Which Risk Factors Drive Oil Futures Price Curves? Speculation and Hedging in the Short-Term and Long-Term

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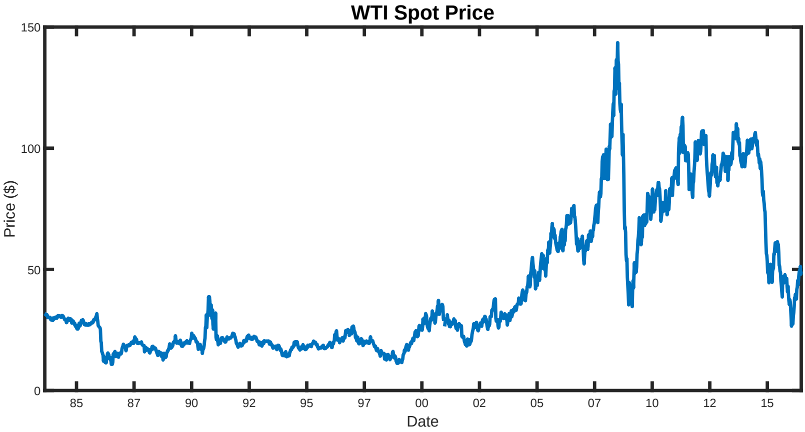
28th February 2018

Outline

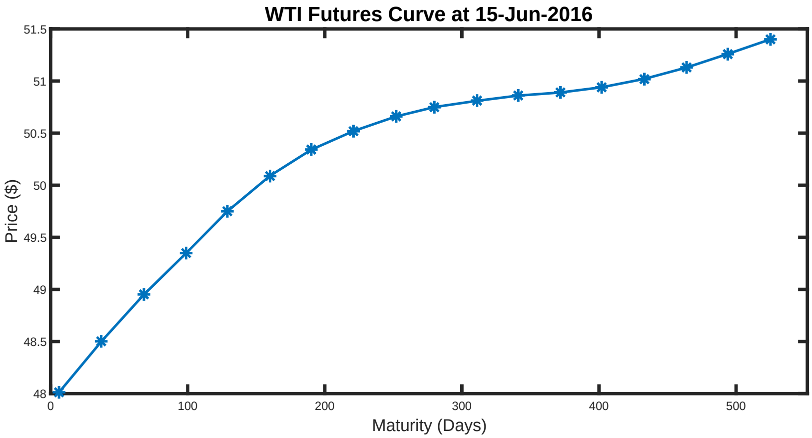
Introduction

- Oil has historically been one of the most closely scrutinized commodities in the market because of the important role it plays in the worldwide economy and international relations.
  - price has a major influence over the respective balance of trade of consuming and producing countries and thus the resulting geopolitical interactions among them.
- Frequent market shocks:
  - demand: influenced by the business cycle, speculation.
  - supply: Oil crises, conflicts in oil-producing countries or discoveries of new fields.
    - New technologies have recently been the main factor influencing the market supply (horizontal drilling and hydraulic fracturing in shale).
  - According to the EIA, in 2015, 24% of the petroleum consumed in the US was imported, which corresponds to the lowest level since 1970.

WTI Crude Oil Spot Price



WTI Crude Oil Futures Price Curve: Example



Review of the Literature

Latent factor models:

- Model the spot price through state space models using a combination of several latent processes
- Gibson and Schwartz 1990; Casassus and Collin-Dufresne 2005 etc. consider the convenience yield as a latent process.

  - the benefits accrued to the owner of the physical commodity by providing him a certain flexibility relative to his reaction in case of market shocks (Kaldor 1939).

- Schwartz and Smith 2000 decomposed the spot price as a combination of short term and long term latent components.
  - showed linear equivalence between modelling the convenience yield or modelling the dynamics of a long and a short term latent factor.

Review of the Literature (2)

Fundamental factor models:

- Daskalaki, Kostakis, and Skiadopoulos 2014: any common factors in the *cross-section* of commodity futures expected returns?
  - none of the models are successful
  - the factors that affect the time series of commodity futures returns differ across commodities!
- Cummins, Dowling, and Kearney 2016: compare fundamental and latent factor models for oil futures price changes
  - model fits indistinguishable
- Several papers dissect the behaviour of the latent processes relative to a set of fundamental factors:
  - Dempster, Medova, and Tang 2012
  - Prokopczuk and Wu 2013
- Choice of explanatory factors for oil price dynamics is still debated in the academic literature.

