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Marc Gronwald

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Abstract

This paper is concerned with the statistical behavior of oil prices in two ways. It, firstly, applies a combined jump GARCH in order to characterize the behavior of daily, weekly as well as monthly oil prices. Secondly, it relates its empirical results to implications of Hotelling-type resource extraction models. The empirical analysis shows that oil prices are characterized by GARCH as well as conditional jump behavior and that a considerable portion of the total variance is triggered by sudden extreme price movements. This finding implies that, first, oil price signals are not reliable and, as a consequence, both finding optimal extraction paths and decisions regarding the transmission to alternative technologies are likely to be compromised. Second, this behavior is in stark contrast to the notion of deterministic trends in the price of oil.

JEL-Code: C220, Q300.

Keywords: oil price, conditional jumps, GARCH, Hotelling, climate change, deterministic trend.

Marc Gronwald
Ifo Institute – Leibniz Institute for Economic Research
at the University of Munich
Poschingerstrasse 5
Germany – 81679 Munich
gronwald@ifo.de

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1 Introduction

Oil prices have been carefully followed and analyzed by empirical and theoretical economists alike for more than three decades. A sufficient understanding of the signals that emanate from the price of oil is essential for various reasons. Certainly not only short-run hedging strategies, but also rather long-run decisions are based on information provided by the price of this essential resource. Oil remains an important input factor influencing a variety of investment decisions in virtually all economic sectors. As a fossil fuel, furthermore, oil is among the main drivers of climate change. The decision when to invest in back-stop technologies is of particular importance. Standard economic theories suggest that also owners of oil resources base their decision when to extract their resource on the price of oil.

This paper's contribution to the oil price literature is twofold. It, firstly, aims at characterizing the behavior of oil prices and, secondly, it discusses how this behavior potentially affects resource extraction decisions as well as decisions regarding the investment in alternative technologies.

The first issue is tackled by applying Chan and Maheu's (2002) combined jump GARCH model to daily, weekly as well as monthly oil price data. Jump models, in general, have proven to be a useful tool for capturing extreme price movements triggered by unexpected news. As the oil market considered being subject to various political influences, jump models lend themselves as a method for modeling oil prices [Jorion, 1988]. Two variants of the model are considered. The time-constant jump intensity model is the simplest way to treat jumps and GARCH in a single approach and the application of this variant yields interesting insights regarding the role of extreme price movements and which portion of the overall variance can be attributed to this particular type of price change [Nimalendran, 1994]. The key results that emerge from this exercise are that oil prices at all frequencies under consideration are characterized by both GARCH and conditional jump behavior and that a considerable part of the variance is attributable to jumps. Thus, extreme price movements are present and the empirical distribution of oil price changes has heavy tails.

The more complex time-varying jump intensity model allows one to study changes in both the intensity of the sudden movements and their contribution to the total variance. Evidence of time-varying jump intensity is found for daily oil prices. It is, furthermore, shown that price movements that are captured by the jump component became less frequent in more recent years. Thus, the portion of the variance triggered by jumps decreased. This finding can be explained by a general increase of the volatility of oil prices. Information criteria as well as likelihood ratio tests clearly indicate that the models applied here provide a good fit to the data. These findings are a valuable supplement to those obtained by Askari and Krichene (2008) and Lee et al. (2010).

They, furthermore, suggest that it is doubtful that oil prices can reliably provide the information they are supposed to do. Thus, finding the optimal depletion path for oil as well the optimal transition to alternative technologies are likely to be compromised.

The framework most widely used for modeling these essential economic decisions goes back to Hotelling (1931). According to the well-known Hotelling rule, the price of an exhaustible resource, in optimum, grows at the rate of interest. This framework currently celebrates a remarkable comeback - Sinn's (2008) influential paper on the so-called Green Paradox employs this framework. Sinn emphasizes that oil is not just an exhaustible resource, but also a fossil fuel and, thus, one of the main sources of carbon emissions. As a consequence, the time path of oil extraction is crucial for the development of the global climate. Sinn (2008) shows that ignoring global warming leads to a current overextraction of oil. Various papers emerged in response to Sinn (2008), see in particular contributions by Hoel (2010) and Withagen and van der Ploeg (2011). Pindyck (1981), however, demonstrated that uncertainty regarding oil prices affects the extraction path; he, however, left open the question whether or not jumps are actually present.

Valuable insights regarding the decision on the development of alternative technologies emerge from Holland's (2008) reconcilement of Hotelling and peak oil models. He shows that oil prices are a better scarcity indicator than oil production is, and, thus, provides information that is crucial for decisions regarding the transition to alternative technologies. Holland, however, expresses concerns regarding the high degree of short-run volatility. This paper's findings show that these concerns seem to be justified.

