Pricing and Hedging Illiquid Energy Derivatives: an Application to the JCC Index

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Summary

In this paper we discuss a simple strategy for pricing and hedging illiquid financial products, such as the Japanese crude oil cocktail (JCC) index, the most popular OTC energy derivative in Japan. First, we review the existing literature for computing optimal hedge ratios (OHR) and we propose a critical classification of the existing approaches. Second, we compare the empirical performance of different econometric models (namely, regression models for price levels, price first differences, and price returns, as well as error correction and autoregressive distributed lag models) in terms of their computed OHR, using monthly data on the JCC over the period Janury 2000-January 2006. Third, we illustrate and implement a reliable procedure to price and hedge a swap contract on the JCC with a variable oil volume. We explain how to compute a bid/ask spread and to construct the hedging position for the JCC swap. Fourth, we evaluate our swap pricing scheme with backtesting and rolling regression techniques. Our empirical findings show that it is not necessary to use complicated econometric techniques, since the price-level regression model permits to compute more precise optimal hedge ratios relative to its competing alternatives.

Keywords: Hedging Models, Cross-Hedging, Energy Derivatives, Illiquid Financial Products, Commodity Markets, JCC Price Index

JEL Classification: G13, G15

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1 Introduction

It is well known that hedging aims at reducing the risk involved in holding a financial asset by taking an exactly offsetting position. In particular, hedging is the most important risk management approach used by a company to reduce its exposure to fluctuations in commodity prices.

The aim of this paper is to explain and analyse the risk associated to illiquid financial products. Dealing with the risk associated to illiquid financial products always involves a basis risk, since a perfect hegde is not possible due to the lack of a related futures market. In this case, the only available solution is cross-hedging.

The main contribution of this paper is to discuss a reliable econometric strategy for pricing and hedging illiquid products, such as the Japanese crude oil cocktail (JCC) index, the most popular OTC energy derivative in Japan. We review the existing literature for computing optimal hedge ratios (OHR) and we propose a critical classification of the existing approaches. We compare the empirical performance of different econometric models (namely, regression models for price levels, price first differences and price returns, as well as error correction and autoregressive distributed lag models) in terms of their computed OHR, using monthly data on the JCC over the period January 2000-January 2006. We illustrate and implement a procedure to price and hedge a swap contract on the JCC with a variable oil volume. Moreover, we explain how to compute a bid/ask spread and to construct the hedging position for the JCC swap. We then evaluate our swap pricing scheme with backtesting and rolling regression techniques. Our empirical findings show that it is not necessary to use complicated econometric techniques, since the price-level regression model permits to compute more reliable optimal hedge ratios relative to its competing alternatives. This result is particularly interesting for traders operating in large energy companies, who have exposures on illiquid markets and intend to directly hedge their positions with simple and versatile techniques.

The paper is structured as follows. In Section 2 we present alternative econometric models for proxy-hedging illiquid positions. In Section 3 we review some of the most important and recent studies on the estimation of OHR. Section 4 is dedicated to the empirical analysis for pricing and hedging a JCC swap. Specifically, we present the data used in the empirical application; we estimate and compare the different econometric specifications in terms of their ability to compute plausible OHR; we present a procedure to price and hedge a swap contract on the JCC; we evaluate the swap pricing scheme with backtesting and rolling regression techniques. Section 5 concludes.

2 Econometric models

There is no general consensus about the appropriate model that should be used to estimate the OHR, although, in the last few years, some researchers have paid particular attention to the statistical properties of the data, such as cointegration and time-varying second moments. In this section we discuss the most popular econometric techniques used in the literature to estimate the OHR.

The OHR for commodities, β, can be computed by minimizing the end-of-period variance of a portfolio composed by two assets: a spot asset (S_t) and a futures contract ($F_{t,T}$) at time t ($t = 1, ..., n$), with maturity T, $T > t$, as described in expression (1):

$$\beta = \frac{cov(S_t, F_{t,T})}{var(F_{t,T})} \tag{1}$$

We assume that β is constant over to time, although recent studies have dealt with time-varying β (e.g. Moschini and Myers, 2002; Kenourgios et al., 2005).

The relationship between spot and futures prices can be represented with the linear regression model:

$$S_t = \alpha + \beta F_{t,T} + \epsilon_t \tag{2}$$

It is important to notice that equation (2), which is expressed in levels, can be also written in price differences as:

$$S_t - S_{t-1} = \alpha + \beta(F_{t,T} - F_{t-1,T}) + \epsilon_t \tag{3}$$

or in price returns as:

$$\frac{S_t - S_{t-1}}{S_{t-1}} = \alpha + \beta \frac{F_{t,T} - F_{t-1,T}}{F_{t-1,T}} + \epsilon_t \tag{4}$$

Equation (4) can be approximated by:

$$\log S_t - \log S_{t-1} = \alpha + \beta(\log F_{t,T} - \log F_{t-1,T}) + \epsilon_t \tag{5}$$

Equations (2) and (3) assume a linear relationship between spot and futures prices, while equation (4) assumes that the two prices follow a log-linear relation. Relative to equations (2)-(3), the hedge ratio (HR) represents the ratio of the number of units of futures to the number of units of spot that must be hedged, whereas, relative to equation (4), HR is the ratio of the value of futures to the value of spot.

Equation (2) is usually estimated with conventional OLS; the estimated β is the OHR given by expression (1), and the regression R-squared (R^2) is used as a measure of the hedging performance. Unfortunately, this specification can easily produce autocorrelated and heteroskedastic residuals (Ederington, 1979; Myers and Thompson, 1989). For this reason, some authors suggest to use equation (3), so that the OLS classical assumption of no correlation in the error terms is not violated (Witt et al., 1987).

Another relevant aspect is data stationarity. It is generally acknowledged that many economic time serie, such as commodity prices, are non-stationary. However, if the spot price S_t and the futures price $F_{t,T}$ are integrated of order one (i.e. stationary in first differences) and it is possible to find a stationary linear combination between S_t and $F_{t,T}$, the two series are said to be cointegrated.

The definition of cointegration was introduced by Engle and Granger (1987), who state that cointegrated variables have an error correction representation (ECM) of the following form:

$$\Delta S_t = \alpha e_{t-1} + \beta \Delta F_{t,T} + \sum_{k=1}^{K} \gamma_k \Delta F_{t-k,T} + \sum_{l=1}^{L} \delta_l \Delta S_{t-l} + \epsilon_t \tag{6}$$

where

$$e_{t-1} = S_{t-1} - \alpha F_{t-1,T} \tag{7}$$

is the error correction term (ECT) measuring the deviation from the long-run equilibrium relationship, $\Delta S_t \equiv \log(S_t/S_{t-1})$ and $\Delta F_{t,T} \equiv \log(F_{t,T}/F_{t-1,T})$. In model (6) the presence of lagged variables, $\Delta F_{t-k,T}$ and ΔS_{t-l}, captures short-run dynamics, while β is the OHR.