Our Contribution

- We propose a general framework which allows one to model, estimate and forecast the dynamics of any latent process analytically through its direct relation with a set of fundamental factors.
- We reconcile two classes of models: the latent multi-factor s.d.e. models and the econometric observable factor regression models.
- The crux of the matter lies in building a model which allows a one-stage estimation with simultaneous inference of the latent factor dynamics and the factor coefficients.
- Avoids estimation error associated to the two-stage approach generally proposed in the literature. In such a model (as in Dempster, Medova, and Tang 2012) the authors recommend to first extract the latent factor estimates and then to perform a linear regression on a set of factors.

Interest of Our Approach

$\rightarrow$ We improve the inference procedure relative to the two-stage method.

$\rightarrow$ We can show how the fundamental factors influence the various parameters of the latent factor models presented in the literature (impacting the mean reverting component, the trend or the volatility).

$\rightarrow$ Allows one to consider factor forecasts to forecast values for the futures prices with confidence intervals associated to this estimate (convenient for risk management and hedging).

Interest of Our Approach (2)

$\rightarrow$ Copes with the topical problem of the marginal contribution of certain fundamental factors relative to the latent process approaches.

$\rightarrow$ We demonstrate through a likelihood ratio test how certain fundamental factors also consistently improve the inference of our state space model parameters.

$\rightarrow$ Allows for clear closed form representations of structural features such as sensitivity, shock transient response and perturbation influence on the model parameters and the driving observable factors.

Notation

$$
\begin{aligned}
S_t &:= \text{spot price} \\
\chi_t &:= \text{short term latent factor} \\
\xi_t &:= \text{long term latent factor} \\
dZ_t &:= \text{a standard Gaussian noise process} \\
\sigma &:= \text{volatility of the Gaussian noise increments} \\
\rho &:= \text{correlation between the latent factor noise processes} \\
\lambda &:= \text{risk premium}
\end{aligned}
$$

SS2000 Model

- The two factor long-term/short-term Schwartz and Smith 2000 model is equivalent to the Gibson and Schwartz 1990 model, but has a number of advantages.
- The factors (i.e. short-term deviations and equilibrium prices) are more "orthogonal" in their dynamics than the convenience yield factor, which leads to results that are more transparent.

The real world dynamics are expressed as follows:

$$X_t = ln(S_t) = \chi_t + \xi_t$$

$$d\chi_t = -\beta\chi_t dt + \sigma_\chi dZ_t^\chi$$

$$d\xi_t = \mu_\xi dt + \sigma_\xi dZ_t^\xi$$

$$\mathbb{E}\left[dZ_t^\chi dZ_t^\xi\right] = \rho dt$$

The risk-neutral formulation (adjusting the drift terms):

$$d\tilde{\chi}_t = (-\beta\chi_t - \lambda_\chi)dt + \sigma_\chi d\tilde{Z}_t^\chi$$

$$d\tilde{\xi}_t = (\mu_\xi - \lambda_\xi)dt + \sigma_\xi d\tilde{Z}_t^\xi$$

SSX Model

- The Schwartz and Smith 2000 model can be extended to allow for mean reversion in the long term drift component.
- Stylized fact that commodity prices mean revert in the long term. Such a feature is first introduced in Peters et al. 2013
- ***Real Process***

$$X_t = ln(S_t) = \chi_t + \xi_t$$

$$d\chi_t = -\beta\chi_t dt + \sigma_\chi dZ_t^\chi$$

$$d\xi_t = (\mu_\xi - \gamma\xi_t)dt + \sigma_\xi dZ_t^\xi$$

$$\mathbb{E}\left[dZ_t^\chi dZ_t^\xi\right] = \rho dt$$

Risk-Neutral Process

$$d\tilde{\chi}_t = (-\beta\chi_t - \lambda_\chi)dt + \sigma_\chi d\tilde{Z}_t^\chi$$

$$d\tilde{\xi}_t = (\mu_\xi - \lambda_\xi - \gamma\xi_t)dt + \sigma_\xi d\tilde{Z}_t^\xi$$

where we assume constant, deterministic unknown risk premia.