Difficulties in finding the optimal moment to switch to alternative technologies is likely to negatively influence not only the economic performance of firms, but also the global climate. Thus, this paper's findings point to enormous potential for future research. Neither scientific papers nor applied policy evaluation studies should rely on implausible assumptions regarding the behavior of oil prices. Although this paper does not provide direct tests of hypotheses derived from the Hotelling framework, but rather a comparison on an illustrative level, it still goes beyond the vast majority of econometric studies of oil prices who are merely interested in the technical performance of their models. In that respect it can be seen to be in the tradition of Pindyck (1999).

The theories discussed above, moreover, imply that the oil price path is generally upward trending. This led many researchers to study whether or not deterministic trends are present in prices of exhaustible resources, see e.g. Slade (1983) and Lee et al. (2006). The finding of jumps, however, is at odds with this notion of deterministic trends in oil prices. The non-existence of a long-run trend, however, implies that resource owners cannot assume that oil prices will increase with a sufficient degree of certainty in the near future. In consequence, there is an incentive to extract a larger amount of the resource for every given remaining stock than indicated by the benchmark extraction path following Hotelling (1931).

The notion that the behavior of oil prices is marked by a considerable idiosyncrasy is also expressed by Hamilton (2008). His survey-paper summarizes that "changes in the real price of oil have historically tended to be (1) permanent, (2) difficult to predict, and (3) governed by very different regimes at different points in time." Similarly, Wirl (2008) emphasizes that the development of oil prices contains many elements of surprise.

Many of the approaches used in a vast literature attempting to explain oil prices, however, contradict each other. In addition to Hotelling's (1931) assertion that oil is an exhaustible resource and that the price of such a resource, in optimum, grows with the rate of interest, papers such as Krichene

(2002) and Dees et al. (2007) employ macroeconomic supply and demand frameworks in order to explain the price of oil. Kaufmann et al. (2008) and Kaufmann and Ullman (2009), what is more, investigate oil price behavior in a more informal way and focus on issues such as OPEC power and the role of speculation.

Oil prices, furthermore, is dealt with in an enormous amount of papers in the area of financial econometrics. Issues under consideration there include oil price volatility, hedging strategies as well as oil price forecasts. Recent papers by Agnolucci (2009), Vo (2009), Wei et al. (2010) as well as Chang et al (2010) epitomize these concerted research efforts. These papers, mainly, use daily oil price data and employ sophisticated empirical techniques. Even the pure fact that techniques such as GARCH models, artificial neural networks and jump-diffusion processes are used signals that the behavior of oil prices is not easy to capture. Lee et al.'s (1995) application of GARCH models to quarterly oil price data, moreover, indicates that this also applies to lower data frequencies.

The remainder of this paper is organized as follows: the following Section 2 provides a descriptive analysis of the data and Section 3 outlines the Chan and Maheu (2002) method. Sections 4 and 5 present the empirical results and a discussion of which. Section 6, finally, concludes.

