The New Commodity Markets:
I. Introduction

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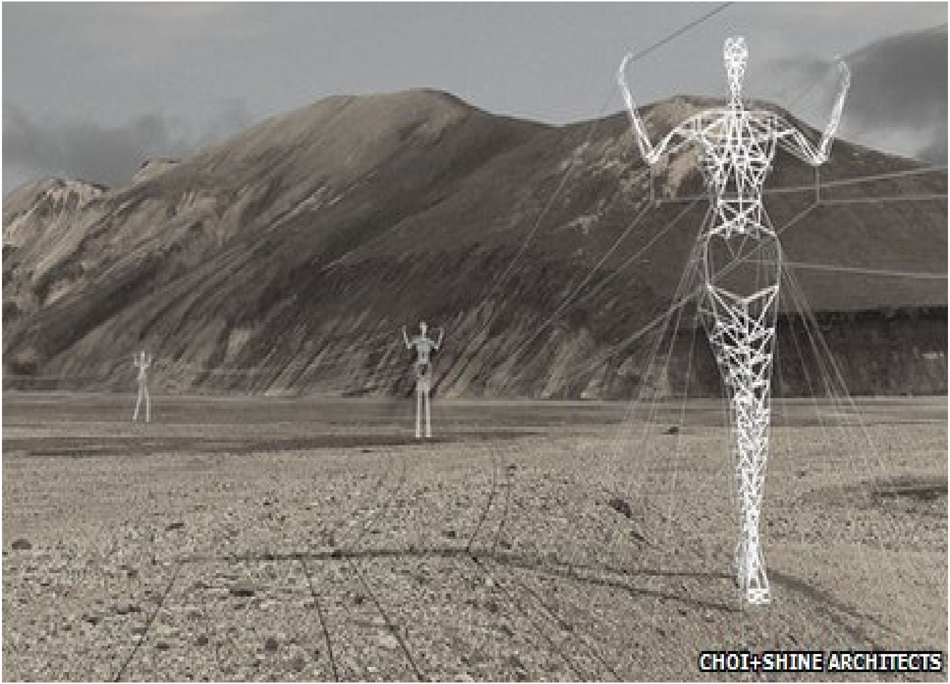

CHOI+SHINE ARCHITECTS

Plan for the Lectures

- **Lecture I: Commodity Markets**
  - Production, Transportation, Storage, Delivery
  - Spot / Forward Markets
  - Convenience Yield
- **Lecture II: Spread Options**
  - Why Spread Options
  - Spark Spread Options
  - *Real Option Theory* Asset Valuation
  - More Asset Valuation
    - Plant Optionality Valuation
    - Financial Valuation
    - Valuing Storage Facilities
  - **Related Markets**
    - Weather Markets
    - Emission Markets

Basic Textbooks on the Subject

- F.E. Benth, J.S. Benth, and S. Koekebakker,
  Stochastic Modeling of Electricity and Related Markets,
  World Scientific, Advanced Series in Statistical Science & Applied Probability, vol.11, 2008
- L. Clewlow, and C. Strickland,
  Energy Derivatives: Pricing and Risk Management,
  Lacima Productions, 2000
- A. Eydeland, and K. Wolyniec,
  Energy and Power Risk Management: New Developments in Modeling, Pricing and Hedging,
  Wiley, Finance, 2003
- H. Geman,
  Commodities and commodity derivatives: Modeling and Pricing of Agriculturals, Metals and Energy,
  Wiley, Finance, 2005
- H. Geman,
  Risk Management in Commodity Markets: From Shipping to Agriculturals and Energy,
  Wiley, Finance, 2008
- R. Weron,
  Modeling and and Forecastig Electricity Loads and Prices: a statistical approach,
  Wiley, Finance, 2007

Commodities: as an Asset Class

- **Pricing by Equilibrium Arguments**
  - Supply / Demand
  - Inventory (Storage / Delivery)
  - Convenience yield
  - Standard Valuation Methods do not apply
    (e.g. present value of flow of future dividend)
- **Physical Markets**
  - Spot (immediate delivery) Markets
  - Forward Markets
- **Volume Explosion with Financially Settled Contracts**
  - Physical / Financial Contracts
  - Exchanges serve as **Clearing Houses**
  - Speculators *provide* **Liquidity**
- **Diversification** (*believed to be negatively correlated with stocks*)

Some Exchanges (US & Europe)

A **given commodity** is traded on **one** (or a small number of) **specialized exchange** (s)

