Modeling ex-ante risk premia in the oil market

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Abstract – Using survey-based data we show that oil price expectations are not rational, implying that the ex-ante premium is a more relevant concept than the widely popular ex-post premium. We propose for the 3- and 12-month horizons a portfolio choice model with risky oil assets and a risk-free asset. At the maximized expected utility the risk premium is defined as the risk price times the expected oil return volatility. A state-space model, where the risk prices are represented as stochastic unobservable components and where expected volatilities depend on historical squared returns, is estimated using Kalman filtering. We find that the representative investor is risk seeking at short horizons and risk averse at longer horizons. We examine the economic factors driving risk prices whose signs are shown to be consistent with the predictions of the prospect theory. An upward sloped term structure of oil risk premia prevails in average over the period.

Keywords: oil market, oil price expectations, ex-ante risk premium

JEL classification : D81, G11, Q43

1 – Introduction

Prior to the 2000s, commodity and financial markets were partially segmented (Bessembinder, 1992), while since the early 2000's, financial institutions regard commodities as an asset class which is particularly relevant to be considered in their portfolio. In this view, crude oil risk premium defined as an excess return in holding oil barrels compared to a riskless asset appears as a central concern for investors willing to build efficient portfolios. Generally speaking, oil risk premium arises because hedgers offer to speculators - who are the counterpart of the derivative contracts - an income required to compensate the non-diversifiable risk they bear.[1] Because oil is both a production input and a financial asset, analyzing the dynamics of crude oil risk premia can help understanding factors driving the oil market, whether they are economic, geopolitical or speculative. The aim of this study is to model e*x-ante* risk premia that we measure using oil price expectations provided by survey data, in contrast to ex-post premia built on ex-post realizations of oil prices. Because they reflect beliefs driving investors' decisions, *ex-ante* premia are especially suitable to be modeled within a simple portfolio choice framework, as we propose in the present paper.

For a given horizon, crude oil risk premium is the relative difference between expected oil prices and oil futures prices. Futures prices being given by the market, the risk premium is measurable provided that an assumption is made on the expected price. It is then crucial to examine how to represent oil price expectations. The common approach implicitly relies on the efficient market hypothesis, which implies that expectations are rational. Accordingly, many econometricians focus on the *ex-post* risk premium in the oil market where the price expected at time t for the horizon $t+\tau$ is replaced by the *ex-post* spot price observed at $t+\tau$. Using a GARCH-M framework to represent the conditional variance[2], many studies found that WTI *ex-post* risk premia are highly time-varying and horizon-dependent (Moosa and Al-Loughani, 1994; Considine and Larson, 2001; Sadorsky, 2002; Gorton and Rouwenhorst, 2006; Cifarelli and Paladino, 2010; Pagano and Pisani, 2009; Melolinna, 2011; Hambur and Stenner, 2016). Another strand of the literature shows that *ex-post* crude oil risk premia are correlated with macroeconomic factors. In this line and proxying expected prices by futures prices, Coimbra and Esteves (2004) find evidence that crude oil forecast errors - i.e., *ex-post*

[1] Notably, Hamilton and Wu (2014) argue that because arbitrageurs take the counterpart of the futures contracts used by investors to hedge against oil price risk, they may expect to receive positive excess returns from their positions.

[2] Note that, beside the literature directly concerned with the analysis of the risk premium in oil markets, other studies have shown that oil return is characterized by a strong conditional volatility (see, among others, Narayan and Narayan, 2007; Ben Sita, 2018).

spot price minus actual futures price, which formally define the *ex-post* crude oil risk premium under rational expectation hypothesis (REH) - are correlated with forecast errors in world economic activity. Pagano and Pisani (2009) show that these futures price-based oil forecast errors can partly be explained by US business cycle indicators. Using a multivariate ICAPM, Cifarelli and Paladino (2010) show that *ex-post* oil risk premia depend on a speculative component represented by the expected variance and on fundamentals such as stock prices and foreign exchange rates. Bhar and Lee (2011) propose a three-factor affine model of crude oil *ex-post* risk premium allowing for a time varying risk price. Using the Kalman filter methodology, the authors show that the term structure of futures prices involve the same risk factors as equities and bonds. Alquist et al. (2013) also derive an affine term structure model to examine how macroeconomic risks drive short and long-term risk premia. Haase and Zimmermann (2013) show that *ex-post* risk premia are directly related to the physical scarcity of commodities with respect to demand. Performing an impulse response analysis from a structural VAR model, Valenti et al. (2018) find that the *ex-post* risk premium is related to changes in oil price triggered by shocks to economic fundamentals such as inflation, production and interest rate spreads. De Souza and Aiube (2020) reconsider Schwartz and Smith (2000) model of commodity price factors where long-maturity futures contracts provide information about the equilibrium price level, and show that introducing a stochastic time-varying oil market price of risk notably improves the model.

Overall, the literature outlined above has evidenced that whether investor's behaviour is based on fundamentals or speculation, it contributes in both cases to explaining *ex-post* risk premium dynamics. Beyond the oil risk premium analysis, a number of empirical studies aim at estimating the weighs associated with these two categories of factors in oil price dynamics. Basically, these weighs are shown to depend upon the period considered. For example, Masters (2008) attributes the rise in crude oil price between 2003 and 2008 mainly to financial speculation, while Hamilton (2009) provides a fundamentals-based explanation to the 2007–2008 oil price shock. The findings by Fattouh et al (2013) are more supportive of the role of economic fundamentals than the role of speculation in driving oil spot price after 2003. While Kaufmann and Ullman (2009) evidence both effects, Kaufmann (2011) reports the poor performance of the macroeconomic oil price models compared to the growing influence of speculation (see also Weiner, 2002 and Sanders et al., 2004). Coleman (2012) shows that oil prices are impacted by fundamentals such as bond yield, economic growth, oil market shocks and geopolitical measures, but also by speculative activities, terrorist attacks and industry events. Using a structural VAR, Liu et al. (2016) analyze the impacts of economic fundamentals and market speculation on real price of crude oil and conclude that speculation does not explain more than 10% of oil price changes.[3]

Despite their interest, the numerous results of the literature on *ex-post* risk premia in the oil market bind to the caveat that the *ex-post* spot price is a biased measure of the *ex-ante* expected price as expectations are not rational. Indeed, many empirical studies suggest that oil returns are not white noise and are partly forecastable[4], which contradicts the rational expectation hypothesis (REH). In this regard, a widespread literature using survey-based data on expected oil price strongly confirm the rejection of the REH. This implies that the *ex-post* risk premium is in fact made up of the "true" premium and a forecast error which is not white noise. Using Consensus Economics surveys on experts' WTI oil price expectations, some authors show that this rejection holds whatever the horizon[5] and that backward looking processes such as the traditional adaptive, extrapolative and mean-reverting mechanisms - and especially a combination of them – are useful in explaining expectations (MacDonald and Marsh, 1993; Reitz et al., 2010; Prat and Uctum, 2011).[6] Bianchi and Piana (2017) confirm this conclusion using Bloomberg surveys. In this study, we corroborate this result by relying on Consensus Economics monthly survey data spanning a particularly extended period of thirty years from 1989 to 2019. Finally, it is important to note that the studies mentioned above which deal with *ex-post* risk premium find that this premium is horizon-dependent. Yet, one can show that if the REH holds, ex-post premia should not depend on the horizon if the price of risk does not either (see, e.g., Prat and Uctum, 2013). Accordingly, studies that address ex-post premia either invalidate the REH or implicitly assume that the price of risk is related to the horizon, which is not consistent with the REH. Overall, these findings on oil

[3] Using event study methodologies, a number of authors show that oil-related news influence oil return and oil volatility dynamics, which suggests that ex-post risk premia are impacted by news occurring in both the current and next periods. These news mainly concern announcements of OPEC strategies and inventory information (Lin and Tamvakis, 2010; Demirer and Kutan, 2010; Schmidbauer and Rösch, 2012; Mensi et al., 2014; Ji and Guo, 2015; Bu, 2014). Although daily unanticipated events should weakly impact monthly data as those we use in the present paper, cumulated events or large event windows are likely to play a role in a monthly basis.

[4] Crude oil futures price is found to be a biased predictor of the future spot price (Moosa and Al-Loughani, 1994; Sadorsky, 2002; Alquist and Kilian, 2010) while macroeconomic variables appear to be partial predictors. Recent studies show that models including economic determinants of oil price such as changes in oil inventories, oil production and global real economic activity, may provide more accurate out-of-sample forecasts than oil futures prices (Alquist et al., 2013; Baumeister, 2014; Baumeister et al., 2014; Baumeister and Kilian, 2012, 2014, 2015). This finding holds even in a real-time forecasting environment, where oil price predictors become available only with a delay and are subsequently revised.

[5] Some studies show that it is possible to improve the quality of oil return forecasts by mixing different approaches, including surveys (Alquist et al., 2013; Baumeister et al., 2014; Sanders et al., 2009). But none of them can make REH-consistent predictions.

[6] Using the same surveys, Alquist and Arbatli (2010) show that the 3 month (12 month) ahead expected change in oil price is correlated with the log-ratio between the 3 month (12 month) to maturity oil futures price and the spot price, hence suggesting that futures price could also help explaining expectations.

price expectations suggest that *ex-ante* risk premium is a more relevant concept than *ex-post* risk premium in analysing investors' decision making.

So far, only a few recent studies have attempted to examine ex-ante oil risk premia and it comes out from these studies that two different ways of investigation have been explored: the first one exploits oil derivative price data while the second one uses survey data revealing experts' oil price expectations. The first approach consists in determining an implied risk premium in the oil market by assessing from option prices the market's forward-looking views on oil return volatility. This needs binding assumptions, such as complete market, risk neutral probability density functions and an *ad-hoc* diffusion process describing the dynamics of spot and of option prices as Brownian motions. In this line, Chiang et al. (2015) develop a four factors affine model that they estimate using data from futures and option prices, augmented with oil-related equity returns. Supposing a risk-neutral Ito diffusion process, the authors determine the implied variances of oil returns and show that implied risk premia are significantly related to macroeconomic variables such as production and the VIX index. Ellwanger (2017) determines the option-implied tail of risk premia, which depend on extreme values of implied volatility of returns. Their results suggest that fears of future extreme oil returns contribute to explain oil risk premia. Considering the distribution of risk premium, Li (2018) finds that the risk aversion coefficient is significantly state-dependent: it is lower when speculative activity (represented by the expected volatility of oil returns) is strong, and can take negative values leading to negative implied risk premium. The merit of the implied risk premium approach compared to *ex-post* risk premium is that, using the price of derivative assets, no more confusion between risk premium and forecast error is of concern. However, a drawback is that it requires binding assumptions on market completeness, distributions and the dynamics process of spot and derivative asset prices.

The second way of tackling *ex-ante* crude oil risk premia consists in using survey data of experts' oil price expectations. This approach also avoids limitations that are inherent to the *ex-post* risk premium as it allows disentangling oil price expectations, forecast errors and *ex-ante* risk premium; moreover it helps circumventing the binding assumptions needed by an implied risk premium analysis. In this line, Bianchi and Piana (2017) use monthly surveys provided by Bloomberg from 2006 to 2016 to measure *ex-ante* risk premia for 2-, 3- and 4-quarter horizons in commodity markets, among which crude oil market. The authors first estimate for every date an adaptive learning process of expected WTI spot price depending on past spot prices and on world industrial production. Based on this expectation process, the authors then calculate *ex-ante* risk premia over the extended period 1995-2016. Using dynamic linear regressions, they finally examine over time the relative importance of alternative risk premium factors and find that the net positions of hedgers, the number of outstanding contracts held by market participants and the persistence of past returns are relevant determinants. Using WTI oil price forecasts data from Bloomberg and the U.S. Energy Information Administration, Cortazar et al. (2019a) calculate weekly *ex-ante* oil risk premia for different horizons over the period 2010-2017 by assuming that implied volatilities are constant over time, and that, under a risk-adjusted probability measure, futures price equals the expected value of the spot price. The authors finally show that, in average, short-term *ex-ante* premia are higher than long-term premia with higher volatility. Cortazar et al. (2019b) propose a three-factor stochastic commodity-pricing model with an affine risk-premium specification and find that inventories, hedging pressure, term spreads, default spreads and the level of interest rates are significant factors of *ex-ante* risk premium.