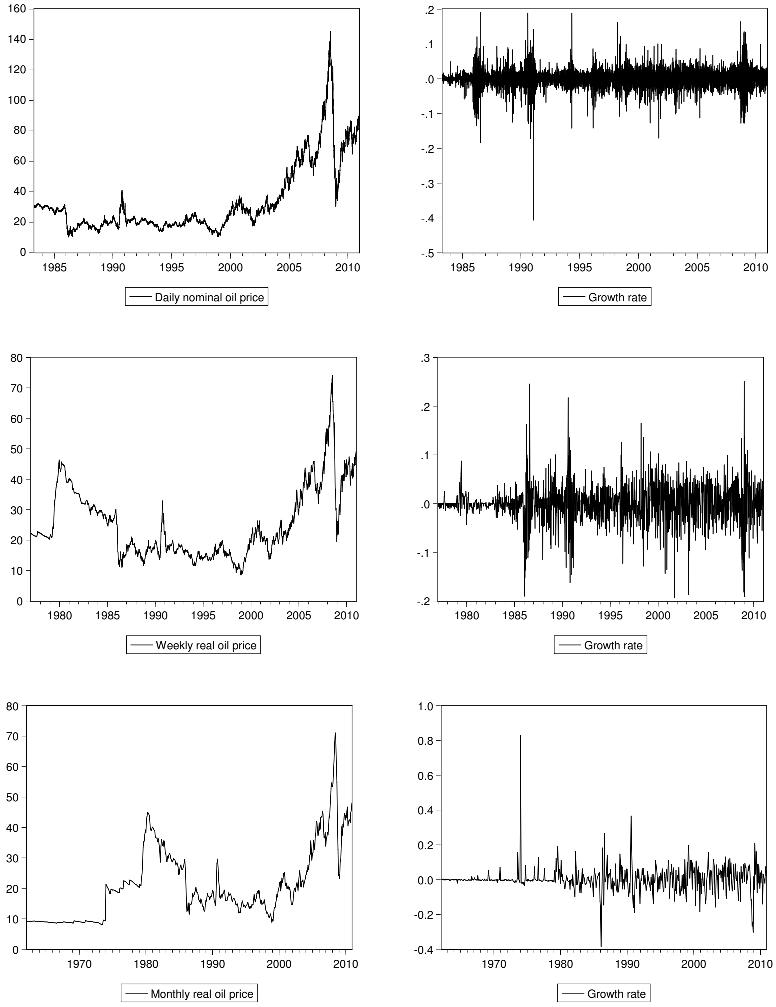
2 Data

The basis for the characterization of the behavior of oil prices (West Texas Intermediate) and the discussion of its implications for important economic decisions is the application of a combined jump GARCH model to daily, weekly as well as monthly data. The sample periods end in December 2010. Due to data availability and in order to ensure that there are no undesired effects of certain periods, the samples begin in April 1983 (daily), January 1977 (weekly) as well as February 1962 (monthly data). Growth rates of nominal daily and real weekly as well as monthly oil prices are used in this study; real oil prices are obtained by deflating the nominal series by the US producer price index.[1]

The following brief descriptive analysis of the data used in this paper vividly illustrates that the model used for modeling oil prices should be able to capture extreme price movements. Figure 1's time series plots of the original data as well as the growth rates clearly indicates that - for all three frequencies - phases with different degrees of volatility are present. Moreover, during all phases sudden extreme price movements that exceed the respective current volatility are present. These extreme movements are associated with famous incidents such as the oil crises, the OPEC collapse or the Gulf War 1990/1991. The kernel density estimates and the quantile-quantile plots displayed in Figure 2 confirm this impression. In both types of diagrams the empirical distributions are plotted together with theoretical normal densities fitted to the data. The deviations from this theoretical benchmark are obvious. There is evidence of heavy tails for all frequencies under consideration here. However, a few interesting differences are also apparent. For the case

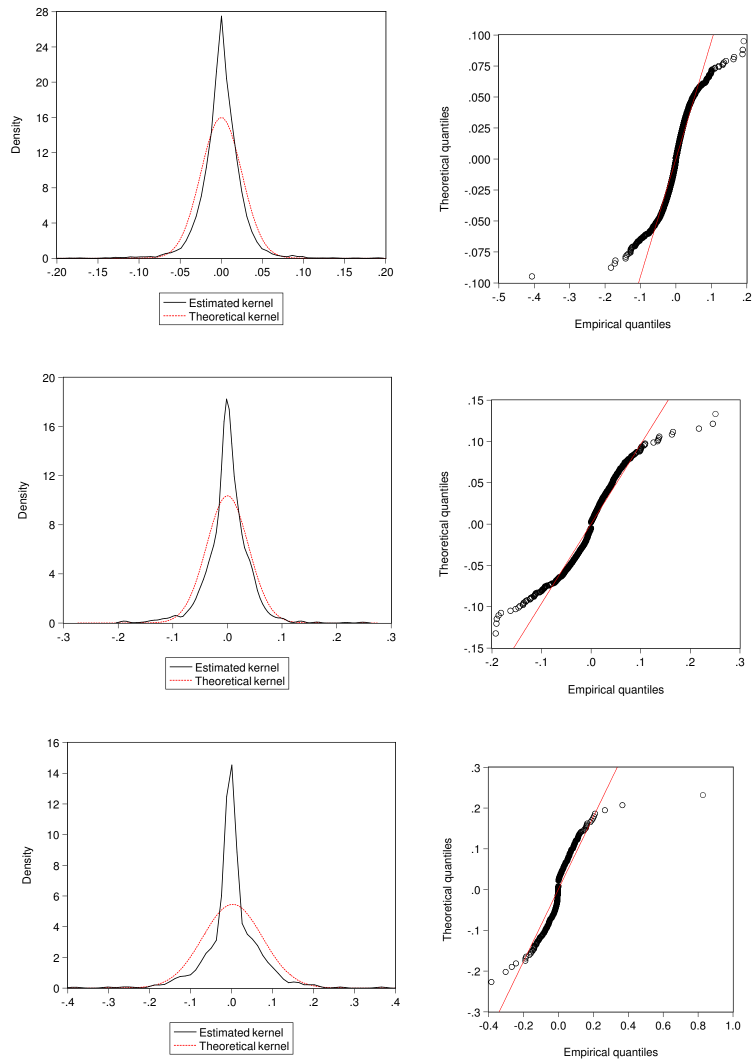
[1]The reason for this procedure is that the applied method requires the data to be stationary. Moreover, the focus of this paper is on extreme oil price movements rather than on extreme levels. Standard unit root tests clearly indicate that unit roots are present in the log-price series. The detailed results can be obtained from the author upon request.

