0.37	0.01	–	–

Panel D: Subsample period: 2007.10 - 2015.12

	Central Moments						Autocorrelation		Correlation	
	Mean	SD	Skew.	Kurt.	Min	Max	AC(1)	AC(2)	Cont.	Lagged
CPI	1.61	4.12	-1.92	12.62	-21.25	12.57	0.52	0.13	0.76***	0.61***
CPI-core	1.76	0.84	-0.52	3.65	-1.35	3.43	0.42	0.25	0.21**	0.16
CPI-food	2.27	2.52	0.92	4.36	-2.06	11.23	0.59	0.56	0.00	0.07
CPI-energy	-0.33	40.01	-1.76	11.79	-216.29	114.80	0.46	0.10	0.78***	0.63***
Oil price changes	-9.45	113.84	-1.51	6.17	-439.88	210.67	0.59	0.28	–	–

Table 2.2: Chow test

This table presents results of Chow test. Core inflation is regressed on the lagged core inflation, contemporaneous and lagged output gap, contemporaneous and lagged oil price changes, a dummy variable that equals to 0 before a break date and 1 thereafter, and an interaction term between the dummy and the lagged oil price changes. π^C is the monthly core inflation rate. y is the monthly log industrial production index. $\bar{y}$ is the Hodrick-Prescott filtered trend of y. Δp^o represents the percentage change in the monthly nominal oil price. The dummy variable of $D_{postVolcker}$ equals 0 before July 1987 and 1 thereafter. The dummy variable of $D_{postCrisis}$ equals 0 before September 2007 and 1 thereafter. The dummy variable of $D_{post1983}$ equals 0 before December 1983 and 1 thereafter. The dummy variable of $D_{postLehman}$ equals 0 before September 2008 and 1 thereafter. Newey-West standard errors with six lags are in parentheses. *, **, and *** denote significance at the 10%, 5%, and 1% level, respectively.

	(1)	(2)	(3)	(4)
	π_t^C	π_t^C	π_t^C	π_t^C
π_{t-1}^C	0.56***	0.40***	0.50***	0.41***
	(0.06)	(0.08)	(0.07)	(0.06)
$y_t - \bar{y}_t$	0.25	-0.14	0.28	0.00
	(0.20)	(0.11)	(0.19)	(0.14)
$y_{t-1} - \bar{y}_{t-1}$	-0.12	0.19	-0.14	0.04
	(0.20)	(0.12)	(0.18)	(0.14)
Δp_t^o	-0.00	0.00	-0.01	0.00
	(0.01)	(0.01)	(0.01)	(0.01)
Δp_{t-1}^o	0.05**	-0.01	0.05	-0.01*
	(0.02)	(0.01)	(0.03)	(0.01)
$D_{postVolcker}$	-1.74***			
	(0.34)			
$D_{postVolcker} * \Delta p_{t-1}^o$	-0.06***			
	(0.02)			
$D_{postCrisis}$		-0.66***		
		(0.12)		
$D_{postCrisis} * \Delta p_{t-1}^o$		0.02**		
		(0.01)		
$D_{post1983}$			-2.34***	
			(0.45)	
$D_{post1983} * \Delta p_{t-1}^o$			-0.06*	
			(0.03)	
$D_{postLehman}$				-0.75***
				(0.13)
$D_{postLehman} * \Delta p_{t-1}^o$				0.02**
				(0.01)
Constant	2.98***	1.73***	3.82***	1.78***
	(0.47)	(0.19)	(0.60)	(0.18)
Adj. R^2	60%	30%	62%	30%
Observations	414	341	426	384
Sample period	1973.3-2007.9	1987.8-2015.12	1973.2-2008.9	1984.1-2015.12

Table 2.3: List of geopolitical and economic events

Oil prices are obtained from the website of U.S. Energy Information Administration. Hamilton (2013) provides the list of oil price shocks. Data on U.S. recessions are obtained from the NBER website. GDP decline refers to the decrease of GDP measured from peak to trough.

Panel A: Oil price shocks

Event	Period	Oil price increase
Arab oil embargo	Nov. 1973 - Feb. 1974	51%
Iranian revolution	May 1979 - Jan. 1980	57%
Iran-Iraq War	Nov. 1980 - Feb. 1981	45%
Gulf War I	Aug. 1990 - Oct. 1990	93%
Venezuela unrest, Gulf War II	Nov. 2002 - Mar. 2003	28%
Strong demand, stagnant supply	Feb. 2007 - Jun. 2008	145%
Libyan Civil War	Feb. 2011 - Oct. 2011	29%

Panel B: U.S. recessions

Event	Period	GDP decline
1973-1975 recession	Nov. 1973 - Mar. 1975	-3.2%
1980 recession	Jan. 1980 - Jul. 1980	-2.2%
Early 1980s recession	Jul. 1981 - Nov. 1982	-2.7%
Early 1990s recession	Jul. 1990 - Mar. 1991	-1.4%
Early 2000s recession	Mar. 2001 - Nov. 2001	-0.3%
Great recession	Dec. 2007 - Jun. 2009	-4.3%

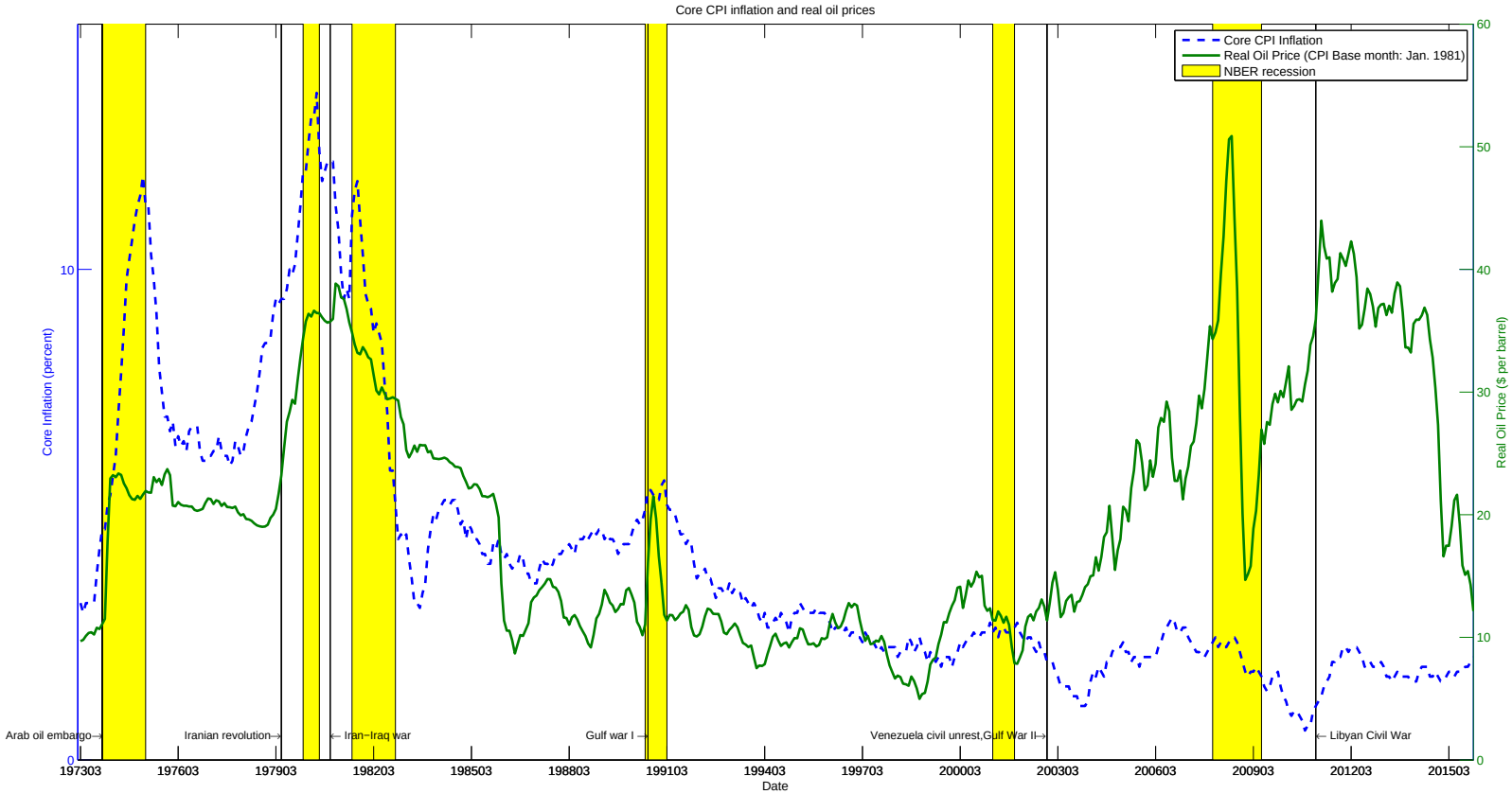

Figure 2.1: Historical prices of crude oil and core inflation.

The core CPI inflation series is monthly year-over-year rates. The real oil price is the refiners' acquisition cost of imported crude oil deflated by CPI inflation with a base month of January 1981. The real oil price is chosen to show the comparable magnitude of oil price changes for the whole sample period.

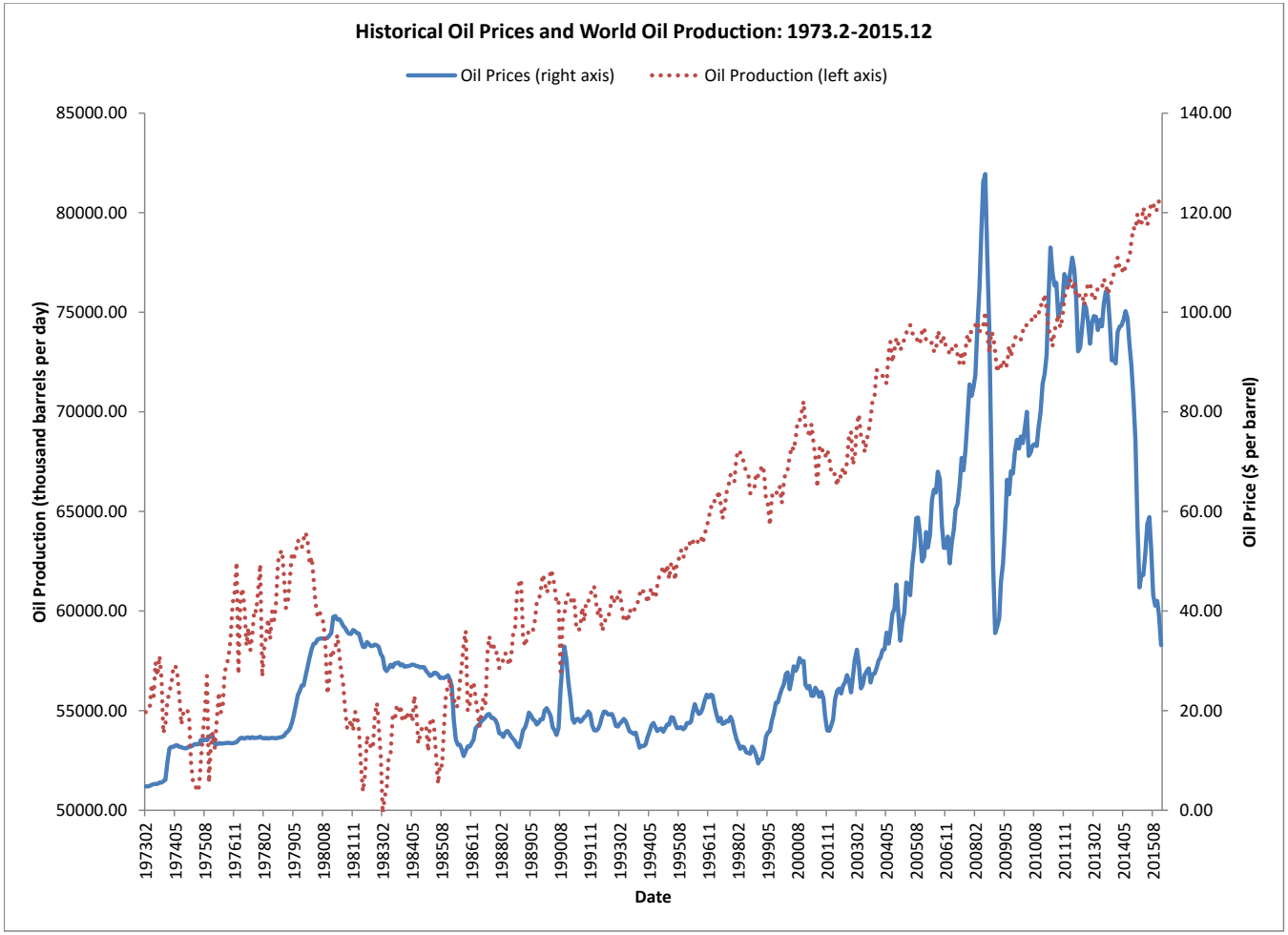

Figure 2.2: The price of oil and world crude oil production.

The oil price refers to the refiners' acquisition cost of imported crude oil. The world oil production is measured in the unit of thousand barrels per day. Both data are obtained from the website of U.S. Energy Information Administration.

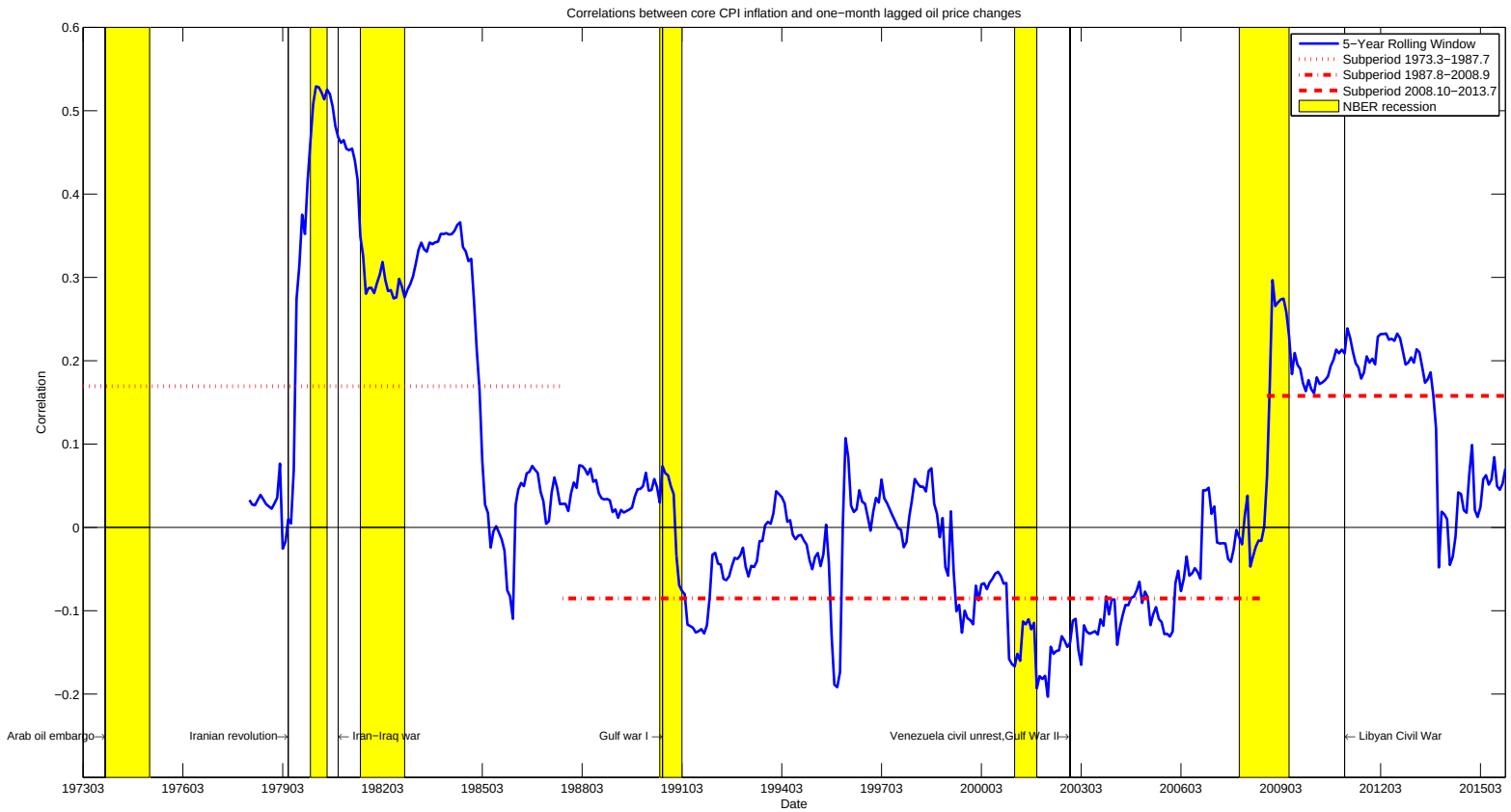

Figure 2.3: Correlations between monthly core inflation and one-month lagged oil price changes.
The core CPI inflation rates are an annualized percent estimated at a monthly frequency. The nominal oil price is the refiners' acquisition cost of imported crude oil. One month lagged oil price changes are used to reflect the time required for firms to respond to oil price changes.

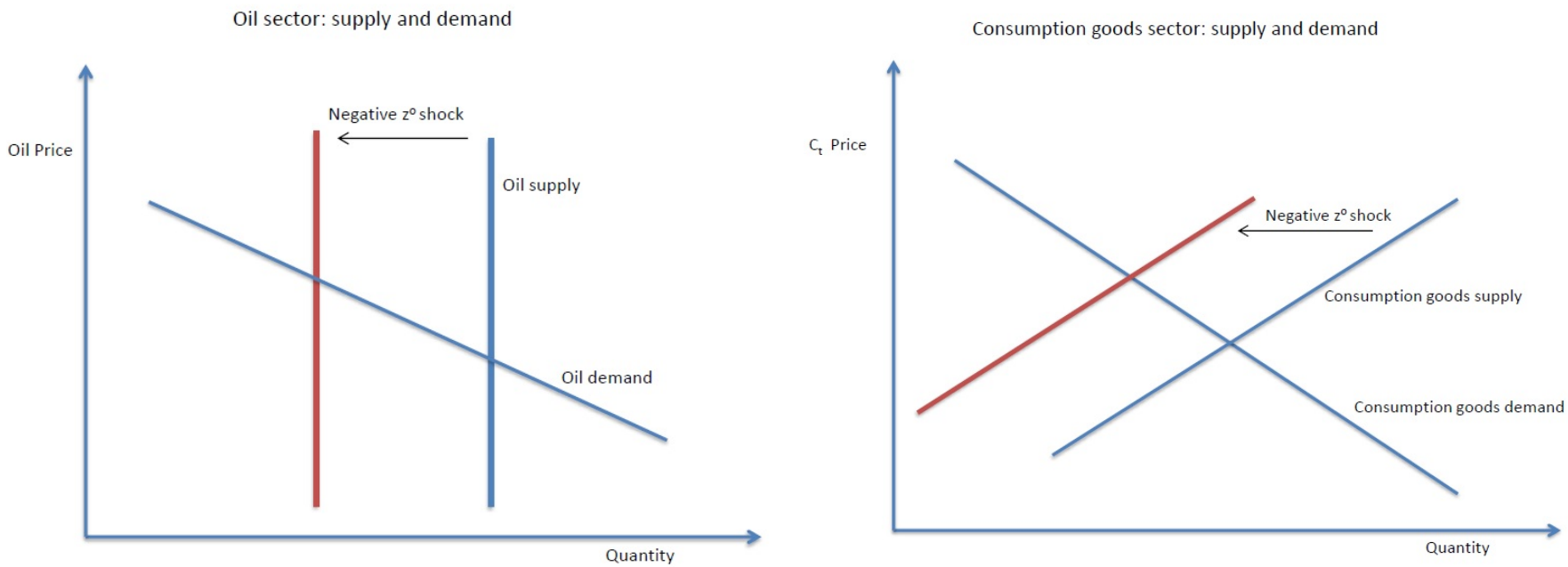

Figure 2.4: A negative productivity shock z_t^o in the oil sector.