The contribution of the present paper to the relevant literature is twofold. First, we measure *ex-ante* crude oil risk premia for 3 and 12-month horizons using expected oil price data provided by Consensus Economics surveys over a substantially long period of thirty years. To our knowledge, there is no previous study in the literature on *ex-ante* risk premia using such an extended length of survey period; indeed, the periods covered by the rare survey-based studies in the literature do not exceed ten years. This gives to our results a more general scope, not specific to a precise time period. Second, the advantage of our approach over the *ex-post* risk premium literature is that using our ex-ante measure, risk premium and forecast error can be disentangled. Compared to studies focusing on *implied* risk premia, our survey-based framework has the advantage that no binding assumptions are needed, especially about option pricing modeling. Moreover, contrary to the *ex-post* or implied approaches, the use of survey data makes it possible to examine the possible influence of heterogeneous beliefs in oil risk premium dynamics, this being to our best knowledge an issue that has never been examined so far. We model *ex-ante* risk premia using a simple portfolio choice model where the representative investor maximizes their future wealth made by a combination of oil asset and the risk-free asset. This program leads to the solution that the premium equals the product of expected variance and the price of risk, both assumed to be time-varying and horizon-dependent. From this result we can also determine the dynamics of the term structure of oil risk premia. Our approach is innovative in that none of the previous survey-based studies devoted to *ex-ante* oil risk premia examines the simultaneous influences of expected variance and price of risk on risk premia. In our framework, speculative and fundamentalist behaviours are captured by both of these two components, even though one cannot separately assess the impact of each type of behaviour.

2. The theoretical model

The *ex-ante* crude oil risk premium is defined as the log-difference between expected and futures oil prices, which identically can be written as the difference between the expected change in spot price and the so-called "basis" defined as the log-difference between futures and spot prices. Accordingly, let p_t be the logarithm of the spot oil price and ${}_{\tau}f_t$ the logarithm of the τ -term maturity futures oil price. E_t stands for the conditional expectation operator at time *t*. The *ex-ante* crude oil risk premium for a τ -month horizon investment is, in percent per month:

$$ {}_{\tau}\phi_t = \frac{100}{\tau}\left[(E_t(p_{t+\tau}) - p_t) - ({}_{\tau}f_t - p_t)\right] \qquad (1) $$

where the first term in the bracket is the expected rate of change in oil price at t for $t+\tau$ while the second term is the basis.

Because oil is a physical asset, the basis encompasses costs and advantages of oil inventories. In this respect, when the market is in "contango", the spread between the futures and spot prices must be large enough to compensate for the costs of carry (including storage cost) and thus to make oil holding profitable.[7] This situation occurs when the spot price is expected to rise, which translates into an upward sloping futures curve. Conversely, the market is in "normal backwardation" when available stock levels are low, futures prices are lower than the spot price because the current price is expected to fall. This implies a downward sloping futures curve. To complete the theory of normal backwardation, Kaldor (1939) adds the concept of "convenience yield", which represents the advantages associated with holding the physical commodity.[8] Indeed, holding physical oil allows for reducing costs related to delivery delays, enhances the ability of responding to unexpected demand and hence keeping regular customers satisfied. Under the no-arbitrage condition, the basis is equal to the total cost of carry (interest paid on the loan used to purchase oil at the spot price plus the marginal storage cost) minus a convenience yield, thus allowing the basis to be positive in case of contango and negative in backwardation (see, among others, Fama and French,1987; Melolinna, 2011; Gorton et al., 2013). :

[7] The total oil storage costs depend on the opportunity cost of not investing in another asset, on the cost of maintaining buildings and facilities (including rents), on the risk of inventories depreciation and on taxes.

[8] Number of authors find evidence for the existence of convenience yields (see, among others, Considine and Larson, 2001; Alquist and Kilian, 2010; Alquist et al., 2013)

$$\frac{100}{\tau}\left({}_{\tau}f_t - p_t\right) = {}_{\tau}r_t + {}_{\tau}sc_t - {}_{\tau}cy_t, \qquad {}_{\tau}sc_t > 0, \ \ {}_{\tau}cy_t > 0 \tag{2}$$

where ${}_{\tau}r_t$ is the τ-month maturity risk-free rate at time t, ${}_{\tau}sc_t$ is a τ-month duration marginal oil storage cost and ${}_{\tau}cy_t$ is the convenience yield associated with this storage, all variables being in % per month. We assume that expected oil return includes these costs and advantages related to oil holdings:

$$E_t(R_{t+\tau}) = \frac{100}{\tau}\left[E_t(p_{t+\tau}) - p_t\right] + {}_{\tau}cy_t - {}_{\tau}sc_t \tag{3}$$

Because the magnitudes ${}_{\tau}sc_t$ and ${}_{\tau}cy_t$ are not directly observable, the expected return can be given a more tractable specification by solving Eqs(2) and (3):

$$E_t(R_{t+\tau}) = \frac{100}{\tau}\left[E_t(p_{t+\tau}) - p_t\right] - \frac{100}{\tau}\left({}_{\tau}f_t - p_t\right) + {}_{\tau}r_t \tag{4}$$

Putting together (1) and (4) yields to an alternative expression of the *ex-ante* risk premium defined as the difference between the expected return and the risk-free rate:

$${}_{\tau}\phi_t = E_t(R_{t+\tau}) - {}_{\tau}r_t \tag{5}$$

Eq(5) says of course nothing about the question of how the risk premium is explained. To address this issue, we refer to the portfolio choice theory where we distinguish the behaviour of the representative investor when they adopt a risk averse attitude and when they are risk seeking. In the standard expected utility theory, risk attitudes are determined by the utility function: an agent is risk averse if their utility function is concave while a convex utility function implies risk seeking behaviour. The risk premium, defined as the difference between the expected value of the uncertain payment and the certainty equivalent, is positive in the former case (investors require a premium for betting) and negative in the latter case (investors accept to pay a premium for betting). Interestingly, based on multiple experimental lotteries, the (cumulative) prospect theory by Kahneman and Tversky (1979) and Tversky and Kahneman (1992) sheds light on the *conditions* under which an individual may adopt risk-averse or risk-seeking attitude. According to the theory, risk aversion and risk seeking are determined jointly by a value function of outcomes (gains and losses) and by some decision weights. The value function is concave in the region of gains and convex in the region of losses, relative to some reference point (e.g., the initial wealth), and due to the loss aversion bias it is steeper over losses than over gains of the same magnitude. Individuals weight the value function not by the objective probabilities associated with the outcomes, but by an inverse-S shaped weighting function of these probabilities. These decision weights state the certainty equivalents in a way that, for both gains and losses, low probabilities are overweighted and high probabilities are underweighted. The weighting and the value functions imply a fourfold pattern of risk attitudes for nonmixed prospects[9]: risk aversion for gains and risk seeking for losses of moderate and high probabilities, risk seeking for gains and risk aversion for losses of small probabilities.

The prospect theory is originally designed to describe decision making under risk in experimental settings and based on lottery-like gambles. As stated by Barberis (2013), there are very few attempts to apply it in economics,[10] mostly due to the unclearness of how its components can be conceptualized in different economic contexts - e.g., which reference point should be chosen, how gains and losses should be defined and what should be the associated objective probabilities. On the other hand, prospect theory does not state how the coefficients of risk aversion and risk preference can be assessed, as these coefficients are the key ingredients of the portfolio choice model which we will introduce later.

We consider a representative investor whose portfolio is composed of a risky asset made of a quantity of oil barrels and a risk-free asset. At time *t*, the investor's investment horizon is of duration τ and the value of the portfolio is given by their wealth ${}_{\tau}W_t$. The share of the risky asset in the portfolio is ${}_{\tau}\theta_t$ with $0 \leq {}_{\tau}\theta_t \leq 1$. We denote $U_A({}_{\tau}W_t)$ the utility function of the investor when the state of nature they perceive leads them to be risk averse and $U_S({}_{\tau}W_t)$ the utility of the investor when they are risk seeking. At any time *t*, $U_A({}_{\tau}W_t)$ and $U_S({}_{\tau}W_t)$ are both increasing functions of wealth ($U'_A > 0, U'_S > 0$). In the state of risk aversion, this function is concave ($U''_A < 0$) and the coefficient of risk aversion is given by ${}_{\tau}\lambda_{A,t} = -\frac{U''_A({}_{\tau}W_t)}{U'_A({}_{\tau}W_t)} > 0$.[11] Risk seeking attitude implies a convex utility function ($U''_S > 0$), and through a similar calculation as for the risk aversion coefficient, the Arrow-Pratt approximation of the expected utility under risk seeking leads to define the absolute risk

[9] Typically, a nonmixed prospect consists in a gain (loss) of probability p against zero gain (loss) of probability 1-p.
[10] See Barberis et al. (2001, 2016) for applications of prospect theory to financial markets and Barberis (2013) for a survey of such studies.
[11] Our assumption that the coefficient of risk aversion depends on the horizon is in line with Eisenbach and Schmalz (2016) who find experimental evidence that risk aversion is horizon-dependent and documents the various origins of horizon-dependent risk aversion preferences.

preference coefficient as ${}_{\tau}\lambda_{S,t} = -\frac{U_S''({}_{\tau}W_t)}{U_S'({}_{\tau}W_t)} < 0$. At any time t, the investor determines the optimal value of ${}_{\tau}\theta_t$ maximizing the expected utility of their wealth for $t+\tau$ conditionally on the set of information used. Assuming that ${}_{\tau}W_t$ is normally distributed, we can put the expected utility in the expectation-variance form so that the investor's program is written as:

$$\max_{{}_{\tau}\theta_t} E_t\{U({}_{\tau}W_{t+\tau})\} = \max_{{}_{\tau}\theta_t} \left\{E_t({}_{\tau}W_{t+\tau}) - \frac{{}_{\tau}\lambda_t}{2} V_t({}_{\tau}W_{t+\tau})\right\} \quad (6)$$

$$\text{s.t. } {}_{\tau}W_{t+\tau} = {}_{\tau}W_t[1 + {}_{\tau}\theta_t R_{t+\tau} + (1 - {}_{\tau}\theta_t)\,{}_{\tau}r_t]$$

where U and ${}_{\tau}\lambda_t$ correspond to U_A and ${}_{\tau}\lambda_{A,t}$ if at time *t* the investor is risk averse and to U_S and ${}_{\tau}\lambda_{S,t}$ if they are risk-seeking. E_t and V_t stand for the conditional expectations operator and conditional expected variance operator, respectively and $R_{t+\tau}$ is the oil return between t and $t+\tau$. The mean-variance expression at the RHS of the objective function (6) is the certainty equivalent, which is the smallest guaranteed amount the risk averse investor would be willing to receive now rather than a higher but uncertain wealth in the future, or the highest guaranteed amount the risk loving investor would be willing to give up now in favor of a higher but uncertain wealth in the future. The risk premium $\frac{{}_{\tau}\lambda_t}{2} V_t({}_{\tau}W_{t+\tau})$, representing the difference between the expected value of the uncertain payment and the certainty equivalent, is positive in case of risk aversion and negative in case of risk seeking. The solution of the program (6) can straightforwardly be written as:

$${}_{\tau}W_t\left[E_t(R_{t+\tau}) - {}_{\tau}r_t - {}_{\tau}\kappa_t\,{}_{\tau}\theta_t^* V_t(R_{t+\tau})\right] = 0 \quad (7)$$

where ${}_{\tau}\kappa_t = {}_{\tau}\lambda_t\,{}_{\tau}W_t$ is the coefficient of relative risk aversion or preference and $V_t(R_{t+\tau})$ is the expected variance of oil return at *t* for $t+\tau$.[12] Using Eq.(5), the solution of the program of the investor can be written in the form:

$${}_{\tau}\phi_t^* = {}_{\tau}\gamma_t V_t(R_{t+\tau}) \quad (8)$$

where

$${}_{\tau}\gamma_t = {}_{\tau}\kappa_t\,{}_{\tau}\theta_t^* \quad (9)$$

[12] Note that V_t being an *expected* variance operator, we have $V_t(r_t) = 0$. It is easy to check that since the second order condition is negative, the first order condition corresponds to a maximum.

is the price of risk at the equilibrium and ${}_\tau\phi_t^*$ the corresponding equilibrium or required value of the ex-ante risk premium. Assuming that the premium offered by the market adjusts instantly to its required value (${}_\tau\phi_t = {}_\tau\phi_t^*$), the structural Eq(7) allows specifying the *ex-ante* risk premium as: [13]

$$ {}_\tau\phi_t = {}_\tau\gamma_t V_t(R_{t+\tau}) \tag{10} $$

To make Eq(10) operational, additional hypotheses must be adopted about the determination of the expected variance of oil returns $V_t(R_{t+\tau})$ and the representation of the time-varying price of risk ${}_\tau\gamma_t$ variables which are, in fact, unobservable. We will present in section 4 the empirical approach we adopted to assess these magnitudes.