If second moments are assumed to be time-varying, the OHR has to be estimated accordingly. In this case, GARCH models (see Bollerslev, 1986) are generally employed. To guarantee a positive conditional variance and to accommodate the so-called leverage effect, the exponential GARCH (EGARCH) model introduced by Nelson (1991) is also considered. Another GARCH-type specification is the exponential weighted moving average (EWMA), which is equivalent to the integrated GARCH model.

Multivariate extensions which have been used in the literature on OHR are the vector autoregressive (VAR) model and the vector error correction (VECM) specification, while a popular multivariate generalisation of the single-equation GARCH model is BEKK (Engle and Kroner, 1995), since it ensures the positive definiteness of the conditional covariance matrix by introducing a general quadratic form for the conditional second moments.

3 Review of the existing literature

This section briefly reviews the literature dealing with the estimation of the OHR. The correct approach to hedging is subject to a controversial debate. On the one hand, the strand of OHR literature which is more oriented to finance has focused on the derivate pricing models. On the other hand, that part of OHR literature which is closer to applied economics has stressed the importance of time-series techniques. Recently, Bryant and Haigh (2005) have compared the two approaches using NYMEX crude oil spot and futures prices, concluding that the latter technique exhibits a superior hedging performance.

Our survey examines the studies on cross-hedging, with particular emphasis on the applications of alternative econometric techniques for the estimation of OHR (see Table 1 for a summary of the main characteristics of the reviewed papers).[1]

In 1969 Johnson stresses the importance of futures markets for hedging operations. He discusses the theory of hedging, adapts it to commodity markets and constructs a model for hedging and speculation. The theory of cross-hedging has developed in a static framework, where futures contracts are held without adjustment (Ederington, 1979; Anderson and Danthine, 1981).

It is important to notice that only a few contributions have been published on cross-hedging commodity prices, while even fewer are the studies on energy commodity prices.

[1] For a more comprehensive review we address the reader to Lien and Tse (2002).

In 2002 Tunaru and Tan examine the exposure to kerosene of an airline company based in an emerging country. The authors assess whether it is better to cross-hedge this commodity with a futures contract or to transform the problem in cross-hedging the currency, due to the fact that futures contracts on kerosene exist only in the Tokyo market. The aim of their paper is to empirically understand if airline companies outside Tokyo are better off using futures in Tokyo and managing currency risk, instead of cross-hedging kerosene with gas oil or heating oil. They analyse weekly data for the period 4 February 1997 - 21 August 2001, showing that jet fuel is highly correlated to almost all futures traded at IPE and NYMEX. Tunaru and Tan regress equation (2) using OLS on a specification in quasi-differences, to account for autocorrelation, and the instrumental variables estimator proposed by Scholes-Williams (1977) to deal with the non-syncronization between spot and futures data.[2]

Coffey et al. (2000) examine five grain co-products and analyse how to manage price risk, as no futures contracts exist for these products. In particular, they cross-hedge the five commodities using a price-level model estimated by GLS in order to correct for autocorrelation.

More interesting approaches have been proposed by authors who concentrate on the comparison between different specifications for the OHR. For instance, Witt et al. (1987) discuss whether it is more appropriate to use price levels, price changes or percentage price changes when estimating the OHR. The authors focus on the estimation of cross-hedging relationships between barley and sorghum cash prices and nearby corn futures prices for the period 1975-1984. Witt et al. conclude that the results obtained using equation (2) are as robust as the findings of equations (3) and (4). They offer detailed suggestions on how the selected model should depend on the type of hedge considered: if the hedge is anticipatory, the best model to employ is equation (2), while in the case of a storage hedge the best performance is achieved by equation (3).

In 2003 Moosa tests the sensitivity of the OHR to model specification, using four different models. He deals with two datasets and compares equations (2), (3) and (6), with or without lagged variables. The first is a monthly dataset on cash and futures prices of Australian stocks (All Ords index and SPI index), which covers the period January 1987 - December 1997; the second dataset is formed by quarterly observations on spot exchange rates of the UK pound and the Canadian dollar against the US dollar from the first quarter of 1980 to the last quarter of 2004. The author concludes that model specification does not significantly affect the computation of the OHR. On the contrary, his results show that correlation between the position to hedge and the instruments used is the most important factor that should be taken into consideration.

Casillo (2004), analysing the index future contract of the Italian derivatives market (FIB30), provides an empirical comparison of alternative econometric techniques for estimating the OHR. Although his empirical analysis is applied to a different financial market, the contribution of the author is important in our context, as he underlines advantages and disadvantages of four different estimation methods. In particular, he evaluates the hedging performance of equation (3), a bivariate VAR model, a VECM specification, as well as a BEKK model. He concludes that the multivariate GARCH model

[2] The Scholes-Williams (SW) instrumental variables estimator for the OHR is defined as: $\beta_{SW} = \frac{\hat{cov}(\Delta S_t, IV_t)}{\hat{cov}(\Delta F_{t,T}, IV_t)}$, where $IV_t = \Delta F_{t-1,T} + \Delta F_{t,T} + \Delta F_{t+1,T} = F_{t+1,T} - F_{t-2,T}$.

is marginally better than its competitors, as it is able to accommodate time-varying OHR.

Some authors account for cointegration using an ECM, while other contributors apply the class of GARCH models assuming that variances and covariances are varying over time. In 1991, Myers proposes two methods for estimating non-constant OHR. The first incorporates time-varying volatility through time-dependent sample variances and covariances of past price prediction errors; the second is a simple GARCH model. Referring to the series of wheat prices over the period January 1977 - May 1983, the author compares the two approaches with the traditional regression method, concluding that the GARCH model performs only marginally better.

Ghosh (1993) proposes an ECM representation to estimate the OHR for non-stationary series. He uses daily data for the period 2 January 1990 - 5 December 1991 on closing prices for the S&P 500 index, the Dow Jones Industrial Average, the NYSE and the daily nearby settlement price of S&P 500 index futures contracts. The author compares the out-of-sample forecasting perfomance of equation (3) with an ECM. He finds that traditional methods underestimate the OHR and suggests that equation (6) can be useful to hedge foreign currency, commodity and interest rates futures.

In 2002 Moschini and Myers estimate the OHR for weekly corn prices using a reformulation of the BEKK model, which allows to test the null hypothesis that the OHR is constant over time. Their results show that the OHR is time-varying and that its variability cannot be explained by seasonality and time-to-maturity effects.

Harris and Shen (2003) propose an alternative way of estimating the OHR, which considers the leptokurtic empirical distribution of the data. They construct a dynamic hedging strategy for daily returns on the FTSE100 index and apply both a rolling window approach and a EWMA model to estimate robust OHR. They find that the variance of the robust OHR obtained with the EWMA model is 70% lower than the OHR calculated with the rolling window approach.
Ghosh and Bolding (2005) estimate the OHR for the Euro market. Using data for the period 2 January 2001 - 7 June 2004 they test for the presence of unit roots, finding that each considered series is integrated of order one. They compare the effectiveness of an ECM specification with equation (3), pointing out the superiority of the out-of-sample forecasts based on the ECM.