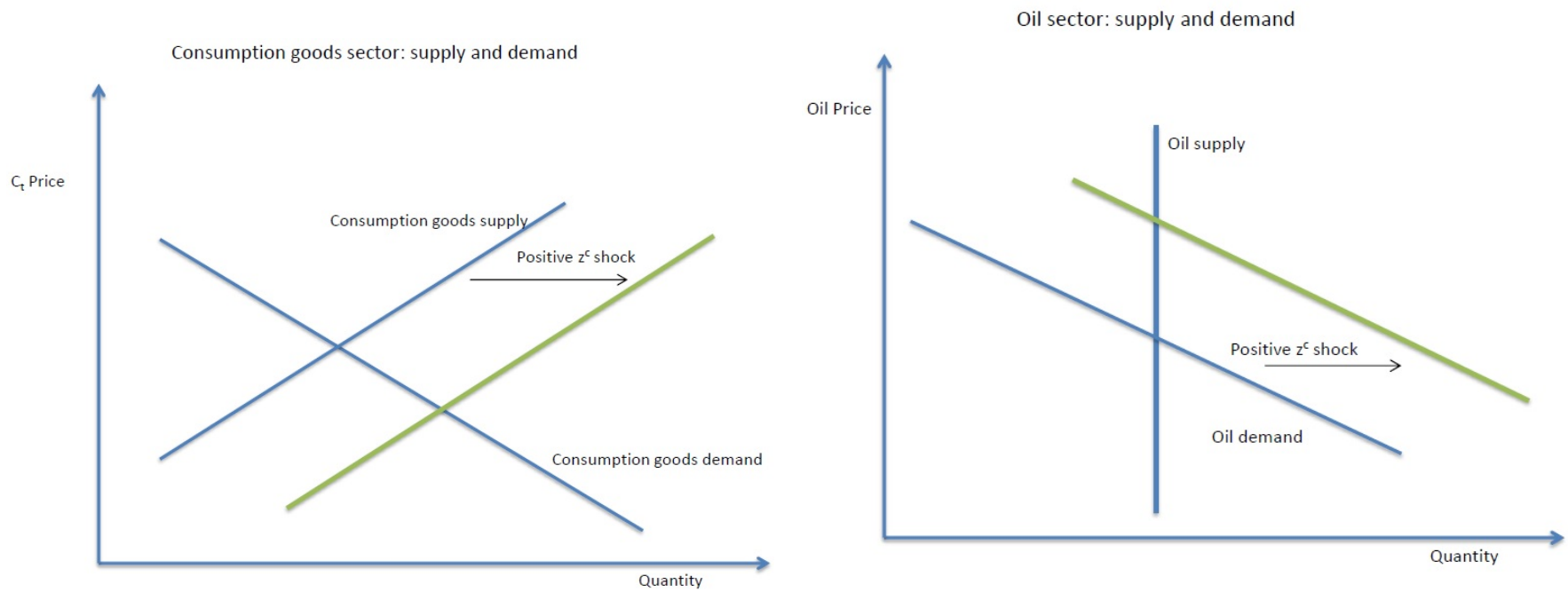

Figure 2.5: A positive productivity shock z_t^c in the consumption goods sector.

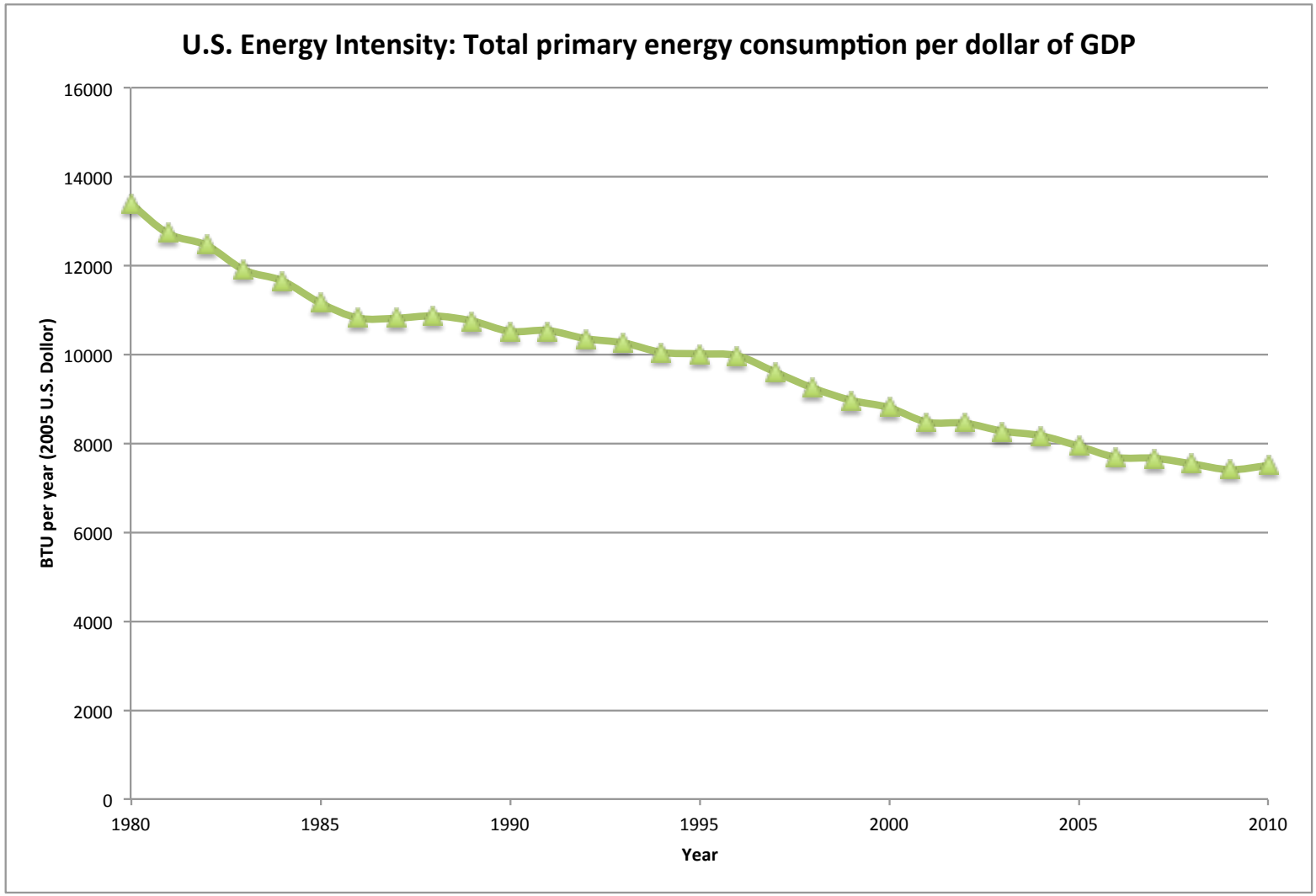

Figure 2.6: U.S. energy intensity from 1980 to 2010.

Energy intensity is measured by the total primary energy consumption per dollar of GDP. Data on U.S. energy intensity are obtained from the website of U.S. Energy Information Administration.

Chapter 3

Oil prices, expected inflation, and bond returns

3.1 Introduction

Oil is the single most important commodity in the world economy: global expenditures on petroleum account for about 4.5% of the world GDP. Oil is also a special commodity, because it is both consumed by households to meet their daily energy needs and used by firms as energy input to produce a wide range of goods and services.[1] Given the importance of oil to the macroeconomy, it is natural to study the extent to which fluctuations in oil prices are related to the prices and expected returns of financial securities. Indeed, many studies, starting with Chen, Roll, and Ross (1986), have investigated the role of oil prices in stock returns.[2] However, few papers have studied the impact of oil prices on bond prices and returns.[3] This is especially surprising since intuition and casual empirical observations suggest an important link. For instance, one day after OPEC announced on November 27, 2014 that it would keep its production ceiling unchanged, the yield on 10-year U.S. Treasury bond fell 8 basis points, along with a sharp 10% drop in the WTI crude oil price.

The purpose of this chapter is to fill this gap by studying the relationship between oil prices and bond returns both empirically and theoretically. Specifically, I first address the question of whether the price of oil

[1]The average U.S. household spends about 4% of pre-tax income on gasoline for day-to-day transportation, and about 40% of industrial energy consumption is accounted for by oil, according to data in 2013 from the U.S. Energy Information Administration.

[2]Driesprong, Jacobsen, and Maat (2008), Kilian and Park (2009), Chiang, Hughen, and Sagi (2014), among others, find that oil prices impact stock returns.

[3]Exceptions are studies by Kang, Ratti, and Yoon (2014) and Baker and Routledge (2015)

price is a significant explanatory variable and predictor of returns on nominal Treasury bonds in excess of Treasury bills. Additionally, since oil price fluctuations are widely thought to affect inflation, consumption, and output, I then examine whether oil prices are relevant determinants for expected inflation and real yields on inflation-indexed bonds.

In my empirical analysis, I find novel evidence that high growth rates of crude oil spot prices can explain low contemporaneous excess returns on nominal 10-year U.S. Treasury bonds, breakeven inflation (the difference between nominal and real yields), and inflation swaps, which provide market-based measures of expected inflation.[4] In addition, oil price growth can predict positive expected excess returns on breakeven inflation and inflation swap rates. Oil prices appear to provide incremental information above and beyond the yield spread, which is a well-known predictor of excess bond returns.

Understanding the connections between oil prices and bond yields proves to be very challenging, because they depend on the underlying causes of oil price changes (Kilian, 2009). An oil price hike could be bad news for the economy if driven by a scarce oil supply, or good news if driven by a strong demand for oil due to economic growth. In addition, simply examining the relationship between nominal yields and oil prices might disguise valuable information. For example, the real rate component and breakeven inflation component in nominal yields may respond differently to oil price changes.

I build a two-sector New Keynesian model to study in a structural way the interactions between (i) supply and demand shocks in the oil market, (ii) expected inflation, and (iii) nominal and real bond yields. I study an economy where oil and core goods are produced in the oil sector and the core sector, respectively. A critical feature of the model is that oil is included in households' utility function and used as an input in the production of core goods as in Blanchard and Galí (2010). In addition, oil is assumed to be complementary to core goods. The elasticity of substitution between oil and core goods is less than one, supported by empirical findings by Ready (2015). Both the complementarity between oil and core goods and the oil input in production bind the oil sector and the core sector together. Thus higher oil prices could be driven by either negative productivity shocks in the oil sector or positive productivity shocks in the core goods sector.[5] The former shock is the negative *supply* shock in the oil market, and the latter acts as the positive *demand* shock

[4] I follow Pflueger and Viceira (2015) in estimating the liquidity premium present in the U.S. TIPS market and construct liquidity-adjusted TIPS yields and breakeven inflation rates. Inflation swaps data have been used by Haubrich, Pennacchi, and Ritchken (2012), Fleckenstein, Longstaff, and Lustig (2013, 2014), and others. Data on inflation swaps are available from July 2004 onward.

[5] Hurricane Katrina in 2005 is a good example of a negative shock to oil supply, and the strong demand for oil in the period of 2004 - 2007 from fast-growing emerging economies, such as China and India, is an example of a positive shock to oil demand due to economic growth.

in the oil market.

The model shows that the conventional wisdom that high oil prices are associated with high expected inflation and high nominal bond yields is not always true. It is true only if high oil prices are driven by the disruption to oil supply. If high oil prices are driven by oil demand shocks, the conventional wisdom is wrong.

Let's consider a positive shock to oil demand due to economic growth. The production of consumption goods increases because of economic growth. Households consume more consumption goods and also demand more oil. Therefore, the price of oil also goes up. However, the price of consumption goods goes down because more consumption goods are available in the economy. Overall, expected total inflation is low. Because the aggregate economy performs well, real yields rise. Nominal yields become relatively low so that nominal bond prices and returns become higher. For positive oil demand shocks due to economic growth, high oil prices are associated with low expected inflation and low nominal yields, in contrast to the conventional wisdom. The model shows that oil supply and demand shocks have opposite impacts on prices and returns of Treasury bonds.

The model is able to replicate the empirical fact that growth rates of oil prices can explain contemporaneous excess returns on 10-year nominal bonds and breakeven inflation. Using simulated data from the baseline model, I show that slope coefficients have the same signs and statistical significance levels. In addition, correlations between the growth in oil prices and changes in nominal yields in the baseline model are close to those in the data.

The model is also able to generate upward sloping nominal yields and sizable positive inflation risk premia, because consumption growth is negatively correlated to CPI inflation. When consumption growth is lower, higher expected inflation makes nominal bonds less valuable. In addition, long-term nominal bonds have lower real payoffs than short-term bonds when expected long-term productivity growth is low. Therefore, buyers of nominal bonds demand higher nominal yields of long-term bonds to compensate for the inflation risk. As in Hsu, Li, and Palomino (2014), both nominal price rigidities of core goods and real wage rigidities are crucial in generating the negative correlation between expected inflation and consumption growth in the model.

This chapter highlights that households' direct consumption of oil and the oil input in production are two essential economic channels for explaining the dynamics between oil prices and bond yields. Variations in oil prices have real effects on household consumption expenditures through distorting households' dis-

cretionary incomes and affecting demand for core goods, which are complementary to oil (Hamilton, 2008; Edelstein and Kilian, 2009). Oil prices also directly affect the price of core goods through the marginal cost of producing core goods, and influence core goods firms' labor demands. The two channels together create the dynamics among oil prices, consumption, and production, all of which determine endogenous inflation, nominal yields, and real yields in equilibrium.

This chapter is related to a growing literature on studying determinants of nominal and real bond yield curves. Previous papers studying real rates, inflation expectations, and risk premia use latent factor term structure models (Ang, Bekaert, and Wei, 2008; Chernov and Mueller, 2012; Haubrich, Pennacchi, and Ritchken, 2012) and New Keynesian macro models (Kung, 2015; Hsu, Li, and Palomino, 2014). However, oil prices have not been considered in this literature. In this chapter, the price of oil is treated as an explicit macroeconomic risk factor. In addition, this chapter builds on the New Keynesian model; moreover, it includes an oil sector and incorporates the dual uses of oil to examine macroeconomic linkages among bond yields, inflation expectations, and supply and demand shocks in the oil markets.

This chapter is also related to several empirical papers that document the connection between oil spot or futures prices and U.S. Treasury bond returns. Kang, Ratti, and Yoon (2014) show that U.S. Treasury bond returns deflated by the U.S. CPI are negatively associated with oil price shocks driven by global aggregate demand for all industrial commodities. Baker and Routledge (2015) document that monthly excess returns on nominal U.S. Treasury bonds are higher when the slope of NYMEX WTI crude oil futures curve is negative. Moreover, few papers study the impact of oil prices on long-term expected inflation, although numerous studies examine the effect of oil prices on contemporaneous core inflation and total inflation, as reviewed in detail in Clark and Terry (2010). Celasun, Mihet, and Ratnovski (2012) find that oil futures price shocks have a statistically significant impact on long-term breakeven inflation. In fact, both real rates and expected inflation are important in understanding nominal bond yields (Duffee, 2014; Pflueger and Viceira, 2015). This chapter is the first to examine not only nominal bond yields as a whole, but also real bond yields and breakeven inflation separately in relation to oil prices.

Last, several recent papers have studied the impact of oil price shocks on equity returns. Driesprong, Jacobsen, and Maat (2008) find that increases in oil prices predict lower future stock returns. Kilian and Park (2009) show that oil supply and demand shocks jointly explain 22% of the long-run variation in U.S. real stock returns. Chiang, Hughen, and Sagi (2014) demonstrate that oil risk factors explain the returns of non-oil portfolios. These papers highlight important implications of oil price risks for equity returns, but

ignore inflation. Unlike these papers, my focus is the impact of oil on bond yields.

I make three contributions to the literature. First, I present novel empirical evidence that crude oil prices have explanatory and incremental forecasting power for nominal and real bond returns and inflation swap rates. Empirical tests using data on TIPS and inflation swap rates provide richer information on understanding behaviors of components of nominal yields than those using data solely on nominal bonds. Second, I extend the New Keynesian model to investigate the theoretical relationships between nominal and real yields, expected inflation, and oil supply and demand shocks. The model offers novel predictions and further highlights key economic transmission channels through which oil price shocks affect bond markets. Last, this chapter shows that oil prices are relevant risk factors for pricing nominal and inflation-indexed Treasury bonds and inflation swaps.

The remainder of this chapter is organized as follows. Section 2 describes the data and presents empirical results. A two-sector New Keynesian model is presented in Section 3. Section 4 discusses model solutions. Theoretical analysis is conducted in Section 5. Section 6 concludes.

3.2 Bond returns and oil prices

In this section, I describe the data and then present empirical evidence of the explanatory and incremental forecasting power of growth rates of crude oil prices for excess returns on nominal bonds, real bonds, and inflation swap rates. Inflation swap rates provide alternative market-based measures of breakeven inflation, compared to those inferred from the differences between nominal yields and real yields. A description of inflation swap contracts is provided in Appendix B.

3.2.1 Data

I use yields on 10-year U.S. Treasury bonds, yields on 10-year U.S. inflation-indexed bonds called TIPS – Treasury Inflation Protected Securities, and 3-month short interest rates to construct bond excess returns. Excess returns on breakeven inflation rates are defined as the difference in excess returns between nominal bonds and TIPS. Data on 10-year nominal U.S. Treasury bond yields, liquidity adjusted 10-year U.S. TIPS yields, and liquidity adjusted breakeven inflation from June 1999 to December 2014 are from Pflueger and Viceira (2015).[6] TIPS yields and breakeven inflation are adjusted for the liquidity risk present in the TIPS market (for details, see Pflueger and Viceira (2015).)

[6] I am very grateful to Carolin Pflueger for providing data constructed in Pflueger and Viceira (2015).

Inflation swap rates, as market-based measures of breakeven inflation, provide a rich dataset on inflation expectations for various horizons. Inflation swap rates from July 2004 to December 2014 are obtained from Bloomberg. The tenors of inflation swap contracts are available in 1 to 10, 12, 15, 20, or 30 years. As the 1-year, 2-year, 5-year, and 10-year maturities are the most common, empirical tests on inflation swap rates focus on these four contracts only.

Crude oil spot prices are based on the refiners' acquisition cost of crude oil from the U.S. Energy Information Administration (EIA) since January 1974. The NYMEX crude oil futures prices of the nearest-to-maturity contracts are from the U.S. EIA since 1986. The various inflation measures are constructed from the seasonally-adjusted Consumer Price Index and sub-indexes from the U.S. Bureau of Labor Statistics since January 1947.

The full sample period is from June 1999 to December 2014. The sample period is constrained by data availability for U.S. TIPS yields and the liquidity variables that are needed to estimate the liquidity premium embedded in TIPS yields. In addition, empirical tests using inflation swap rates are run over the sub-sample period from July 2004 to December 2014 due to the data availability for U.S. inflation swap rates.

3.2.2 Excess returns on nominal bonds, TIPS, and breakeven inflation

Do crude oil prices have explanatory and incremental forecasting power for bond returns? I use reduced-form regressions to address this question. The independent variable is the growth rate of crude oil spot prices, denoted by g^{Oil}. I also include two control variables. The first one is the term spread, which is a well-known predictor variable for bond returns (Ludvigson and Ng, 2009). Another one is the inflation of the CPI-All Items less Energy price index, which contains inflation-related information for the breakeven inflation component in the nominal bond yields.

Excess bonds returns refer to one-period buy-and-hold returns in excess of Treasury bill rate. Excess return of the n-period Treasury bond is defined as $xr^{\$}_{t+1} = ny^{\$}_{n,t} - (n-1)y^{\$}_{n-1,t+1} - y^{\$}_{1,t}$, where $y^{\$}_{n,t}$ is the nominal yield of the n-period at time t and $y^{\$}_{1,t}$ is the rate of the one-period nominal Treasury bills. Similarly, the liquidity-adjusted log excess return of the n-period inflation-indexed bond is defined as $xr^{TIPS}_{t+1} = ny^{TIPS,adj}_{n,t} - (n-1)y^{TIPS,adj}_{n-1,t+1} - y^{TIPS}_{1,t}$, where $y^{TIPS,adj}_{n,t}$ is the liquidity-adjusted real yield of the n-period TIPS at time t and $y^{TIPS}_{1,t}$ is the yield of the one-period real bond. Because the TIPS market is less liquid than the Treasury market, especially in the early years of the TIPS market and during the 2007 financial crisis, TIPS yields are priced higher to compensate for the liquidity risk. The liquidity-adjusted TIPS

yield is estimated as $y_{n,t}^{TIPS,adj} = y_{n,t}^{TIPS} - L_{n,t}$, where $L_{n,t}$ is the liquidity premium, as in Pflueger and Viceira (2015). The liquidity-adjusted log excess breakeven return is defined as $xr_{t+1}^{BE} = xr_{t+1}^{\$} - xr_{t+1}^{TIPS}$, representing the log excess return of a portfolio that is long one nominal bond and short one TIPS bond with the same maturity.

Table 3.1 Panel A shows the results of regressing the 3-month overlapping excess returns on nominal bonds, TIPS, and breakeven inflation using the corresponding term spread and the CPI-less energy inflation, and then adding the log growth of crude oil spot prices. Columns (1) and (3) show that oil price growth g_t^{Oil} is a significant explanatory variable for contemporaneous excess returns on nominal bonds and breakeven inflation. Increases in the oil price tend to go along with decreases in the expected excess return on nominal bonds and breakeven inflation, implying that realized breakeven inflation and nominal yields are higher. In addition, g_t^{Oil} contributes additional explanatory power over and beyond the term spread and the CPI-less energy inflation, as reflected by increases in the adjusted R^2.