3 – Data

Concerning oil price expectations, « Consensus Economics » (CE) asks at the beginning of each month about 180 economy and capital market specialists in about 30 countries to predict values for different horizons of a large number of variables, among which oil prices. Respondents are commercial or investment banks, industrial firms and forecast companies, whose forecasts influence many market participants' decisions. These experts are identified with a confidential code which only mentions their country. They are asked to answer only when the oil market concerns them enough. Therefore, the consensus (arithmetic average of the individually expected values of oil price) is not biased a priori by noise traders since only informed agents do respond. [14] Besides, since the individual answers are confidential (i.e. only the consensus is disclosed to the public with a time lag) and because each individual is negligible within the consensus, it does not seem to be justified to object that, for reasons which are inherent to speculative games, individuals might not reveal their « true » opinion. At each monthly survey, CE requires a very specific day for the answers. This day is as a rule the same for all respondents, located between the 1st and the 7th of the month from the beginning of the survey until March 1994 and between the 4th and the 16th of

[13] Eq (10) is formally still valid under the hypothesis of no monetary illusion. In this case, the left hand side remains unchanged since the expected rate of inflation must be subtracted from both the expected oil return and the risk-free rate. In the right hand side, however, the expected variance of real oil returns is of concern.
[14] In fact, about two thirds of the 180 experts answer the questions concerning future values of oil price, and this confirms that responding experts are those who are informed about the oil market.

the month since April 1994.[15] The consensus of predictions for 3-month and 12- month horizons is published in the monthly CE newsletter, along with the oil price observed at the date when forecasts are required. These consensus and observed price time series are used in this paper over the period November 1989 to September 2019.

More precisely, experts are requested by CE to forecast the US$ spot price per barrel of the West Texas Intermediate (WTI) from the beginning of the survey (October 1989) until December 2012. Since January 2013, the price which is asked to be forecasted is that of the Brent. This switch in the survey oil benchmark can be understood within the following context. Historically, the prices for WTI and Brent have moved together very closely until the US shale oil boom triggered a raise in crude oil inventories in Cushing (Oklahoma). As a result, since the end of 2010, the WTI spot price shrank at levels which were considered as being excessively low, boosting Brent to become the international oil reference. Although the spread between WTI and Brent prices substantially narrowed at the end of 2014 after the increase in Seawave Pipeline oil transporting capacities from Cushing to US Gulf Coast, Brent remained the most widely used benchmark because it is easy to refine into high-demand products such as petrol and, since it is extracted in the North Sea, it is easy to transport to distant locations.

The shift from WTI to Brent as oil benchmark operated by CE occurred at a date when the gap between the two oil prices was still persistent. It follows that a similar gap exists between the two expected oil prices provided by the CE respondents. However, by concatenating the rate of change series from the two benchmarks, we can build whole-period series of observed changes in crude oil price irrespective of whether the benchmark is WTI or Brent. Continuity at the January 2013 break date is achieved provided that the log-difference between December 2012 and November 2012 values of the WTI price is followed by the log-difference between January 2013 and December 2012 values of the Brent price. As for the expected change in oil price, because WTI and then Brent price expectations are formed at the same dates as WTI and Brent observed prices, taking their log-differences raises no problem of continuity at the January 2013 break date.

CE data also provide at time t the standard deviation of expected prices across respondents; the coefficient of variation (i.e. the ratio of the standard deviation to the consensus) at each point in time lies between 2.3% and 19.75% for the 3-month horizon and between 4.3% and 23.25% for the 12-month horizon. This implies that some heterogeneity is

[15] The effective horizons, however, always remain equal to 3 and 12 months. If, for instance, the answers are due on the 3rd of May (which was the case in May 1993), the future values are asked for August 3, 1993 (3 month-ahead expectations) and for January 3, 1994 (12 month-ahead expectations).

present in individual expectations without, however, compromising the statistical sense of the consensus.

We now turn to the crude oil futures prices and risk-free interest rates data. Consistently with the 3- and 12-month time horizons of price expectations, we consider the prices of 3- and 12-month to maturities futures contracts quoted in NYMEX, both extracted from Macrobond database at the same days as the survey expectations. To represent the risk-free interest rates, we use the US Treasury Bills market rates. Our choice is motivated by the following key features. T-Bills are short-term zero-coupon debt instruments issued by the U.S. Department of the Treasury with a maturity of one year or less. They are regarded as having no default risk as they are backed by the U.S. government. Their interest income is exempt from state and local taxes but subject to federal taxes. They are easily marketable in the secondary bond market and highly liquid, enabling investors to easily manage their liquidity constraints. The 3- and 12-month US T-Bills rates have been retrieved from Consensus Economics so as to maintain, here again, the same reference dates.

With these survey-based expected oil price and crude oil futures data in hand, we can construct the series of *ex-ante* crude oil risk premia for our two horizons according to Eq.(1). Figures 1 and 2 present these magnitudes for the 3- and 12-month horizons, respectively. It can be seen that ex-ante oil risk premia exhibit significant disparities regarding the horizons, with much higher amplitudes for the 3-month horizon than for the 12-month horizon. On the other hand, note that both the expected change in oil price and the basis play a significant role in the measurement of oil risk premium.

Figure 1. 3-month ex-ante risk premium, oil basis and expected change in oil price

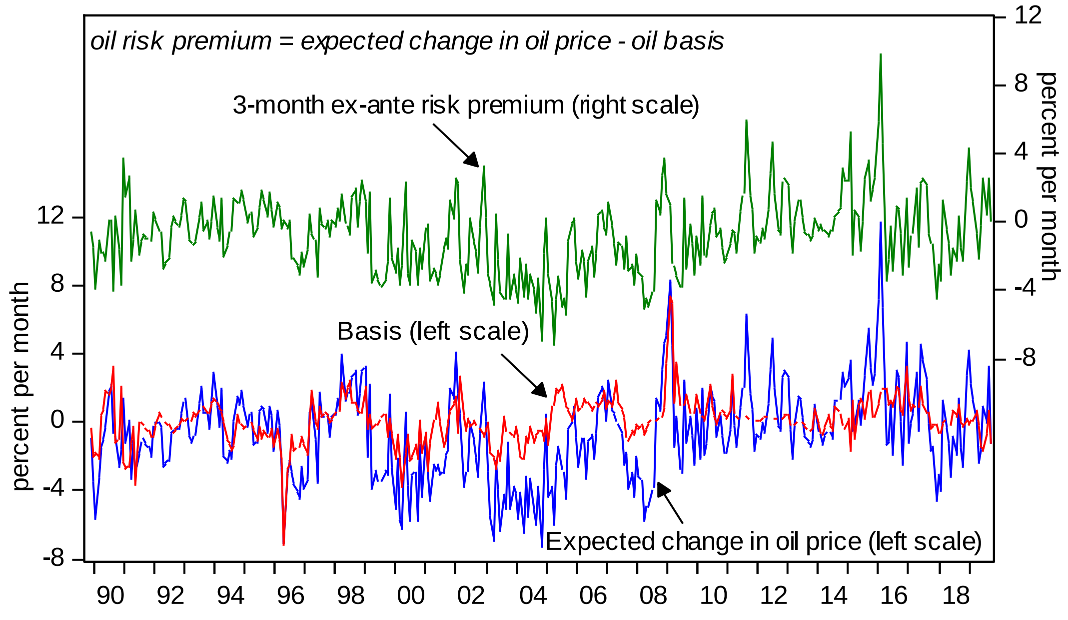
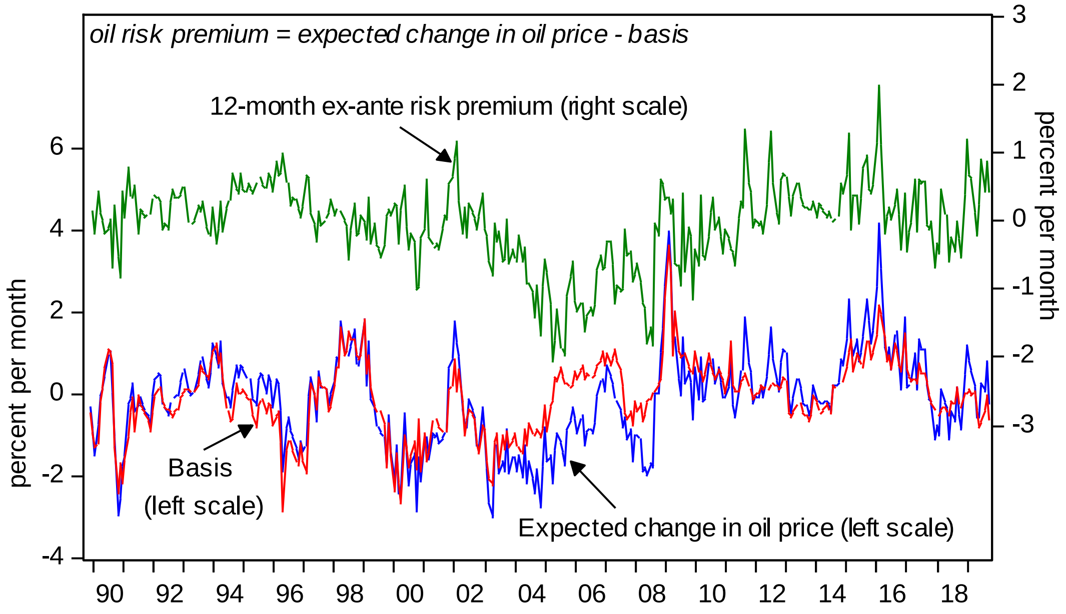


Figure 2. 12-month ex-ante oil risk premium, oil basis and expected change in oil price



It is also instructive to compare ex-ante and ex-post risk premia.[16] Figures 3 and 4 display these two premia for each horizon and exhibit two striking features. First, there is no significant correlation between the two types of risk premia: the correlation coefficients are -0.06 for the 3-month horizon and = -0.01 for the 12-month horizon. Second, the ex-post premia exhibit much broader variability compared to the ex-ante premia: the standard deviations of the former are about 3 times higher than those of the latter for the 3-month horizon, and about 4 times for the 12-month horizon. These very different time patterns between ex-ante and ex-post premia result from large forecast errors in oil price expectations. This provides support to our emphasis towards the ex-ante approach in modeling risk premia.

[16] The τ-month horizon ex-post risk premium at time t is calculated as the log-difference between the τ-month horizon ex-post crude oil price and the τ-month maturity oil futures price.