Kenourgios et al. (2005) apply both a constant and a time-varying model for second moments and investigate the hedging performance of the S&P 500 futures contracts using data for the period July 1992- June 2002. They compare equation (3) with ECM, GARCH and EGARCH models. The authors find out that the ECM generates a larger risk reduction.

4 Pricing and hedging the JCC swap

4.1 Data

The aim of this paper is to cross-hedge and price a swap on the JCC using the econometric models described in Section 2. The dataset consists of monthly observations on the JCC from January 2000 to January 2006. JCC represents the average CIF value of all crude and raw oils imported in Japan in a specific period. Its price is determined as follows:

$$P_m(JCC) = \frac{V_m}{Q_m} \tag{8}$$

where V_m is the sum of the values of imported crude and raw oils at month m expressed in thousands of Japanese Yen (JPY), and Q_m is the sum of the quantities, expressed in kiloliters, of imported crude and raw oils relative to the m-th month, $m = 1, ..., M$. Data on the JCC index are published only with a monthly frequency and can be downloaded from the web site of the Petroleum Association of Japan (http://www.paj.gr.jp/html/statis/index_e.html), where the JCC series is available also in US dollars.[3] It has to be noted that in Japan crude oil imports are subject to a tariff of 215 JPY/kilolitre. Moreover, Japanese crude oil is mostly imported from the Middle East via tankers. The mechanism used to set the price of a crude oil cargo depends on several, country-specific factors. Most often crude oil is priced on an average of published prices on the Bill of Lading (B/L) date; that is, the price of the B/L date plus or minus a defined number of working days around this date.

Our dataset also includes the daily closing prices of the most prompt contract on the futures curve on WTI (WTI1 in Figure 1), as well as the one-month, two-month, three-month and four-month WTI futures prices. The most prompt WTI futures price series with monthly frequency has been obtained by aggregating the corresponding daily observations, with a simple arithmetic mean which takes into account that the contract rolls over on, or around, the 20-th day of each calendar month. The correlation coefficient between JCC and WTI is, not surprisingly, very high (0.988), as suggested also by Figure 1, where both series show a very similar behaviour.

4.2 Econometric analysis

In this section we analyze the JCC and WTI price series using models (2), (3), (5) and (6), aiming to point out potential differences and similarities among the alternative econometric specifications we have selected for estimating the OHR. As already discussed in the review section, the literature has proposed several models to estimate the OHR, depending on the statistical properties of the series involved.

The Augmented Dickey-Fuller (ADF) test supports the hypothesis that the JCC and WTI price series are integrated of order one and stationary in first differences. Results are reported in Table 2, where the ADF t-statistic is presented for both series in levels and first differences. Table 2 reports also the ADF test on the residuals of the Engle-Granger cointegration regression of the JCC price on the WTI futures price, which supports the presence of cointegration between the two variables.

[3] This is actually the JCC series used in our paper.

Hedge ratios for the JCC, denoted with β, are reported in Table 3, which also includes the coefficients for the constant term and for the ECT in model (6). The specification in levels shows the highest adjusted R^2, although this model is slightly less statistically adequate than its competitors, as its residuals are affected by autocorrelation and heteroskedasticity and the presence of cointegration between the two series is not exploited. Although a direct comparison of the β coefficients across models is not appropriate, as the dependent variable is not the same for each specification, nonetheless it is informative to compare the model in price differences with the model for price returns and the ECM. Model (6) shows more plausible estimates for the OHR, while specifications (3) and (5) seem to significantly underestimate the OHR. Furthermore, the ECM model has the highest adjusted R^2 and the ECT is significant and negative, supporting the convergence of the system to a long-run equilibrium.

In addition to the econometric and statistical implications of the estimated models, it is crucial to fully understand the economic and financial interpretation of the estimated parameters. In this case, in order to hedge a swap on the JCC price index, the specifications which consider as dependent variable the price difference are not appropriate, since they only permit to directly price and hedge a swap for the next month. Conversely, when longer hedging periods are considered, several hedge ratios must be estimated according to the specific hedging period, e.g. for a three-month hedging period the model should consider the third difference of the price. On this last respect, the price-level regression allows to estimate an OHR which can be used regardless of the specific swap month, providing the trader with a simple and flexible instrument.

In order to better evaluate the empirical performance of the econometric models used to price and hedge the JCC swap, it is important to analyse the time series behaviour of the regression residuals. The underlying idea is that, if it is not possible to eliminate the serial correlation in the residuals, residual autocorrelation should be priced into the swap.

Two additional specifications can contribute to improve the statistical adequacy of the price-level regression. The first specification involves the introduction of a moving average (MA) structure, which completely solves the autocorrelation problem and partially accommodates residual heteroskedasticity:

$$S_t = \alpha + \beta F_{t,T} + \epsilon_t, \epsilon_t = u_t + \delta u_{t-1} + \gamma u_{t-2} \tag{9}$$

The second model is the ARDL(1,1) specification:

$$S_t = \lambda + \alpha F_{t,T} + \delta F_{t-1,T} + \gamma S_{t-1} + \epsilon_t \tag{10}$$

where the OHR can be obtained as:

$$\beta = \frac{\alpha + \delta}{1 - \gamma} \tag{11}$$

Expression (11) is strictly related to the OHR estimated with the price-level regression model.

Results for these regressions are summarized in Table 4. Interestingly, both specifications are statistically adequate.

We facilitate the overall comparison of the models applied in our analysis by presenting some diagnostic tests on the residuals and a set of out-of-sample forecasts. Specifically, we calculate the Breusch-Godfrey serial correlation LM test (B-G test), the White heteroskedasticity test (W test) and the Jarque-Bera normality test (J-B test), as well as the standard errors of the regression (S.E.), the number of observations (N.) and the number of parameters (N.p.) (see Table 5). The model in levels is affected by residual autocorrelation and heteroskedasticity, while the other models do not point out any form of misspecification. It is worth noticing that the residuals are in general not normally distributed, since the Jarque-Bera tests sistematically reject the joint null hypothesis of zero skewness and zero excess kurtosis.

The out-of-sample analysis is run using the sample period January 2000-January 2005 for estimation and the last year of observations for forecast evaluation. Moreover, an additional forecasting exercise for February, March and April 2006 is proposed (Figure 2).

Figure 2 is divided into two panels. The first panel compares the observed JCC values with the forecast values from the price-level model, the price-difference model, the price-returns model and the ECM. The second panel reports the actual JCC values and the forecast values of the ARDL(1,1) specification and the price-level model corrected for the presence of MA error terms. Both panels also include the forecasts for the period February 2006-April 2006. The number associated with JCC refers to the estimated model, e.g. JCC2 refers to the price-level regression represented by model (2).