Table 3.2 shows the results of predictive regressions. Column (1) shows that the lagged oil price growth g_{t-1}^{Oil} significantly forecasts the excess returns of nominal bonds. Column (3) shows that the oil price growth g_t^{Oil} is a significant predictor for the excess returns of the breakeven inflation. Column (2) shows that g_t^{Oil} and g_{t-1}^{Oil} have opposite predictions on excess returns on real bonds. In addition, g_t^{Oil} and g_{t-1}^{Oil} contribute additional forecasting power over and beyond the term spread and the CPI-less energy inflation, reflected by increases in the adjusted R^2. The forecasting power of g_t^{Oil} is also economically significant. For instance, a 10% increase in oil price predicts a 0.5% increase in the expected excess return on breakeven inflation. Columns (4) to (6) present robustness checks of using the sum of g_t^{Oil} and g_{t-1}^{Oil} as the regressor, in the spirit of Dimson beta. Results confirm that growth rates of oil prices have the strongest forecasting power for excess returns on breakeven inflation.

Because the expected nominal bond excess returns, the expected real bond excess returns, and the expected excess returns on breakeven inflation could be viewed as nominal rate risk premia, real rate risk premia, and inflation risk premia, respectively, the above forecasting regression results indicate that growth rates of oil prices are a significant predictor for nominal rate risk premia and inflation risk premia.

3.2.3 Excess returns on inflation swap rates

To gain some insight into the connection between oil prices and breakeven inflation of different maturities, I use data on inflation swap rates. Figure 3.1 plots inflation swap rates along with the log growth of

oil spot prices from July 2004 to December 2014. Inflation swap rates of different maturities co-move over time, whereas short-term swap rates are more volatile than long-term swap rates. Most noticeably, swap rates co-move with crude oil prices starting in July 2008. All swap rates dropped in August 2008, the month in which the U.S. refiners' acquisition cost of crude oil started to drop after reaching the peak of $127 in July 2008. I also look at whether uncertainty in the oil market is associated with uncertainty in the inflation swap market. Figure 3.2 shows a striking co-movement between standard deviations of 10-year inflation swap rate changes and the log growth of the nearest-to-maturity oil futures prices, estimated by using daily observations in each month. I use the nearest-to-maturity oil futures prices as the proxy for spot prices because crude oil spot prices are not available at a daily frequency. An analysis of latent factors of inflation swap rates is provided in Appendix C.

In the same spirit of explaining and forecasting excess returns of breakeven inflation shown in column (3) in Table 3.1 Panel A and Table 3.2, I use oil price growth to explain and forecast excess returns on these inflation swap rates. Table 3.3 shows results for both contemporaneous and predictive regressions for 1-year, 2-year, 5-year, and 10-year inflation swap rates. Slope coefficients on g_t^{Oil} have the same signs and significance levels as those in column (3) in Table 3.1 Panel A and Table 3.2.

To sum up, the above regression results present novel empirical evidence that oil price changes contain incremental information for bond returns and breakeven inflation. However, interpreting empirical evidence is challenging, mainly because the economic signal of oil price changes is ambiguous. Kilian (2009) shows that the impact of oil price shocks on the economy depends on the type of fundamental shocks that drive oil prices. In addition, empirical tests on real bond returns and inflation swap rates are constrained by the short history of data on TIPS and inflation swap rates. All limited empirical evidence can benefit from a theoretical analysis. I proceed with examining the theoretical impact of shocks in the oil market on bond returns and inflation expectations in a structural model.

3.3 A two-sector New Keynesian model

The modeling framework builds on the workhorse New Keynesian model (Galí, 2008), which is the most suitable DSGE framework for analyzing nominal bond yields, real bond yields, and inflation processes; and their interactions with economic fluctuations.

There are three important departures from the basic New Keynesian model. First, an oil sector is included in addition to the standard consumption goods sector. The two sectors are labelled as the oil sector

and the core sector. Oil and core goods are produced by a representative oil firm and monopolistic core goods firms, respectively. The inflation of oil prices represents energy inflation, while the inflation of core goods prices represents core inflation. Second, oil is included in a household's utility function, to capture the fact that households spend about 4% of their pre-tax income on gasoline for transportation needs. In addition, household consumption of oil is assumed to be complementary to the consumption of core goods, as in Ready (2015).[7] Third, oil is also used as an energy input in core goods firms' production functions, reflecting the fact that 40% of industrial energy comes from oil.

The oil price is assumed to be flexible, consistent with the average duration of 10-18 days between price changes in retail gasoline and of 2.4 days in wholesale gasoline (Douglas and Herrera, 2010). The core goods price is assumed to be sticky, supported by the fact of the average frequencies of 8 to 11 months of price changes of 350 product categories underlying the U.S. CPI (Nakamura and Steinsson, 2008). Last, the adjustment of real wages is assumed to be sluggish as in Blanchard and Galí (2007).

The productivity shock in the energy sector represents the oil supply shock. The productivity shock in the core sector is the supply shock in the core sector, but acts as demand shock in the oil market. Note that demand for oil comes from both households and core goods firms.

3.3.1 Households

An infinitely-lived representative household has recursive utility (Epstein and Zin, 1989; Weil, 1989)

$$V_t = (1-\beta)U(X_t,N_t)^{1-\rho} + \beta\left(E_t V_{t+1}^{\frac{1-\gamma}{1-\rho}}\right)^{\frac{1-\rho}{1-\gamma}} \tag{3.1}$$

where β is the time discount factor, γ is the relative risk aversion, and $1/\rho$ is the elasticity of inter-temporal substitution (EIS). The period utility $U(X_t,N_t)$ is given by

$$U(X_t,N_t) = \left(\frac{X_t^{1-\rho}}{1-\rho} - \phi\kappa_t\frac{N_t^{1+\nu}}{1+\nu}\right)^{\frac{1}{1-\rho}},\ \phi>0,\ \nu>0 \tag{3.2}$$

where X_t is the consumption bundle of oil and the final core goods, N_t is households' labor supply to intermediate core goods firms, and $1/\nu$ is the Frisch elasticity of labor supply. The process κ_t is chosen to ensure balanced growth and will be specified in the core goods sector below. As the households value

[7] Oil is complementary to the consumption of some durable goods, such as motor vehicles. As the model does not distinguish between durable goods and non-durable goods, the complementarity of oil is modeled in a reduced form.

leisure, there is disutility from supplying labor to the intermediate goods firms.

The consumption bundle is a constant elasticity of substitution (CES) aggregation of oil and the final core goods,

$$X_t \equiv [(1-\xi)C_t^{1-\frac{1}{\eta}} + \xi(O_t^H)^{1-\frac{1}{\eta}}]^{\frac{1}{1-\frac{1}{\eta}}} \tag{3.3}$$

where C_t is the final core goods, O_t^H is the consumption of oil by households, ξ measures the weight of O_t^H in the consumption bundle, and η measures the elasticity of substitution between oil and the consumption goods. The price of the consumption bundle is defined as $P_t^X \equiv [(1-\xi)(P_t^C)^{1-\eta} + \xi(P_t^O)^{1-\eta}]^{1/(1-\eta)}$, where P_t^C and P_t^O are the prices of the final core goods and oil, respectively. It can be shown that $(1-\xi)C_t P_t^C + \xi O_t^H P_t^O = X_t P_t^X$.

The representative household is endowed with all the shares of the oil firm and core goods firms and receives dividends from the oil sector and the core goods sector. The household chooses the optimal consumption of the final core goods and oil, the holding of bonds, and labor supply to maximize the utility given in equation (3.1)

$$\max_{C_t, O_t^H, B_t, N_t} V_t, \tag{3.4}$$

subject to the intertemporal budget constraint

$$X_t P_t^X + B_t \leq B_{t-1} R_{t-1} + W_t N_t + D_t^C + D_t^O \tag{3.5}$$

where B_t is the holding of the one-period riskless bond, W_t is the wage, and D_t^C and D_t^O are the dividends from the intermediate core goods sector and the oil sector, respectively. In addition, households can trade one-period riskless bonds available in zero net supply.

The numéraire in the model is the one-period riskless bond. The bond costs one dollar in the period t and pays R_t dollars in the next period $t+1$. Thus R_t corresponds to the gross nominal interest rate.

Following Blanchard and Galí (2007), I model real wage rigidities in a reduced way without specifying the exact friction in the labor market. The process of real wages is given by

$$\frac{W_t}{P_t^C} = \left(\frac{W_{t-1}}{P_{t-1}^C}\right)^{\rho_w} \left(-\frac{U_{N,t}}{U_{C,t}}\right)^{1-\rho_w} \tag{3.6}$$

where ρ_w is an index of real wage rigidities and $-U_{N,t}/U_{C,t}$ is the marginal rate of intra-temporal substitution

between the labor supply and consumption of core goods. A high value of ρ_w indicates a more sluggish adjustment of real wages.

The stochastic discount factor (SDF) is derived from the optimization of the household's problem. The one-period real SDF $M^R_{t,t+1}$ is the marginal rate of substitution between time t and time $t+1$

$$M^R_{t,t+1} = \beta \left(\frac{X_{t+1}}{X_t}\right)^{\frac{1}{\eta}-\rho} \left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\eta}} \left(\frac{V_{t+1}^{1-\rho}}{\left(E_t V_{t+1}^{(1-\gamma)/(1-\rho)}\right)^{1/(1-\gamma)}}\right)^{\rho-\gamma} \tag{3.7}$$

The one-period nominal SDF is defined as $M^{\$}_{t,t+1} \equiv M^R_{t,t+1} \frac{P^C_t}{P^C_{t+1}}$. The SDF here also depends on household gasoline consumption because X_t depends on the consumption of oil.

3.3.2 Oil sector

A representative oil firm produces oil. As in Kogan, Livdan, and Yaron (2009), the oil production function takes a simple form

$$Y^O_t = Z^O_t K^O_{t-1} \tag{3.8}$$

where K^O_{t-1} is the installed capital, and Z^O_t is the total factor productivity (TFP) in the oil sector.

I assume that $z^o_t \equiv log Z^O_t$ follows an AR(1) process

$$z^o_t = \rho_o z^o_{t-1} + \sigma_o \varepsilon^o_t, \tag{3.9}$$

where $\varepsilon^o_t \sim i.i.d.N(0,1)$.

The law of motion for capital is given by

$$K^O_t = (1-\delta^o)K^O_{t-1} + \Phi^O\left(\frac{I^O_t}{K^O_{t-1}}\right)K^O_{t-1} \tag{3.10}$$

$$\Phi^O\left(\frac{I^O_t}{K^O_{t-1}}\right) = \frac{b^o}{1-1/\zeta^o}\left(\frac{I^O_t}{K^O_{t-1}}\right)^{1-1/\zeta^o} + g^o \tag{3.11}$$

where I^O_t is the new investment, δ^o is the depreciation rate of existing capital, and the function $\Phi^O(I^O_t/K^O_{t-1})$ is a positive, concave function, as in Jermann (1998). The parameter ζ^o is the elasticity of the investment capital ratio with respect to Tobin's q.

For the sake of simplicity, I abstract from the oil inventory and the oil cartel.[8] Oil is sold to the intermediate goods firms to produce intermediate goods and to the households for their consumption. Note that the oil price P_t^O is flexible because the oil firm faces no price adjustment costs.

Given the oil price of P_t^O and the final core goods price of P_t^C, the oil firm chooses the optimal investment to maximize its firm value:

$$V_t^O \equiv \max_{I_t^O} E_t \sum_{j=0}^{\infty} M_{t,t+j}^{\$} D_{t+j}^O \tag{3.12}$$

where $D_{t+j}^O \equiv Y_{t+j}^O P_{t+j}^O - I_{t+j}^O P_{t+j}^C$ is the dividend in period $t+j$ and $M_{t,t+j}^{\$}$ is the nominal SDF derived from the household's optimality conditions. The oil firm dividend goes to the household.

3.3.3 Core goods sector

The core goods sector is comprised of a final core goods firm and a continuum of monopolistic intermediate core goods firms.

Final core goods

A representative final core goods firm combines a continuum of intermediate core goods into the final core goods. The final core goods firm operates in a perfectly competitive market and thus is a price taker. The firm uses a constant elasticity of substitution (CES) production technology to produce the final core goods.

$$Y_t^C \equiv \left(\int_0^1 (Y_t^C(i))^{\frac{\varepsilon-1}{\varepsilon}} di \right)^{\frac{\varepsilon}{\varepsilon-1}} \tag{3.13}$$

where $Y_t^C(i)$ is the quantity of intermediate core goods i, $i \in [0,1]$. The parameter ε measures the elasticity of substitution between intermediate core goods.

The final core goods are either consumed by the household or used as investment for new capital by the oil firm and intermediate core goods firms.

$$C_t + I_t^O + \int_0^1 I_t^C(i) di \leq Y_t^C \tag{3.14}$$

where $I_t^C(i)$ is the investment made by the intermediate core goods firm i.

[8] Carlson, Khokher, and Titman (2007) and Kogan, Livdan, and Yaron (2009) do not consider these two features in their models either. Inventory is not critical in the model, but the presence of inventory can mitigate oil supply and demand shocks on oil spot prices.

Given the final core goods price of P_t^C and the price of intermediate core goods i of $P_t^C(i)$, the final core goods firm chooses the optimal demand of core goods i by maximizing its profit in each period

$$\max_{Y_t^C(i)} P_t^C Y_t^C - \int_0^1 P_t^C(i) Y_t^C(i) di \tag{3.15}$$

Furthermore, the optimal demand for the intermediate core goods i can be expressed as

$$Y_t^C(i) = \left(\frac{P_t^C(i)}{P_t^C}\right)^{-\varepsilon} Y_t^C \tag{3.16}$$

Equations (3.13) and (3.16) together imply that the final core goods price is an aggregate price index of intermediate core goods prices: $P_t^C \equiv [\int_0^1 (P_t^C(i))^{1-\varepsilon} di]^{\frac{1}{1-\varepsilon}}$. Furthermore, it can be shown that $\int_0^1 P_t^C(i) Y_t^C(i) di = P_t^C Y_t^C$.

Intermediate core goods

Intermediate core goods are produced by a continuum of monopolistic firms indexed by $i \in [0,1]$. The production of intermediate core goods i is given by

$$Y_t^C(i) = [K_{t-1}^C(i)]^{\omega} [Z_t^C N_t(i)]^{\alpha} [O_t^I(i)]^{1-\alpha-\omega} \tag{3.17}$$

where Z_t^C is the common productivity across all intermediate core goods firms, $K_{t-1}^C(i)$ is the capital, $N_t(i)$ is the labor employed, and $O_t^I(i)$ is the quantity of oil used in production. The oil share of production is measured by $1-\alpha-\omega$.

The law of motion for capital is given by

$$K_t^C(i) = (1-\delta^c) K_{t-1}^C(i) + \Phi^C\left(\frac{I_t^C(i)}{K_{t-1}^C(i)}\right) K_{t-1}^C(i) \tag{3.18}$$

$$\Phi^C\left(\frac{I_t^C(i)}{K_{t-1}^C(i)}\right) = \frac{b^c}{1-1/\zeta^c}\left(\frac{I_t^C(i)}{K_{t-1}^C(i)}\right)^{1-1/\zeta^c} + g^c \tag{3.19}$$

where $I_t^C(i)$ is the new investment, δ^c is the depreciation rate of existing capital, and the function $\Phi^C(I_t^C(i)/K_{t-1}^C(i))$ is a positive, concave function, as in Jermann (1998). The parameter ζ^c represents the elasticity of the investment capital ratio with respect to Tobin's q.

Following Croce (2014), I assume that the productivity growth rate, $\Delta z^c_{t+1} \equiv log(Z^C_{t+1}/Z^C_t)$, has a long-run risk component and a short-run risk component:

$$\Delta z^c_{t+1} = x^c_t + \sigma_c \varepsilon^c_{t+1} \tag{3.20}$$

$$x^c_t = \rho_{xc} x^c_{t-1} + \sigma_{xc} \varepsilon^{xc}_t \tag{3.21}$$

where $\varepsilon^c_t \sim i.i.d.N(0,1)$ and $\varepsilon^{xc}_t \sim i.i.d.N(0,1)$. In addition, all shocks are assumed to be mutually independent.

Following Rotemberg (1982) and Ireland (1997), I assume that each monopolistic firm changes its price every period but faces a real quadratic cost of price changes.

$$\Gamma(P^C_t(i)) \equiv \frac{\vartheta}{2}\left(\frac{P^C_t(i)}{\overline{\pi} P^C_{t-1}(i)} - 1\right)^2 Y^C_t \tag{3.22}$$

The parameter ϑ measures the degree of price stickiness, which is common to all intermediate core goods firms. The variable $\overline{\pi}$ is the target gross core inflation rate in the steady state. If the price grows at the rate of target inflation, the cost of the price adjustment is zero. If $\vartheta = 0$, there is no adjustment cost of price changes. Because of the quadratic cost of price changes, fewer final goods are available for consumption and investment. The presence of nominal price rigidity leads to inefficiency.[9]

As shown in (3.16), the optimal demand for the intermediate core goods i is downward-sloping, which is determined by the relative prices. Monopolistic firm i chooses the optimal price of its goods and the optimal investment to maximize its firm value:

$$V^C_t(i) \equiv \max_{P^C_t(i), I^C_t(i)} \sum_{j=0}^{\infty} E_t M^{\$}_{t,t+j} D^C_{t+j}(i) \tag{3.23}$$

where $D^C_{t+j}(i) \equiv Y^C_{t+j}(i) P^C_{t+j}(i) - \Psi_{t+j}(Y^C_{t+j}(i)) - \Gamma(P^C_{t+j}(i)) P^C_{t+j} - I^C_{t+j}(i) P^C_{t+j}$ is the dividend in period $t+j$ and $M^{\$}_{t,t+j}$ is the nominal SDF derived from the household's optimality conditions. The production cost

[9] An equivalent inflation dynamic can also be derived under the assumption of a staggered price-setting mechanism (Calvo, 1983).Ascari, Castelnuovo, and Rossi (2011) discusses the similarities and differences between the two approaches. The Rotemberg approach is better than the Calvo approach for replicating the dynamics of inflation at the macro level. An advantage of the assumption of quadratic price adjustment costs is that it leads to a tractable symmetric equilibrium. Because of the presence of nominal rigidity, real quantities depend on nominal prices and the nominal interest rate, which is governed by monetary policy.

function $\Psi_{t+j}(Y^C_{t+j}(i))$ for a given level output $Y^C_{t+j}(i)$ is defined below.

Given the oil price P^O_t and the wage W_t, the firm i chooses the optimal demand for labor and oil to minimize production cost:

$$\begin{aligned} \min_{N_t(i),O^I_t(i)} \Psi(Y^C_t(i)) &\equiv W_t N_t(i) + O^I_t(i) P^O_t. \\ s.t.\ \ Y^C_t(i) &= [K^C_{t-1}(i)]^{\omega} [Z^C_t N_t(i)]^{\alpha} [O^I_t(i)]^{1-\alpha-\omega} \end{aligned} \tag{3.24}$$

Last, the process κ_t is defined as $\kappa_t \equiv (Z^C_{t-1})^{1-\rho}$ to ensure balanced growth.

3.3.4 Central bank

To complete the model, I assume that the central bank follows the Taylor rule in setting the nominal interest rate.

$$R_t = \bar{R} \left(\frac{\pi^{CPI}_t}{\bar{\pi}} \right)^{\phi_\pi} \left(\frac{Y^C_t}{\bar{Y}} \right)^{\phi_y},\ \phi_\pi \geq 0,\ \phi_y \geq 0 \tag{3.25}$$

where $\bar{R}$, $\bar{\pi}$, and $\bar{Y}$ are the gross interest rate, the target gross total inflation, and the output of core goods in steady state, respectively.

3.3.5 Symmetric equilibrium

The equilibrium of the model is characterized by the solutions of the household's problem (3.4), the oil firm's problem (3.12), the final core goods firm's problem (3.15), and the intermediate core goods firms' problems (3.23). The first order conditions of these problems are presented in Appendix D.

The equilibrium is symmetric. All intermediate core goods firms have identical cost minimization problems and value maximization problems. Thus, they choose the same optimal demand for labor and oil: $N_t(i) = N_t$ and $O^I_t(i) = O^I_t$. Furthermore, they choose the same optimal selling price and investment: $P^C_t(i) = P^C_t$ and $I^C_t(i) = I^C_t$. Finally, all markets are clear.

3.3.6 Measures of inflation, yields, and inflation swaps

This sub-section first defines three measures of inflation and then uses the SDF to price nominal and real zero-coupon bonds and zero-coupon inflation swap contracts.

Inflation measures

In the model, the core CPI price index, the energy CPI price index, and the CPI price index are represented by the prices of the final core goods, oil, and the consumption bundle, respectively. Let $\pi_t^C \equiv P_t^C/P_{t-1}^C$ denote core CPI inflation, $\pi_t^O \equiv P_t^O/P_{t-1}^O$ denote energy CPI inflation, and $\pi_t^{CPI} \equiv P_t^X/P_{t-1}^X$ denote CPI inflation.