Exchange	**Location**	**Contracts**
Chicago Board of Trade (CBOT)	Chicago	Grains, Ethanol, Metals
Chicago Mercantile Exch. (CME)	Chicago, US	Meats, Currencies, Eurodollars
Intercontinental Exch. (ICE)	Atlanta, US	Energy, Emissions, Agricultural
Kansas City Board of Trade (KCBT)	Kansas City, US	Agricultural
New York Merc. Exch. (NYMEX)	New York, US	Energy, Prec. Metals, Indust. Metals
Climex (CLIMEX)	Amsterdam, NL.	Emissions
NYSE Liffe	Europe	Agricultural
European Climate Exch. (ECX)	Europe	Emissions
London Metal Exch. (LME)	London, UK	Industrial Metals, Plastics

Gaining Exposure to Commodity

- Purchasing Physical Commodity
  - Transportation / Delivery
  - Storage /Perishability
- Purchasing Stock in Commodity Intensive Businesses
  - Indirect exposure
  - Shares of natural resource companies non-perfectly correlated with commodity prices
- Investing in Commodity Futures & Options
  - Transparency & Integrity (clearing)
  - Small initial investment (margin calls)
  - Careful Rolling (e.g. to avoid physical delivery)
- Investing in Commodity Indexes and Commodity Funds
  - Passive investment (no need for a CTA)
  - Can reconstruct *historical* performance

Original Commodity Indexes

	CRB/CCI	GSCI	Rogers RMI	DJ-AIG
Started	11957/986	1992	1998	1999
Exchange Traded	Yes	Yes	No	No
Number of Components	17	22	35	20
Energy	18%	50%	44%	31%
Metals (Gold)	24 6	12 2	21 3	29 9
Grains	18	18	21	21
Food/Fiber	30	10	11	10
Livestock	12	11	3	9

MAJOR COMMODITY INDEXES

Sector	Commodity	Exchange	Ticker	S&P - GSCI Weights	DJ-UBSCI Weights
Number				24	19
Total Weights				99.99%	100.00%
Energy	Oil (Brent crude)	IPE	LO	13.25%	
Energy	Oil (WTI crude)	NYM	CL	37.51%	13.75%
Energy	Oil (GasOil)	IPE	QS	4.54%	
Energy	Oil (#2 Heating)	NYM	HO	4.19%	3.65%
Energy	Natural gas	NYM	NG	4.14%	11.89%
Energy	Oil (RBOB)	NYM	RB	4.75%	3.71%
Industrial Metals	Aluminum	LME	AH	2.33%	7.00%
Industrial Metals	Copper	LME	CA	3.22%	7.31%
Industrial Metals	Lead	LME	PB	0.45%	
Industrial Metals	Nickel	LME	NI	0.78%	2.88%
Industrial Metals	Zinc	LME	ZS	0.60%	3.14%
Precious Metals	Gold	CMX	GC	3.01%	7.86%
Precious Metals	Silver	CMX	SI	0.32%	2.89%

Major Commodity Indexes (cont.)

Sector	Commodity	Exchange	Ticker	S&P - GSCI Weights	DJ-UBSCI Weights
Agriculture	Cocoa	CSC	CC	0.40%	
Agriculture	Coffee ”C”	CSC	KC	0.76%	2.97%
Agriculture	Corn	CBT	C	3.55%	5.72 %
Agriculture	Cotton #2	NYC	CT	1.19%	2.27%
Agriculture	Wheat (Kansas)	KCBT	KW	0.82%	
Agriculture	Soybean oil	CBT	BO		2.88%
Agriculture	Soybeans	CBT	S	2.64%	7.60%
Agriculture	Sugar	CSC	SB	2.33%	2.99%
Agriculture	Wheat (Chicago)	CBT	W	3.90%	4.80%
Livestock	Feeder cattle	CME	FC	0.61%	
Livestock	Lean hogs	CME	LH	1.51%	2.40%
Livestock	Live cattle	CME	LC	3.19%	4.29%

DB Liquidity Commodity Index (DBLCI)

- Launched in 2003
- Equally weighted
- Basis for Index Tracking Funds

	Index Weight	Contract Months	Exchange
Energy			
WTI Crude Oil	35.00%	Jan-Dec	NYMEX
Heating Oil	20.00%	Jan-Dec	NYMEX
Precious Metals			
Gold	10.00%	Dec	COMEX
Industrial Metals			
Aluminium	12.50%	Dec	LME
Grains			
Corn	11.25%	Dec	CBOT
Wheat	11.25%	Dec	CBOT

Impact of long-only index funds

Empirical Facts

- In 2006 - 2007, index fund investment increased **from 90 billion to 200 billion** USD (source: Barclays)
- Simultaneously, **commodity prices increased 71%** as measured by the CRB index
- Prices declined from June 2008 through early 2009