HMF Model

- So far these models are purely stochastic (mathematical) models, i.e. the factors utilised to explain the futures curve dynamics are stylized latent stochastic processes.
- The HMF model structure developed below allows for several nested sub-classes of model. The link function relating the fundamental factors to the latent s.d.e. model factors can be achieved in the **long term equilibrium** price and the **rates of mean reversion**.
  - Structurally different effects as well as differing interpretation.
  - Allows the development of generalised diffusion dynamics for the multi-factor s.d.e. model,
  - whilst still incorporating closed form analytic risk neutral futures price.
- Furthermore, the latent factors in this model can be easily incorporated in a statistically consistent manner with lagged observable factors, instantaneous effects and even forward looking, smoothing based information models.

HMF SDE Formulation

- *Spot price dynamic* under the HMF model:

$$X_t = ln(S_t) = \chi_t + \xi_t$$

$$d\chi_t = -\beta_t(\boldsymbol{m}_t^{K,K'})\chi_t dt + \sigma_\chi dZ_t^\chi, \tag{1}$$

$$d\xi_t = \left(\mu_{\xi,t}(\boldsymbol{m}_t^{K,K'}) - \gamma_t(\boldsymbol{m}_t^{K,K'})\right)\xi_t)dt + \sigma_\xi dZ_t^\xi, \tag{2}$$

$$\mathbb{E}\left[dZ_t^\chi dZ_t^\xi\right] = \rho_{\chi\xi} dt, \tag{3}$$

HMF SDE Formulation

where the linking functions between the observable factors and the latent factor dynamics are defined as follows:

$$\beta_t(\boldsymbol{m}_t^{K,K'}) = \psi_{c1} + \frac{1}{K' + K + 1} \sum_{j=1}^{J} \sum_{k=-K}^{K'} \psi_{1,j} m_{t+k,j}, \qquad (4)$$

$$\mu_{\xi,t}(\boldsymbol{m}_t^{K,K'}) = \psi_{c2} + \frac{1}{K' + K + 1} \sum_{j=1}^{J} \sum_{k=-K}^{K'} \psi_{2,j} m_{t+k,j}, \qquad (5)$$

$$\gamma_t(\boldsymbol{m}_t^{K,K'}) = \psi_{c3} + \frac{1}{K' + K + 1} \sum_{j=1}^{J} \sum_{k=-K}^{K'} \psi_{3,j} m_{t+k,j}, \qquad (6)$$

- where $m_{t,j}$ is the value of the observable factor j at time t, J is the number of factors considered, and $K \in \mathbb{Z}$, $K' \in \mathbb{Z}$, with $-K \leq K'$, determine the time period over which the factors are summed.
- Here, we assume for parsimony that $\psi_{1,j}$, $\psi_{2,j}$, and $\psi_{3,j}$ are constant loadings for each factor across each time window considered.

HMF PDE Expression

- We can derive the futures price $F_{t,T}$ using the Backward-Kolmogorov equation:

$$F_{t,T} = \tilde{\mathbb{E}}[S_T | S_t] = \tilde{\mathbb{E}}[e^{\chi_T + \xi_T} | \chi_t, \xi_t]$$

- Thus we can express the **futures price** as

$$F_{t,T} = e^{B_{0,t}(\tau) + B_{1,t}(\tau)\chi_t + B_{2,t}(\tau)\xi_t}$$

and hence we have the following expression for the log futures price

$$lnF_{t,T} = e^{-\beta_t \tau}\chi_t + e^{-\gamma_t \tau}\xi_t + B_{0,t}(\tau)$$

with:

$$\begin{aligned} B_{0,t}(\tau) = &-\frac{\sigma_\chi^2}{4\beta_t}(e^{-2\beta_t d\tau} - 1) - \frac{\sigma_\xi^2}{4\gamma_t}(e^{-2\gamma_t d\tau} - 1) + \frac{\lambda_\chi}{\beta_t}(e^{-\beta_t d\tau} - 1) \\ &- \frac{1}{\gamma_t}(\mu_{\xi,t} - \lambda_\xi)(e^{-\gamma_t d\tau} - 1) - \frac{\rho_{\chi\xi}\sigma_\chi\sigma_\xi}{(\beta_t + \gamma_t)}(e^{-(\beta_t + \gamma_t)d\tau} - 1) \qquad (7) \end{aligned}$$