To gain insight into relations of oil prices to core inflation, the core inflation equation can be expressed in the log-linearization form

$$\widetilde{\pi}_t^c = \beta E_t \widetilde{\pi}_{t+1}^c + \lambda \widetilde{\psi}_t \tag{3.26}$$

where $\lambda \equiv \frac{\varepsilon-1}{\vartheta}$ is decreasing in the index of price stickiness ϑ, ψ_t represents the real marginal costs of producing intermediate goods, and tilde variables denote the log deviation from steady state. Core inflation depends on the expected inflation in the next period and the change of the real marginal production cost.

The effect of oil price on core inflation is reflected through the real marginal costs of producing intermediate core goods.

$$\widetilde{\psi}_t = \frac{1-\alpha-\omega}{1-\omega}\widetilde{p}_t^o + \frac{\alpha}{1-\omega}\widetilde{w}_t - \frac{1}{1-\omega}\widetilde{z}_t^c + \frac{\omega}{1-\omega}(\widetilde{y}_t^c - k_{t-1}^c) \tag{3.27}$$

Yields and inflation swap rates

I use the pricing kernel derived from the optimality conditions of the household's problem to value zero-coupon nominal bonds, zero-coupon real bonds, and zero-coupon inflation swaps.

The nominal yield of an n-year zero-coupon nominal Treasury bond and the real yield of an n-year zero-coupon real Treasury bond are defined as:

$$y_t^n = -\frac{1}{n}E_t(m_{t,t+n}^{\$}) - \frac{1}{2n}Var_t(m_{t,t+n}^{\$}) \tag{3.28}$$

$$r_t^n = -\frac{1}{n}E_t(m_{t,t+n}^{R,X}) - \frac{1}{2n}Var_t(m_{t,t+n}^{R,X}) \tag{3.29}$$

where $m_{t,t+n}^{\$} \equiv logM_{t,t+n}^{\$}$ and $m_{t,t+n}^{R,X} \equiv logM_{t,t+n}^{R,X}$.

The breakeven inflation rate is the difference in yield-to-maturity between an n-year zero-coupon nomi-

nal Treasury bond and an n-year zero-coupon real Treasury bond. The breakeven inflation rate measures the n-year inflation swap rate.

Alternatively, the zero-coupon inflation swap rate can be directly estimated. When an inflation swap contract is initialized, the present value of expected cash flow at maturity should be zero. Assuming that the notional amount is one dollar and that the inflation index refers to the CPI index, the zero-coupon inflation swap fixed rate s_t^n is given by:

$$0 = -E_t[M^{\$}_{t,t+n} e^{ns_t^n}] + E_t[M^{\$}_{t,t+n} \pi^{CPI}_{t,t+n}] \tag{3.30}$$

Note that s_t^n is known at time t and that the real SDF $M^{R,X}_{t,t+n} \equiv M^{\$}_{t,t+n} \pi^{CPI}_{t,t+n}$.

The swap rate is further expressed as:

$$s_t^n = \frac{1}{n} E_t \hat{\pi}^{CPI}_{t,t+n} - \frac{1}{2n} Var_t \hat{\pi}^{CPI}_{t,t+n} + \frac{1}{n} Cov_t(m^{R,X}_{t,t+n}, \hat{\pi}^{CPI}_{t,t+n}) \tag{3.31}$$

where $\hat{\pi}^{CPI}_{t,t+n} \equiv log \pi^{CPI}_{t,t+n}$ is the log CPI inflation. On the right-hand side of the equation, the first term is the expected inflation, the second term is the Jensen's inequality adjustment of the expected inflation, and the third term is the inflation risk premium.

The swap rate (ignoring the Jensen's inequality adjustment) consists of the inflation expectation and the inflation risk premium. If inflation is high in "bad" states, where marginal utility is high, the covariance term will be positive. If inflation is positively correlated with the real SDF, the inflation risk premium will be positive and the swap rate will be higher than the expected inflation. The fixed receiver asks for a higher rate to compensate for the risk of the realization of unexpected high inflation in the "bad" states of the world.

3.4 Model solution

In this section, I discuss the choices of parameter values. The model is solved in Dynare using a second-order approximation at a quarterly frequency.

3.4.1 Parameters

Table 3.4 reports the parameter values used in the baseline calibration of the model. I choose parameter values reported in previous studies whenever possible, or by matching the selected moments in the data. Parameters are grouped into four categories.

I choose a value of 0.997 for the time discount rate β, which corresponds to an annual real interest rate of 1.2% in the long run. Households prefer an early resolution of uncertainty. If the relative risk aversion γ takes a value of 10 and the elasticity of intertemporal substitution $1/\rho$ is set at 2, the nominal yield curve is slightly upward sloping and the 10-year inflation risk premium is about 8 basis points. In order to match the term spread of nominal yields, I also consider the RRA γ and the EIS $1/\rho$ of the values of 20 and 5, respectively, in some calibrations. The weight of oil in the consumption bundle ξ is set at 0.1, close to the weight of energy components in the CPI.[10] The elasticity of substitution between oil and core goods η is set at 0.25, the same value as used in Ready (2015), implying complementarity between the two types of consumption. The real rage rigidity index ρ_w is set at 0.95 to be close to the ratio of $\sigma(w)/\sigma(y^c) = 0.44$, a key moment of wages in the data. The labor supply N is fixed at 0.33 in the deterministic steady state so that households spend one-third of their discretionary time working. The Frisch elasticity of labor supply is pinned down as 0.2498 by the the labor supply in the deterministic steady state.

For most parameters associated with production functions, I follow related papers. The constant elasticity of substitution of intermediate core goods ε is set at 6 (which corresponds to a markup of 20%). The degree of capital adjustment cost (ζ^o and ζ^c) is set at 4.8, both in the oil sector and intermediate goods sector. Free parameters b^o and g^o are chosen such that there is no adjustment cost for the oil sector in the deterministic steady state. In particular, I set $b^o = (\delta^o)^{1/\zeta^o}$ and $g^o = \frac{1}{1-\zeta^o}\delta^o$. Similarly, free parameters b^c and g^c are chosen such that there is no adjustment cost for the intermediate goods firms in the deterministic steady state. In particular, I set $b^c = (\delta^c)^{1/\zeta^c}$ and $g^c = \frac{1}{1-\zeta^c}\delta^c$. I choose a higher value of 0.05 for the depreciation rate of the oil capital δ^o (which corresponds to an annualized rate of 20%). The depreciation rate of consumption goods capital δ^c is equal to 0.02. The capital share ω and labor share of output α are set at 0.33 and 0.57, respectively. Thus the oil share of output $1-\alpha-\omega$ is equal to 0.1.[11] I choose 25 for the degree of price adjustment cost ϑ, which is close to the values suggested by Ireland (2000).

Coefficients in the Taylor rule ϕ_π and ϕ_y are set at 1.5 and 0.125, respectively, which are standard values in the monetary literature. The target inflation $\bar{\pi}$ is set at 1.0092 (which corresponds to an annual inflation of 3.68%, close to the average U.S. core inflation).

[10] Note that the parameter ξ measures the share of oil in the consumption bundle. The chosen value of 10% for ξ does not contradict the fact that an average U.S. household spends 4% of pre-tax income on gasoline. The percentage of energy expenditure of all household expenditure is higher than 4% because of income tax and savings. Both theoretical analysis and model predictions are robust to a wide range of parameter values of ξ.

[11] As in the case of the parameter ξ, the oil share of output is also a key variable in the model, affecting many quantities in the model. However, both theoretical analysis and model predictions are robust to a wide range of parameter values of $1-\alpha-\omega$.

Parameter values of three productivity shocks are chosen to match the moments of the relative oil prices, core inflation, CPI inflation, 5-year nominal yields, and the term spread of 5-year nominal bonds.

3.4.2 Model moments

Moments from data and the model are summarized in Table 3.5. The model is able to roughly match the moments of the relative oil prices, core inflation, CPI inflation, 5-year nominal yields, nominal yield spread between 5-year and 1-quarter, and correlations between growth rates of oil prices and changes in yields and breakeven inflation.

Note that the focus of the chapter is not the term structure of nominal yields or the equity premium. Rather, reporting these moments illustrates that the model can generate with reasonable magnitude the features of nominal yields and equity returns. The term spread of 5-year nominal yields in the model is about 58% of the values in the data. The inflation risk premium for 5-year nominal yields is 28 basis points. However, the volatility of 5-year nominal yields in the model is much smaller than that in the data, which is a well-known problem in the literature. Although the model is not calibrated to match moments of equity premium, the model generates a sizable equity premium.

Last, the model is also able to match other key macroeconomic data, in addition to inflation data. The bottom panel in Table 3.5 shows that the relative volatilities and autocorrelations of the final good consumption, wage, and output in the model are close to the empirical counterparts. In particular, the negative correlation between consumption growth and inflation from the model closely matches that in the data.

3.5 Oil prices, expected inflation, and bond yields

In this section, I first discuss the economic drivers of oil prices: supply and demand shocks in the oil market. Afterwards, I examine how expected inflation, real yields, and nominal yields respond to supply and demand shocks that drive oil prices. Last, I discuss key economic channels and the inflation risk premium in the model.

3.5.1 Oil prices and three productivity shocks

This sub-section analyzes the impulse response functions around the stochastic steady state to a negative productivity shock ε_t^o in the oil sector, a positive transitory productivity shock ε_t^c, and a positive permanent productivity shock ε_t^{xc} in the core goods sector. The size of the shock is one standard deviation of each

shock. The impulse response functions plot the percentage deviation from the stochastic steady state. In the baseline solution of the model, the productivity z_t^o process in the oil sector is transitory ($\rho_o = 0.45$) and volatile ($\sigma_o = 9.5\%$ per quarter). The shock to the productivity growth ε_t^c is less volatile ($\sigma_c = 1.2\%$) per quarter, and the process x^c is persistent ($\rho_{xc} = 0.9$) and even less volatile ($\sigma_{xc} = 0.17\%$).

Figure 3.3 illustrates the response of a set of key variables to a negative productivity shock ε_t^o in the oil sector. For a 9.5% decrease in oil productivity, the real oil price jumps by 11%, which is a big price hike. Core inflation also increases by 0.36%, because the rise in the oil price is passed on through the higher production cost of core goods. The relative change of the core goods price is small in part because the core goods price is sticky, and in part because the share of oil in production is the smallest among all the factors of production. Households greatly reduce oil consumption, with a sharp drop of 5.3%. The income effect leads to households demanding fewer core goods. Households consume fewer core goods, resulting in a 2.5% drop. Even though the weight of oil in the CPI is only 0.1, CPI inflation still increases by roughly 0.5% because of the 11% big jump in oil prices.

Because households consume both less oil and fewer core goods, the economy after a big oil disruption is in a "bad" state for households. If the oil supply disruption is transitory, oil production will gradually recover. The oil price and the core goods price revert to their long-run trends. One quarter later, the real oil price drops by 5%, leading to a lower expected energy inflation. An initial big increase in realized energy inflation is followed by a decrease in expected energy inflation as a "correction" sets in. The impact of oil supply on the economy disappears after 4 quarters.

Figure 3.4 shows responses for a positive transitory productivity shock to ε_t^c (1.2% increase) in the core goods sector. The productivity jumps to a higher level and stays there afterwards. The intermediate core goods firms produce more and sell core goods at lower prices because the marginal production cost decreases. Core inflation decreases by 0.1% initially and gradually recovers to the long-run value. Given the lower prices of core goods, households consume more, in a nearly 0.3% increase. Meanwhile, households also want to consume more oil because oil is complementary to the consumption of core goods. Because oil production is inelastic in the short run and the capital is predetermined in the last quarter, the oil price has to rise to clear the oil market. The real oil price rises by 1%. Since the relative price of oil to core goods increases, the substitution effect mitigates the rising demand for oil due to the complementarity. Households barely increase demand for oil by 0.07%. Overall, the magnitude of the rise in the oil price is mild, the realized CPI inflation decreases, and the expected CPI inflation remains below the long-run trend for about

25 quarters.

Because households consume both more oil and consumption goods, the economy after a positive transitory productivity shock in the core goods sector is a "good" state for households. When oil demand is driven by economic growth, higher oil prices are accompanied by lower inflation and vice versa.

Figure 3.5 shows different responses for a positive permanent productivity shock to ε_t^{xc} (0.17% increase) in the core goods sector. Because it is a positive shock to the growth rate of productivity and the process x^c is very persistent, the level of productivity Z^C keeps increasing for a substantial length of time. As the economy grows, intermediate core goods firms produce more and sell core goods at lower prices because the marginal production cost decreases. Core inflation decreases by 0.03% initially and keeps declining before recovering to the long-run value. Core goods firms increase their investment in new capital to maximize the benefit of rising productivity. Because the expected consumption of core goods will be high in subsequent periods, households reduce consumption by 0.7% in the first period. Meanwhile, households also consume less oil in the first period because oil is complementary to consuming core goods. Because oil production is inelastic in the short run, real oil prices initially decrease to clear the oil market by 0.1%. As the productivity level Z^C steadily increases, the output of core goods increases, and households increase their consumption of core goods and oil. Real oil prices start to rise from the second period.

Overall, the magnitude of the rise in the oil price is big and lasts for a very long time. Realized CPI inflation decreases and expected CPI inflation remains below the long-run trend for more than 40 quarters. Because households consume both more oil and consumption goods, the economy after a positive permanent productivity shock in the core goods sector is a "good" state for households.

Because the oil market is competitive, the oil price quickly responds to either type of shocks. On the other hand, core inflation gradually responds to shocks because of the presence of the nominal price rigidity of core goods and the real wage rigidity. In addition, the magnitude of the response of the gross core inflation rate is also determined by the parameter values of the oil share in production and the elasticity of substitution between oil and consumption goods. In the model, a mixture of three types of productivity shocks can generate many rich dynamics among oil prices, inflation processes, and total consumption processes.

3.5.2 Expected inflation, real yields, and nominal yields

This sub-section discusses how real yields, breakeven inflation, and nominal yields respond differently to each productivity shock. The impulse response functions plotted in Figure 3.6 to 3.8 highlight that the

impacts of oil price increases driven by three specific productivity shocks are different in terms of directions, magnitudes, and lengths.

As shown in Figure 3.6, real yields of both maturities increase for all three productivity shocks. The response of real yields to the negative productivity shock in the oil sector relies on the transitory property of the Z^O process. Although the realized consumption of core goods and oil is lower, households will expect a positive overall consumption growth as productivity in the oil sector returns to normal. The response of real yields to either transitory or permanent positive productivity shocks in the core goods sector is straightforward. The growth rate of overall consumption is positive after either of the shocks. Because the x^c process is very persistent, the effect of ε_t^{xc} shock on the real yields lasts over 25 quarters.

Figure 3.7 plots impulse response functions of 1-quarter and 5-year breakeven inflation (i.e., inflation swap rates) to a negative productivity shock ε_t^o in the oil sector, a positive transitory productivity shock ε_t^c, and a positive permanent productivity shock ε_t^{xc} in the core goods sector. When an oil supply shock occurs, breakeven inflation jumps because the expected inflation after the shock is positive, as discussed earlier. One-quarter breakeven inflation goes up significantly, while 5-year breakeven inflation slightly rises. As the productivity shock in the oil sector is transitory, the impact disappears after 5 periods. Figure 3.7 also illustrates that a positive transitory productivity shock ε_t^c in the core goods sector has a very small impact on breakeven inflation. Unlike the transitory shock ε_t^c, the positive permanent shock ε_t^{xc} has a big and long-lasting impact on both 1-quarter and 5-year breakeven inflation.

For a given maturity, the nominal yield is the sum of the real yield and breakeven inflation. Figure 3.8 plots impulse response functions of the 1-quarter and 5-year nominal yields to a negative productivity shock ε_t^o in the oil sector, a positive transitory productivity shock ε_t^c, and a positive permanent productivity shock ε_t^{xc} in the core goods sector. For the negative productivity shock in the oil sector, the nominal yields unambiguously go up because both real yields and breakeven inflation positively respond to the shock. However, the response of nominal yields to productivity shocks in the core goods sector is ambiguous, depending on the relative magnitude of the positive responses of real yields and the negative responses of breakeven inflation. Under the calibration of the baseline model, nominal yields go down, especially in response to the permanent positive productivity shock.

The conventional wisdom that high oil prices cause higher expected inflation and nominal yields is true only for the disruption in the oil supply. Admittedly, the above model predictions depend on the assumptions of the properties of the three productivity shocks, and the model considers only three important productivity

shocks in the economy. Nevertheless, the model illustrates the necessity of identifying the type of shocks that drive oil prices, and of decomposing nominal yields into real yields and breakeven inflation. This approach provides a more informative analysis on the interaction between oil prices and bond yields.

3.5.3 Bond return regressions on simulated data

Similar to the empirical counterpart in Panel A, Table 3.1 Panel B shows the contemporaneous regressions of excess returns on 10-year nominal bonds, real bonds, and breakeven inflation on oil price growth rates using simulated data from the baseline model. The model is able to replicate the empirical slope coefficients of the same signs and statistical significance levels while the R^2 are fairly large.

The coefficient on g_t^{Oil} in columns (1) and (3) in the data and the model is negative and significant. In the model when the price of oil rises, breakeven inflation rises for productivity shocks in the oil sector but falls for productivity shocks in the core goods sector. Similarly, nominal yield rises for oil supply shocks but might rise or fall for productivity shocks in the core goods sectors. Higher nominal yields and higher breakeven inflation lead to lower excess returns on nominal bonds and breakeven inflation, respectively. According to the model, contemporaneous regression results suggest that in the data productivity shocks in the oil sector have larger effects than productivity growth shocks.

In the model when the price of oil rises, real yields rise for all shocks. Excess returns on real bonds thus negatively respond to positive oil price growth, so the slope coefficient on oil price growth should be negative. In column (2), the coefficient on g_t^{Oil} is negative in the data and in the model simulation. However, the negative slope coefficient in the model is significant, while it is insignificant in the data. This implies that the model predicts a stronger positive response of real yields to increases in oil prices than that presented in the data.

Because three productivity shocks are homoskedastic in the model, risk premia are constant over time. Thus the model is incapable of replicating the empirical predictive regressions presented in Table 3.2 . Time-varying volatility of productivity shocks will be considered in future research.

3.5.4 Key economic mechanisms

To gain insight into the role of oil usage in households' consumption and in firms' production and the importance of productivity shocks in both sectors, I estimate model implied statistics for alternative specifications. Table 3.6 reports four cases. Column (3) shows that if oil is not included in the consumption

bundle, core and CPI inflation and 5-year nominal yields become much lower. This shows that oil prices significantly affect the level of inflation and nominal yields. If oil is not used as an input in core goods firms' production, Column (4) shows that correlations between oil price growth and changes in nominal yields implied from the model are very different from those in the data. In addition, relative oil prices are very volatile, and the term spread and 5-year inflation risk premium dramatically increase. This highlights that the direct connection between the two sectors can smooth shocks across sectors; the connection helps to reconcile the empirical correlations between bond yields and oil prices.

The last two columns in the table indicate that productivity shocks in the core sector alone fail to generate volatile oil prices, and productivity shocks in the oil sector alone fail to generate sizable term spreads and the inflation risk premium. To sum up, the dual roles of oil and shocks in the two sectors are necessary and important elements of the model.

Table 3.7 reports unconditional variance decompositions for the baseline model. Consistent with the analysis above, the productivity shock in the oil sector accounts for the majority of variation in relative oil prices, 1-quarter nominal yields, and 1-quarter real yields. On the other hand, the permanent productivity shock in the core goods sector is important for long-term nominal and real yields, breakeven inflation, and the long-term inflation risk premium. Last, the transitory productivity shock in the core goods sector plays a smaller role.

3.5.5 Term structure of nominal yields

The nominal yields curve is upward sloping in the model. The sluggish adjustment of real wages is a key real friction to generate the negative correlation between consumption growth and expected inflation, which in turn leads to the positive inflation risk premium and upward sloping nominal yields.[12] The role of real wage rigidities in the context of the term structure of nominal yields has been examined in Hsu, Li, and Palomino (2014). However, this chapter incorporates the real wage rigidities in a simpler and reduced way.

3.5.6 Inflation risk premium

To gain some insight into the inflation risk premium, I examine the processes of the SDF and the inflation swap rate for one period only.

[12] It is well known that standard dynamic stochastic general equilibrium models fail to generate the upward sloping nominal yields curves. Kung (2015) and Hsu, Li, and Palomino (2014) are the two exceptions.