Possible explanations

- Large scale speculative buying by index funds created a bubble, (futures prices far exceeded fundamental values)
- Some economists (**Krugman** 2008; **Pirrong** 2008; **Sanders** and **Irwin** 2008, **Hamilton** 2009, **Kilian** 2009) are **skeptic** about the ”bubble theory”

> *”... Prices of commodities are set by **supply-demand**, rapid growth in emerging economies (e.g. China) increased demand and caused the 2008 surge in price. ....”*

Commodity Index Investing under Attack

- Increased participation in futures markets by nontraditional investors deemed **disruptive**
- **Blamed for the 2007-2008 Food Crisis**: "*Casino of Hunger: How Wall Street Speculators Fueled the Global Food Crisis*"
- A report from **U.S. Senate Permanent Subcommittee on Investigation**

> *"... finds that there is significant and persuasive evidence to conclude that these commodity index traders, in the aggregate, were one of the major causes of unwarranted changeshere increasesin the price of wheat futures contracts relative to the price of wheat in the cash market....."*

- **48 Agriculture Ministers** meeting in Berlin said there were

> *"... concerned that excessive price volatility and speculation on international agricultural markets might constitute a threat to food security, according to a joint statement handed out to reporters on Jan. 22, 2011...."*

Return Correlations Are No Longer What They Used to Be

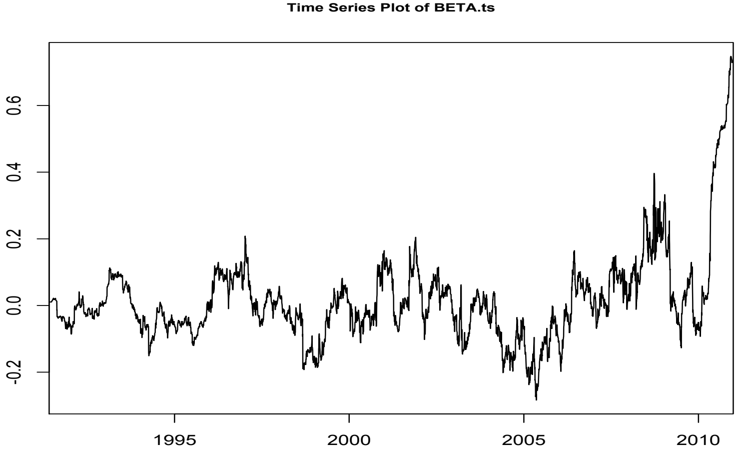
Empirical Facts

- Commodity Index trading **tightened correlations** between commodities (**Tang-Xiong** 2010)
- Scale dependent phenomenon: **Do high frequency traders see these correlation increases?**

Financialization of Commodities: two talks during this workshop

- **Wei Xiong**
- **Ronnie Sircar**

Are Commodities Uncorrelated with Equities?