Figure 1: Price of Oil



of the daily data the mere number of extreme price movements seems to be larger and there are more extreme negative movements than positive ones. Both the weekly and the monthly data, in contrast, appear to have different properties. Here, the extent of these extreme movements is larger, but there are more intriguing positive price changes. In any case, the growth rates of

Figure 2: Descriptive graphs



the price of oil do not seem to be governed by a normal distribution. Volatility is changing over time and there is evidence of extreme price movements for all frequencies under consideration and throughout the entire sample period. This needs to be taken into account when it comes to empirically analyzing oil price data. Models such as the ARJI-GARCH model proposed by Chan and Maheu (2002) have proven to be useful in this regard. The following section outlines this method.

3 Method

The Chan and Maheu (2002) method applied in this paper combines conditional jump with frequently applied GARCH models. Consider the following model:

$$y_t = \mu + \sum_{i=1}^{l} \phi_i y_{t-i} + \sqrt{h_t} z_t + \sum_{k=1}^{n_t} X_{t,k} \tag{1}$$

with $z_t \sim NID(0,1)$. h_t follows a GARCH(p,q) process [Bollerslev, 1986]:

$$h_t = \omega + \sum_{i=1}^{q} \alpha_i \epsilon_{t-i}^2 + \sum_{i=1}^{p} \beta_i h_{t-i} \tag{2}$$

The conditional jump size $X_{t,k}$, given the history of observations $\Phi_{t-1} = \{y_{t-1}, \ldots, y_1\}$, is assumed to be normally distributed with mean θ_t and variance δ_t^2; n_t describes the number of jumps that arrive between $t-1$ and t and follows a Poisson distribution with $\lambda_t > 0$:

$$P(n_t = j|\Phi_{t-i}) = \frac{\lambda_t^j}{j!} e^{-\lambda_t} \tag{3}$$

λ_t is called jump-intensity. Two variants of the model are applied: a constant jump-intensity model with $\lambda_t = \lambda$, $\theta_t = \theta$, and $\delta_t^2 = \delta^2$ and a time-varying jump-intensity model. For the latter, λ_t is assumed to follow the auto-regressive process

$$\lambda_t = \lambda_0 + \sum_{i=1}^{r} \rho_i \lambda_{t-i} + \sum_{i=1}^{s} \gamma_i \xi_{t-i}. \tag{4}$$

The jump-intensity residual ξ_t is calculated as

$$\xi_{t-i} \equiv E[n_{t-i}|\Phi_{t-i}] - \lambda_{t-i} = \sum_{j=0}^{\infty} jP(n_{t-i}|\Phi_{t-i}) - \lambda_{t-i}. \tag{5}$$

Using the observation x_t and Bayes rule, the probability of the occurrence of j jumps at time t can be written as

$$P(n_t = j|\Phi_t) = \frac{f(x_t|n_t = j, \Phi_{t-1})P(n_t = j|\Phi_{t-1})}{P(x_t|\Phi_{t-1})} \tag{6}$$

Finally, let Σ^2 denote the total variance of y_t. According to Nimalendran (1994), Σ^2 can be decomposed in the diffusion-induced and the jump-induced variance and be written as follows:

$$\Sigma^2 = h_t + \lambda_t(\theta^2 + \delta^2). \tag{7}$$

Chan and Maheu (2002)'s method (and bivariate extensions of which) has been successfully applied to various types of financial market data, e.g. stock market returns [Chan and Maheu, 2002], exchange rates [Chan, 2003; Chan, 2004], and copper prices [Chan and Young, 2006]. There are two other recent papers which use jump models in order to investigate the behavior of oil price data. Askari and Krichene (2008), however, restrict themselves to applying a time-invariant jump intensity model and to using only daily data from 2002-2006. Lee et al. (2010) also consider daily data only and do not discuss economic implications of their results. Moreover, none of the two papers considers the variance decomposition procedure put forward by Nimalendram (1994).