Models (2), (9) and (10) show more accurate forecasts than their competitors. In other terms, the graphical analysis provided in Figure 2 suggests that the simple price-level model and the price-level model corrected for autocorrelation outperform more complicated econometric specifications.

4.3 Swap pricing and hedging

In energy markets, a swap can be set up as a contract for differences (CFD), meaning that there is no exchange of a floating versus a fixed, but only the settlement of a difference. The CFD defines the fixed volume or quantity over a specified period of time, and it is usually settled for a particular frequency: monthly, quarterly, semi-annual or annual.

A commodity swap can be interpreted as a strip of forward contracts, implying that the payoff at each reset date is equal to the payoff of the forward contracts. Therefore, the value of the swap can be written as a weighted average of the underlying forwards (see, among others, Geman, 2005).

In this section we present and discuss a reliable mechanism to price and hedge a swap contract on the JCC index. We start with the simple case of a "one-month" swap contract (or forward contract) on the JCC to illustrate and clarify the main aspects of our pricing and hedging procedure. We then implement our approach on the more interesting and relevant case of a "multi-month" swap contract.

Consider a "one-month" swap on the JCC index at a future month $m^\star$ and indicate with $V_{m^\star}$ the corresponding notional volume of oil. Since the JCC is published with a monthly frequency, the "one-month" swap on the JCC index is identical to a forward contract settled by difference, according to the definition of CFD provided at the beginning of this section.

It is important to notice that the JCC monthly value is the average price paid by crude oil buyers during each month and depends on all the crude oil flows which are exchanged daily during each month. Thus the typical hedger of a "one-month" swap on the JCC would require a hedging instrument which varies continuously in order to replicate the JCC index behaviour. A typical payer of the JCC swap would like to sell JCC futures in order to hedge his/her position.[4] Unfortunately, futures contracts of this type are not available. Instead, he or she has to sell futures contracts on a related commodity which is imperfectly correlated with the JCC. On this respect, the WTI futures contract is the most natural hedging instrument, since it is highly correlated with the JCC index and it is traded on a daily basis. The swap payoff at cash settlement for the swap payer relative to a future month $m^\star$, $\Pi_{m^\star}(swap)$, is defined as:

$$\Pi_{m^\star}(swap) = V_{m^\star}[P_{m^\star}(JCC) - P_{m^\star}(swap)] \tag{12}$$

where $P_{m^\star}(swap)$ is the swap fixed price and $P_{m^\star}(JCC)$ is the price of JCC index at the future month $m^\star$.

The value of $P_{m^\star}(swap)$ is determined by assuming that the expected value of the payoff defined in equation (12) equals zero:

$$E[\Pi_{m^\star}(swap)] = E[V_{m^\star}(P_{m^\star}(JCC) - P_{m^\star}(swap))] = 0 \tag{13}$$

Equation (13) can be solved for $P_{m^\star}(swap)$ to obtain the expression of the swap price for the JCC:

$$P_{m^\star}(swap) = E[P_{m^\star}(JCC)] \tag{14}$$

The swap price on the JCC index for a future month $m^\star$ is calculated daily according to a two-step procedure. First, estimate the OHR β by regressing the JCC price, $P_m(JCC)$, $m = 1, ..., M$, on the most prompt WTI futures price observed on a monthly frequency, using one of the econometric models discussed in the previous section. Second, multiply the estimated OHR, $\hat{\beta}$, by a weighted sum of the WTI futures prices at maturities $m^\star$ and $m^\star + 1$, and add the estimated constant term, $\hat{c}$, according to the following expression:

$$P_{d,m^\star}(swap) = \hat{\beta}\left(\frac{\bar{n}_{m^\star-1}}{n_{m^\star-1}} F_{d,m^\star}(WTI) + \frac{\tilde{n}_{m^\star-1}}{n_{m^\star-1}} F_{d,m^\star+1}(WTI)\right) + \hat{c} \tag{15}$$

where $F_{d,m^\star}(WTI)$ indicates the WTI futures price observed on the d-th day, $d = 1, ..., D$, with delivery at month $m^\star$; $\bar{n}_{m^\star-1}$ is the number of trading days within month $m^\star - 1$ for the WTI futures

[4] The JCC swap payer pays the JCC fixed price and receives the JCC floating price, where the JCC fixed price is calculated according to equation (15) and the JCC floating price is the JCC actual price.

contract with delivery at month $m^\star$; $\tilde{n}_{m^\star-1} = n_{m^\star-1} - \bar{n}_{m^\star-1}$; $n_{m^\star-1}$ is the number of trading days within month $m^\star - 1$.

The rationale of expression (15) is that $P_{d,m^\star}(swap)$ represents the price an economic agent has to pay to hedge his/her exposure on the JCC index. The error terms of the regression model which is behind equation (15) measure the basis risk, while the constant term captures the fixed component of the swap price that the WTI futures price is not able to explain.

Notice that we use different proportions of two WTI futures contracts in order to construct a portfolio for pricing and hedging the JCC swap. This choice is motivated by observing that two most prompt WTI futures contracts are traded within the month which the JCC price is referred to.[5] The idea is that, during the period of calculation of the JCC index for the reference month $m^\star$, we have to decompose the hedging strategy using a contract which is as close as possible to a spot contract, i.e. the front contract. Furthermore, the introduction of futures contracts is crucial in order to price a swap several months in advance to the delivery date.

The hedging position of the swap payer will consist of selling the correct amount of the most prompt WTI futures contacts, i.e. $\frac{\bar{n}_{m^\star-1}}{n_{m^\star-1}} F_{d,m^\star}(WTI) + \frac{\tilde{n}_{m^\star-1}}{n_{m^\star-1}} F_{d,m^\star+1}(WTI)$.[6] In order to close the financial position, it will be necessary to buy $(1/n_{m^\star-1})\beta$ units of the most prompt WTI futures contracts in each single trading day of the selected month $(m^\star - 1)$, where $n_{m^\star-1}$ is the number of trading days within that month. According to this procedure, at the end of the month the payer of the JCC swap will have no position on future contracts, whereas his/her net balance will be determined by the sum of the difference paid and received during the life of the future contract, plus or minus the difference between the selling price and the buying price.[7]

With a simple procedure (see Section 4.4 for details), it is possible to calculate the maximum absolute value of ϵ, where ϵ is the sum of two components, namely the difference between the estimated swap price in equation (15) and the actual value of the JCC index (i.e. the JCC price difference), and the difference between the revenues from selling a given amount of the most prompt WTI futures contracts and the costs from buying $(1/n_{m^\star-1})\beta$ units of the same futures contracts in order to close the hedging position (i.e. the JCC hedge difference). We then define a bid/ask spread, which allows to offset the remaining risk and whose size is given by the maximum value of the recorded errors ϵ:

[5] Each WTI futures contract with delivery date in month $m^\star$ is traded until, or around, the 20-th day of month $m^\star - 1$, according to the rule that the futures contract expires on the third business day prior to the 25-th calendar day of the month preceding the delivery month. If the 25-th calendar day is a non-business day, the trading activity on the futures contract ceases on the third business day prior to the business day preceding the 25-th calendar day. Thus, within the $m^\star - 1$-th month, which is composed by $n_{m^\star-1}$ trading days, two contracts are traded. The first contract has delivery at month $m^\star$ and is traded during the first $\bar{n}_{m^\star-1}$ trading days. The second contract has delivery at month $m^\star + 1$ and is traded during the remaining $\tilde{n}_{m^\star-1}$ trading days.