State Space Formulation

- *Measurement Equation:*
  Let $y_t(\tau) = lnF_t(\tau)$.

$$\begin{bmatrix} y_t(\tau_1) \\ y_t(\tau_2) \\ \vdots \\ y_t(\tau_N) \end{bmatrix} = \begin{bmatrix} e^{-\beta_t\tau_1} & e^{-\gamma_t\tau_1} \\ e^{-\beta_t\tau_2} & e^{-\gamma_t\tau_2} \\ \vdots & \vdots \\ e^{-\beta_t\tau_N} & e^{-\gamma_t\tau_N} \end{bmatrix} \begin{bmatrix} \chi_t \\ \xi_t \end{bmatrix} + \begin{bmatrix} B_{0,t}(\tau_1) \\ B_{0,t}(\tau_2) \\ \vdots \\ B_{0,t}(\tau_N) \end{bmatrix} + \begin{bmatrix} \epsilon_t(\tau_1) \\ \epsilon_t(\tau_2) \\ \vdots \\ \epsilon_t(\tau_N) \end{bmatrix} \tag{8}$$

$$y_t(\tau) = \Lambda_t(\tau) f_t + B_{0,t}(\tau) + \epsilon_t(\tau) \tag{9}$$

  where $\epsilon_t(\tau)$ is the observation error at time t of contract with maturity τ.

- *Transition Equation:*

$$\begin{bmatrix} \chi_t \\ \xi_t \end{bmatrix} = \begin{bmatrix} 0 \\ \mu_{\xi,t}\Delta t \end{bmatrix} + \begin{bmatrix} e^{-\beta_t\Delta t} & 0 \\ 0 & e^{-\gamma_t\Delta t} \end{bmatrix} \begin{bmatrix} \chi_{t-1} \\ \xi_{t-1} \end{bmatrix} + \begin{bmatrix} \eta_t^{\chi} \\ \eta_t^{\xi} \end{bmatrix}, \tag{10}$$

$$f_t = c_t + A_t f_{t-1} + \eta_t \tag{11}$$

  with the error terms following a white noise (WN) distribution given by

$$\begin{bmatrix} \eta_t \\ \epsilon_t \end{bmatrix} \sim WN\left(\begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} Q & 0 \\ 0 & H \end{bmatrix} \right) \tag{12}$$

State Space Formulation

where

$$Q = \begin{bmatrix} \sigma_\chi^2 \frac{1-e^{-2\beta_t \Delta t}}{2\beta_t} & \rho_{\chi\xi}\sigma_\chi\sigma_\xi \frac{1-e^{-(\beta_t+\gamma_t)\Delta t}}{\beta_t+\gamma_t} \\ \rho_{\chi\xi}\sigma_\chi\sigma_\xi \frac{1-e^{-(\beta_t+\gamma_t)\Delta t}}{\beta_t+\gamma_t} & \sigma_\xi^2 \frac{1-e^{-2\gamma_t \Delta t}}{2\gamma_t} \end{bmatrix}, \tag{13}$$

$$H = \begin{bmatrix} s_1 & 0 & 0 & \dots & 0 \\ 0 & s_2 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & s_N \end{bmatrix} \tag{14}$$

and

$$\Lambda_t(\tau) = \begin{bmatrix} e^{-\beta_t \tau_1} & e^{-\gamma_t \tau_1} \\ e^{-\beta_t \tau_2} & e^{-\gamma_t \tau_2} \\ \vdots & \vdots \\ e^{-\beta_t \tau_N} & e^{-\gamma_t \tau_N} \end{bmatrix} \tag{15}$$

$$f_t = \begin{bmatrix} \chi_t \\ \xi_t \end{bmatrix}, \quad c_t = \begin{bmatrix} 0 \\ \mu_{\xi,t}\Delta t \end{bmatrix}, \quad A_t = \begin{bmatrix} e^{-\beta_t \Delta t} & 0 \\ 0 & e^{-\gamma_t \Delta t} \end{bmatrix}. \tag{16}$$