Figure 3. Ex-ante and ex-post 3-month horizon crude oil risk premia

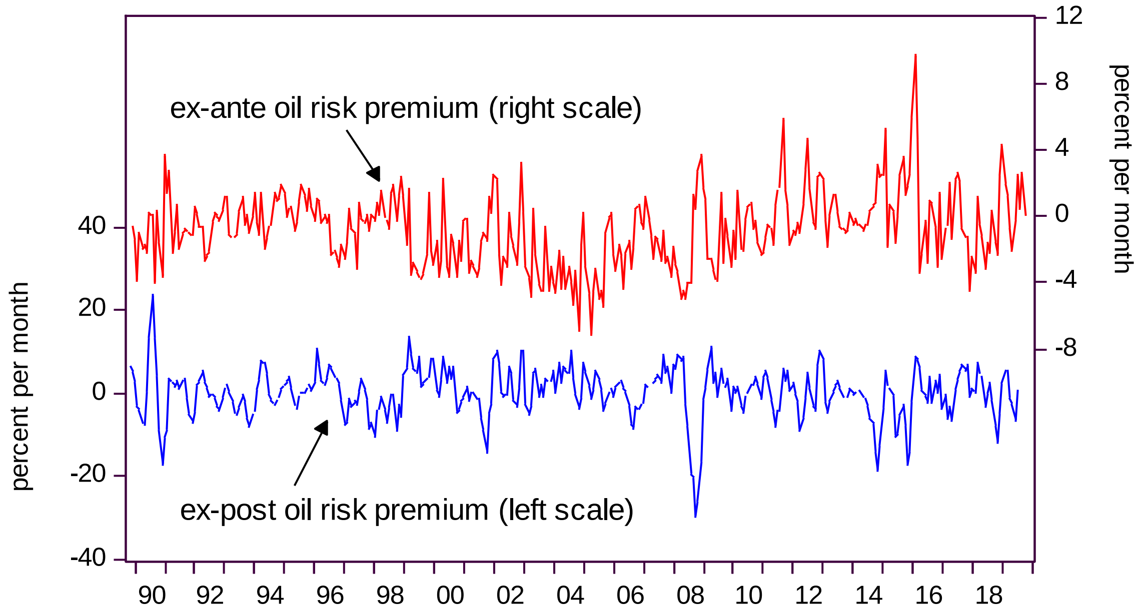
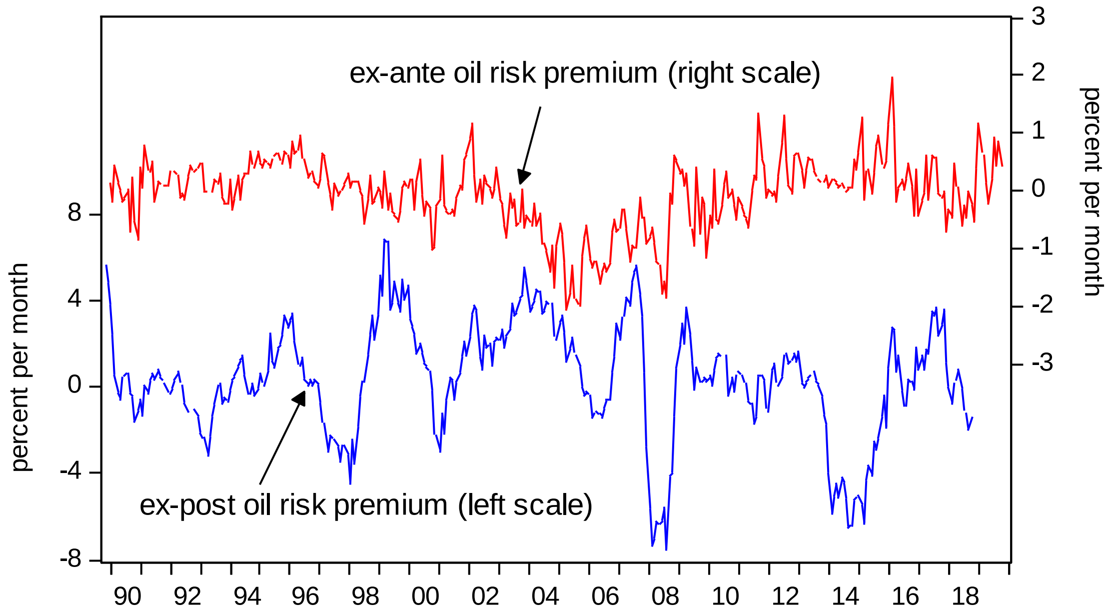


Figure 4. Ex-ante and ex-post 12-month horizon crude oil risk premia



4. Empirical analysis

If the efficient market hypothesis holds (i.e., the price is expected rationally), returns are white noise plus drift. In this case, if the price of risk is independent of the state of the nature, then the expected return, its variance and thus the risk premium are constant and the same for all horizons of investment. However, as stated in the introduction, if oil price is not expected rationally, returns are somewhat predictable and expected returns and risk premia are time-varying and horizon-dependent.

4.1 Are oil price expectations rational?

To check if the ex-ante risk premium is the relevant concept in decision making under risk, we must examine whether or not price expectations are rational. Testing for the REH requires that unbiasedness and orthogonality tests be performed, given that the latter test is no more needed if the former test is rejected. Our unbiasedness test equation is

$$p_{t+\tau} - p_t = \alpha + \beta[E_t(p_{t+\tau}) - p_t] + \nu_{t+\tau} \qquad (11)$$

and states that the τ-month change in the market oil price is fully driven by investors' τ-month expectation in the rate of change in oil price, provided that the null $\alpha = 0$, $\beta = 1$ is jointly satisfied and $\nu_{t+\tau}$ is white noise. To ensure that our estimates are robust to heteroskedasticity and autocorrelation, we estimated Eq.(11) using the Newey-West methodology. Results are reported in Table 1, columns 2 and 4. For both horizons, although α is not significantly different from zero, β is significantly different from 1, leading to strongly reject the null. Moreover, the DW statistics show that residuals are not white noise. However, Eq.(11) includes at the right-hand-side an expectation variable containing a measurement error. Such an error is known to cause inconsistent estimates and especially an attenuation bias in β (note that the reverse causality in the unbiasedness test equation would avoid such a measurement error bias but would lead to an endogenous regressor problem). To test for unbiasedness by accounting for possible measurement error, we used the TSLS methodology based on appropriately chosen instrumental variables (IV).[17] Columns 3 and 5 show that there is no significant change in TSLS estimates compared to OLS estimates, implying that the rejection of the unbiasedness test hypothesis $\beta = 1$ is not attributable to an attenuation bias due to measurement errors in the regressor. Moreover, regarding the ΔJ statistics which tests the null that the measurement error bias is zero, it can be seen that the null is not rejected at all levels for both horizons. Finally, DW statistics strongly suggest that residuals of the unbiasedness test equations are not white noise, thus rejecting on their own the REH. One can conclude from these results that experts' oil price expectations are not rational, so that the expected variance and the risk premium in the crude oil market are time and horizon-dependent and that the ex-ante approach to modeling crude oil risk premium is appropriate.

[17] The instrumental variables must be correlated with the regressor of Eq.(11) and uncorrelated with its residuals. For each τ, these instruments are the current and lagged values of expected changes in oil price at the two horizons and actual and lagged GDP expectations for the current year, with appropriate lag orders.

Table 1. Unbiasedness with no measurement error bias test results

	τ =3		τ=12	
	OLS	TSLS	OLS	TSLS
Intercept	0.39 (0.55)	0.40 (0.56)	0.39 (0.31)	0.39 (0.31)
$E_t(p_{t+\tau}) - p_t$	0.14 (0.16)	0.19 (0.16)	0.54** (0.27)	0.67** (0.33)
R^2	0.004	0.004	0.05	0.05
DW	0.58	0.56	0.14	0.13
ΔJ-statistic p-value	-	0.13	-	0.11

Notes. Numbers between square brackets are the t-statistic p-values. Values in columns 2 and 4 are the standard unbiasedness test results. Values in columns 3 and 5 are the TSLS estimation results which are appropriate to testing for the presence of a measurement bias due to $E_t(p_{t+\tau}) - p_t$. The ΔJ statistic is the difference between the TSLS objective function including the IVs plus the regressor under test and the objective function with the IVs only. Under the null of no measurement error bias ΔJ is distributed as a χ^2 with 1 d.o.f. (number of regressors tested). All estimates are performed using the Newey-West heteroskedasticity and autocorrelation-consistent covariance matrix. ** stands for significance at the 5% level.

4.2 Estimating the state-space model

We must first determine how the expected variance and the price of risk at the RHS of Eq(10) are determined. It is widely documented in the literature that the expected variance captures fundamentalist and speculative behaviours (see Introduction). Expected variance is indeed correlated with indicators of speculative activity such as black market trade, market share of non-commercial traders, trading volume, open interest (see, among others, Du et al., 2011; Nicolini et al., 2013). Another acknowledged factor of volatility is heterogeneity of beliefs and preferences (Li and Muzere, 2010; Weinbaum, 2009). These issues suggest that the greater the speculation in the market, the higher the volatility.[18]

We now focus on the question of how to measure the conditional expected variance of oil return in Eq.(10), which is an unobservable variable. Two approaches can be envisaged to undertake the determination of the expected variance of oil return,. One can first pre-estimate $V_t(R_{t+\tau})$ assuming it follows a GARCH process. This approach implies, however, that the estimation of $V_t(R_{t+\tau})$ and of our structural model of the ex-ante risk premium are carried out separately. One can alternatively represent the expected variance as a weighted average of the actual and lagged instantaneous variances defined by the squared returns and estimate the lag

[18] Of course, the data cannot distinguish between the possibility that hedgers make market prices while speculators take the counterpart of hedgers' orders, and the opposite possibility that speculators drive price movements (Wiener, 2002).

weights and the lag order in the course of the estimation of the structural model.[19] As a result, none of the GARCH models implemented (with or without asymmetry, with or without the conditional variance in the mean equation) was found to verify the ex-ante risk premium equation (10). We therefore have chosen the weighted average approach to assess expected conditional variance, such that:

$$V_t(R_{t+\tau}) = \frac{\sum_{j=0}^{m_\tau} {}_{\tau}\omega_j \, \sigma_{t-j}^2}{\sum_{j=0}^{m_\tau} {}_{\tau}\omega_j}, \qquad {}_{\tau}\omega_0 = 1 \tag{12}$$

where ${}_{\tau}\omega_j / \sum_{j=0}^{m_\tau} {}_{\tau}\omega_j$ is the weight of the j'th lag and $\sigma_t^2 = R_t^2$ is the observed volatility at time t. We define the instantaneous return R_t as the last one-month risk-free interest rate plus the basis-adjusted change in oil price:

$$R_t = 100(p_t - p_{t-1}) - 100\left({}_{1}f_{t-1} - p_{t-1}\right) + {}_{1}r_{t-1} \tag{13}$$

so that after appropriate rearrangement the τ-month horizon expected return (4) can be derived. [20]

The price of risk, in turn, represents the sensitivity of the risk premium to the expected variance, the latter reflecting the "quantity of risk" felt by the investor. As indicated in Eq.(9), this sensitivity is defined as the product of the coefficient of relative risk aversion (or preference) by the share of the risky asset in the portfolio. These two components being time-varying, the price of risk is also time varying. In particular, recall from Eqs(9) and (10) that our price of risk (and thus our risk premium) can take positive or negative values depending on whether investors are predominantly risk-averse (${}_{\tau}\kappa_t > 0$), or risk-seeking (${}_{\tau}\kappa_t < 0$). Support is provided to these views by, for example, Bhar and Lee (2011) who estimate a time-varying price of risk in a three-factor *ex-post* crude oil risk premium model and Li (2008) who finds, in an *implied* risk premium framework, that the risk aversion and therefore the price of risk are state-dependent and can take alternate signs.

Unfortunately, it seems not possible to know at time *t* how the representative investor behaves against risk and what makes them change their risk attitude from one period to

[19] An alternative average-based assessment of the conditional variance is considered by Considine and Larson (2001) who measure their historic price volatility by averaging over each month daily standard deviations of prices over the last 20 trading days.