First, project the log real SDF process $m^{R,X}_{t,t+1}$ on the space spanned by the three productivity shocks

$$m^{R,X}_{t,t+1} = E_t m^{R,X}_{t,t+1} - \lambda^o_{t+1}\frac{\varepsilon^o_{t+1}}{\sigma_o} - \lambda^c_{t+1}\frac{\varepsilon^c_{t+1}}{\sigma_c} - \lambda^{xc}_{t+1}\frac{\varepsilon^{xc}_{t+1}}{\sigma_x c} \tag{3.32}$$

where ε^o_{t+1}, ε^c_{t+1}, and ε^{xc}_{t+1} defined in the model section are orthogonal to each other. The quantities λ^o_{t+1}, λ^c_{t+1}, and λ^{xc}_{t+1} are the market prices of risk for the three productivity shocks, respectively.

Similarly, project the log CPI inflation process $\hat{\pi}^{CPI}_{t,t+1}$ on the space spanned by the three productivity shocks:

$$\hat{\pi}^{CPI}_{t,t+1} = E_t \hat{\pi}^{CPI}_{t,t+1} + \beta^o_{t+1}\varepsilon^o_{t+1} + \beta^c_{t+1}\varepsilon^c_{t+1} + \beta^{xc}_{t+1}\varepsilon^{xc}_{t+1}. \tag{3.33}$$

Parameters λ and β can be estimated from the impulse responses of the real SDF and the CPI inflation to the three shocks. The market prices of risk are approximated by:

$$\lambda^o_{t+1} = -\sigma_o \frac{\partial m^{R,X}_{t,t+1}}{\partial \varepsilon^o_{t+1}},\ \ \lambda^c_{t+1} = -\sigma_c \frac{\partial m^{R,X}_{t,t+1}}{\partial \varepsilon^c_{t+1}},\ \ \lambda^{xc}_{t+1} = -\sigma_o \frac{\partial m^{R,X}_{t,t+1}}{\partial \varepsilon^{xc}_{t+1}}. \tag{3.34}$$

The inflation betas are approximated by:

$$\beta^o_{t,t+1} = \frac{\partial \hat{\pi}^{CPI}_{t,t+1}}{\partial \varepsilon^o_{t+1}},\ \ \beta^c_{t,t+1} = \frac{\partial \hat{\pi}^{CPI}_{t,t+1}}{\partial \varepsilon^c_{t+1}},\ \ \beta^{xc}_{t,t+1} = \frac{\partial \hat{\pi}^{CPI}_{t,t+1}}{\partial \varepsilon^{xc}_{t+1}}. \tag{3.35}$$

Finally, the inflation risk premium of the one-period inflation swap is given by:

$$Cov_t(m^{R,X}_{t,t+1}, \hat{\pi}^{CPI}_{t,t+1}) = -\beta^o_{t+1}\sigma_o\lambda^o_{t+1} - \beta^c_{t+1}\sigma_c\lambda^c_{t+1} - \beta^{xc}_{t+1}\sigma_{xc}\lambda^{xc}_{t+1}. \tag{3.36}$$

Table 3.8 presents the market price of risk and the one-period inflation risk premium for each shock, estimated from the impulse response functions of the real SDF and CPI. The market prices of risk per quarter are 0.11%, 0.23%, and 0.04% for productivity shocks ε^o in the oil sector, ε^c and ε^{xc} in the core goods sector, respectively. The betas of CPI inflation are negative for all three shocks. CPI inflation decreases for a positive oil supply shock and positive transitory or permanent innovations in productivity in the core goods sector. Households' marginal utility moves along with CPI inflation: an economic environment with high CPI inflation is viewed as a "bad" state and vice versa. Therefore, the inflation risk premium is positive. The inflation risk premium for one quarter is 0.6 basis points, 1.7 basis points, and 0.9 basis points for the ε^o, ε^c , and ε^{xc} shocks, respectively. Thus the one-quarter inflation risk premium is 3.2 basis points in total.

In the model, the average values of the 5-year and 10-year inflation risk premium are 29 basis points and 48 basis points per quarter, respectively. In the data, the 10-year inflation risk premia have an average of about 40 and 20 basis points per year for TIPS-based measures and inflation swap-based measures. Figure 3.9 plots the inflation risk premia of 10-year inflation swap rates. The inflation risk premium is positive most of the time and time varying, and was negative in late 2008 and early 2009.[13]

3.6 Conclusion

I first provide novel empirical evidence of the connection between oil prices, breakeven inflation, and real and nominal Treasury bond returns; I then build a two-sector New Keynesian model to study their theoretical relationships. The responses of real yields, breakeven inflation, and nominal yields to increases in oil prices depend on the type of shocks that drive oil prices. The complementarity between oil and core goods consumption and oil input in production are important economic channels for studying the dynamics of oil prices and bond yields. Overall, the model is able to replicate several key empirical relationships between oil prices and bond yields. The model also generates upward sloping nominal yield curves and sizable positive inflation risk premia. For the sake of simplicity, the current version of the model considers three productivity shocks only, omitting true demand shocks, such as preference shocks in the representative agent's utility function. Additional preference shocks and the time-varying volatility of productivity shocks will be considered in future research. The implications of the impact of oil price shocks on long-term expected inflation are also useful for monetary policy and risk management.

[13] I use the Survey of Professional Forecasters (SPF) CPI expectation as the proxy for expected inflation, which is available at a quarterly frequency. The inflation risk premia are estimated as the differences between liquidity adjusted breakeven inflation and the 10-year inflation swap rate and the median of the SPF 10-year CPI.

Table 3.1: Excess bond returns: Contemporaneous regressions

In Panel A, the log growth of crude oil spot prices is used to explain contemporaneous 3-month overlapping excess returns on 10-year U.S. Treasury nominal bonds, 10-year U.S. inflation-indexed bonds (TIPS), and breakeven inflation, in addition to the corresponding term spreads and the inflation of the CPI-All Items less Energy price index. Excess returns are defined in the text. The yield (breakeven inflation) term spread is the difference between a 10-year and one-quarter yields (breakeven inflation). U.S. 10-year TIPS yields and breakeven inflation are liquidity-adjusted as in Pflueger and Viceira (2015). g_t^{Oil} denotes the 3-month overlapping quarterly log growth of crude oil spot prices. $\pi_t^{CPI\ excl.\ energy}$ is the quarterly inflation of the seasonally-adjusted Consumer Price Index - All Items less Energy. The sample period is 1999.6 - 2014.12. Standard errors are Newey-West adjusted with six lags. Panel B presents results of replicating contemporaneous regressions using simulated data from the baseline model. Each simulation generates a series of quarterly growth rates of oil prices, nominal yields, real yields, and breakeven inflation for 64 quarters. Regressions on these simulated data are repeated 3,000 times. Standard errors are reported in bracket. ***, **, and * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Panel A. Data

	(1) $xr_t^{\$}$	(2) xr_t^{TIPS}	(3) xr_t^{BE}
g_t^{Oil}	-0.08***	-0.03	-0.05***
	(0.02)	(0.03)	(0.01)
$Nominal\ term\ spread_t$	2.45*		
	(1.51)		
$Liq.\ Adj.\ TIPS\ term\ spread_t$		2.37*	
		(1.69)	
$Liq.\ Adj.\ breakeven\ term\ spread_t$			1.28
			(1.47)
$\pi_t^{CPI\ excl.\ energy}$	1.56	1.34	-0.09
	(3.07)	(2.93)	(1.39)
Const.	-0.00	-0.00	0.00
	(0.02)	(0.02)	(0.01)
Adj. R^2 $(excl.\ g^{Oil})$	1.6%	0.5%	1.4%
Adj. R^2 $(incl.\ g^{Oil})$	10.9%	2.5%	10.9%

Panel B. Model

	(1) $xr_t^{\$}$	(2) xr_t^{TIPS}	(3) xr_t^{BE}
g_t^{Oil}	-0.16***	-0.06***	-0.09***
	(0.04)	(0.01)	(0.04)
$Nominal\ term\ spread_t$	-3.65**		
	(1.67)		
$TIPS\ term\ spread_t$		0.97	
		(0.59)	
$Breakeven\ term\ spread_t$			-21.1***
			(5.99)
$\pi_t^{CPI\ core}$	-2.74*	0.09	-6.29***
	(1.48)	(0.28)	(2.07)
Const.	0.03	-0.00	0.10***
	(0.01)	(0.00)	(0.03)
R^2	33.1%	60.8%	28.9%

Table 3.2: Excess bond returns: Predictive regressions

The log growth of crude oil spot prices is used to forecast 3-month overlapping log excess returns on 10-year U.S. Treasury nominal bonds, the liquidity-adjusted log excess returns on 10-year U.S. inflation-indexed bonds (TIPS), and the liquidity-adjusted log excess breakeven inflation returns, in addition to the corresponding term spreads and the inflation of the CPI-All Items less Energy price index. Excess returns are defined in the text. The yield (breakeven inflation) term spread is the difference between a 10-year and one-quarter yields (breakeven inflation). U.S. 10-year nominal and liquidity-adjusted TIPS yields, liquidity-adjusted breakeven inflation, and the liquidity risk premium are from Pflueger and Viceira (2015). g_t^{Oil} denotes the 3-month overlapping quarterly log growth of crude oil spot prices. $\pi_t^{CPI\ excl.\ energy}$ is the quarterly inflation of the seasonally-adjusted Consumer Price Index - All Items less Energy. The sample period is 1999.6 - 2014.12. Standard errors are Newey-West adjusted with six lags. ***, **, and * denote statistical significance at the 1%, 5%, and 10% level, respectively.

	(1)	(2)	(3)	(4)	(5)	(6)
	$xr_{t+1}^{\$}$	xr_{t+1}^{TIPS}	xr_{t+1}^{BE}	$xr_{t+1}^{\$}$	xr_{t+1}^{TIPS}	xr_{t+1}^{BE}
g_t^{Oil}	0.01	-0.04	0.05***			
	(0.03)	(0.02)	(0.01)			
g_{t-1}^{Oil}	0.04**	0.04**	0.01			
	(0.02)	(0.02)	(0.01)			
$g_t^{Oil} + g_{t-1}^{Oil}$				0.03*	-0.00	0.03***
				(0.01)	(0.02)	(0.01)
$Nominal\ term\ spread_t$	4.76***			4.76***		
	(1.50)			(1.53)		
$Liq.\ Adj.\ TIPS\ term\ spread_t$		4.27***			3.70**	
		(1.58)			(1.51)	
$Liq.\ Adj.\ breakeven\ term\ spread_t$			5.87**			5.22***
			(1.58)			(1.44)
$\pi_t^{CPI\ excl.\ energy}$	5.61*	2.38	2.98**	5.70*	2.16	2.83**
	(3.19)	(2.68)	(1.25)	(3.23)	(2.70)	(1.39)
Const.	-0.04*	-0.02	-0.02***	-0.04*	-0.01	-0.02***
	(0.02)	(0.02)	(0.01)	(0.02)	(0.02)	(0.01)
Adj. R^2 $(excl.\ g^{Oil})$	10.1%	4.4%	10.7%	10.1%	4.4%	10.7%
Adj. R^2 $(incl.\ g^{Oil})$	12.5%	9.7%	21.5%	12.0%	3.9%	17.9%

Table 3.3: Excess returns on inflation swap rates

The log growth of crude oil spot prices is used to explain contemporaneous and forecast expected future 3-month overlapping excess returns on 1-, 2-, 5-, and 10-year inflation swaps, in addition to the inflation swap term spreads and the inflation of the CPI-All Items less Energy price index. The excess return of n-period inflation swap is defined as $xr^n_{t+1} \equiv ns_{n,t} - (n-1)s_{n-1,t+1} - E_t\pi^{CPI}_{t+1}$, where $s_{n,t}$ is the rate of the n-period inflation swap and $E_t\pi^{CPI}_{t+1}$ is the expected CPI inflation from t to $t+1$. The quarterly expected CPI inflation $E_t\pi^{CPI}_{t+1}$ is estimated from the lagged CPI, the lagged output gap, and the lagged log growth of crude oil prices in the past 12 months. The quarterly expected CPI inflation is the fitted value of the regression $\pi^{CPI}_{t+1} = \beta_0 + \sum_{j=1}^4 \beta^\pi_j \pi^{CPI}_{t-j+1} + \sum_{k=1}^4 \beta^y_k (y_{t-k+1} - \bar{y}_{t-k+1}) + \sum_{l=1}^4 \beta^o_l g^{Oil}_{t-l+1} + \varepsilon_{t+1}$ in the period January 1982 to December 2014. y is the quarterly log industrial production index from the U.S. Board of Governors of the Federal Reserve System. $\bar{y}$ is the Hodrick-Prescott filtered trend of y. g^{Oil}_t is the quarterly log growth of crude oil prices. The inflation term spread is the difference between 10-year inflation swap rate and one-quarter expected CPI inflation. $\pi^{CPI\ excl.\ energy}_t$ is the quarterly inflation of the seasonally-adjusted Consumer Price Index - All Items less Energy. The sample period is July 2004 - December 2014. Newey-West standard errors with six lags are in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% level, respectively.

Panel A. Contemporaneous

	(1) xr^{1y}_t	(2) xr^{2y}_t	(3) xr^{5y}_t	(4) xr^{10y}_t
g^{Oil}_t	-0.04***	-0.05***	-0.08***	-0.08***
	(0.01)	(0.01)	(0.02)	(0.02)
$Infl.\ swap\ term\ spread_t$	-0.79***	-1.02**	-1.22*	-1.52
	(0.27)	(0.46)	(0.72)	(1.18)
$\pi^{CPI\ excl.\ energy}_t$	0.79**	0.92	0.16	0.41
	(0.36)	(0.74)	(1.14)	(1.79)
Const.	-0.51**	-0.48	0.09	0.11
	(0.21)	(0.38)	(0.59)	(0.96)
Obs.	123	123	123	123
Adj. R^2	49.6%	45.6%	46.8%	31.1%

Panel B. Predictive

	(1) xr^{1y}_{t+1}	(2) xr^{2y}_{t+1}	(3) xr^{5y}_{t+1}	(4) xr^{10y}_{t+1}
g^{Oil}_t	0.01***	0.02***	0.03***	0.04***
	(0.00)	(0.01)	(0.01)	(0.01)
g^{Oil}_{t-1}	0.01**	0.01	0.02	0.03
	(0.01)	(0.01)	(0.02)	(0.02)
$Infl.\ swap\ term\ spread_t$	-1.29***	-1.96***	-2.79**	-2.81
	(0.39)	(0.62)	(1.24)	(1.79)
$\pi^{CPI\ excl.\ energy}_t$	-0.39	-0.81	-2.40*	-2.31*
	(0.66)	(0.82)	(1.23)	(1.20)
Const.	-0.03	0.23	1.15	1.22
	(0.39)	(0.51)	(0.78)	(0.75)
Obs.	123	123	123	123
Adj. R^2	22.8%	19.9%	16.6%	13.6%

Table 3.4: Parameter values

Parameter values are at a quarterly frequency. Parameters are grouped into four categories: preferences, production, shocks, and monetary policy.

Group	Description	Symbol	Value
Preferences	Time discount rate	β	0.997
	Relative risk aversion	γ	10 (20)
	EIS	$1/\rho$	2 (5)
	Coefficient of disutility	ϕ	3.6272
	Frisch elasticity of labor supply	ν	0.2498
	Oil share of the consumption bundle	ξ	0.1
	Elasticity of substitution of oil and core goods	η	0.25
	Index of real wage rigidity	ρ_w	0.95
	Labor supply in the DSS	N	0.33
Production	CES of intermediate core goods	ε	6
	Degree of price adjustment cost	ϑ	25
	Degree of oil capital adjustment cost	ζ^o	4.8
	Degree of core goods capital adjustment cost	ζ^c	4.8
	Depreciation rate of oil capital	δ^o	0.05
	Depreciation rate of core goods capital	δ^c	0.02
	Capital share of output	ω	0.33
	Labor share of output	α	0.568
	Oil share of output	$1-\alpha-\omega$	0.102
Shocks	z^o-shock in the DSS	$\bar{z^o}$	0
	AR(1) coefficient of z^o-shock	ρ_o	0.45
	Standard deviation of z^o-shock	σ_o	9.5%
	z^c-shock in the DSS	$\bar{z^c}$	0
	Standard deviation of SRR shock	σ_c	1.2%
	AR(1) coefficient of LRR shock	ρ_{xc}	0.9
	Standard deviation of LRR shock	σ_{xc}	0.17%
Policy	Core inflation target	$\bar{\pi}$	1.0092
	Sensitivity of the interest rate to inflation	ϕ_π	1.5
	Sensitivity of the interest rate to output	ϕ_y	0.125

Table 3.5: Moments

This table reports the means, standard deviations, autocorrelations of growth reates of relative oil prices, core inflation, CPI inflation, 5-year nominal yields, yields spread between 5-year and 1-quarter, 5-year inflation risk premium, and equity premium of the core goods sector from the data and the model. The reported statistics from the data are numbers at a quarterly frequency for the period of 1987Q4 to 2014Q4. y^{40}, y^{20}, and y^{1} refer to 10-year, 5-year, and 1-quarter nominal yields, respectively. r^{40} and be^{40} refer to 10-year real yields and breakeven inflation, respectively. g_t^{Oil} represents the growth rate of nominal oil prices. r^c and rf refer to the aggregate equity return and the risk-free rate, respectively. The model is calibrated at a quarterly frequency.

	Data	Model
Relative oil prices		
$E(\Delta log(P_t^O/P_t^C))$	0.45%	0.02%
$\sigma(\Delta log(P_t^O/P_t^C))$	18.48%	13.26%
$AC(\Delta log(P_t^O/P_t^C))$	0.008	-0.219
Inflation		
$E(\pi_t^C)$	0.64%	0.62%
$\sigma(\pi_t^C)$	0.29%	0.60%
$AC(\pi_t^C)$	0.717	0.619
$E(\pi_t^{CPI})$	0.66%	0.62%
$\sigma(\pi_t^{CPI})$	0.62%	0.67%
$AC(\pi_t^{CPI})$	0.046	0.447
5Y nominal yields, spread, inflation risk premium		
$E(y^{20})$	1.17%	0.94%
$\sigma(y^{20})$	1.16%	0.25%
$AC(y^{20})$	0.951	0.887
$E(y^{20}-y^{1})$	0.31%	0.18%
$IRP(y^{20})$		0.28%
Correlations		
$Corr(\Delta y_t^{20}, g_t^{Oil})$	0.408	0.473
$Corr(\Delta y_t^{40}, g_t^{Oil})$	0.397	0.386
$Corr(\Delta r_t^{40}, g_t^{Oil})$	0.218	0.706
$Corr(\Delta be_t^{40}, g_t^{Oil})$	0.389	0.133
Equity premium		
$E(r^c - rf)$	1.38%	0.86%
$\sigma(r^c - rf)$	10.23%	1.98%
Other macroeconomic moments		
$\sigma(c)/\sigma(y^c)$	0.51	0.91
$\sigma(w)/\sigma(y^c)$	0.44	0.64
$AC(c)$	0.53	0.50
$AC(w)$	0.36	0.87
$AC(y^c)$	0.57	0.68
$Corr(\Delta c, \pi^{CPI})$	-0.56	-0.47

Table 3.6: Data and model implied statistics for alternative specifications

The table reports summary statistics for key variables from the data and the model with alternative specifications. y^{40}, y^{20}, and y^{1} refer to 10-year, 5-year, and 1-quarter nominal yields, respectively. r^{40} and be^{40} refer to 10-year real yields and breakeven inflation, respectively. g_t^{Oil} represents the growth rate of nominal oil prices. Column (2) is the baseline model. Column (3) refers to a specification that there is no oil in households' utility function. Column (4) refers to a specification that there is no oil input in firms' production function. Column (5) is the baseline model without the productivity shock in the oil sector, i.e., $\varepsilon^o = 0$. Column (6) is the baseline model without the productivity shock in the core sector, i.e., $\varepsilon^c = 0$ and $\varepsilon^{xc} = 0$.