Kalman Filter

- Kalman filtering followed by marginal likelihood estimation under the recursive least squares estimation method
  - provides the best linear unbiased estimators of the model parameters and latent states, see discussions in Peters et al. 2013; Schwartz and Smith 2000.
- *Prediction stage:*

$$\hat{f}_{t|t-1} = c_t + A_t \hat{f}_{t-1|t-1}$$

$$P_{t|t-1} = A_t P_{t-1|t-1} A_t^T + Q$$

- *Update stage:*

$$\hat{f}_{t|t} = \hat{f}_{t|t-1} + K_t(y_t - \Lambda_t \hat{f}_{t|t-1} - B_{0,t}(\tau))$$

$$P_{t|t} = P_{t|t-1} - K_t \Lambda_t P_{t|t-1}$$

where the weighting function K_t is named the Kalman Gain and is equal to:

$$K_t = P_{t|t-1} \Lambda_t^T (\Lambda_t P_{t|t-1} \Lambda_t^T + H)^{-1}$$

MLE Estimation

- To derive the maximum likelihood estimation we start from *the prediction error*:

$$v_t = y_t - \hat{y}_{t|t-1} = y_t - \Lambda_t \hat{f}_{t|t-1} - B_{0,t}(\tau)$$

while the *variance of this prediction error* can be written as:

$$W_t = Var(v_t) = H + \Lambda_t P_{t|t-1} \Lambda_t^T$$

- Then, since the prediction error is assumed to be Gaussian we have:

$$y_t | y_{t|t-1} \sim \mathcal{N}(\Lambda_t \hat{f}_{t|t-1} + B_{0,t}(\tau), W_t)$$

MLE Estimation

- Based on this conditional distribution, we can now compute the *log-likelihood function* of $\Theta = \{\beta_t, \sigma_\chi, \lambda_\chi, \mu_\xi, \sigma_\xi, \gamma_t, \lambda_\xi, \rho_{\chi\xi}, s_1, \ldots, s_N\}$
- by computing the joint density of $y_t | y_{t|t-1}$, $t = 1, 2, \ldots, T$.

$$l(\Theta) = -\frac{NT}{2} log(2\pi) - \frac{1}{2}\sum_{t=1}^{T} log|W_t| - \frac{1}{2}\sum_{t=1}^{T} v_t^T W_t^{-1} v_t$$

- We can maximise this log likelihood function using an optimisation algorithm, i.e. the interior-point algorithm implementation in the MATLAB fmincon function.

Factors Description

Table: List of financial and physical factors (and their abbreviations) investigated in this modelling framework.

Factor	Abbreviation	Type
Baltic Dry Index	BDI	Physical
Dollar Index	DXY	Financial
Ending Stocks	End Stocks	Physical
Goldman Sachs Commodity Index	GSCI	Financial
Leverage Ratio	Lev Rat	Financial
Refinery Utilization	Ref Util	Physical
S&P 500 Index	S&P500	Financial
SPEC Ratio	SPEC	Financial
United States Inflation	US Infl	Financial
United States Field Production	US Prod	Physical
United States 10 year Treasury Interest Rate	US 10y IR	Financial

Factors Description

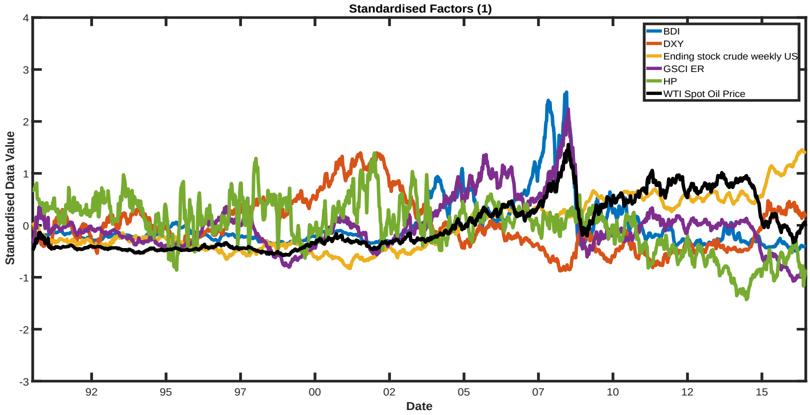


Figure: Standardised time series of the following factors: BDI, DXY, Ending Stocks, GSCI Excess Returns and Hedging Pressure.