[20] From Eq.(13), take the 1-month ahead expectation $E_t R_{t+1} = 100(E_t p_{t+1} - p_t) - 100\left({}_{1}f_t - p_t\right) + {}_{1}r_t$ and form the τ-month expected return by extending up to τ the horizon subscripts of the expected return and price and the maturity subscript of the futures, thus obtaining Eq(4).

another. Even assuming that this risk-averse or risk-seeking attitude could be known, the extent of its effect on the price of risk would remain undetermined. This is why we cannot determine *a priori* the *sign* and the *magnitude* of the coefficient of risk aversion (or preference) ${}_{\tau}\kappa_t$, and thus the value of the price of risk. To tackle this indetermination, we represent the price of risk as an unobservable stochastic state variable within a state-space (2-horizon) multivariate model that we estimate using Kalman filtering. The general form of our two state equations is an autoregressive process with drift. This representation lets the sign and the amplitude of the state variables be determined freely at each point in time so that our price of risk fits at best the ex-ante risk premium for each horizon. Note that such a risk price dynamics is general enough to collapse to a simple random walk or to a constant as particular cases.

From its constituent components (the share of the risky asset in the portfolio and the relative coefficient of risk aversion/preference), it seems intuitive that the price of risk in our *ex-ante* risk premium model might depend on the economic environment perceived by investors and on psychological factors. To our knowledge, no identification of the relevant economic determinants of the price of risk has ever been proposed in the literature on *ex-ante* oil risk premium. However, we can conjecture that those evidenced for explaining *ex-post* risk premia might be good candidates. These are oil market-type factors, such as refinery shutdowns, political history of oil exporting countries or oil inventory changes and macroeconomic-type variables, including production, inflation, interest rates, exchange rates, stock prices (see introduction). As for identifying the psychological effects whose importance appears more acutely in an *ex-ante* risk premium approach through the risk aversion coefficient, some studies on risk premium determination in stock markets provide useful insights.[21]

The risk price autoregressive process mentioned above can be thought of as including additional exogenous variables, namely macroeconomic and oil market-specific factors. As a result from preliminary attempts, very few variables were found to be significant and moreover they were barely significant. However we did not include them because they did not significantly lower the information criteria of our risk premium model. Such a result may be due to the fact that, adding such variables to the AR process implies the restriction that the impacts of these macroeconomic variables are all subject to the same geometric decay as we

[21] Hoffmann and Post (2017) use brokerage records and investor surveys to show that investors' past personal portfolio returns have a positive impact on their return expectations and risk tolerance (i.e., a negative impact on their risk aversion). Berrada et al. (2018) provides empirical evidence that stockholders' risk aversion depends on their social and cultural beliefs. Pastor and Veronesi (2013) show that political uncertainty leads to a risk premium whose magnitude is larger when economic conditions are weaker.

move into the past. To avoid these drawbacks, we choose to examine the links between price of risk and economic conditions in a subsequent stage, once the price of risk is measured over the whole period through the stochastic state assessment. Our 2-horizon multivariate state-space model is built upon two measurement equations describing the *ex-ante* oil risk premium relationships given by Eq(8) along with Eqs (1), (10) and (11) and two state equations specifying the dynamics of the price of risk:

$$E_t(R_{t+3}) - {}_3r_t = {}_3\gamma_t V_t(R_{t+3}) + {}_3\varepsilon_t \tag{14a}$$

$$E_t(R_{t+12}) - {}_{12}r_t = {}_{12}\gamma_t V_t(R_{t+12}) + {}_{12}\varepsilon_t \tag{14b}$$

$${}_3\gamma_t = {}_3\delta_0 + \sum_{i=1} {}_3\delta_i \, {}_3\gamma_{t-i} + {}_3\eta_t \tag{15a}$$

$${}_{12}\gamma_t = {}_{12}\delta_0 + \sum_{i=1} {}_{12}\delta_i \, {}_{12}\gamma_{t-i} + {}_{12}\eta_t \tag{15b}$$

where ${}_3\varepsilon_t, {}_{12}\varepsilon_t, {}_3\eta_t$ and ${}_{12}\eta_t$ are *Niid* innovations with mean zero and constant variances ${}_3\sigma_\varepsilon^2, {}_{12}\sigma_\varepsilon^2, {}_3\sigma_\eta^2$ and ${}_{12}\sigma_\eta^2$, respectively, with possible correlation within signal errors and within state errors ($cov({}_3\varepsilon_t, {}_{12}\varepsilon_t) = \rho, cov({}_3\eta_t, {}_{12}\eta_t) = \varphi$) but with no cross-correlation at any lag and horizon between signal and state errors ($cov({}_\tau\varepsilon_t\,, {}_{\tau'}\eta_{t'}) = 0 \; \forall\tau, \tau' \; \forall t, t'$).

Starting from initial values for the price of risk and for the vector of parameters $\beta = \{ {}_\tau\sigma_\varepsilon^2, {}_\tau\sigma_\eta^2, \rho, \varphi, {}_\tau\omega_j, {}_\tau\delta_0, {}_\tau\delta_i; \tau = 3{,}12; i, j = 1{,}2, \dots \}$, the Kalman filter calculates predicted and updated (filtered) values of the states and their covariances at any time $t = 1, \dots T$ based on actual and past observations. Given these predicted values, the log-likelihood (L) of the system is maximized to find new optimal values for β. Using the latter vector new sets of predicted states and of their covariances are generated, and so on. It is shown that the likelihood L is increased as β is updated across iterations (Dempster et al, 1977). Since this paper is concerned with a structural model, these filtered state estimates are given a smoothed interpretation by forming inferences about the states based on the whole set of data.

Table 2 summarizes the estimation results. Both state equations were found to take an AR(1) form without drift, that is, only ${}_3\delta_1$ and ${}_{12}\delta_1$ were significant. Robust and significant lag orders in the conditional expected variance (12) were found to be m_3 =4 and $m_{12} = 9$ for the 3- and 12-month month horizons, respectively. For the latter horizon, the lag parameters decline in average by intervals of four lags within which they do not change significantly at the 5% level; for the short horizon, the investor builds up their judgement on the basis of statistically equally weighted actual and past volatilities. The high values of R^2 and R_D^2 measures indicate that our *ex-ante* risk premia model fit well the data for both horizons and outperform by far a simple random walk with drift. To check for the statistical properties of the signal residuals, we perform appropriate diagnostic tests upon the smoothed signal disturbances standardized by their time-varying standard errors. Harvey's (1989) Ljung-Box Q* test fails to reject the null of no serial autocorrelation in the signal residuals at the 5% level of significance for $\tau = 3$ and at the 1% level for $\tau = 12$, corroborating that our model is well specified. From the McLeod and Li (1983) test results, we conclude that no ARCH effects are present in the residuals for both horizons at the 5% level. Non-rejection of the null of homoskedasticity is consistent with the time-invariant (or time-homogenous) feature of our state-space model, which assumes that the slope parameters and the parameters of the residual covariance matrices are constant. According to the Bowman-Shenton normality statistic, the signal residuals have a normal distribution over the whole sample at the 5% level irrespective of the horizon, indicating that no significant number of outliers is present. Overall, these good residual properties suggest that it would not be relevant to add explanatory factors to Eqs (15a) and (15b).

Table 2: Kalman filter estimation results

	τ =3		τ=12
Signal equations			
${}_{\tau}\omega_1$	0.65*** (0.15)		0.80*** (0.11)
${}_{\tau}\omega_2$	0.99*** (0.23)		0.98*** (0.13)
${}_{\tau}\omega_3$	0.85*** (0.21)		0.97*** (0.17)
${}_{\tau}\omega_4$	0.67*** (0.20)		0.97*** (0.17)
${}_{\tau}\omega_5$			0.61*** (0.14)
${}_{\tau}\omega_6$			0.73*** (0.14)
${}_{\tau}\omega_7$			0.67*** (0.14)
${}_{\tau}\omega_8$			0.61*** (0.12)
${}_{\tau}\omega_9$			0.39*** (0.10)
${}_{\tau}k_{\varepsilon}$	0.31** (0.14)		-3.09*** (0.14)
State equations			
${}_{\tau}\delta_1$	0.87*** (0.02)		0.95*** (0.01)
${}_{\tau}k_{\eta}$	0.47** (0.19)		-2.11*** (0.13)
Residual covariance within			
signal eqns. ρ		0.21*** (0.03)	
state eqns. φ		0.37*** (0.06)	
R^2	0.83		0.93
R_D^2	0.80		0.86
$Q^*(6)$	9.02		13.16
$MLL(2)$	4.16		1.37
BS	8.63		7.36
AIC		4.01	
SC		4.24	
HQ		4.10	
L		-678.94	

Notes: The data covers the period September 1990 – September 2019 (349 obs.). The Table presents final estimations of Eqs. (14a) to (15b) after eliminating the state intercepts which were found to be insignificant. Numbers in brackets are the standard errors of estimation. To ensure positivity, the standard deviations of ${}_{\tau}\varepsilon_t$ and ${}_{\tau}\eta_t$ ($\tau = 3,12$) are estimated as the exponential functions of the scalars ${}_{\tau}k_{\varepsilon}$ and ${}_{\tau}k_{\eta}$, respectively. R_D^2 is a goodness of fit measure (Harvey, 1989) which states that the model does better (worse) than a random walk with drift if the statistic is positive (negative). *AIC*, *SC* and *HQ* stand for the Akaike, Schwarz and Hannan-Quinn information criteria, respectively, while *L* is the log-likelihood value. *Q** is a Ljung-Box form statistic to test for residual autocorrelation in the signal (Harvey, 1989). *MLL* is the McLeod-Li test statistic to test for the presence of an ARCH effect in the signal residuals, which takes the form of a Ljung-Box statistic applied to squared residuals with no d.o.f adjustment needed (McLeod and Li, 1983). *BS* is the Bowman-Shenton normality test statistic. The *Q** -statistic with *p*=ln(349)≈ 6 lags follows a χ^2 with *p*-*h*+1= 5 d.o.f., where *h*=2 is the number of hyperparameters. The *MLL* statistic with 2 lags and the *BS* statistic both follow a χ^2 with 2 d.o.f. Asymptotic critical values for χ^2 with (2; 5) d.o.f. are (5.99; 11.1) at the 5% level and (9.21; 15.1) at the 1% level. ** and *** stand for the significance at the 5% and 1% levels, respectively.