[6] This is due to the positive correlation between the JCC price index and the most prompt futures price, as well as to the fact that the payer of the JCC swap is, by definition, paying the fixed price.

[7] Our analysis does not take into account the time value of money and the future/forward convexity adjustment problem.

$$\begin{cases} P_{bid} = P(swap) - \max|\epsilon| \\ P_{ask} = P(swap) + \max|\epsilon| \end{cases} \tag{16}$$

The dimension of the bid/ask spread is directly proportional to the risk aversion of the price maker. With this respect, the bid/ask spread defined by expression (16) should be considered a conservative swap pricing criterion, coherent with a highly risk-adverse behaviour. Conversely, in a competitive market a price maker will probably set a smaller bid/ask spread.

In any case, it is reasonable to price the bid/ask spread of the swap according to the empirical distribution of the errors ϵ in expression (16). If the errors ϵ are normally distributed, we can use the symmetric tails of the normal distribution to construct the price. Alternatively, should the hypothesis of normality be rejected, we can consider a given percentile of the empirical distribution of ϵ, which depends on the trader's risk preferences. For instance, assuming that expected profits are positive 95 percent of the times, we can construct the swap price by adding and subtracting in expression (16) the 95-th percentile of the distribution of ϵ, instead of its maximum value.

The "one-month" swap example is crucial for discussing the more relevant case of a "multi-month" swap on the JCC index. For instance, consider a swap on the JCC index for the future q-th quarter of a given year, with a variable oil volume profile for the future m-th month in the q-th quarter, V_{m_q}. Ignoring the time value of money, the payoff for this "multi-month" swap is:

$$\Pi_q(swap) = \sum_{m_q=1}^{M_q} V_{m_q}[P_{m_q}(swap) - P_{m_q}(JCC)] \tag{17}$$

where M_q=3. The choice of a simple and versatile econometric model for estimating the OHR β, such as specifications (2) and (14), significantly simplifies the procedure to price and hedge the "three-month" swap (17), since the same OHR can be applied for each of the three months of the q-th quarter of the given year. In this context, the (daily) swap price is the weighted average of the swap prices computed on each of the three months in the q-th quarter, with the variable volumes as weights:

$$P_{d,q}(swap) = \frac{1}{M_q} \sum_{m_q=1}^{M_q} V_{m_q}\hat{\beta} P_{d,m_q}(swap) + \hat{c} \tag{18}$$

where $P_{d,m_q}(swap)$ is given by expression (15).

The bid/ask spread is constructed according to equation (16), after running a backtest for each "one-month" swap in the considered quarter and averaging out the results. This bid/ask spread could be reduced by exploiting the correlation among the errors of different months. Alternatively, the formulation proposed in our paper seems to be more protective. In our framework, the final "three-month" swap price is:

$$\begin{cases} P_{bid} = P(swap) - \frac{1}{M_q}\sum_{m_q=1}^{M_q} \max\left|\epsilon_{m_q}\right| \\ P_{ask} = P(swap) + \frac{1}{M_q}\sum_{m_q=1}^{M_q} \max\left|\epsilon_{m_q}\right| \end{cases} \tag{19}$$

The hedging position for a swap payer is to sell the correct amount of WTI futures contracts delivering in each of the three months according to the variable volume. The financial position will be closed for each month using the same procedure as described for the "one-month" swap.

4.4 Evaluating the swap pricing scheme: backtest and rolling regressions

In order to empirically test the pricing mechanism described in the previous section: i) we explain how to calculate the profit and loss ($P\&L$) for the swap trader; ii) we illustrate our approach using two practical examples of a "one-month" JCC swap; iii) we test whether our econometric models are robust to the selection of the relevant sample period.

The swap price is calculated according to equation (15), using the two best performing econometric specifications, namely the simple price-level model and the ARDL model. The availability of daily observations on the one-month, two-month, three-month and four-month WTI futures prices enables us to compute the swap price for each of the subsequent four delivery months.

Since the WTI futures prices are observed on a daily basis, we calculate the JCC swap price for every available observation using equation (15), and we compare the daily swap price with the corresponding monthly actual value of the JCC price. Specifically, our sample on WTI futures prices runs from 2 January 2001 to 30 September 2005, while the JCC swap price is computed on 1184 observations (see Tables 6 and 7).[8]

Our pricing method consists of the following steps. First, multiply the β coefficient reported in Tables 3 and 4 by the daily WTI futures price and add the estimated constant term, according to expression (15), in order to obtain the estimated swap price. Second, calculate the difference between the daily estimated swap price and the actual JCC price index observed for the corresponding month (i.e. the JCC price difference). Third, calculate the difference between the prices of the WTI futures contracts sold and bought in order to close the financial position (i.e. the JCC hedge difference). Fourth, compute the $P\&L$ as the sum between the JCC price difference and the JCC hedge difference.

The analysis of the JCC price difference is extremely important, since it is directly affected by the performance of the econometric models used to estimate the HR. For this reason, we have checked for robustness of our pricing scheme by repeating steps one and two of our procedure for WTI futures contracts at one-month, two-month, three-month and four-month maturities.

[8] More precisely, as the number of trading days is different in each year, the sample size of 1184 daily observations is obtained as follows: 246 daily observations for year 2001; 250 daily observations for years 2002 and 2003; 249 daily observations for year 2004; 189 daily observations for year 2005.

Table 6 presents the maximum and the minimum values of the JCC price difference, as well as the associated mean and standard deviation. The swap price for the first month produces the highest positive difference (+16.50) when priced with the ARDL model, while the lowest negative difference (−8.72) is obtained if estimated with the price-level model. Moreover, with both econometric models positive differences decrease as the reference month for the swap increases. The minimum among the maximum values of the JCC price difference is generated by the price-level model for a four-month WTI futures (i.e. 13.19 for the price-level model versus 13.40 of the ARDL), whereas the minimum among the minimum difference values is obtained again by the price-level model for a three-month WTI futures (i.e. −8.72 for the price-level model versus −9.12 of the ARDL). The difference mean values are monotonically increasing within each model as the maturity of the WTI futures price increases. Moreover, the difference mean values obtained by the price-level model are, for each corresponding maturity, systematically lower than the mean difference produced by the ARDL specification.