Factors Description

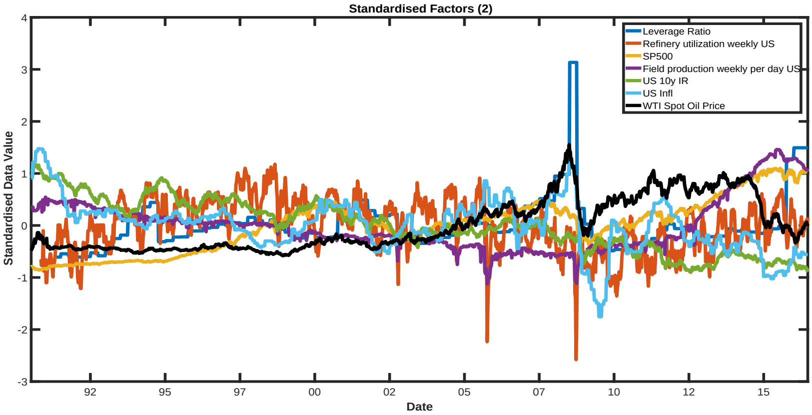


Figure: Standardised time series of the following factors: Leverage Ratio, Refinery Utilization, S&P500, US Production, US 10 year Interest Rate, and US Inflation rate.

Factors Description

Physical

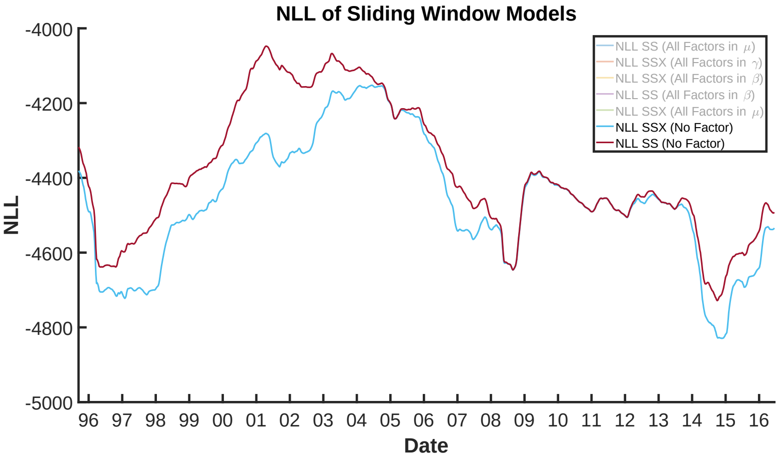
- Baltic Dry Index (BDI): weighted average of various sized dry-vessel prices across 23 different shipping routes. The supply of cargo ships is quite inflexible and so the BDI index mainly fluctuates following the demand for raw materials and hence it is seen by some as a leading indicator of economic activity.
  - Bakshi, Panayotov, and Skoulakis 2011; Geman and Smith 2012; Henderson, Pearson, and Wang 2014.
- US weekly crude oil Ending Stocks: number of barrels of oil in inventories at the end of each week in the United States
  - Gorton, Hayashi, and Rouwenhorst 2013; Dempster, Medova, and Tang 2012.
- Weekly refinery utilization rate: percentage of the operable crude oil distillation units utilized at this time
  - Kaufmann et al. 2008.
- US Field Production: number of barrels of crude oil produced on a weekly basis in the US
  - Dvir and Rogoff 2014.