	(1) Data	(2) Baseline	(3) $\xi = 0$	(4) $1-\alpha-\omega = 0$	(5) $\varepsilon^o = 0$	(6) $\varepsilon^c = \varepsilon^{xc} = 0$
Relative oil prices						
$E(\Delta log(P_t^O/P_t^C))$	0.45%	0.02%	0.00%	0.00%	0.00%	0.00%
$\sigma(\Delta log(P_t^O/P_t^C))$	18.48%	13.26%	14.37%	34.06%	1.20%	12.83%
$AC(\Delta log(P_t^O/P_t^C))$	0.008	-0.219	-0.268	-0.171	0.395	-0.209
Inflation						
$E(\pi_t^C)$	0.64%	0.62%	0.21%	0.71%	0.64%	0.90%
$\sigma(\pi_t^C)$	0.29%	0.60%	0.55%	0.79%	0.46%	0.44%
$AC(\pi_t^C)$	0.717	0.619	0.661	0.931	0.965	0.585
$E(\pi_t^{CPI})$	0.66%	0.62%	0.21%	0.71%	0.64%	0.90%
$\sigma(\pi_t^{CPI})$	0.62%	0.67%	0.55%	0.85%	0.46%	0.52%
$AC(\pi_t^{CPI})$	0.046	0.447	0.661	0.768	0.972	0.351
5Y nominal yields						
$E(y^{20})$	1.17%	0.94%	0.45%	1.27%	0.96%	1.20%
$\sigma(y^{20})$	1.16%	0.25%	0.23%	0.47%	0.31%	0.04%
$AC(y^{20})$	0.951	0.887	0.961	0.954	0.976	0.428
Yield spread: 5Y − 1Q						
$E(y^{20} - y^{1})$	0.31%	0.18%	0.14%	0.45%	0.18%	0.00%
5Y inflation risk premium						
$IRP(y^{20})$		0.28%	0.24%	0.59%	0.29%	0.00%
Correlations						
$Corr(\Delta y_t^{20}, g_t^{Oil})$	0.408	0.473	0.622	0.126	-0.199	0.988
$Corr(\Delta y_t^{40}, g_t^{Oil})$	0.397	0.386	0.514	0.109	-0.058	0.989
$Corr(\Delta r_t^{40}, g_t^{Oil})$	0.218	0.706	0.648	0.671	0.109	0.981
$Corr(\Delta be_t^{40}, g_t^{Oil})$	0.389	0.133	0.233	-0.023	-0.068	0.997

Table 3.7: Variance decompositions for the baseline model

This table reports the unconditional variance decompositions for the baseline model for the three productivity shocks ε^o, ε^c, and ε^{xc}. Variance decompositions are in percentage terms. The parameters values of the baseline model are given in Table 3.4. y^{20} and y^1 refer to 5-year and 1-quarter nominal yields, respectively. s^{20} and s^1 refer to 5-year and 1-quarter breakeven inflation, respectively.

	ε^o	ε^c	ε^{xc}
Real oil prices and inflation			
$log(P_t^O/P_t^C)$	90.76	5.78	3.47
π_t^{CPI}	54.15	5.73	40.12
π_t^C	44.78	7.27	47.95
1Q and 5Y nominal yields			
y^1	63.81	3.66	32.53
y^{20}	1.76	6.36	91.89
1Q and 5Y real yields			
r^1	88.73	3.19	8.08
r^{20}	20.66	3.6	75.74
1Q and 5Y breakeven inflation			
s^1	11.52	8.36	80.13
s^{20}	0.22	5.35	94.43
1Q and 5Y inflation risk premium			
IRP^1	0.02	7.08	92.9
IRP^{20}	0.05	30.96	68.99

Table 3.8: Decomposition of the one-period inflation risk premium

This table presents the market price of risk of three productivity shocks, the beta of CPI inflation, and the inflation risk premium for the base calibration. The prices of risk and the inflation risk premia are reported at a quarterly frequency.

Price of risk	
λ^o	0.11%
λ^c	0.23%
λ^{xc}	0.04%
Inflation beta	
β^o	-0.05
β^c	-0.07
β^{xc}	-0.20
Inflation risk premium	
IRP^o	0.6 bps
IRP^c	1.7 bps
IRP^{xc}	0.9 bps

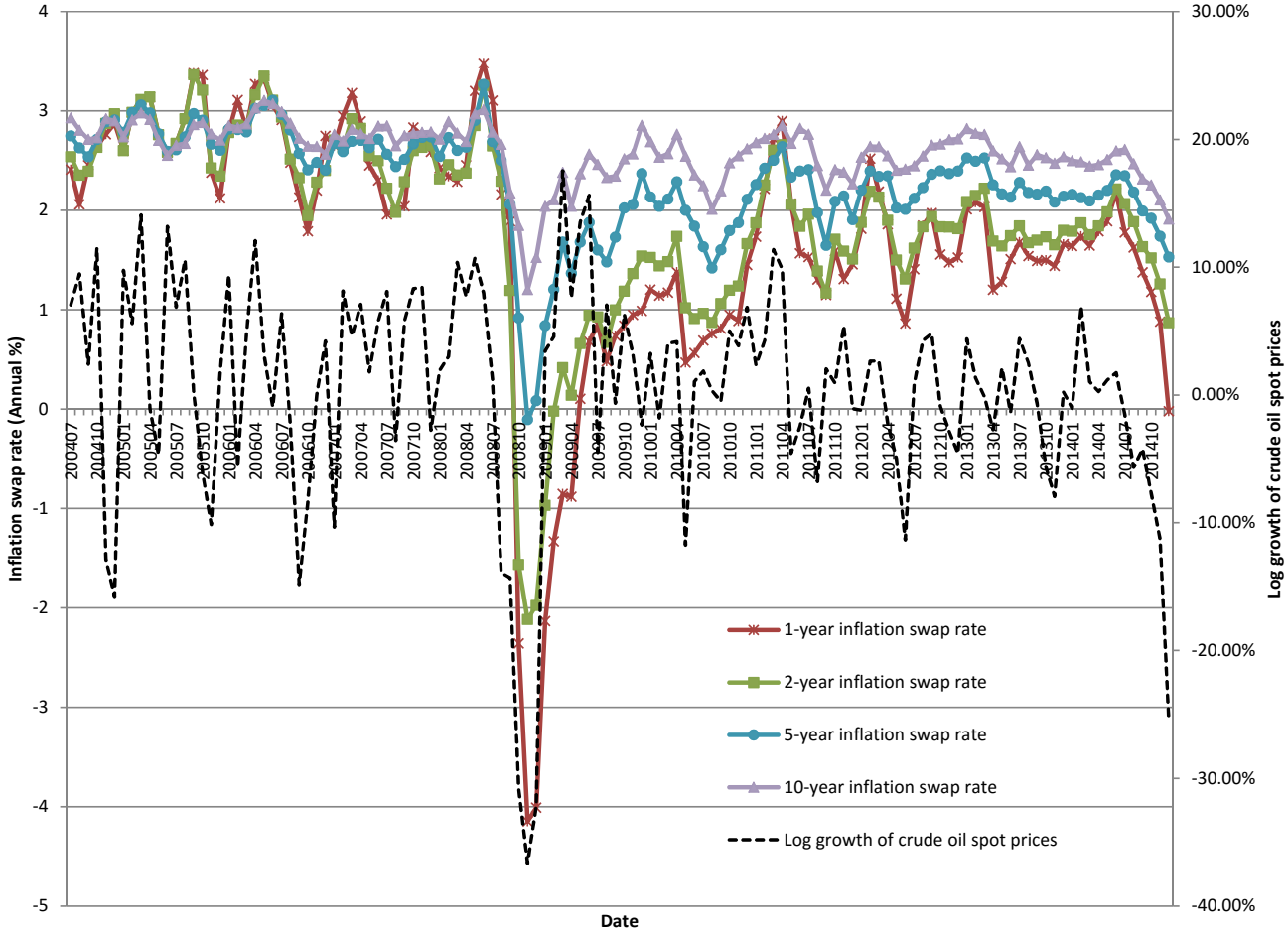

Figure 3.1: Inflation swap rates and crude oil spot price growth.

The figure plots the monthly U.S. zero-coupon inflation swap rates of 1-, 2-, 5-, 10-year maturities and the growth rate of crude oil prices from July 2004 to December 2014. Inflation swap rates are expressed as annual percentage. Data on inflation swap rates are from Bloomberg. Crude oil spot prices are the U.S. refiners' acquisition costs of crude oil from U.S. Energy Information Administration (EIA).

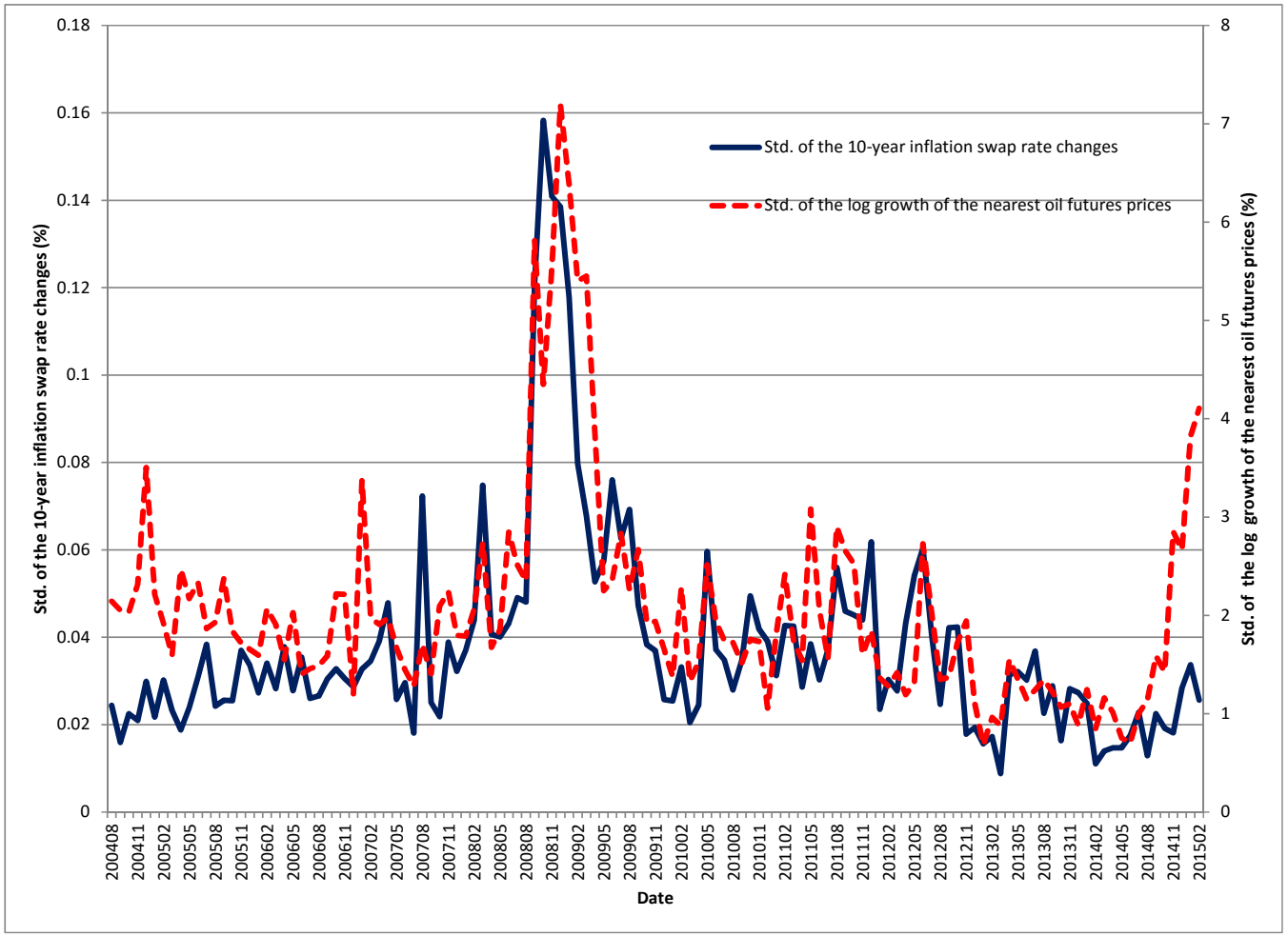

Figure 3.2: Standard deviations of changes in 10-year inflation swaps and growth rates of the nearest-to-maturity oil futures.

The standard deviations of changes in 10-year inflation swap rate changes and growth rates of the nearest-to-maturity NYMEX crude oil futures prices are estimated based on daily observations within each month. Daily inflation swap rates are from Bloomberg. The NYMEX crude oil futures prices of the nearest contract are from the U.S. Energy Information Administration (EIA).

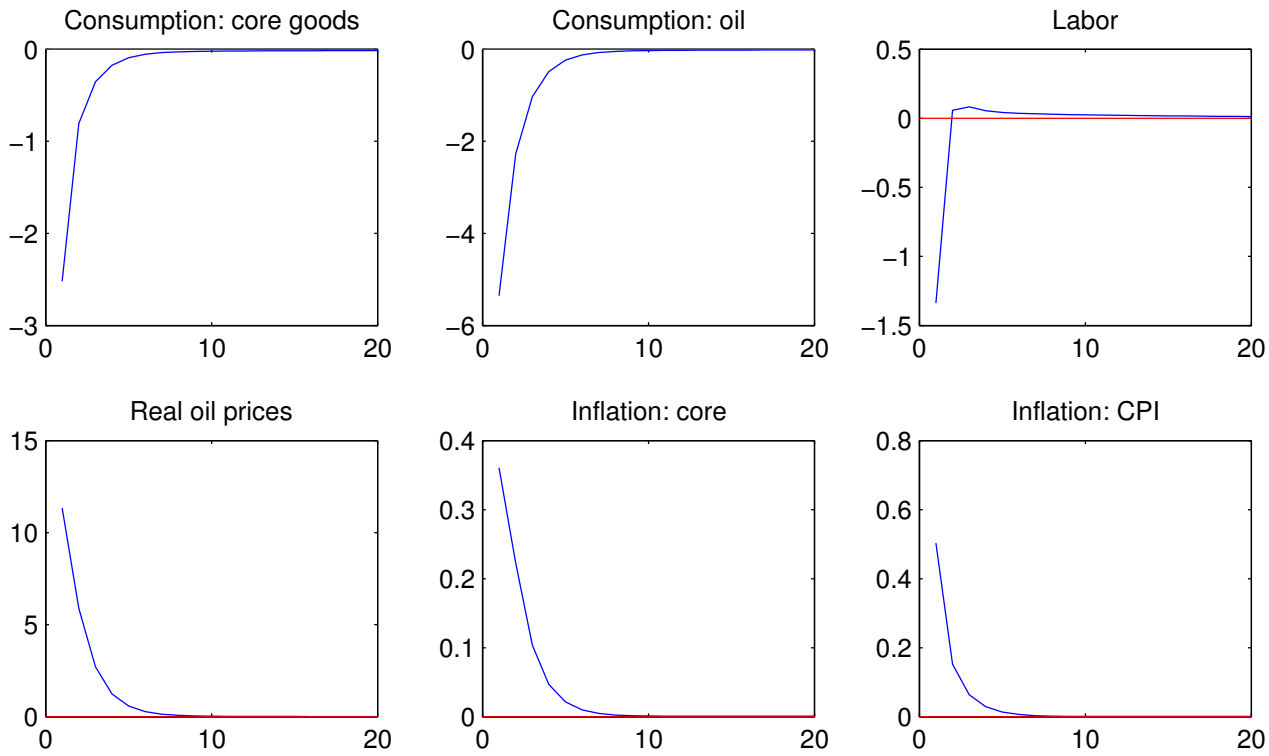

Figure 3.3: Impulse response functions to a negative ε_t^o shock.

This figure plots impulse response functions of core goods, households' consumption of oil, labor supply, real oil prices (P_t^O/P_t^C), core inflation, and CPI inflation. The y-axis shows the percentage deviation. The size of ε_t^o shock is one standard deviation $\sigma_o = 9.5\%$.

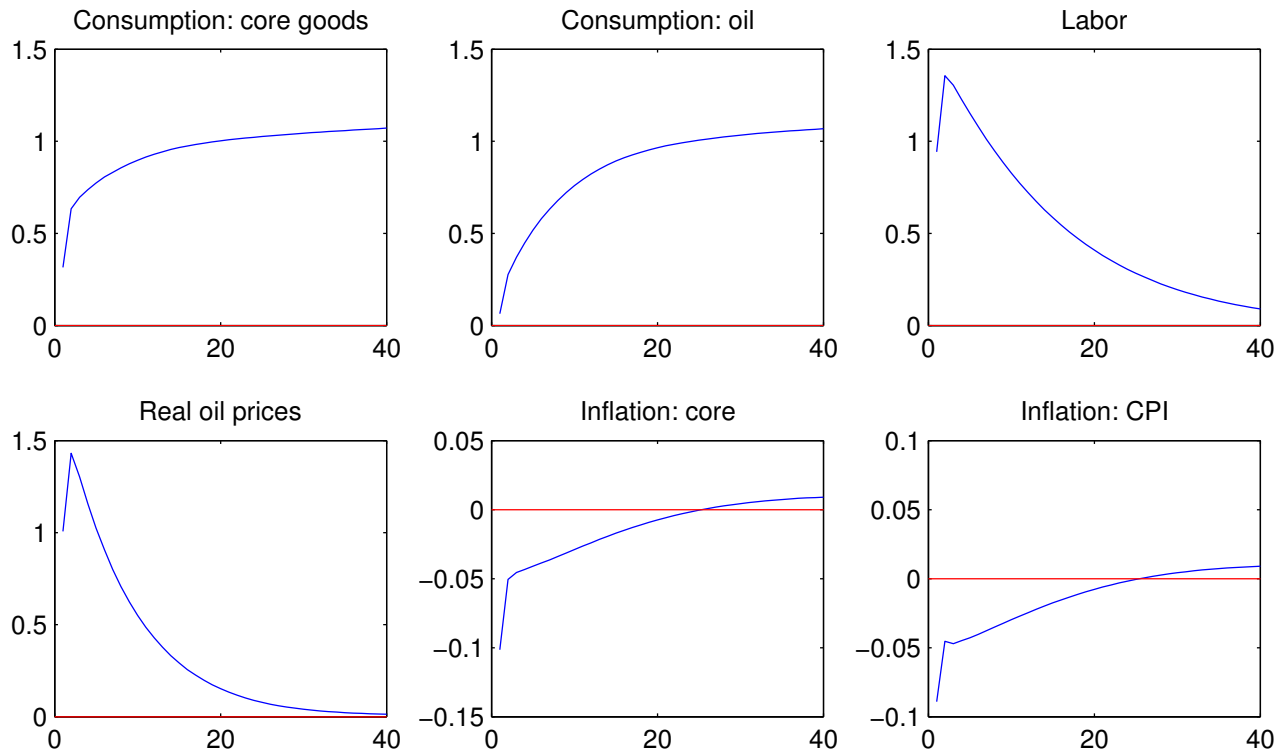

Figure 3.4: Impulse response functions to a positive ε_t^c shock.

This figure plots impulse response functions of core goods, households' consumption of oil, labor supply, real oil prices (P_t^O/P_t^C), core inflation, and CPI inflation. The y-axis shows the percentage deviation. The size of the ε_t^c shock is one standard deviation $\sigma_c = 1.2\%$.

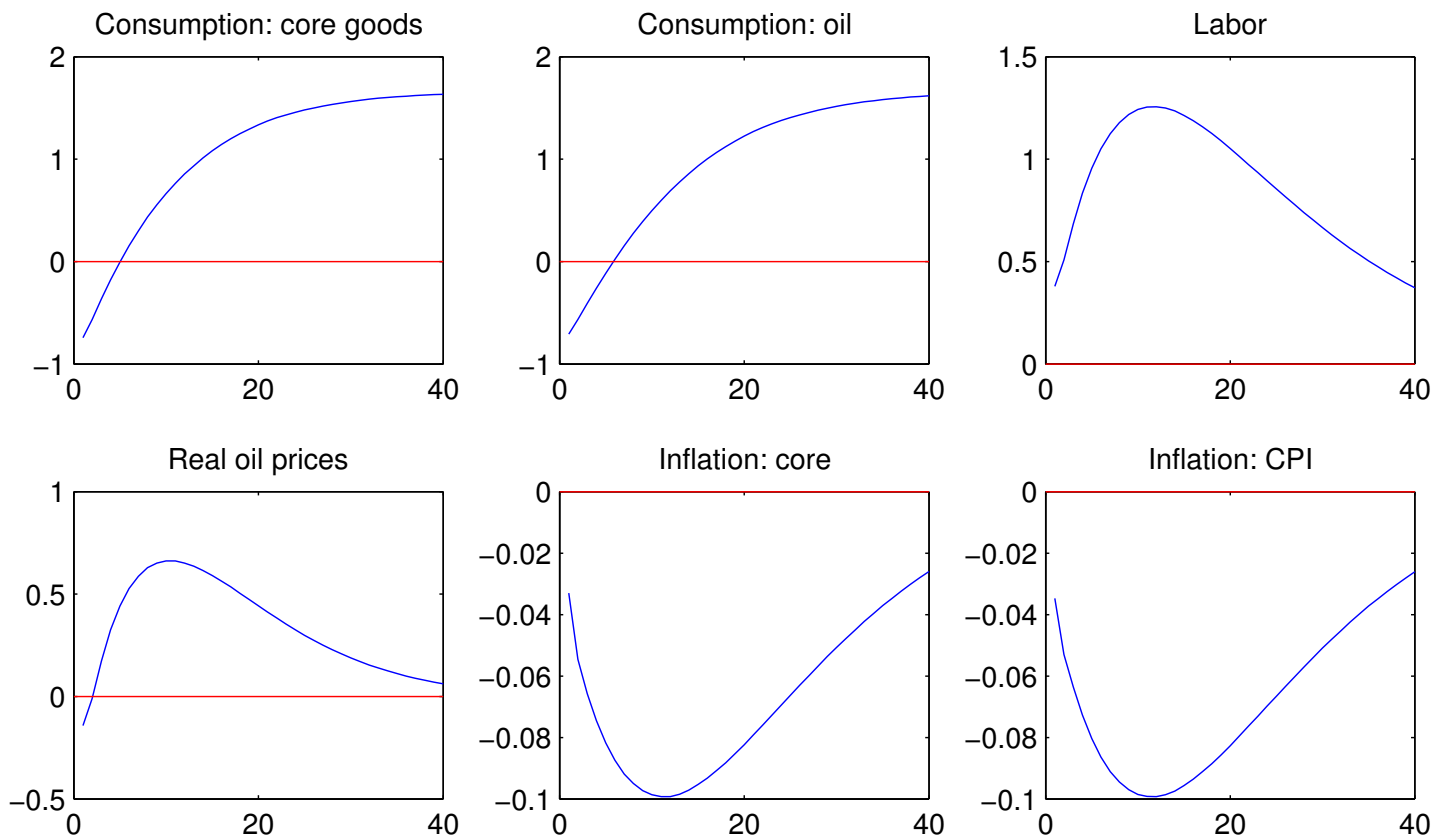

Figure 3.5: Impulse response functions to a positive ε_t^{xc} shock.