It is crucial to understand if the estimation procedure is robust to the choice of the sample period. For this purpose, we have re-estimated models (2) and (10) with a 24-month-window rolling regression. The maximum value of the β coefficient estimated with the price-level model is 0.89, the minimum value is 0.68, whereas the average value, out of 48 regressions, is 0.80. The constant term associated with the maximum estimated β takes, for the same model, a maximum value of 8.83 and a minimum value of 1.26, with an average value of 4.61. Moreover, the maximum and minimum values associated with the β coefficient estimated with the ARDL model are 0.926 and 0.257 respectively, with an average value of 0.784. The estimated constant term is within the interval (5.672, −0.993), with an average value of 2.594. Overall, the price-level model seems to be less sensitive to sample selection than the ARDL model.

We have further investigated the stability of our procedure to calculate the JCC price difference by using a rolling regression approach. The JCC price difference is calculated for each model and for each swap, using the maximum and the minimum estimated β coefficient and the associated constant term (see Table 7). The empirical findings are mixed, although in general they are in favour of the price-level model. When the maximum difference values are considered (see second column of Table 7), the ARDL model outperforms the price-level model for the four-month WTI futures in correspondence of the maximum value of the estimated β coefficient (maximum error values are 12.38 and 13.28, respectively), while for the minimum β values the empirical performance of the four-month WTI futures based on the price-level model is better than the corresponding swap calculated on the ARDL specification (maximum difference values are 16.62 and 44.38, respectively). If we concentrate on the minimum difference values (see third column of Table 7), the price-level model is always preferable to the ARDL model. In particular, the difference of the three-month WTI futures based on model (2) for the maximum value of β is closer to zero than the corresponding difference calculated with model (14) (i.e. −8.96 versus −10.47). The difference of the four-month WTI futures based on the price-level model is lower than the corresponding difference of the two-month and three-month WTI futures computed with the ARDL specification. Finally, within each model and conditional on a specific maximum or minimum value of β, the mean difference values are monotonically increasing as the maturity of the WTI futures price increases.

A backtest for two different swap prices on the JCC will help the reader to understand our pricing and hedging procedure. It has to be noted that backtesting is widely used in investment banks to evaluate the efficiency of pricing models. In this context, our backtesting exercise should be interpreted as an in-sample hedging performance evaluation method.

The first example considers a trader who is requested on April 3, 2006 to price a swap on the JCC for October 2006. The WTI futures prices for October 2006 and November 2006 are US dollars (USD) 69.56 and 69.66, respectively. The most prompt WTI average futures price in September 2006 is USD 63.89, while the JCC floating price for October 2006 is USD 64.44. The HR $\hat{\beta}$ and the constant term $\hat{c}$ are estimated using model (2) and are equal to 0.88 and 2.19, respectively. If the trader's customer decides to close the contract and to receive the fixed price against paying the floating JCC price, the trader will sell the correct amount of WTI futures contracts at the closing price, and he/she will receive around USD 69.59 per contract.[9] Since the trader prices the swap according to equation (15), the swap price is USD 63.15 at mid market, i.e. without taking into account the bid/ask spread. In the delivery month the trader's *P&L* will be computed by summing the difference between the JCC floating price and the JCC fixed price (i.e. the JCC price difference), with the difference between the prices of the WTI futures contracts sold and bought (i.e. the JCC hedge difference). In this particular example, the trader makes a profit of USD 6.98 USD per unit.[10]

In the second example that the trader is asked on February 1, 2005 to price a JCC swap for October 2005. The WTI futures prices for October 2005 and November 2005 are USD 46.56 and 46.27, respectively. The most prompt WTI average futures price in September 2005 is USD 65.55. Assuming that the JCC floating price for October 2005 is USD 59.89 and using the same values for the estimated HR $\hat{\beta}$ and constant term $\hat{c}$, the trader will price the swap considering the correct amount of two WTI future contracts with maturity on October 2005 and November 2005, relative to the number of trading days in September 2005. As in the previous example, the trader will then sell WTI futures contracts and receive around USD 46.46 per unit. At the end of the period, after buying WTI futures contracts in order to close the position, the trader will suffer from a loss of USD 2.09 per unit. A simple extension of the backtest procedure to the whole sample enables the trader to construct the bid/ask spread according to equation (16).

5 Conclusions

The main contribution of this paper is to present a simple strategy for pricing and hedging illiquid products, such as the Japanese crude oil cocktail (JCC) index, the most popular OTC energy derivative in Japan. We have reviewed the existing literature for computing optimal hedge ratios (OHR) and we have proposed a critical classification of the existing approaches. We have compared the em-

[9] USD 69.59 is computed as: $\frac{13}{20}69.56 + \frac{7}{20}69.66$, where 20 is the number of trading days in September 2006, 13 is the number of trading days for the WTI futures contract with maturity on October 2006, and 7 is the number of trading days for the WTI futures contract with maturity on November 2006. [10] USD 6.98 is obtained as the sum between the JCC price difference (USD 1.28 = 64.44 − 63.15) and the JCC hedge difference (USD 5.7 = 69.59 − 63.89).

pirical performance of different econometric models (namely, regression models for price-levels, price first differences, price returns, as well as error correction and autoregressive distributed lag models) in terms of their computed OHR, using monthly data on the JCC over the period Janury 2000-January 2006. We have illustrated and implemented a procedure to cross-hedge and price a swap contract on the JCC price index with a variable oil volume. Moreover, we have explained how to compute a bid/ask spread and to construct the hedging position for the JCC swap.

In order to empirically test the pricing mechanism described in the previous section, we have explained how to calculate the $P\&L$ for the swap trader, we have illustrated our approach using two practical examples of a "one-month" JCC swap and we have tested whether our procedure is robust to the selection of the relevant sample period. The swap price is calculated using the two best performing econometric specifications, namely the simple price-level model and the ARDL model. The availability of daily observations on the one-month, two-month, three-month and four-month WTI futures prices enables us to compute the swap price for each of the subsequent four delivery months.

Our pricing method consists of the following steps. First, multiply the β coefficient by the daily WTI futures price and add the estimated constant term, in order to obtain the estimated swap price. Second, calculate the difference between the daily estimated swap price and the actual JCC price index observed for the corresponding month (i.e. the JCC price difference). Third, calculate the difference between the prices of the WTI futures contracts sold and bought in order to close the financial position (i.e. the JCC hedge difference). Fourth, compute the $P\&L$ as the sum between the JCC price difference and the hedge difference.