Factors Description

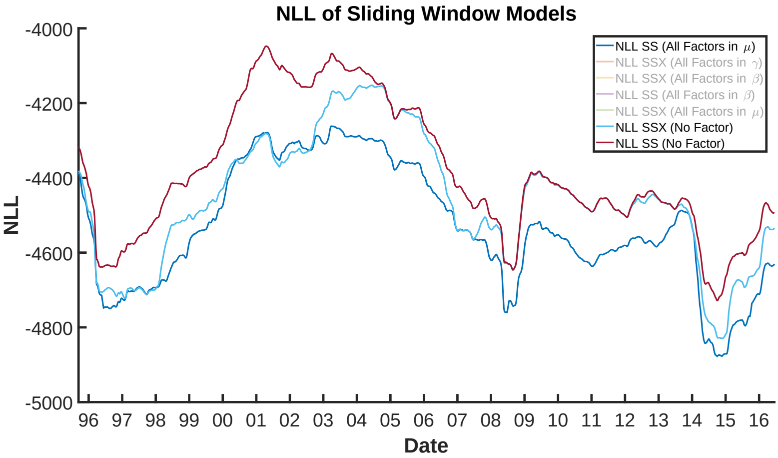
Financial

- US Dollar Index: Weighted average of the dollar's value relative to other select currencies (Euro, Japanese yen, British pound sterling, Canadian dollar, Swedish krona and the Swiss franc). Affects both the supply and the demand side.
    - Tang and Xiong 2012; Dempster, Medova, and Tang 2012
- Hedging pressure: the ratio of net open non-speculative investor futures positions to the total open interest in the market
    - Basu and Miffre 2013; Acharya, Lochstoer, and Ramadorai 2013.
- Leverage ratio: which represents the level of tightness of financial intermediaries' funding constraints, computed as the ratio of dealers' assets to liabilities
    - Adrian, Etula, and Muir 2014; Daskalaki, Kostakis, and Skiadopoulos 2014; Acharya, Lochstoer, and Ramadorai 2013; Bessembinder 1992.
- S&P500: market capitalization weighted average of the 500 largest public companies in the US
    - Daskalaki, Kostakis, and Skiadopoulos 2014.
- Goldman Sachs Commodity Index (GSCI): weighted average of 24 commodities among which crude oil and other energy products represent about 64% of the index
    - Büyüksahin and Robe 2014.

Results and Discussion: Sliding Window Analysis



Results and Discussion: Sliding Window Analysis



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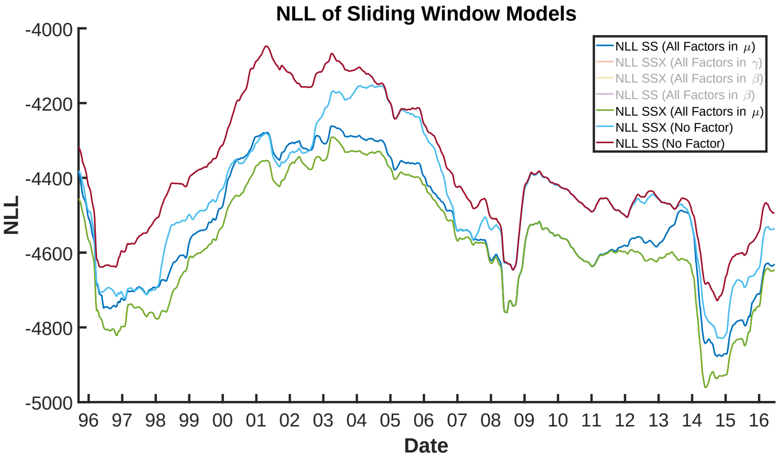
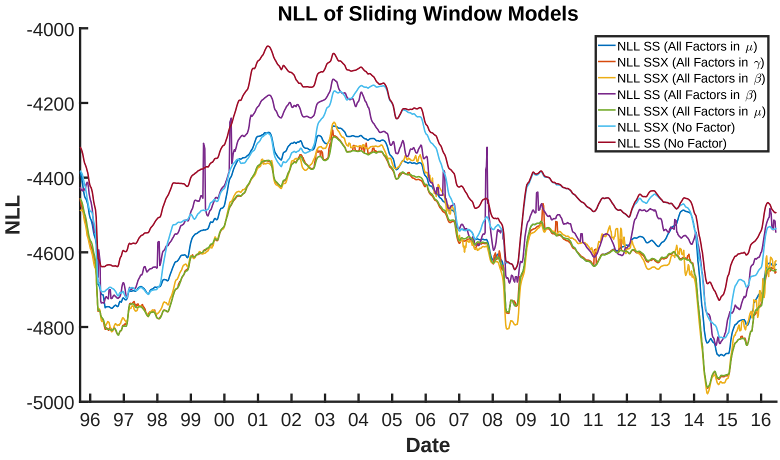


Results and Discussion: Sliding Window Analysis



Results and Discussion

We consider five equal sized samples of length five years as according to Postali and Picchetti 2006 the average long term cycle in the crude oil industry has been estimated to be 4-6 years:

- 2011 to 2016 has seen the financialisation of the commodity market, Henderson, Pearson, and Wang 2014; Büyüksahin and Robe 2014; Singleton 2014.
- 2006 to 2011 which includes the financial crisis of 2008.
- 2000 to 2006 with the burst of the dot-com bubble.
- 1995 to 2000 with the LTCM collapse
- 1990 to 1995 including the Iraqi Army's occupation of Kuwait in August 1990.