Figure 5. Crude oil price of risk for the 3-month horizon investment

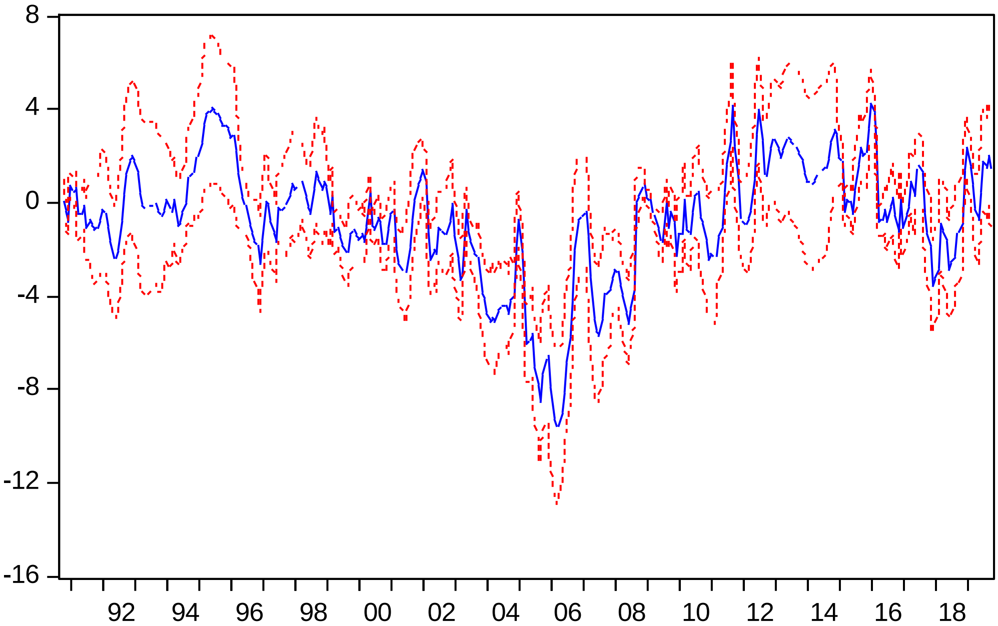
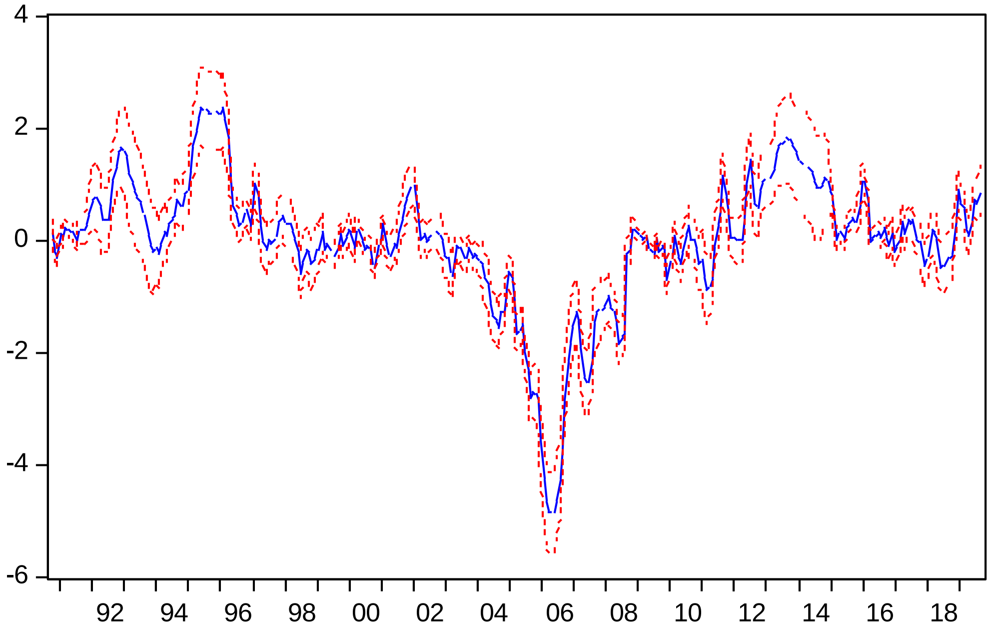


Figure 6. Crude oil price of risk for the 12-month horizon investment



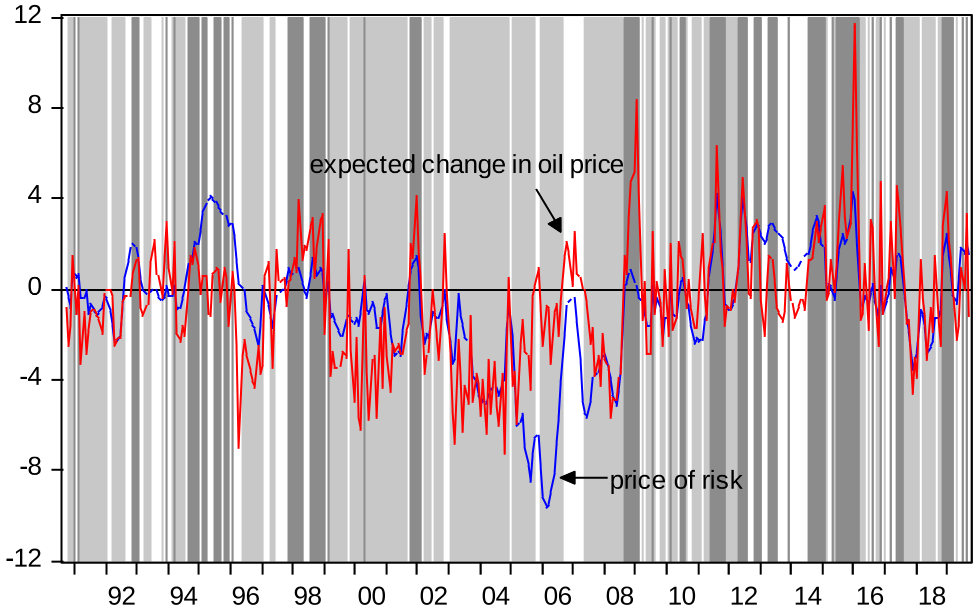
Figures 5 and 6 display the estimated values of price of risk generated by the state equations (smoothed inference) for the 3- and 12-month horizons, respectively. It can be seen that the price of risk is either positive or negative, depending on the periods. Two observations can be made from these results. First, 65% of the values of risk price are negative (35% are positive) for the 3-month horizon and 53% of these values are positive

(47% are negative) in the case of the 12-month horizon. This suggests that at the shorter horizon investors are much more frequently prone to be risk seeking than risk averse, while in the longer horizon they are barely more frequently risk averse than risk seeking. This result conforms to the evidence that speculators' horizon favors the short term. Second, the alternating dynamic of the price of risk can be given a state dependent risk attitude interpretation in accordance with the prospect theory. As a result of their gamble-based experiments, Kahneman and Tversky (1979) found that 84% of individuals are risk-averse in the area of gains while 69% of them are risk-seeking in the area of losses. For comparison purposes, we must discuss how we can represent the patterns of preferences "risk aversion in the region of gains" and "risk-seeking in the region of losses" in the case of our representative investor. Recall from Eq.(9) that in the state of risk aversion the price of risk is positive, while it is negative in the state of risk-seeking. Let the region of gains be represented in our context by the subset of observations S_1 where the expected change in oil price is positive, and the region of losses by the subset of observations S_2 where the expected change in oil price is negative. We can then consider the joint event E_1: "the price of risk and the expected change in oil price are both positive" and the joint event E_2: "the price of risk and the expected change in oil price are both negative" as the states from our context that are analogous to Kahneman and Tversky's patterns of preference mentioned above. For the two horizons, Figures 7 and 8 exhibit respectively the occurrences of E_1 (dark shaded areas) and of E_2 (light shaded areas).[22] To express these occurrences in percentage terms, we divide the numbers of realizations of E_1 and E_2 by the numbers of observations in S_1 and S_2 and get 70% and 81% at the 3-month horizon and 76% and 59% at the 12-month horizon, yielding 73% and 70% on average for the two horizons. These two magnitudes, and especially the second one corresponding to risk seeking in the region of losses, are consistent with Kahneman and Tversky's experiments. This deserves emphasis in that it makes our results from our expected utility framework compatible with the prospect theory predictions. In particular, we can interpret in this context the downward movement of the price of risk between 2002 and 2008 for both horizons (Figures 5 and 6). This period was characterized by an upsurge in oil price as a result of the strong growth in global economic activity driven by emerging market economies (and especially China), on the one hand, and of geopolitical tensions in Middle East, on the other hand, together with an increasingly tight oil supply since 2004 (Hamilton, 2009). We can also observe that although oil price expectations for both horizons were

[22] In the unshaded areas, the price of risk and the expected change in oil price have opposite signs. These fewer cases are not of interest here, since they correspond to the Kahneman and Tversky's remaining two patterns of preference (risk aversion with perspectives of losses and risk seeking with perspectives of gains) that were adopted by a minority of individuals.

steadily revised upwards as the spot price rose, expected values were systematically lower than actual values (Figure 9). This suggests that the bullish oil market was expected by agents to end up by a trend reversion in the near future, as they believed that the oil price soar was not linked to economic fundamentals but resulted from speculation (also referred to as financialization of oil futures markets; see Masters, 2008).[23] Therefore, as long as market participants observe that they make positive forecast errors, that is, the spot price keeps rising although they continuously expect a decrease, maintaining or increasing the share of their oil holdings would be profitable at the very short run but at the cost of a substantial risk taking, the risk that, at some point, their mean-reversion expectations are fulfilled. Thus, accepting to bear this risk makes them risk seekers, implying negative price of risk over this period. Interestingly, we find here the two ingredients (persistent expected decreases in the spot price representing a potential loss and negative price of risk reflecting risk tolerant investors) which provide over our sub-period of interest a form of consistency with the prospect theory pattern stating that risk-seeking preferences are prominently adopted in situations of losses.

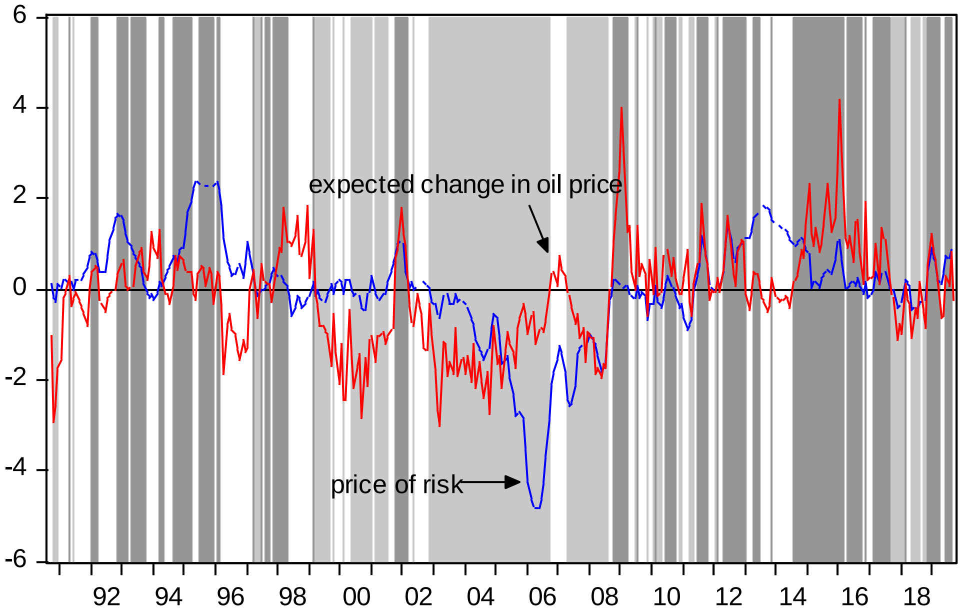
Figure 7. Risk attitudes relative to expected oil price dynamics - 3-month horizon



Notes : Dark shaded areas: risk aversion in periods of expected rise in oil prices
Light shaded areas: risk seeking in periods of expected fall in oil prices

[23] In fact, empirical literature has not found support for this popular view that speculators played a significant role in the rise of oil prices during 2000-2008; see, e.g., Buyuksahin and Harris (2011), Fattouh, Kilian and Mahadeva (2013). The latter authors have instead put emphasis on the co-movement between spot and futures prices based on common fundamentals.