We have checked for robustness of our pricing scheme by repeating steps one and two of our procedure for WTI futures contracts at one-month, two-month, three-month and four-month maturities. It is also crucial to understand if the estimation procedure is robust to the choice of the sample period. For this purpose, we have re-estimated models (2) and (10) with a 24-month-window rolling regression. We have further investigated the stability of our procedure to calculate the JCC price difference by using a rolling regression approach.

Finally, a backtest for two different swap prices on the JCC has been illustrated to help the reader to understand our pricing and hedging procedure.

Overall, our empirical findings have shown that it is not necessary to use complex econometric techniques, since the price level regression model permits to compute more reliable optimal hedge ratio relative to its competing alternatives. This result is particularly interesting for traders operating in large energy companies, who have exposures on illiquid markets and intend to directly hedge their positions with simple and versatile techniques.

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Table 1: Summary of the surveyed literature

Year	Authors	Model	Data	Time period	Frequency
1987	Witt et al.	(2), (3),(4)	Barley and sorghum cash prices, nearby corn future prices	1975-1984	weekly
1991	Myers	(3), GARCH	wheat prices	6/1977-5/1983	weekly
1993	Gosh	(3), (6)	Closing price for the S&P 500 index, Dow Jones Industrial Average, New York Stock Exchange composite index and daily nearby settlement price of S&P 500 index future contracts	2/1/1990-5/12/1991	daily
2000	Coffey et al.	(2)	Five grain co-products	1981-1998	weekly
2002	Moschini and Myers	BEKK	Corn prices	1/1976-6/1997	weekly
2002	Tunaru and Tan	(2)	Kerosene price and crude oil futures traded at IPE and NYMEX, heating oil (NYMEX),unleaded regular gas (NYMEX),liquid propane gas (NYMEX)	4/2/1997-21/8/2001	weekly
2002	Harris and Shen	EWMA	FTSE100 index	4/5/1985-3/5/2002	daily
2003	Moosa	(2), (3),(6)	Cash and futures prices of Australian stocks (All Ords index and SPI index)	1/1987 - 12/1997	monthly
			Spot exchange rates of the UK pound and the Canadian dollar against US dollar	1/1980-4/2004	quarterly
2004	Casillo	(3), VAR, VECM, BEKK	MIB30 index and FIB30	28/11/1994-10/6/2004	daily
2005	Gosh and Bolding	(3),(6)	Euro spot and futures traded on the Chicago Mercantile Exchange	2/1/2001-7/6/2004	daily
2005	Kenourgios et al.	(3),(6), GARCH, EGARCH	S&P 500 future contract	7/1992-6/2002	weekly

Table 2: Augmented Dickey-Fuller (ADF) unit root tests

	JCC	WTI	Coint. residuals
ADF (series in level)	0.709	0.292	-4.008**
ADF (series in first differences)	-6.787**	-7.766**	-

Notes: *(**) indicates rejection of the null hypothesis of a unit root at 10%(5%) significance level; Coint. residuals = residuals from the cointegrating regression of the JCC price on the WTI futures price.

Table 3: Estimated optimal hedge ratios (January 2000 - January 2006)

	Model (2)	Model (3)	Model (5)	Model (6)
β	0.876** (0.016)	0.589** (0.052)	0.641** (0.055)	0.718** (0.061)
constant	2.193** (0.598)	0.156 (0.140)	0.003 (0.004)	0.002 (0.004)
ECT(-1)	-	-	-	-0.275** (0.109)
Adj.R^2	0.976	0.641	0.653	0.677

Notes: *(**) indicates statistical significance at 10%(5%); standard errors are reported in parentheses.

Table 4: Estimated optimal hedge ratios (January 2000 - January 2006)

	Model (9)	Model (10)
β	0.855** (0.025)	0.909**(0.067)
constant	2.978** (0.919)	0.326 (0.499)
MA(1)	0.662**(0.117)	-
MA(2)	0.318**(0.117)	-
Adj.R^2	0.984	0.987

Notes: *(**) indicates statistical significance at 10%(5%); standard errors are reported in parentheses.

Table 5: Diagnostic tests for model residuals

	Model (2)	Model (3)	Model (5)	Model (6)	Model (9)	Model (10)
B-G test	28.17(0.000)	0.382(0.825)	0.140(0.932)	1.540(0.463)	3.014(0.221)	1.677(0.432)
J-B test	65.76(0.000)	35.02(0.000)	112.98(0.000)	117.01(0.000	31.07(0.000)	45.94(0.000)
W test	11.69(0.003)	1.864(0.393)	1.360(0.035)	1.440(0.837)	6.505(0.038)	8.985(0.174)
S.E.	1.590	1.175	0.035	0.034	1.266	1.153
N.	73	72	72	72	73	72
N. p.	2	2	2	3	4	4

Notes: P-values are reported in parentheses.

Table 6: Backtests for price-level model (2) and ARDL model (14)

Model	Mean	Maximum	Minimum	Standard deviation
Model (2) (1-month)	1.40	16.17	-9.42	4.27
Model (2) (2-month)	1.48	14.55	-9.06	4.04
Model (2) (3-month)	1.66	13.68	-8.72	3.94
Model (2) (4-month)	1.90	13.19	-8.80	3.89
Model (14) (1-month)	2.12	16.50	-9.37	4.29
Model (14) (2-month)	2.20	14.82	-9.12	4.07
Model (14) (3-month)	2.38	13.92	-9.15	3.98
Model (14) (4-month)	2.63	13.40	-9.23	3.94

Notes: Number of daily observations = 1184; Mean (maximum) [minimum] = mean (maximum) [minimum] of the difference between the estimated swap price and the floating JCC price (i.e. the JCC price difference).

Table 7: Backtests for price-level model (2) and ARDL model (14) (rolling regressions)

Model	Mean	Maximum	Minimum	Standard deviation
Model (2) (Max β, 1-month)	1.75	16.33	-9.42	4.27
Model (2) (Max β, 2-month)	1.83	14.67	-9.06	4.05
Model (2) (Max β, 3-month)	2.01	13.78	-8.96	3.96
Model (2) (Max β, 4-month)	2.25	13.28	-9.04	3.91
Model (2) (Min β, 1-month)	1.80	18.93	-9.01	4.88
Model (2) (Min β, 2-month)	1.86	17.68	-9.25	4.65
Model (2) (Min β, 3-month)	2.00	17.00	-9.22	4.53
Model (2) (Min β, 4-month)	2.18	16.62	-8.96	4.45
Model (14) (Max β, 1-month)	1.35	15.54	-10.48	4.31
Model (14) (Max β, 2-month)	1.43	13.82	-10.47	4.10
Model (14) (Max β, 3-month)	1.62	12.90	-10.51	4.02
Model (14) (Max β, 4-month)	1.86	12.38	-10.59	3.98
Model (14) (Min β, 1-month)	23.23	45.26	9.79	8.38
Model (14) (Min β, 2-month)	23.25	44.78	9.70	8.29
Model (14) (Min β, 3-month)	23.30	44.52	9.70	8.24
Model (14) (Min β, 4-month)	23.37	44.38	9.81	8.20

Notes: Number of daily observations = 1184; Mean (maximum) [minimum] = mean (maximum) [minimum] of the difference between the estimated swap price and the floating JCC price (i.e. the JCC price difference); Model (i) (Max[Min] β, j-month) indicates the JCC price difference based on model (i) (i=2,14), calculated for the j-month WTI futures price (j=1,...,4) and the Maximum [Minimum] value of the estimated β; Standard deviation = standard deviation of the JCC price difference.