Three Highest AIC Criterion Contributors:

	1990-1995			1995-2000			2000-2006			2006-2011			2011-2016		
Covariate	ST Mean Reversion	LT Mean Reversion	LT Trend	ST Mean Reversion	LT Mean Reversion	LT Trend	ST Mean Reversion	LT Mean Reversion	LT Trend	ST Mean Reversion	LT Mean Reversion	LT Trend	ST Mean Reversion	LT Mean Reversion	LT Trend
BDI										-0.009	-0.029				
DXY				-0.193	0.01	-0.032	-0.422	0.021	-0.07	0.009	0.032	-0.028			
End Stocks								-0.037	0.117						
GSCI	-0.042		0.127	0.177	-0.011	0.034						0.191	-0.042	0.054	0.168
Lev Rat	-0.02	0.21	0.053				-0.344	0.017	-0.054				0.011		-0.036
Ref Util		0.172													
SP500	0.046	0.266	-0.129	-0.185	0.008	-0.025	-0.289				0.026	0.045	-0.017	-0.051	0.07
Hedging Pressure															
US Prod										0.002				-0.036	

Results and Discussion

- We notice that the relevant factors are not necessarily the same across the three latent factor parameters (Dempster, Medova, and Tang 2012).
- *Dollar* is *negatively impacting the long term trend* μ_ξ and the *long term mean reversion* parameters between 1995 and 2011 (Akram 2009).
- The *US production of oil* has recently weighed a lot more in the dynamics of the oil price term structure (pushed into contango) while it was not so influential in the past.
  - This highlights the influence on oil price and the futures curve of the advances in the application of horizontal drilling and hydraulic fracturing (Outlook 2013; Dvir and Rogoff 2014).
- *Negative* relation between the *inventories* and the level of *backwardation* of the curve
  - Matching with competitive rational expectations model of storage (Pindyck 1994; Routledge, Seppi, and Spatt 2000; Casassus and Collin-Dufresne 2005; Gorton, Hayashi, and Rouwenhorst 2013)

Results and Discussion

- Although the sign of the inventories' coefficients associated to the long term mean reversion is mostly negative and statistically significant, this effect has however not been as meaningful as the US oil production or the refinery utilization rate for the last five years.
  - We are in a potential shift of regime towards an *unrestricted supply* where the US production can satisfy the shocks on demand (Dvir and Rogoff 2014).
- Our model also confirms that the equity commodity relation may revert, weaken or at least not be consistently significant over time (Kilian and Park 2009; Büyüksahin, Haigh, and Robe 2009; Büyüksahin and Robe 2014).
  - We propose that this change in the sign of the relation between oil and equity is linked to the significant increase of the US supply capacity in the last decade which has reduced the impact of the demand shocks for precautionary reasons.

Results and Discussion

- The impact of the *hedging pressure* upon the trend of the crude oil price is not obvious and even insignificant over the last decade.
  - Nevertheless, the influence of the hedgers seems to influence the *two mean reversion* components of the crude oil dynamic which are directly linked to the slope of the futures curve.
- Adding a *mean reversion* component in the long term latent process and combining it with the mean reverting dynamic of the short term latent process devised by Schwartz and Smith (2000) model is shown to improve the likelihood.

Conclusion

- We propose a model combining two mean reverting latent factors for which the stochastic dynamic can be expressed as a function of a set of observable factors.
- We furthermore contribute to the literature by proposing an innovative state-space framework which allows us to extract latent stochastic factors as well as all static model parameters in a statistically consistent manner.
- This model bridges the existing gap between the latent factor modelling literature and the two-step regression models generally proposed to explain the previously estimated latent factor stochastic dynamics as functions of macroeconomic and microeconomic factors.
- Finally, our results shed light upon the relation between crude oil term structure behaviour and financial or physical phenomena. The recent increase of the US oil production over the last decade has significantly influenced the behaviour of the crude oil long term equilibrium price and futures term structure (Dvir and Rogoff 2014).

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