This figure plots impulse response functions of core goods, households' consumption of oil, labor supply, real oil prices (P_t^O/P_t^C), core inflation, and CPI inflation. The y-axis shows the percentage deviation. The size of the ε_t^{xc} shock is one standard deviation $\sigma_{xc} = 0.17\%$.

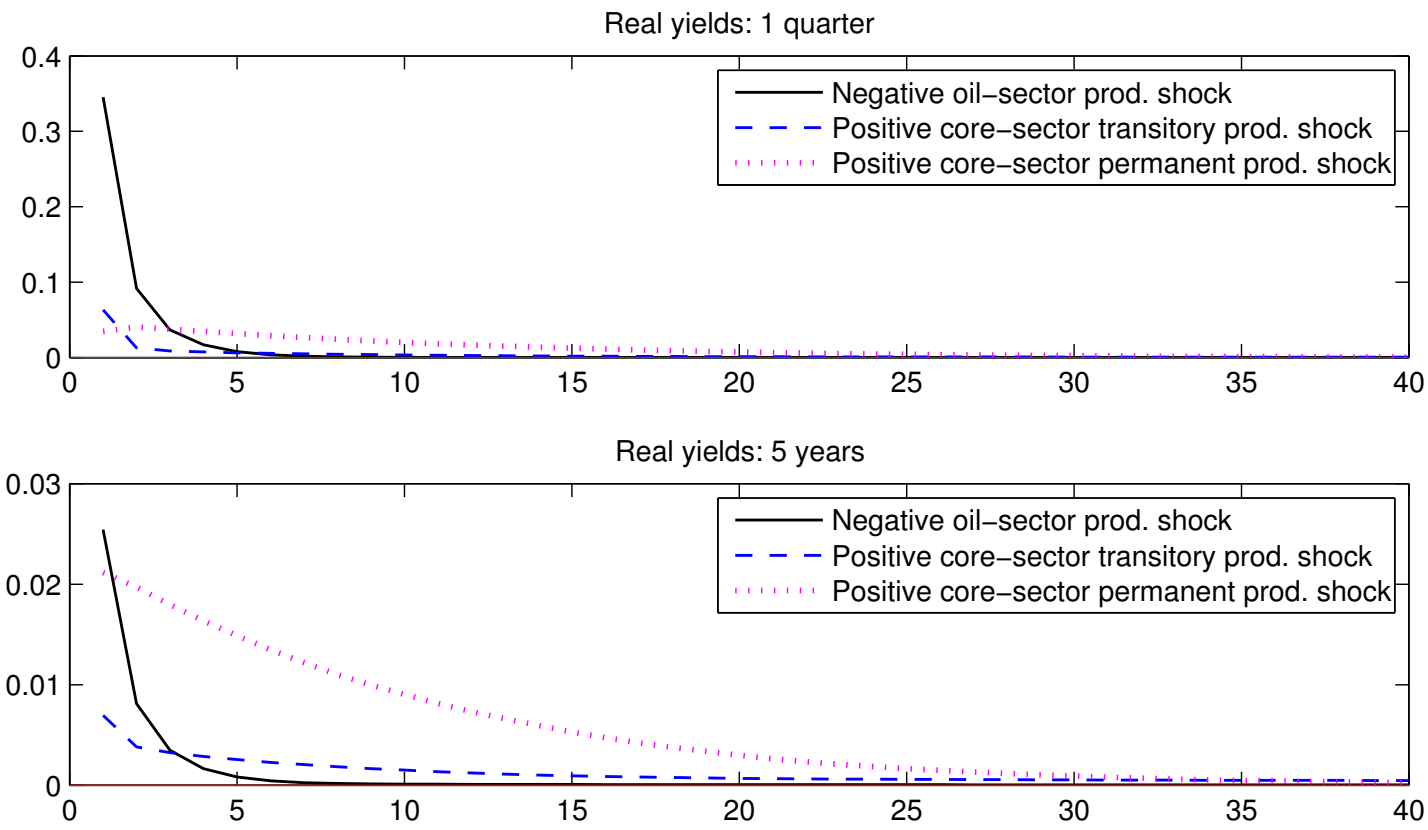

Figure 3.6: Impulse response functions of 1-quarter and 5-year real yields to three productivity shocks. The size of each shock is one standard deviation: $\sigma_o = 9.5\%$, $\sigma_c = 1.2\%$, and $\sigma_{xc} = 0.17\%$.

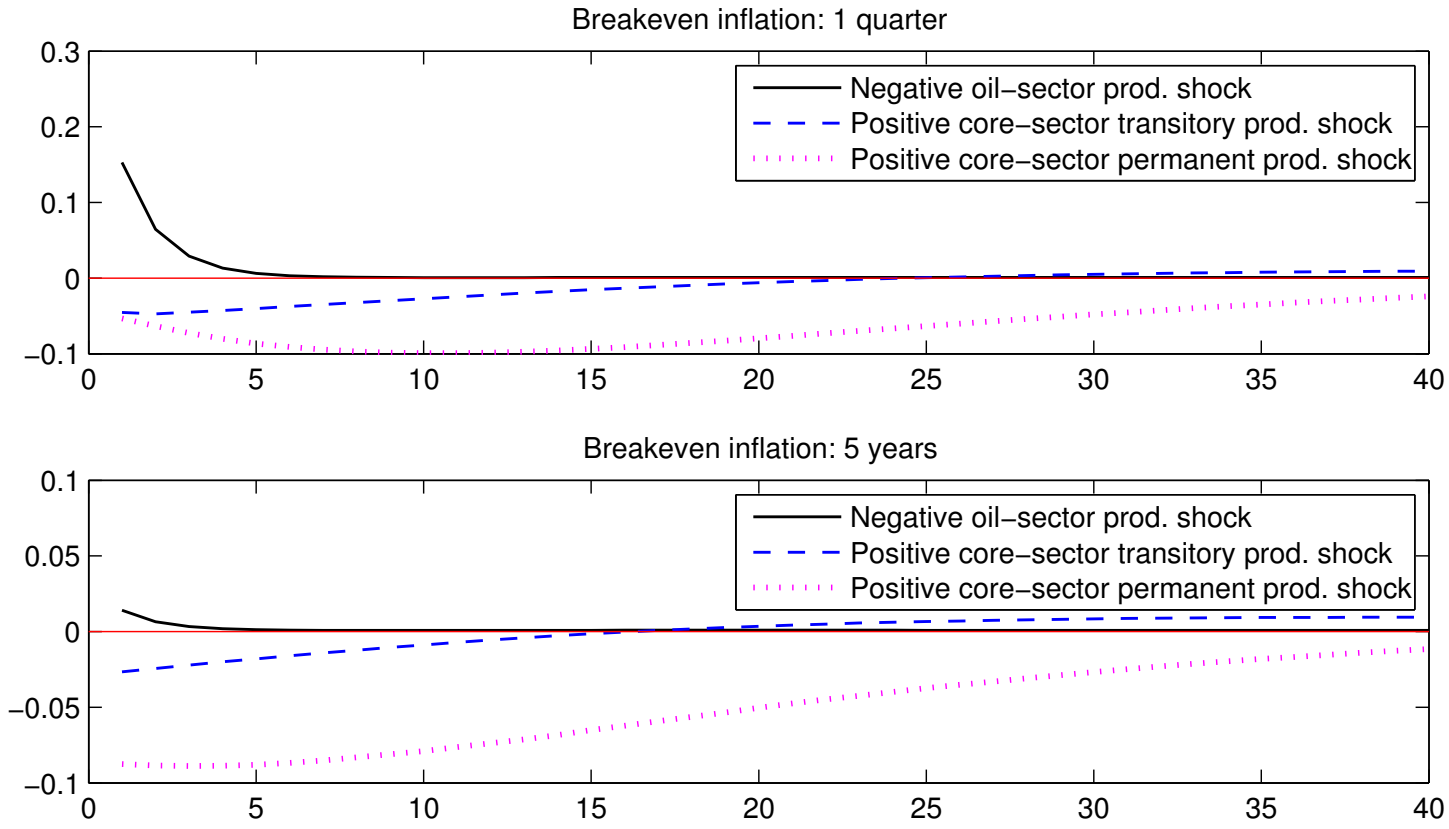

Figure 3.7: Impulse response functions of 1-quarter and 5-year breakeven inflation rates to three productivity shocks. The size of each shock is one standard deviation: $\sigma_o = 9.5\%$, $\sigma_c = 1.2\%$, and $\sigma_{xc} = 0.17\%$.

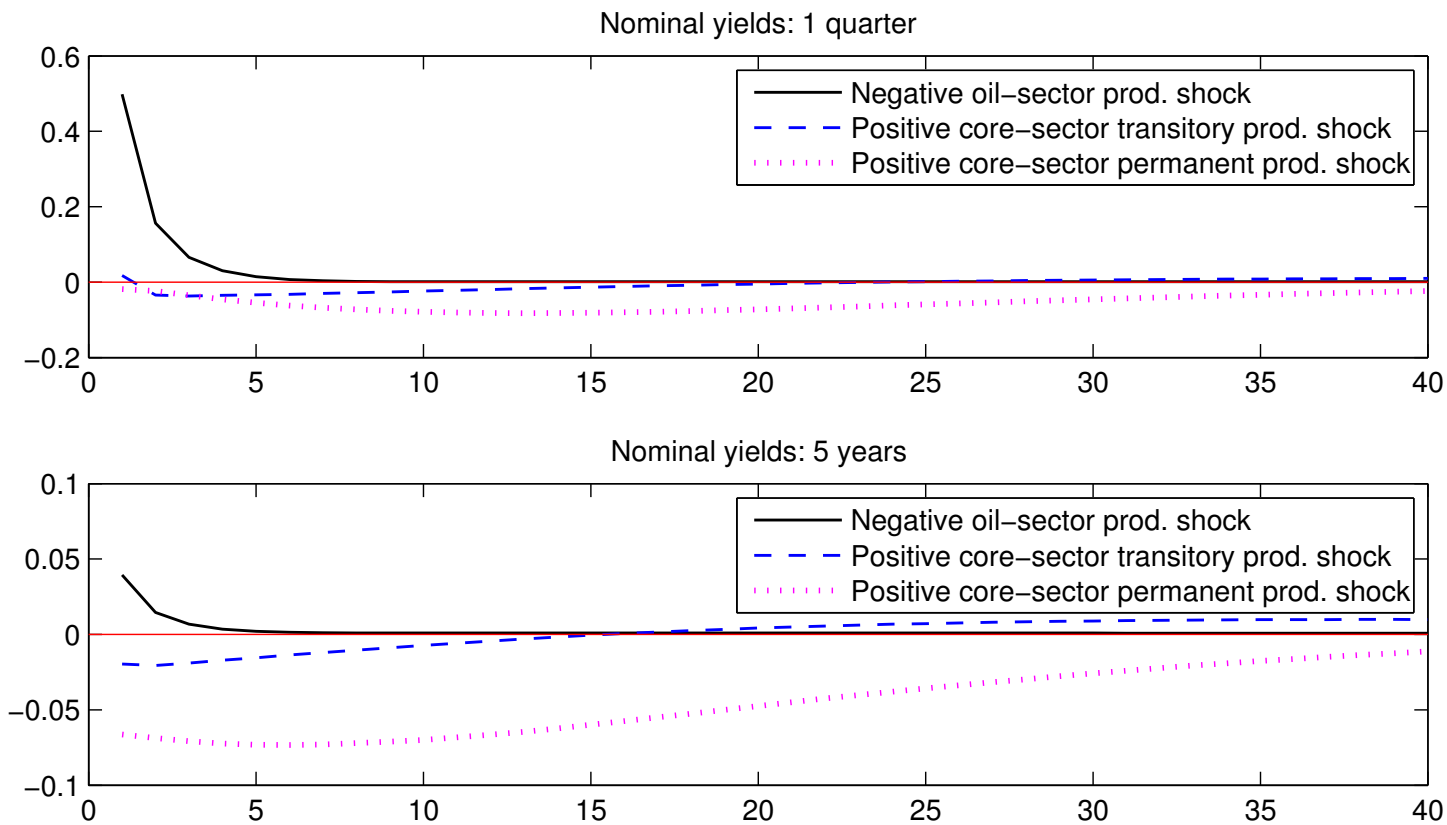

Figure 3.8: Impulse response functions of 1-quarter and 5-year nominal yields to three productivity shocks. The size of each shock is one standard deviation: $\sigma_o = 9.5\%$, $\sigma_c = 1.2\%$, and $\sigma_{xc} = 0.17\%$.

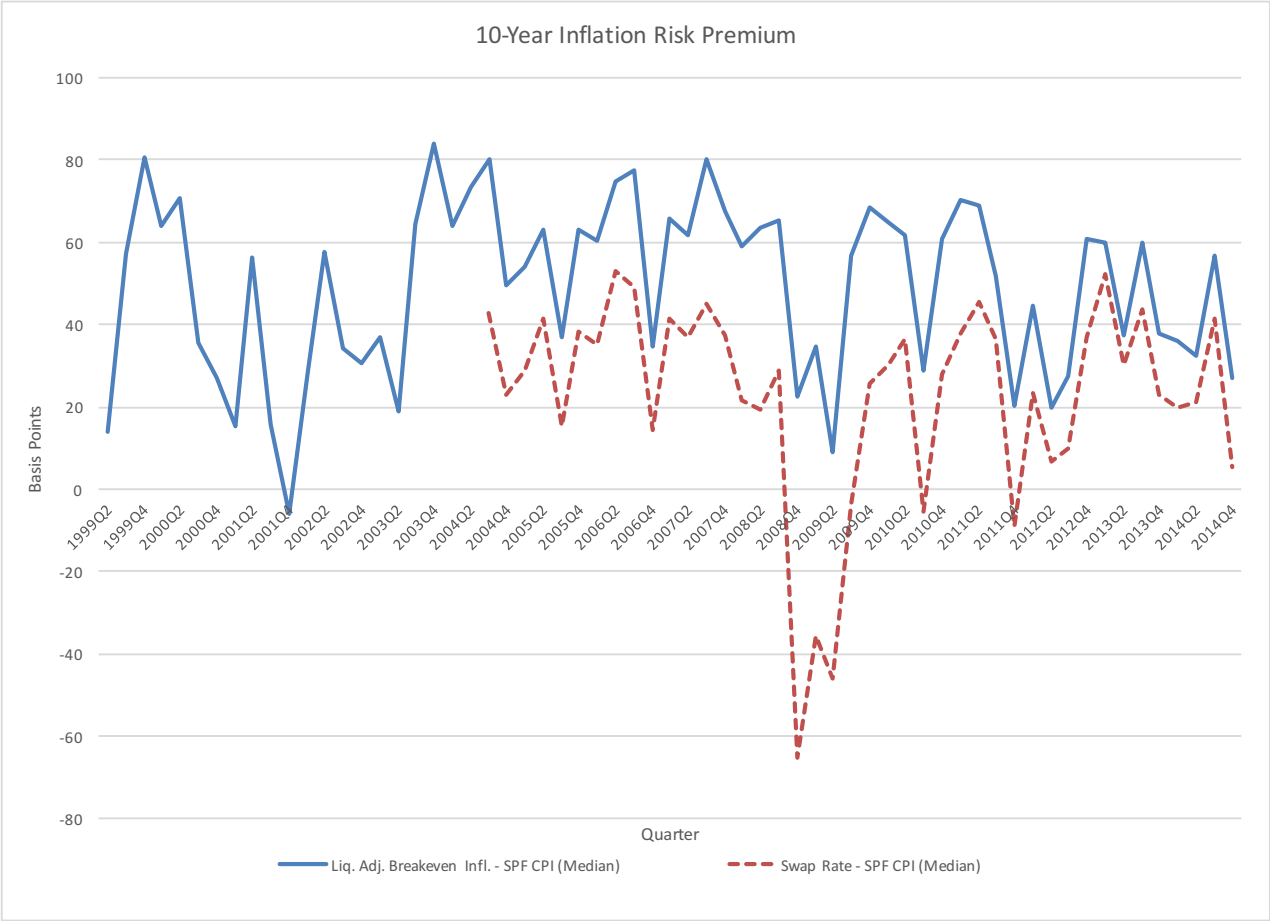

Figure 3.9: Inflation risk premia.

The solid line represents the inflation risk premia estimated from the difference between the liquidity-adjusted 10-year breakeven inflation and the median of the forecasts for the Survey of Professional Forecast 10-year CPI from 1999Q2 to 2014Q4. The dashed line represents the inflation risk premia estimated from the difference between the 10-year inflation swap rate and the median of the forecasts for the Survey of Professional Forecasters 10-year CPI from 2004Q3 to 2014Q4. Data on the liquidity-adjusted 10-year breakeven inflation are from Pflueger and Viceira (2015). Data on the Survey of Professional Forecasters 10-year CPI are from the Federal Reserve Bank of Philadelphia.

Chapter 4

Conclusion

This dissertation studies the relationship between oil prices, inflation, and Treasury bond returns both empirically and theoretically. Chapter 2 documents a puzzling time-varying trend in correlations between U.S. core inflation and one-month lagged oil price changes, which is the first time reported in the literature. The chapter then builds a two-sector general equilibrium model to show that oil supply and demands shocks are able to generate either co-movements or opposing movements between core inflation and oil prices. In Chapter 3, I provide novel empirical evidence that the price of oil price is a significant explanatory variable and predictor of excess returns on nominal Treasury bonds. Additionally, I present theoretical analysis that oil prices are relevant determinants for expected inflation and real yields on inflation-indexed bonds.

Chapter 2 sheds light on understanding and identifying intrinsic shocks in oil price shocks. Empirical results confirm the presence of two structural breaks in correlations between U.S. core inflation and changes in oil prices in the mid-1980s and during the 2007 financial crisis. The resurgence of the correlations after the 2007 financial crisis is puzzling, in contrast to the economy's declining energy intensity. Theoretical analysis shows that the relation between the price of oil and inflation risk depends on the type of shocks embedded in oil price changes. The economic mechanisms in the model and historical events together provide a consistent and logical explanation of the time-varying correlations observed in the data.

Chapter 3 highlights that the complementarity between oil and core goods consumption and oil input in production are important economic channels for studying the dynamics of oil prices and bond yields. Overall, the two-sector New Keynesian model is able to replicate several key empirical relationships between oil prices and bond yields. The model also generates upward sloping nominal yield curves and sizable positive inflation risk premia; it is well-known that these two features are very challenging to achieved in

macro-finance models. Empirical results suggest that the impact of oil prices on nominal bonds is through the impact on expected inflation. The model shows that oil supply and demand shocks have opposite impacts on bond yields and expected inflation. The conventional wisdom that high oil prices lead to high expected inflation and nominal yields is true only if high oil prices are driven by a negative shock to the supply of oil. In contrast, when oil prices are driven by a positive shock to productivity growth, high oil prices can lead to low expected inflation and nominal yields.

The connection between the oil market and the economy and the financial markets is complex in nature. The oil market is a global market. Oil prices are globally determined, and oil futures and other related financial products are traded at several international derivatives exchanges. Research on the area is traditionally done in economic literature. Research from the finance perspective is still under-explored overall. My dissertation focuses on the impact of oil price changes on inflation, expected inflation, and Treasury bond returns, at the aggregate level.

Chapter 2 has practical implications for central banks and pension fund managers. The sign of correlation indicates whether the intrinsic shocks embedded in the price of oil are supply shocks or aggregate demand shocks. A better understanding of time-varying correlation based on the supply and demand shocks in the oil market can help investors to more effectively hedge inflation, and it can also help central banks to better gauge information regarding inflation from oil price shocks.

In Chapter 3, empirical tests using data on TIPS and inflation swap rates provide richer information on understanding behaviors of components of nominal yields than those using data solely on nominal bonds. In addition, the chapter offers novel predictions and further highlights key economic transmission channels through which oil price shocks affect bond markets. Most importantly, the chapter shows that oil prices are relevant risk factors for pricing nominal and inflation-indexed Treasury bonds and inflation swaps. The implications of the impact of oil price shocks on long-term expected inflation are also useful for monetary policy and risk management.