4 Results

This section presents the results obtained from applying Chan and Maheu's (2002) method to oil price's growth rate. Table 1 displays the estimates for

Table 1: Constant and time-varying jump-intensity models

Frequency	Daily		Weekly	Monthly
Parameter	Constant	ARJI	Constant	Constant
μ	3.6E-04	3.8E-04	4.8E-16	-1.7E-03
	(0.0542)	(0.0284)	(0.0001)	(0.0001)
ϕ_1	-0.0260	-0.0272	-0.2267	0.2022
	(0.0327)	(0.0208)	(0.0001)	(0.0001)
ω	4.8E-07	4.0E-07	2.8E-31	1.6e-06
	(0.0224)	(0.0415)	(0.0001)	(0.0030)
α	0.0631	0.0397	0.1637	0.3884
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
β	0.9240	0.9464	0.8199	0.5236
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
δ	0.0411	0.0343	0.0383	0.0943
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
θ	-6.1E-03	-4.3E-03	5.6e-03	0.0242
	(0.0279)	(0.0229)	(0.1094)	(0.0310)
λ	0.0644	0.0377	0.1375	0.1639
	(0.0001)	(0.0002)	(0.0001)	(0.0001)
ρ	-	0.7048	-	-
		(0.0001)		
γ	-	0.5661	-	-
		(0.0001)		
Jump-induced variance(%)	17.58	31.58	13.24	27.14

Note: p-values in parentheses.

the constant and, for the daily data also the autoregressive, jump-intensity model. In each model, one lag of the endogenous variable as well as a constant are included. The key messages that emerges from this exercise is

Table 2: Model performance

Model selection criteria							
	Daily			Weekly		Monthly	
Criterion	GARCH	Constant	ARJI	GARCH	Constant	GARCH	Constant
LogL	17,540.68	17,717.25	17,745.59	3,857.00	3,913.92	858.92	1,101.84
AIC	-4.9606	-5.0097	-5.0171	-4.345	-4.411	-2.919	-3.740
BIC	-4.9557	-5.0019	-5.0074	-4.331	-4.386	-2.882	-3.680
HQ	-4.9589	-5.0070	-5.0138	-4.339	-4.402	-2.905	-3.716
Likelihood ratio test							
Models	Test statistic						
CJI vs. GARCH		353.15***			113.83***		485.83***
ARJI vs. GARCH			409.81***				
ARJI vs. CJI			56.66***				

Note: GARCH denotes a standard GARCH(1,1) model, CJI the time-constant jump intensity model and ARJI the autoregressive jump intensity model.

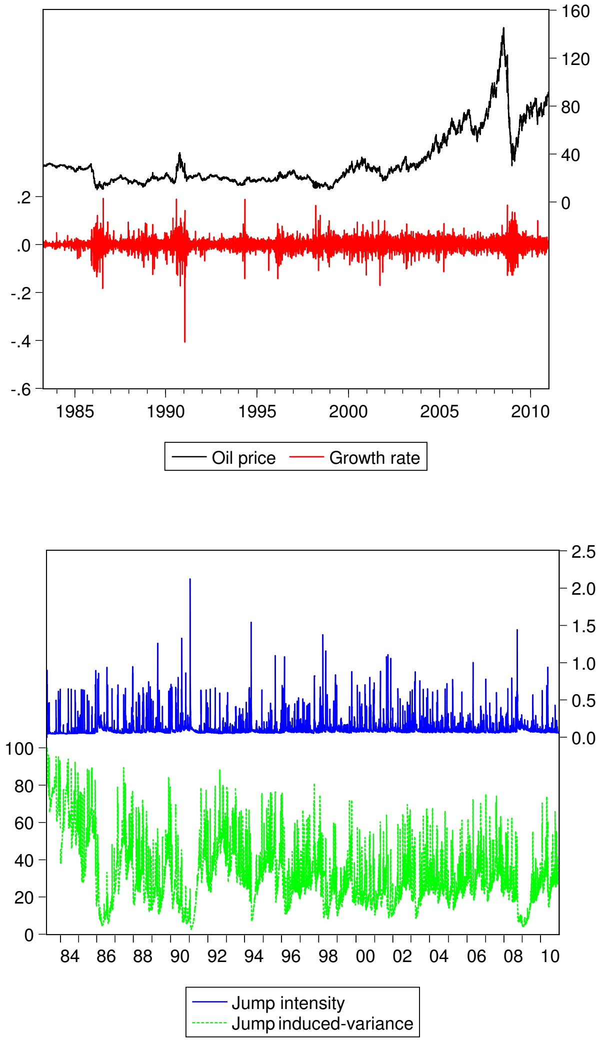
that - with only one exception - all jump parameters are highly significant. While for the weekly and monthly data evidence of constant jump intensity is found, the daily data is characterized by time-varying jump intensity. Consulting the parameter estimates provides further valuable insights. While the average jump size θ is found to be negative for both models with daily data, estimates for the two other frequencies suggest that an average jump is positive. This result is anticipated from Section 2's descriptive analysis. Employing the variance decomposition procedure put forward by Nimalendram (1994) highlights the jump component's impact: up to 30% of the variance is attributable to jumps.