Figure 1: JCC price and one-month WTI (WTI1) futures price (January 2000 - January 2006)

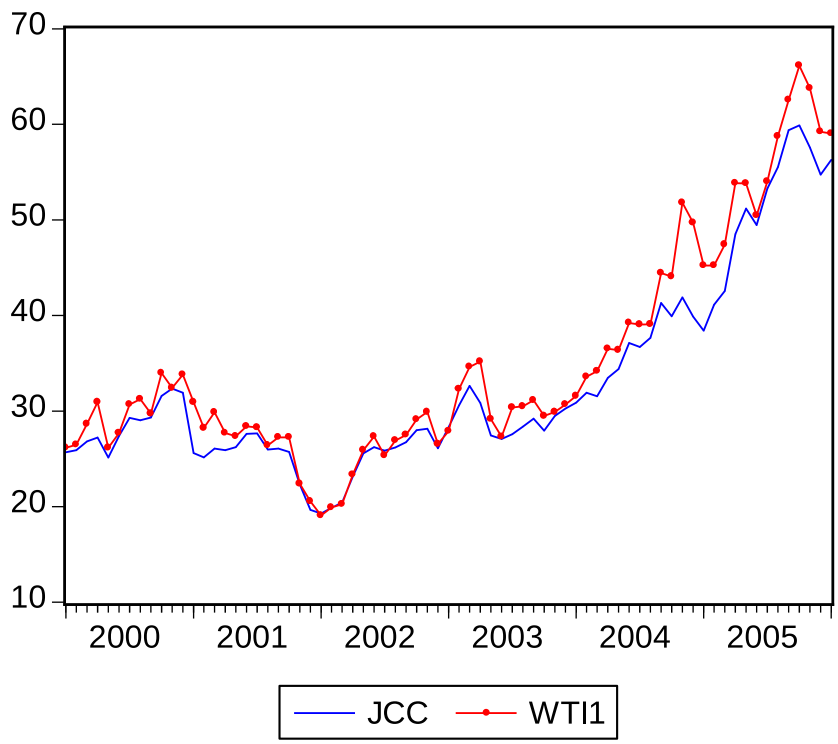
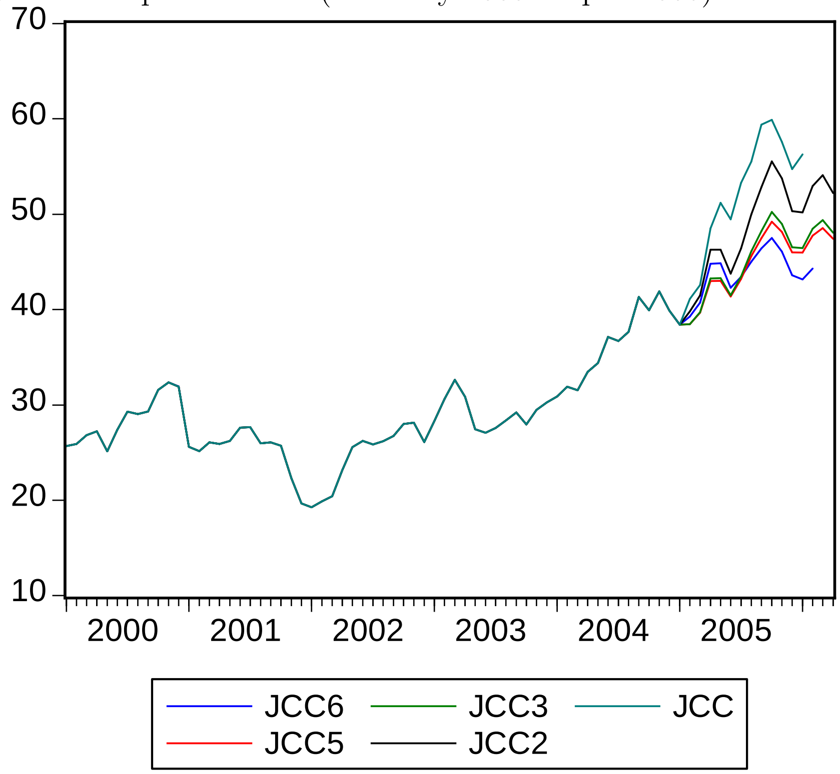
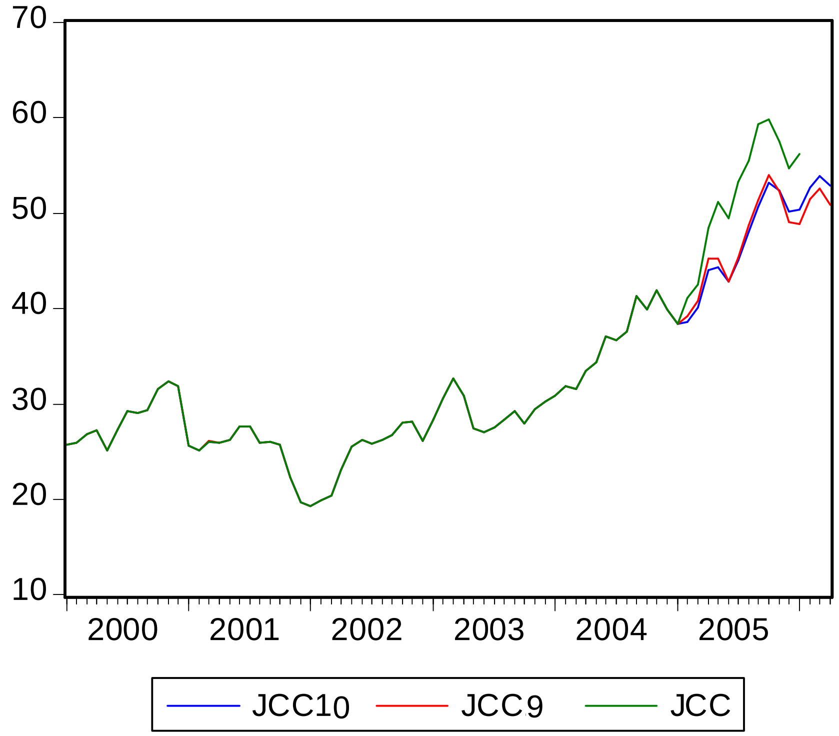


Figure 2: Out-of-sample forecasts (February 2005 - April 2006)





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