For the sake of simplicity, the model in Chapter 3 considers three productivity shocks only, omitting true demand shocks, such as preference shocks in the representative agent's utility function. Additional preference shocks and the time-varying volatility of productivity shocks will be considered in future research.

Last, research from the international perspective will be interesting as well. For empirical tests, I use U.S. data on inflation, inflation swaps, and Treasury bonds. My choice is constrained by the availability of data on other countries. Nevertheless, using U.S. data is reasonable given that U.S. is the largest consumer

of oil and its financial markets is the largest in the world. Applying my work to international government bond markets will be considered in future research.

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Appendix A

Equilibrium conditions of the two-sector general equilibrium model

First order conditions

$$\frac{\xi}{1-\xi}\left(\frac{C_t}{O_t^H}\right)^{-\gamma} = \frac{P_t^C}{P_t^O} \tag{A.1}$$

$$1 = \beta E_t \left\{ \left(\frac{C_{t+1}}{C_t}\right)^{-\gamma} \left(\frac{\xi (C_{t+1})^{1-\gamma} + (1-\xi)(O_{t+1}^H)^{1-\gamma}}{\xi (C_t)^{1-\gamma} + (1-\xi)(O_t^H)^{1-\gamma}}\right)^{\gamma/(1-\gamma)} \frac{P_t^C}{P_{t+1}^C} R_t \right\} \tag{A.2}$$

$$R_t^O = Z_t^O P_t^O \tag{A.3}$$

$$R_t^C = \alpha Z_t^C (O_t^I)^{1-\alpha} P_t^C \tag{A.4}$$

$$P_t^C (1-\alpha) Z_t^C (O_t^I)^{-\alpha} = P_t^O \tag{A.5}$$

Market clearing conditions

$$O_t^H + O_t^I = Y_t^O \tag{A.6}$$

$$C_t = Y_t^C \tag{A.7}$$

Equilibrium quantities (log-linearization)

$$\widetilde{c}_t = \frac{\gamma O^I + O^H}{(1-\gamma)\alpha O^H + \gamma Z^O}\widetilde{z}_t^c + \frac{(1-\alpha)\gamma Z^O}{(1-\gamma)\alpha O^H + \gamma Z^O}\widetilde{z}_t^o \tag{A.8}$$

$$\widetilde{o}_t^h = \frac{(\gamma-1)O^I}{(1-\gamma)\alpha O^H + \gamma Z^O}\widetilde{z}_t^c + \frac{[\alpha+(1-\alpha)\gamma]Z^O}{(1-\gamma)\alpha O^H + \gamma Z^O}\widetilde{z}_t^o \tag{A.9}$$

$$\widetilde{o}_t^i = \frac{(1-\gamma)O^H}{(1-\gamma)\alpha O^H + \gamma Z^O}\widetilde{z}_t^c + \frac{\gamma Z^O}{(1-\gamma)\alpha O^H + \gamma Z^O}\widetilde{z}_t^o \tag{A.10}$$

Equilibrium real oil price (log-linearization)

$$\widetilde{p}_t^o = \frac{\gamma Z^O}{(1-\gamma)\alpha O^H + \gamma Z^O}(\widetilde{z}_t^c - \alpha\widetilde{z}_t^o) \tag{A.11}$$

Appendix B

Inflation swap contracts

Inflation swap rates provide the market-based measures of the breakeven inflation. An inflation swap is a bilateral contractual agreement. Inflation swap rates refer to the zero-coupon fixed rate leg against a floating leg on the CPI appreciation on U.S. Consumer Price Index for Urban Consumers, Not Seasonally Adjusted (CPUR-NSA) over the maturity.The U.S. inflation swap market is an over-the-counter market and has developed quickly in recent years. The U.S. Swap Data Repository (SDR) shows that the gross USD notional volume is $12 to $20 billion per month.[1] In practice, because the CPI index is known with a lag, the floating payment is estimated on inflation over the period starting three months before the start date and ending three months before the termination date. The data on the inflation swap rates are available starting from July 2004 from Bloomberg.

The zero-coupon inflation swap fixed rate consists of the expected inflation and the inflation risk premium. Inflation swap rates are quoted as annually compounded rates. Table B.1 presents the summary statistics of the inflation swap rates and rate spreads. The average inflation swap curve is upward sloping in the period from July 2004 to December 2014.

[1]Reported by Amir Khwaja from Clarus Financial Technology. The report is available at http://www.clarusft.com/inflation-swaps-what-the-data-shows/.

Table B.1: Summary statistics of the U.S. zero-coupon inflation swap rates

Swap rates are reported as annual percentage. The 1-, 2-, 5-, and 10-year maturities are the most common. The whole sample period is from July 2004 to December 2014.

	2004.7-2012.12		2004.7-2008.7		2008.8-2014.12	
	Mean	Std.	Mean	Std.	Mean	Std.
1-year	1.71	1.28	2.69	0.42	1.09	1.26
2-year	1.90	0.96	2.68	0.34	1.40	0.89
5-year	2.29	0.54	2.74	0.19	2.00	0.49
10-year	2.59	0.29	2.81	0.13	2.46	0.29
20-year	2.78	0.29	2.98	0.14	2.65	0.29
30-year	2.86	0.30	3.10	0.18	2.72	0.26
10-year − 1-year	0.88	1.03	0.12	0.37	1.36	1.03

Appendix C

Latent factors of inflation swap contracts

I use principal components analysis to estimate latent factors that explain variations in inflation swap rates. Similar to the latent factors of nominal bond yields, the first three principal components (PCs) of the 1-year, 2-year, 5-year, and 10-year inflation swap rates explain 95.5%, 3.7%, and 0.6% of the variation of inflation swap rates, respectively. Because inflation swap rates for short maturities are more volatile than for long maturities, I first standardize swap rates by dividing the standard deviation of swap rates. I then use principal component analysis to estimate latent factors of standardized inflation swap rates. Based on coefficient patterns of the first three principal components on the underlying swap contracts, as shown in Figure C.1, the first three PCs could be labelled as the level, slope, and curvature factors, respectively. As the first two PCs account for 99.2% of the variation, the following tests focus on the level and slope factors.

Two tests are conducted to answer whether information contained in oil prices is useful for forecasting breakeven inflation. First, are oil prices spanned by latent factors of inflation swap rates? It turns out that the log growth of crude oil spot prices is mostly not explained by latent factors of inflation swap rates. The adjusted R^2 is 32.2% of the contemporaneous regression of oil price growth on the first three PCs (not shown). Second, the more interesting question is whether g^{Oil} can forecast latent factors over and above the information in inflation swap rates. Table C.1 shows the results of forecasting changes of the level and slope factors, the average of inflation swap rates, and the spread of inflation swap rates between 10-year and 1-year. Oil price growth can significantly forecast the changes of the level factor, the average, and the spread. Increases in the adjusted R^2 also show the incremental forecasting power of oil prices, except for the slope factor.

Table C.1: Level and slope factors of inflation swap rates

The change of the level and slope factors, the change of the average of inflation swap rates, and the change of the spread of inflation swap rates are regressed on the lagged log growth of crude oil prices and the lagged level and slope factors. The level and slope factors are the first and the second principal components of 1-, 2-, 5-, and 10-year inflation swap rates from July 2004 to December 2014. ΔPC_{t+1}^{Level} and ΔPC_{t+1}^{Slope} denote the monthly change of level and slope factors, respectively. $\Delta\bar{s}_{t+1}$ represents the monthly change of the average of 1-, 2-, 5-, and 10-year inflation swap rates. $\Delta Spread_{t+1}^{10y-1y}$ is the monthly change of the spread between 10-year and 1-year inflation swap rates. g_t^{Oil} is the log growth of monthly crude oil prices. The F-test for no predictability is shown. Newey-West standard errors with four lags are in parentheses. ** and * denote statistical significance at the 1% and 5% levels.

	(1)	(2)	(3)	(4)
	ΔPC_{t+1}^{Level}	ΔPC_{t+1}^{Slope}	$\Delta\bar{s}_{t+1}$	$\Delta Spread_{t+1}^{10y-1y}$
g_t^{Oil}	0.04*	-0.00	0.02*	-0.02**
	(0.02)	(0.00)	(0.01)	(0.01)
PC_t^{Level}	-0.14**	0.03	-0.05**	0.04*
	(0.04)	(0.02)	(0.01)	(0.02)
PC_t^{Slope}	0.10	-0.43**	-0.04	0.36
	(0.25)	(0.12)	(0.11)	(0.18)
Const.	1.70	-2.83**	0.15	1.83
	(1.50)	(0.76)	(0.64)	(1.14)
Obs.	124	124	124	124
Adj. $R^2(PCs\ only)$	2.7%	20.1%	2.8%	8.3%
Adj. $R^2(PCs + g^{Oil})$	11.4%	19.2%	11.8%	13.3%
F-ratio	4.95**	8.30**	5.11**	5.73**

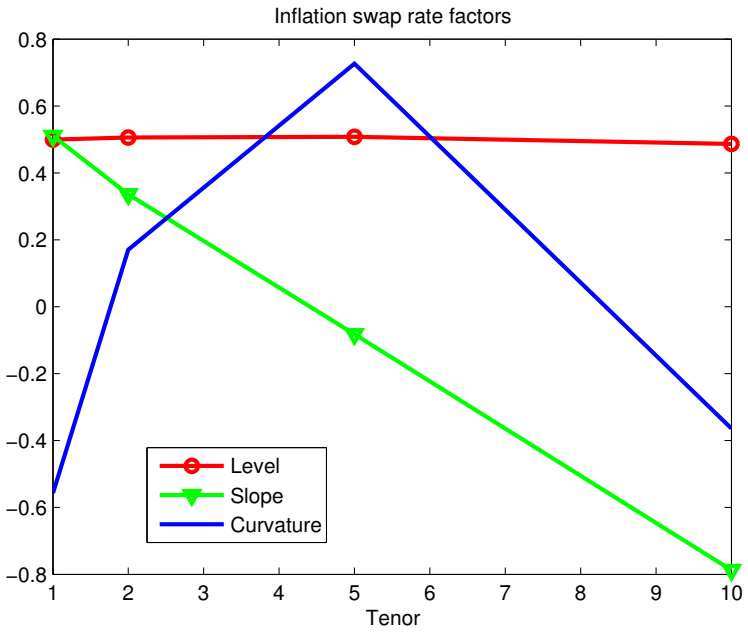

Figure C.1: Loadings of the first three principal components of the inflation swap rates.
This figure plots the loadings of the first three principal components of the inflation swap rates of 1-, 2-, 5-, and 10-year maturities.

Appendix D

Equilibrium conditions of the two-sector New Keynesian model

D.1 Households

The Lagrangian of the household's problem is

$$\mathscr{L}^{HH} = V_0 + \sum_{t=0}^{\infty} \mu_t \left\{ (1-\beta) U_t^{1-\rho} + \beta \left(E_t V_{t+1}^{\frac{1-\gamma}{1-\rho}} \right)^{\frac{1-\rho}{1-\gamma}} - V_t \right\} + \\ \sum_{t=0}^{\infty} \lambda_t \left\{ R_{t-1} B_{t-1} + W_t N_t + D_t^C + D_t^O - (1-\xi) C_t P_t^C - \xi O_t^H P_t^O - B_t \right\}. \tag{D.1}$$

First order conditions with respect to choice variables C_t, O_t^H, N_t, and B_t give rise to the following equations

$$\frac{\phi \kappa_t N_t^{\nu}}{X_t^{1/\eta-\rho} C_t^{-1/\eta}} = \frac{W_t}{P_t^C} \tag{D.2}$$

$$\left(\frac{O_t^H}{C_t} \right)^{-1/\eta} = \frac{P_t^O}{P_t^C} \tag{D.3}$$

$$1 = E_t \beta \left(\frac{X_{t+1}}{X_t} \right)^{\frac{1}{\eta}-\rho} \left(\frac{C_{t+1}}{C_t} \right)^{-\frac{1}{\eta}} \left(\frac{V_{t+1}^{1-\rho}}{\left(E_t V_{t+1}^{(1-\gamma)/(1-\rho)} \right)^{1/(1-\gamma)}} \right)^{\rho-\gamma} \frac{P_t^C}{P_{t+1}^C} R_t \tag{D.4}$$

Equation (D.2) represents the intratemporal relationship between consumption of core goods and labor

supply. Equation (D.3) describes the intratemporal substitution between oil and consumption of core goods. Equation (D.4) is the Euler equation for consumption of core goods.

The nominal stochastic discount factor (SDF) $M^{\$}_{t,t+1}$ is defined as

$$M^{\$}_{t,t+1} \equiv \beta \left(\frac{X_{t+1}}{X_t}\right)^{\frac{1}{\eta}-\rho} \left(\frac{C_{t+1}}{C_t}\right)^{-\frac{1}{\eta}} \left(\frac{V_{t+1}^{1-\rho}}{\left(E_t V_{t+1}^{(1-\gamma)/(1-\rho)}\right)^{1/(1-\gamma)}}\right)^{\rho-\gamma} \frac{P_t^C}{P_{t+1}^C}. \tag{D.5}$$

The real stochastic discount factor (SDF) $M^{R,C}_{t,t+1}$, in the unit of core goods, could be defined as

$$M^{R,C}_{t,t+1} = M^{\$}_{t,t+1} \frac{P_{t+1}^C}{P_t^C}. \tag{D.6}$$

Alternatively, the real SDF can also be expressed in the unit of the consumption bundle

$$M^{R,X}_{t,t+1} \equiv M^{\$}_{t,t+1} \frac{P_{t+1}^X}{P_t^X}. \tag{D.7}$$

D.2 The oil firm

The Lagrangian of the oil firm's problem is

$$\mathscr{L}^O = E_t \sum_{j=0}^{\infty} M^{\$}_{t,t+j} \left\{ Z^O_{t+j} K^O_{t+j-1} P^O_{t+j} - I^O_{t+j} P^C_{t+j} + q^o_{t+j}[(1-\delta^o)K^O_{t+j-1} + \Upsilon^O(I^O_{t+j}, K^O_{t+j-1}) - K^O_{t+j}] \right\} \tag{D.8}$$

where the Lagrangian multiplier q^o_t is the shadow value of the capital (i.e., the Tobin's q).

The first order condition with respect to I^O_t is

$$P^C_t = q^o_t \Phi^O_I(I^O_t, K^O_{t-1}) K^O_{t-1} \tag{D.9}$$

where Φ^O_I is the partial derivative of Φ^O with respect to I^O_t.

The first order condition with respect to K^O_t is

$$q^o_t = E_t M^{\$}_{t,t+1} \left\{ F^O_K(Z^O_{t+1}, K^O_t) P^O_{t+1} + q^o_{t+1}[(1-\delta^o) + \Phi^O_K(I^O_{t+1}, K^O_t) K^O_t + \Phi^O(I^O_{t+1}, K^O_t)] \right\} \tag{D.10}$$

where $F^O_K(Z^O_{t+1}, K_t) \equiv Z^O_{t+1}$ and Φ^O_K is the partial derivative of Φ^O with respect to K^O_t.

D.3 The final goods firm

The first order condition of the final firm's problem is given in equation (3.16).

D.4 Intermediate goods firms

The Lagrangian of the intermediate goods firm's problem is

$$\mathscr{L}^C = E_t \sum_{j=0}^{\infty} M^{\$}_{t,t+j} \{ [P^C_{t+j}(i) Y^C_{t+j}(i) - \Psi_{t+j}(Y^C_{t+j}(i)) - P^C_{t+j} \frac{\vartheta}{2} \left(\frac{P^C_{t+j}(i)}{\overline{\pi} P^C_{t+j-1}(i)} - 1 \right)^2 Y^C_{t+j} - P^C_{t+j} I^C_{t+j}(i)] \\ + q^c_{t+j} [(1-\delta^c) K^C_{t+j-1} + \Upsilon^C (I^C_{t+j}, K^C_{t+j-1}) - K^C_{t+j}] \} \tag{D.11}$$

where the Lagrangian multiplier q^c_t is the shadow value of the capital (i.e., the Tobin's q).

The first order condition with respect to I^C_t is

$$P^C_t = q^c_t \Phi^C_I (I^C_t(i), K^C_{t-1}(i)) K^C_{t-1}(i) \tag{D.12}$$

where Φ^C_I is the partial derivative of Φ^C with respect to I^C_t.

The first order condition with respect to K^C_t is

$$q^c_t = E_t M^{\$}_{t,t+1} \left\{ F^C_K (Z^C_{t+1}, K^C_t(i)) P^C_{t+1}(i) + q^c_{t+1} [(1-\delta^c) + \Phi^C_K (I^C_{t+1}(i), K^C_t(i)) K^C_t(i) + \Phi^C (I^C_{t+1}(i), K^C_t(i))] \right\} \tag{D.13}$$

where $F^C_K (Z^C_{t+1}, K^C_t(i))$ is the marginal productivity of capital and Φ^C_K is the partial derivative of Φ^C with respect to K^C_t.

The first order condition with respect to $P^C_t(i)$ is

$$P^C_t Y^C_t \left[(1-\varepsilon) \left(\frac{P^C_t(i)}{P^C_t} \right)^{-\varepsilon} \frac{1}{P^C_t} + \psi_t \varepsilon \left(\frac{P^C_t(i)}{P^C_t} \right)^{-\varepsilon-1} \frac{1}{(P^C_t)^2} - \vartheta \left(\frac{P^C_t(i)}{\overline{\pi} P^C_{t-1}(i)} - 1 \right) \frac{1}{\overline{\pi} P^C_{t-1}(i)} \right] \\ + M^{\$}_{t,t+1} P^C_{t+1} Y^C_{t+1} \vartheta \left(\frac{P^C_{t+1}(i)}{\overline{\pi} P^C_t(i)} - 1 \right) \frac{P^C_{t+1}(i)}{\overline{\pi} (P^C_t(i))^2} = 0 \tag{D.14}$$

where ψ_t is the marginal cost defined in equation (D.18).

In a symmetric equilibrium, equation (D.14) is rewritten as

$$\vartheta \left(\frac{\pi^C_t}{\overline{\pi}} - 1 \right) \frac{\pi^C_t}{\overline{\pi}} = (1-\varepsilon) + \varepsilon \hat{\psi}_t + \vartheta E_t \left\{ M^{R,C}_{t,t+1} \left(\frac{\pi^C_{t+1}}{\overline{\pi}} - 1 \right) \frac{\pi^C_{t+1}}{\overline{\pi}} \frac{Y^C_{t+1}}{Y^C_t} \right\} \tag{D.15}$$

where $\hat{\psi}_t \equiv \psi_t / P_t^C$ is the real marginal cost and $M_{t,t+1}$ is the real SDF defined in equation (D.6).

The first order condition of the cost minimization problem for a given level of output $Y_t^C(i)$ is

$$\frac{\alpha O_t^I(i)}{(1-\alpha-\omega)N_t(i)} = \frac{W_t}{P_t^O} \tag{D.16}$$

Minimized cost function for a given level of output $Y_t^C(i)$ is

$$\Psi(Y_t^C(i)) = (1-\omega)\alpha^{-\frac{\alpha}{1-\omega}}(1-\alpha-\omega)^{-\frac{1-\alpha-\omega}{1-\omega}}(Z_t^C)^{-\frac{\alpha}{1-\omega}}(K_{t-1}^C(i))^{-\frac{\omega}{1-\omega}}(W_t)^{\frac{\alpha}{1-\omega}}(P_t^O)^{\frac{1-\alpha-\omega}{1-\omega}}(Y_t^C(i))^{\frac{1}{1-\omega}}. \tag{D.17}$$

Marginal cost function for a given level of output $Y_t^C(i)$ is

$$\psi(Y_t^C(i)) \equiv \Psi'(Y_t^C(i)) = \alpha^{-\frac{\alpha}{1-\omega}}(1-\alpha-\omega)^{-\frac{1-\alpha-\omega}{1-\omega}}(Z_t^C)^{-\frac{\alpha}{1-\omega}}(K_{t-1}^C(i))^{-\frac{\omega}{1-\omega}}(W_t)^{\frac{\alpha}{1-\omega}}(P_t^O)^{\frac{1-\alpha-\omega}{1-\omega}}(Y_t^C(i))^{\frac{\omega}{1-\omega}}. \tag{D.18}$$

D.5 Market clearing conditions

In equilibrium, all markets are clear. The aggregate oil resource constraint is

$$O_t^H + O_t^I = Y_t^O. \tag{D.19}$$

In the symmetric equilibrium, the aggregate resource constraint of final consumption goods becomes

$$C_t + I_t^O + I_t^C = \left(1 - \frac{\vartheta}{2}\left(\frac{\pi_t^C}{\overline{\pi}} - 1\right)^2\right) Y_t^C. \tag{D.20}$$

where $\pi_t^C = P_t^C / P_{t-1}^C$.