Finally, the usefulness of the jump models is further documented by both the standard information criteria and the likelihood ratio test, see Table 2. It is evident that the constant jump intensity GARCH model outperforms a standard GARCH(1,1) model (estimated as benchmark). For the daily data, moreover, the ARJI model is found to outperform both the benchmark GARCH(1,1) and the constant jump intensity GARCH model.

The finding of time-varying jump intensity for the daily data allows one to investigate the jump behavior of oil prices in greater depth. In particular, it is possible to infer whether different regimes are present.[2] Figure 3 displays plots of the level of oil prices as well as their growth rate together with, first, the time-varying jump intensity and, second, the time-varying portion of variance which is attributable to jumps. There are various findings: the jump-intensity generally takes values between 0 and 2.5. Mostly it is close to 0; only when large price movements occur the intensity does increase. These increases exceed values of 0.5 only in rare cases. Taking a close look at the development of the jump intensities shows that there is a change in this behavior. Intensities of about 0.5 occur more often in the pre-Gulf War period than in the subsequent more tranquil period. The beginning of the oil price increase in 1998 marks another change in that regard. The extreme jumps, in addition to that, also seem to be more frequent in earlier parts of the sample. Moreover, the intensity does not return to its close-to-zero level in a few cases only: after the OPEC collapse, during the oil price decline after the Gulf War and during the price collapse witnessed in the second half of 2008. Thus, the general behavior of oil prices has undergone a remarkable change: earlier parts of the sample are generally characterized by a more tranquil oil price behavior with only occasional large movements. These movements,

[2] This procedure takes care of the structural break analysis conducted by Lee et al. (2010). The approach applied here, however, is more flexible as it does not rely on the results of structural break tests. Moreover, Lee et al. (2010) consider data only up to the end of 2007 and it is not unlikely that the number of breakpoints changed due to the oil price hike observed in 2008.

Figure 3: Jump intensities



however, exceeded other price movements of that time to a larger extent and, therefore, are regarded as jumps. During later periods, the general variability of oil prices increased and, compared to that, the extent the extreme price movements exceed other ones is smaller. In consequence, there are fewer moments with extreme jump intensities.

These findings are also reflected by the time-varying portion of jump-induced variance: In particular in earlier stages and after the Gulf War the portion is found to be close to 100 %. With the beginning of the oil price increase in 1998, the portion began to fluctuate between 20 and 70 per cent. Noticeable are the decreases to values of less than 10 percent which occur the same three times the jump intensity does not return to the close-to-zero level. These three periods are marked by an extreme initial price movement. In the aftermath of each of those, the market became generally more volatile, but a larger portion of this volatility is captured by the GARCH component of the model.

To summarize, there is a considerable degree of variability not only in oil prices themselves, but also in the behavior. Chan and Maheu's (2002) combined jump GARCH model has proven to be a useful tool for capturing the peculiar behavior of oil prices. The jump parameters are significant and it is shown that the jump models provide a good fit to the data. In other words, oil prices are not only characterized by time-varying volatility, but also by extreme price movements which exceed the current respective market volatility. These jumps capture extreme price movements which are often driven by political influences. The portion of the variance attributable to the jumps is considerably high, but lower in more recent periods than compared in the early 1980ies. This is explained by a general increase in the volatility of oil prices.

Having summarized the empirical results, one specific characteristic of the estimated model (Equation 1) is now highlighted. The model contains a GARCH as well as a jump component, but no correction mechanism. Thus, these sudden movements moves oil prices away from its previous level. Oil prices do not exhibit a stable and predictable behavior, which implies that price signals cannot be regarded as particularly reliable.