Figure 8. Risk attitudes relative to expected oil price dynamics - 12-month horizon



Notes: Dark shaded areas: risk aversion in periods of expected rise in oil price
Light shaded areas: risk seeking in periods of expected fall in oil price

Figure 9. Observed and expected crude oil price (Consensus Economics), 2002 - 2008

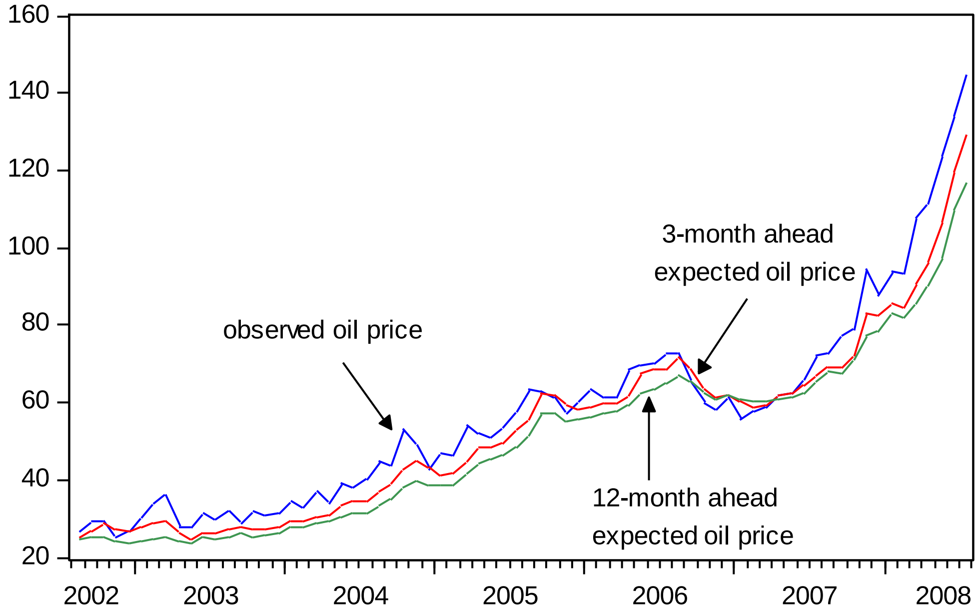
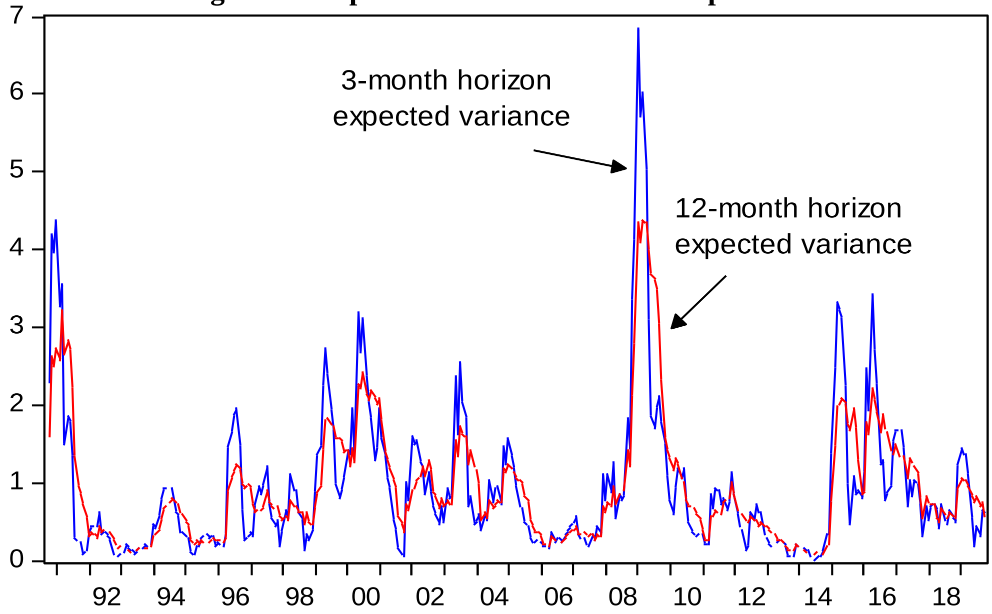


Figure 10 displays for each horizon the expected conditional variance of oil returns as described in Eq (12), calculated using the Kalman estimates of ${}_{\tau}\omega_j$'s (Table 2). As expected, a peak is formed at the global financial crisis period for both horizons and the 12-month horizon variance appears to be tighter than the 3-month horizon variance. As a result, the expected variance is not significantly correlated with the price of risk, since the coefficients of correlation are 0.036 for the 3-month horizon and -0.033 for the 12-month horizon. This shows that the two elements contributing to describe the dynamics of risk premia are independent and therefore fully complementary components. This statistical property suggests that the expected variance mainly reflects the speculative component while the price of risk mainly conveys economic factors of *ex-ante* risk premia, these being macroeconomic as well as oil market specific factors.

Figure 10. Expected variance of oil return per horizon



Figures 11 and 12 compare the observed values of the *ex-ante* risk premium with the fitted values obtained from the estimation of the measurement equations (14a) and (14b), along with Eqs.(15a), (15b) and (12), for the 3- and the 12-month horizon, respectively. For both horizons, it can be seen that the estimated values follow closely the main fluctuations of the observed values, with a finer adjustment for the 12 month horizon as indicated by the R^2 statistics (Table 2). Overall, regarding the well-behaved residuals of our state-space model, we can conclude that, despite its relative simplicity, our model accurately describes the dynamics of *ex-ante* premia.

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Figure 11. Observed and fitted values of the 3-month ex-ante risk premium

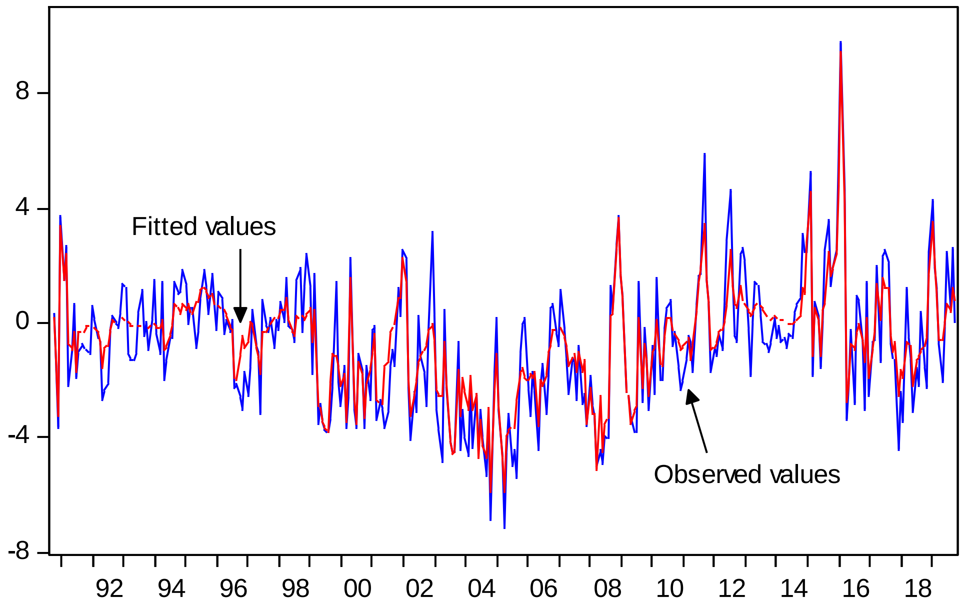
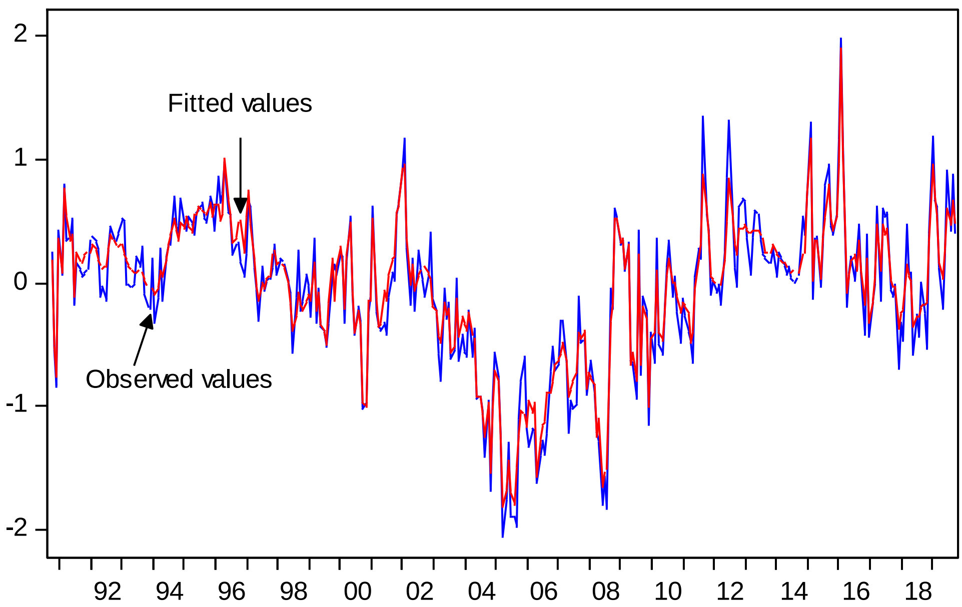


Figure 12. Observed and fitted values of the 12-month ex-ante risk premium



4.3 Empirical identification of risk price driving factors

In section 4.2 we were able to measure our unobservable risk prices through the estimation of our state variables, however the economic factors underlying these variables remain unidentified and this leaves the determinants of risk premia unknown. In this section we focus on examining the economic factors of the price of risk which drive the part of the risk premium that is not explained by the expected variance.

The autoregressive feature of the price of risk suggests that it is correlated with macroeconomic and oil market-related variables. We tested a number of factors which were found to be significant in explaining ex-post oil risk premia (see introduction). These include CPI or WPI-based observed and expected rates of inflation, observed and expected changes in GDP and industrial production, changes in interest rates and term spreads between the 10 year Treasury Bond yield and the 12- or 3-month Treasury Bills rate, the VIX index (CBOE), the S&P500 stock returns, the NBER probabilities of US recessions, the rate of change in crude oil price, the rate of change in oil stocks, the change in the rate of utilization of refinery capacity, calculated as the ratio of refinery throughput to refinery capacity (or maximum throughput), (the log of) oil reserves lifetime, constructed as the ratio of proved oil reserves to oil production (see Coleman, 2012), and OPEC crude oil production. Except the latter variable all the others are US-based factors. As an indicator of forecast heterogeneity, we considered the coefficient of variation of CE experts' oil price expectations, defined as the ratio of the cross-section standard error of oil price expectations to the cross-section mean. Expected macroeconomic variables (expectations are for the end of the current year, in percent per month) are extracted from CE at the survey date, observed macroeconomic and oil market-related variables from Datastream and financial indices and recession probabilities from the Federal Reserve of Saint Louis (FRED). We test all these factors as potential economic drivers of our risk price variables for both the 3- and 12-month horizons. However, the presence of common factors in the two regression equations implies that errors across the two equations are contemporaneously correlated, leading to consistent but inefficient estimators if the equations are estimated separately using OLS. To address this issue, we estimate our two equations by using the seemingly unrelated regression (SUR) methodology which is appropriate when the errors are mutually correlated and heteroskedastic.[24] Our SUR estimation results are displayed in Table 3.

[24] Note that if the two equations have identical right-hand-side variables, the SUR method does not add to the estimator efficiency and becomes equivalent to performing two separate OLS regressions. As our final sets of significant regressors are not identical, the SUR approach applies.

Table 3: Seemingly unrelated regression of oil price of risk

	τ =3	τ=12
intercept	61.50*** (6.05)	35.39*** (7.60)
Heterogeneity of oil price expectations (lagged)	-0.07** (-2.02)	-0.08*** (-4.34)
WPI-based inflation	-0.74*** (-3.56)	-0.33*** (-3.84)
CPI-based expected inflation	-0.80*** (-6.83)	-0.35*** (-6.32)
Expected growth of the Industrial Production/GDP ratio	0.70*** (8.17)	0.22*** (5.71)
Expected growth in GDP	-0.75*** (-6.92)	-0.23*** (-4.58)
10yearTB-1yearTB spread	-	0.17*** (5.53)
VIX	0.03* (1.88)	0.01* (1.83)
NBER probabilities of US recessions	-	0.004** (2.27)
Rate of change in oil price	-0.04*** (-4.87)	-
Rate of change in oil price (lagged)	-0.02*** (-3.04)	-
Change in refinery capacity utilization	156.33*** (2.30)	140.46*** (4.35)
Log of Reserves lifetime	-4.83*** (-5.82)	-2.80*** (7.34)
Rate of change in oil stock	-19.14** (-1.97)	-10.64** (2.40)
$\bar{R}^2$	0.34	0.36
DW	0.24	0.18

Notes. Numbers in brackets are the *t*-statistics. The Table presents final regression results once insignificant regressors have been removed. Symbols *, ** and *** indicate significance at the 10%, 5% and 1% levels, respectively.

We interpret the impact mechanism of many variables upon oil risk price through their effects on the share of the risky asset in the portfolio ${}_{\tau}\theta_t^*$ or on the relative risk aversion (or risk preference) coefficient ${}_{\tau}\kappa_t$, see Eq(9).

Heterogeneity of oil price expectations

To describe the effect of forecast heterogeneity on oil risk price, we assume that in forming their opinions investors are reluctant to deviate from the market opinion (Orléan, 1992; Laurent, 1995). Consequently, individuals who realize that they have overestimated or underestimated at time t-1 future oil price with regard to market expectation should be prompted to adjust their opinions towards the market opinion. As a result, the sum of the upward and downward adjustments towards the consensus between time t-1 and t should lower heterogeneity, the size of this contraction being proportional to the level of the initial heterogeneity. Investors who revise their forecasts downwards will accordingly reduce the share of the oil asset in their portfolios at time t, this leading to a decrease in the price of risk. Conversely, those who update their opinion upwards will purchase new oil assets and will consequently tend to push the risk price up.[25] One can expect a positive overall impact of forecast heterogeneity on the price of risk if overestimating agents are dominant in average during the period and a negative effect if underestimating agents dominate the market. We find support for the latter case since the estimated slope of the lagged value of the coefficient of variation is negative for both horizons.

Macroeconomic factors

When the production growth rate is expected to increase, two opposite effects on price of risk can be envisaged: a positive ripple effect and a negative confidence effect. Concerning the first effect, an increase in expected industrial production growth reflects a higher expected oil demand, as the industrial sector is the most energy-consuming sector. Such a rising oil needs outlook should have a direct upward effect on the holdings of barrels of crude oil and therefore on the share of the risky asset in the portfolios, implying a higher price of risk. Our finding that expected growth in the ratio of industrial production to GDP is positively related to the price of risk is in line with this conjecture. As for the second channel, when they expect a higher level of economic activity, investors in general and oil asset holders in particular may feel more confident in the stability of the economy, so that they may become less risk averse, or more risk seeking, depending on their risk attitude at that period. It follows that the coefficient ${}_{\tau}\kappa_t$ and thus the price of risk should tend to decline. This result conforms to the widely agreed outcome of the empirical financial literature that the market risk premium is countercyclical (Pagano and Pisani, 2009; Alquist et al, 2013; Chin and Liu, 2015). In the same vein, the influence of the probability of recessions in the US economy is positive for the 12-month horizon, signalling a rise in the perceived uncertainty over longer horizons and a consequent upward adjustment in ${}_{12}\kappa_t$, and hence on the price of risk. Concerning the impact

[25] If, because of individuals' aversion to deviating from the consensus, the dispersion of individual opinions shrinks during the time span between t-1 and t, the arrival of new information at time t will of course give rise to a new oil price forecast heterogeneity that may be greater or smaller than the one prevailing at time t-1.

of the current and expected inflation on the oil price of risk, we would expect their sign to be positive under the assumption that investors use crude oil future contracts as a hedging tool against inflation (increase in ${}_{\tau}\theta_t^*$), and negative if they rather rely on the risk-free debt securities as safe haven investments (decrease in ${}_{\tau}\theta_t^*$). Our negative estimates support the latter case.

Financial factors

The negative impact of the term spread of interest rates on the price of risk can be explained through the individual influences of its components, the expected change in the short rate and the liquidity premium. The downward trend in Treasury Bills rates over our period suggests that the expected change in the short rate is negative on average, and this can be viewed as an incentive for investors to increase ${}_{\tau}\theta_t^*$. As for the liquidity premium, it should be strongly positive to offset the negative average change in the short rate given that the term spread is positive on average. The liquidity constraint perceived by investors should then be high enough to induce them into a risk aversion attitude. As a result, the dynamics of the two components of the term spread have a positive impact on the price of risk at the 12-month horizon only, suggesting that liquidity plays a significant role only beyond a certain duration of the investment.[26] A positive impact on the price of risk is also provided by the VIX index. This index is commonly viewed as a fear gauge in financial markets. A surge in this index should directly involve an upward shift in ${}_{\tau}\kappa_t$, which will raise oil price of risk.

Oil market-related factors

When oil market is bullish, investors may wish to increase their oil holdings with the expectation that they can sell these holdings in the future at a higher price. Such a long position implies a rise in the share of the risky asset in their portfolios. In the meantime, if investors believe this strategy profitable, they may be motivated to take more risk especially for shorter horizons and this translates into a lower risk preference parameter. Thus, two simultaneous but controversial influences of ${}_{\tau}\theta_t^*$ and ${}_{\tau}\kappa_t$ can be thought of as acting on the price of risk. Regarding our finding that current and lagged oil price returns negatively impact the 3-month oil price of risk, we report a dominant effect of the parameter ${}_{3}\kappa_t$ (note that the

[26] Spreads between 10-year TB bonds and 3-month TB rates and between 12-month and 3-month TB rates were alternatively introduced in the 3-month risk price equation but none of them was found to be significant.

change in oil price was not found to be a significant factor for the 12-month horizon). This interpretation agrees with the results of Hoffmann and Post (2017).[27] Similarly, a rise in oil stocks can have contradictory effects on the price of risk through the channels of marginal storage costs and convenient yield : an increase in marginal storage costs, which is a powerful disincentive for maintaining oil holdings (fall in ${}_{\tau}\theta_t^*$ and thereby in the price of risk); in the meantime, oil stocks lower the non-delivery risk to oil consumers in case of unexpected rise in oil demand, which is a motive to build up inventories (rise in ${}_{\tau}\theta_t^*$). Our results suggest that the marginal cost effect outperforms the convenient yield effect, since a rise in oil inventories reduces oil price of risk at both horizons. An increase in the rate of utilization of refinery capacity stems from a higher growth in crude oil production than in refinery capacities. As production approaches capacity, the diminishing unused capacity may trigger a rise in oil prices. Nonetheless, if investors anticipate that the rate of capacity utilization will meet such critical levels of rising prices, they would enter into a speculative strategy by consolidating their stocks, which results in a rise in ${}_{\tau}\theta_t^*$. This tends to explain the positive relationship we evidenced between the rate of refinery capacity utilization and the price of risk. The same transmission channel as an increase in the utilization of refinery capacity should be at play following a shortening in oil reserves lifetime: indeed, such an outlook should be an incentive for investors to raise their share of oil assets for speculative purposes in the extent that accelerating scarcity may be viewed as a signal of a higher oil price in the future. Our results are consistent with this view.[28]

4.4. What do our results say about the term structure of ex-ante oil risk premia?

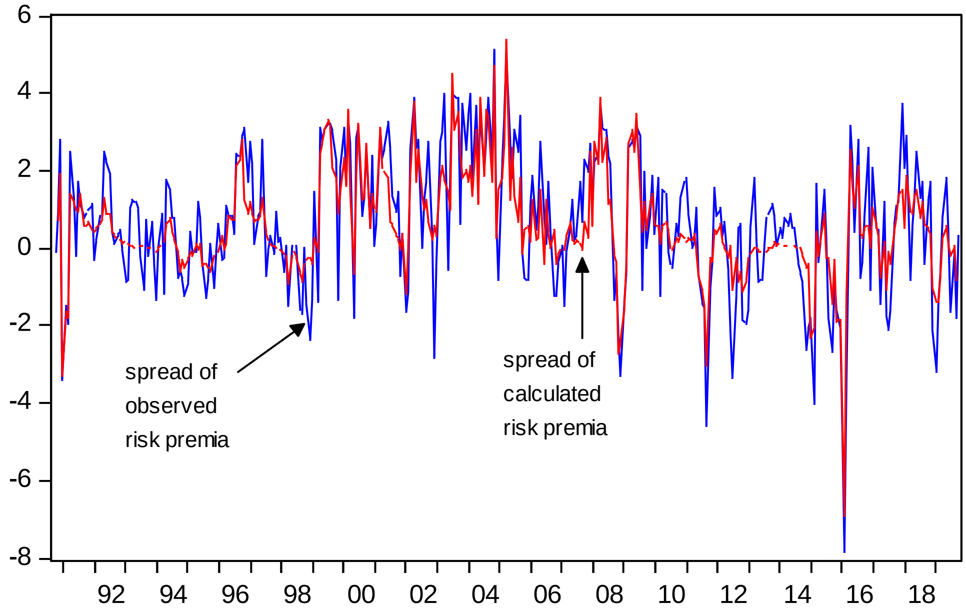
Analyzing the term structure of oil risk premia is a central issue in that observing and understanding this structure conditions the decision-making of an investor willing to choose the most relevant horizon for investing in crude oil. Although this field of research is a natural extension of the present study, an in-depth analysis of the term spread of risk premia is beyond its scope. Nevertheless, direct implications of our findings in this matter are worth to be mentioned. We can infer from our theoretical results that the term structure of risk premia depends at any time on expected volatilities and on the prices of risk at the horizons of the spread. As these risk prices are found to be driven by a number of economic factors, the same factors can be considered as candidates for partially explaining the spread of risk premia.

[27] See footnote 21.

[28] Note that in the long term the effect should be reversed, since oil scarcity would lead to the soar of alternative energy industries and prompt investors to shift towards other investment assets in place of oil assets.

Among those, significant factors such as the expected change in oil price, observed and expected inflation, observed and expected output growth and the term structure of interest rates were evidenced. Figure 13 compares the observed values of the term spread between the 12- and the 3-month ex-ante oil risk premia to the values of the spread calculated using the estimated state-space model parameters provided in Table 2. Although less volatile, the estimated spread reproduces the major trends of the observed values.

Figure 13. Spread between the 12-month and the 3-month ex-ante oil risk premia



In addition, it can be seen that, even though the sign of the spread alternates over time, the dominant slope of our oil risk premia term structure is clearly positive. Over the whole period, we find a proportion of 67% of positive values for the spread with median and mean values of 0.69% and 0.68% per month, respectively.[29] Using different survey data and different methodologies, Bianchi and Piana (2017) and Cortazar et al. (2019a) found a downward sloping term structure of ex-ante oil risk premia over the periods spanning from december 2006 to january 2016 and from january 2010 to june 2017, respectively. Note, however, that this finding is specific to the sample periods used that are much shorter than ours. The sign of the term structure can obviously change depending on periods – as is the case with interest rate term spreads – and only an extended period such as ours can help to detect a dominant structure.

[29] For comparison, it is well known that, due to a risk (or liquidity) premia in long term rates, the term structure of interest rates is also most often upward sloping. Contrariwise, the term structure of equity risk premia is mostly found to be downward sloping (see, among others, Binsbergen and Koijen, 2017).

5. Conclusion

This article aims at modeling ex-ante risk premia in the crude oil market for the 3- and 12-month horizons. We show that ex-ante premia exhibit very different dynamics compared to ex-post premia, which is the most widely studied risk premium concept in the literature. We calculate our ex-ante oil risk premia for both horizons using oil price expectations provided by Consensus Economics surveys over thirty years, such a length of time giving our results a more general scope than the shorter periods considered by previous studies. Oil price expectations are shown not to be rational, implying that in driving decision making, the concept of ex-ante risk premium is more relevant than that of ex-post risk premium.

We model oil risk premium for each of the two horizons within the portfolio choice theory framework, where the representative investor maximizes the expected utility of their future wealth made of a combination of barrels of oil and risk-free asset (T-Bills). The solution of this program determines the risk premium as the product of the expected variance of oil returns and the price of risk, both assumed to be time-varying and horizon-dependent. The expected variance depends on actual and past instantaneous variances. We represent the price of risk as an unobservable stochastic state variable within a state-space (two-horizon) multivariate model of ex-ante risk premia that we estimate using the Kalman filter methodology.

We find that ex-ante oil risk premia exhibit significant disparities regarding the horizons, with much higher amplitudes for the 3-month horizon than for the 12-month horizon. The resulting spread between the two risk premia exhibits a dominant upward slope over our extended period. The risk prices taking positive or negative values across time reflect alternating risk attitudes over time. Risk seeking behaviour is strongly associated with the short horizon while risk aversion is barely dominant in the longer horizon. We show that regarding risk aversion over gains (expected rise in oil price) and risk seeking over losses (expected drop in oil price) our temporal pattern of risk attitudes is consistent with the predictions of prospect theory. Finally, we identify various factors of different sources that influence the price of risk: macroeconomic factors (expected growth and inflation), financial factors (term spread of interest rates, VIX) and factors that are specific to the oil market (heterogeneity of oil price expectations, change in oil price, change in oil inventories, utilization of refinery capacity, oil reserves lifetime). Overall, these influences represent the effects of fundamentalist and speculative behaviours upon the price of risk.

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