It is plausible to assume that this behavior influences important decisions which are based on information provided by the price of oil. Among the most important ones are the decision when to invest in alternative technologies and when to extract oil. As oil is not just a normal input factor, but also a exhaustible fossil resource, these decisions do not only affect economic performances of firms, but also the further development of the global climate. To better understand the possible effect of the behavior of the price of oil on these decisions, the next section relates this paper's empirical findings to the theories by Hotelling (1931) and Holland (2008).

5 Discussion

The extent to which the problem of climate change is going to compound largely depends on the development of the stock of carbon in the atmosphere. This stock is mirrored by the amount of carbon in situ. Therefore, the decision when to extract the fossil fuel resources and when to switch to alternative technologies have important implications that go beyond those of other decisions considered in economic studies. The theoretical framework predominantly used to model these decisions goes back to Hotelling (1931). This seminal paper derived the famous Hotelling rule according to which the price of oil, in optimum, grows with the rate of interest. This framework currently celebrates a remarkable comeback. Sinn (2008) proposes an extension of a traditional Hotelling resource extraction model and links the issue of resource extraction to that of climate change. He shows that the Pareto-optimal extraction of oil under consideration of global warming is smaller than without considering this issue. In other words, if resource owners do not take global warming into account, there is a current overextraction of oil.[3] Sinn (2008), furthermore, shows that, under certain conditions, climate policies can induce incentives for the resource owners to bring forward rather than postpone the extraction of their oil. Sinn refers to this effect as Green Paradox and his paper sparked enormous research efforts. The papers by e.g. Withagen and van der Ploeg (2011) on the role of backstop technologies as well as Hoel (2010) on carbon tax expectations epitomize the offshoot of this literature.

The Hotelling-framework, however, has been criticized for not being able to reproduce a pattern observed in actual extraction paths: a bell shaped path with a unique production peak. Thus, Hotelling-type resource extraction models are at odds with the so-called peak oil literature which goes back to Hubbert (1956). His seminal paper bases its considerations on geological properties of oil fields and was able to correctly predict the peak in US oil production. This model class, however, ignores important economic

[3]For an earlier, "non-Hotelling" consideration of this issue see Withagen (1994).

issues such as price effects. In order to reconcile these two areas of research, Holland (2008) proposes four theoretical models that deal with issues such as demand shifts, technological change, reserves growth and site development. Holland's (2008) core conclusion is derived from a combination of these four models. According to that, oil prices are a better indicator of resource scarcity than oil production is. This finding is of particular importance for decisions regarding the transition to alternative technologies. These theoretical considerations, however, suggest that the oil price path is either upward trending or U-shaped. Whether or not there is empirical support for this feature can been investigated by testing for the existence of deterministic trends in oil prices. The corresponding research efforts, however, did not yield unambiguous results. While Slade (1988) finds evidence of stochastic trends, Slade (1982) and Lee et al. (2006) conclude that quadratic trends and deterministic trends with structural breaks, respectively, are present. Pindyck (1999), finally, promotes the view that the real oil price fluctuates around a long-term trend which itself is fluctuating stochastically. These findings are nicely summarized by Livornis (2009, p. 37): on the one hand, he finds, that "overall one cannot conclude that the Hotelling Rule has been a significant force governing the evolution of observed price paths for nonrenewable resources". On the other, "nothing we have observed in the evolution of prices is inconsistent with the Hotelling Rule."

Having sketched these considerations, the relationship between them and this paper's results is now discussed.[4] By proceeding in this particular way

[4]Investigating the underlying causes of oil price volatility in general and extreme oil price movements in particular falls outside the scope of this paper. Thus, no attempt is undertaken to investigate whether or not the extreme movements reflect changes in

this paper goes beyond many others papers that are concerned with the behavior of oil prices. In this regard, it is in the spirit of Pindyck (1999). The empirical findings presented here suggest that assuming oil prices to follow an upward trend is, at any rate, debatable. Strong evidence of conditional heteroscedasticity and heavy tails in the empirical distribution of oil price changes is found. What is more, there is also evidence of conditional jumps, which implies that there are "discontinuous" price movements. As the empirical model includes no correction mechanism for these jumps, their occurrence is at odds with the notion of deterministic trends in oil prices. It is, however, generally in line with Pindyck's (1999) stochastically fluctuating trends in real oil prices.[5]

It is not unlikely that this behavior of oil prices affects the decisions when to extract the oil and when to invest in alternative technologies. This conclusion is based on general insights that emerged from the real option literature. Dixit and Pindyck's (1994) consideration of different stochastic processes in real option models clearly shows that assumptions regarding this process are crucial for the optimal investment rule. This issue is also addressed in Miller and Zhang (1996), Baker et al. (1998), Pindyck (1999), and Postali and Picchetti (2006). Most certainly, decisions regarding oil extraction paths and the transition to alternative technologies are not as straightforward as suggested by Holland (2008). What is more, the non-existence of a long-run trend is likely to cause a current overextraction of oil

fundamental values or are excessive. For discussions of sources of oil price volatility, see e.g. Kaufmann (1995) as well as Wirl (2008).

[5]It should be noted that Pindyck's (1999) empirical approach also allows for downward sloping trends.

compared to the benchmark path of the standard Hotelling model.

The theories by Hotelling (1931), Sinn (2008), and Holland (2008) need to be extended by explicit assumptions about the resource price behavior. In an earlier paper, Pindyck (1981) considers a resource extraction model with resource prices that are assumed to fluctuate around a long-run upward trend. It is shown that uncertainty about future prices clearly affects resource extraction paths. Pindyck (1981) as well as Dixit and Pindyck (1994), however, leave the question open whether or not a jump-process should be used to represent the price of oil. This paper serves as a delayed response to this question and, at the same time, points to enormous potential for future research.

6 Conclusions

The price of oil exhibits an idiosyncratic behavior for a few decades now. Subsequent to the oil crises of the 1970s and the OPEC collapse in the mid-1980s, a high-volatile, but horizontal movement has been apparent. The 2000s began with a long-lasting increase of oil prices, followed by the peak at about 150 US Dollar per barrel, and the subsequent crash-like decline. The most recent months are characterized by a slightly upward trending behavior.

Having a sufficient understanding of oil price dynamics is not only important for short-term hedging strategies, also long-run decisions are influenced by signals that emanate from oil prices. A strong link exists between uncertainty about future oil prices and investment behavior. The irreversible investment literature emphasizes the inverse relationship between uncertainty and investment caused by the option value of waiting for a better time to invest [Bernanke, 1983; Dixit and Pindyck, 1994]. Furthermore, oil price shocks make parts of the existing capital stock obsolete [Finn, 2000]; which, naturally, also affects investment decisions.

Oil, however, is more than just an important input factor, it is also an exhaustible fossil fuel. Thus, the usage of this type of resource is among the main drivers of climate change. Sparked by Hotelling's (1931) seminal study, the question when to optimally extract exhaustible resources has been investigated in a vast number of papers. Sinn's (2008) discovery of the Green Paradox is based on an extension of a standard Hotelling resource extraction model. What is more, Holland (2008) reconciles the non-economic peak-oil literature with Hotelling-type theories and shows that oil prices are a better indicator of scarcity than oil production.

The aim of this paper is to characterize the behavior of oil prices and to discuss the relationship to Hotelling-type resource extraction models. The first issue is tackled by applying a combined jump GARCH model proposed by Chan and Maheu (2002) to daily, weekly as well as monthly oil price data. Jump models have proven to be a useful tool for modeling sudden price changes that are due to unexpected news. As the global oil market is subject to various political influences, this model class lends itself for modelling oil prices' behavior. The paper finds strong evidence of conditional jump behavior at all frequencies under consideration. This implies that oil prices are marked by "discontinuous" movements. Moreover, the portion of variance attributable to jumps is found to be up to 30 %. For the daily oil price data, furthermore, there is evidence of time-varying jump intensity.

Based on this finding it is possible to identify different periods: while in the 1980s jumps were more frequent, they occur less often in more recent periods. The explanation for this finding is the general increase in oil price volatility since the end of the 1990s. The finding that discontinuous price movements are present is at odds with the of deterministic trends in oil prices. In contrast, Pindyck's (1999) notion of stochastically fluctuating trends appears to have a better empirical foundation. This, however, implies that resource owners cannot assume with a sufficient degree of certainty that oil prices will increase in the near future. This non-existence of a long-term upward trend is likely to cause a current overextraction of oil compared to the benchmark Hotelling model.

Moreover, this paper's findings create additional concerns regarding the adequacy of Hotelling-type models for oil price modeling purposes. Holland (2008), for instance, admits that, "given substantial short-run volatility in oil prices, it may be difficult to identify the underlying, long-run price trend from short-run changes in prices". What is more, Hamilton (2008) even concludes that "many economists often think of oil prices as historically having been influenced little or none at all by the issue of exhaustibility". Even if one is not willing to go that far, this paper's results indicate that the behavior of oil prices is difficult to predict and that decisions based on oil price signals are challenging tasks. These decisions, however, do not only affect economic figures, they also have an influence on climate change. This paper clearly indicates that researchers and politicians alike should be aware of the behavior of the price of oil when designing and evaluating climate policies.

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