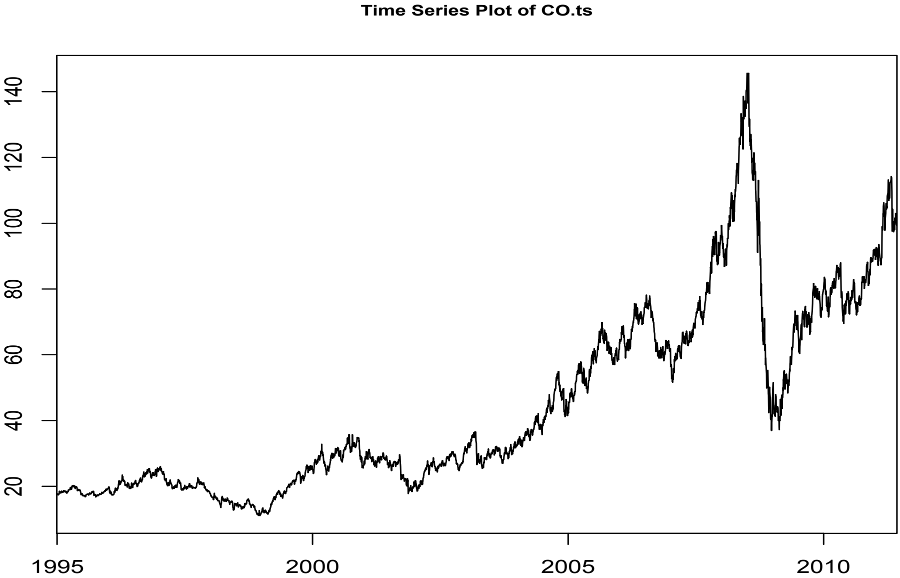


Instantaneous Dependence (β) of GSCI-TR returns upon S&P 500 returns

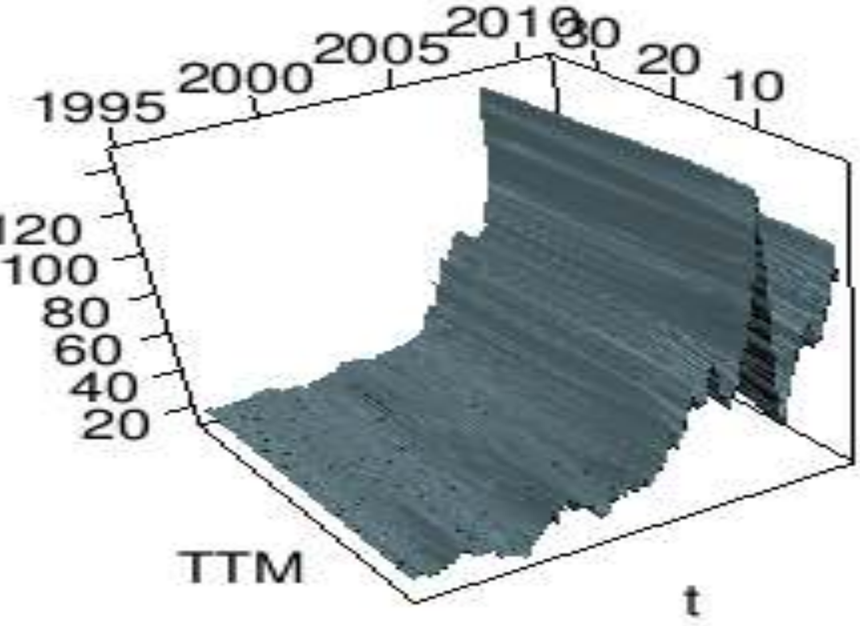
FIRST CHALLENGE: CONSTRUCTING FORWARD CURVES

- **How can it be a challenge?**
  - **Just do a PCA !**
    - *"OK"* for Crude Oil (backwardation/contango → 3 factors)
    - Not settled for Gas
    - Does not work for Electricity
  - Extreme **complexity** & **size** of the data (location, grade, peak/off peak, firm/non firm, interruptible, swings, etc)
  - Incomplete and inconsistent sources of information
  - **Liquidity** and wide **Bid-Ask** spreads (**smoothing**)
  - **Length** of the curve (**extrapolation**)
- ***Dynamic models à la HJM***:
  Seasonality? Mean reversion? Jumps? Spot models? Factor Models? Cost of carry / convenience yield? Consistency? Historical? Risk neutral models? .....

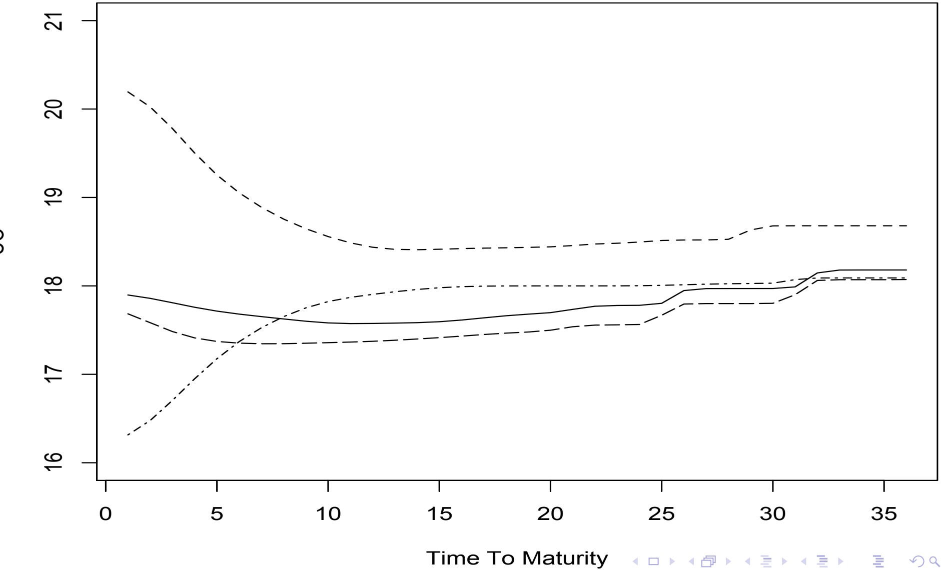
CRUDE OIL


Time Series Plot of CO.ts
140
120
100
80
60
40
20
1995
2000
2005
2010

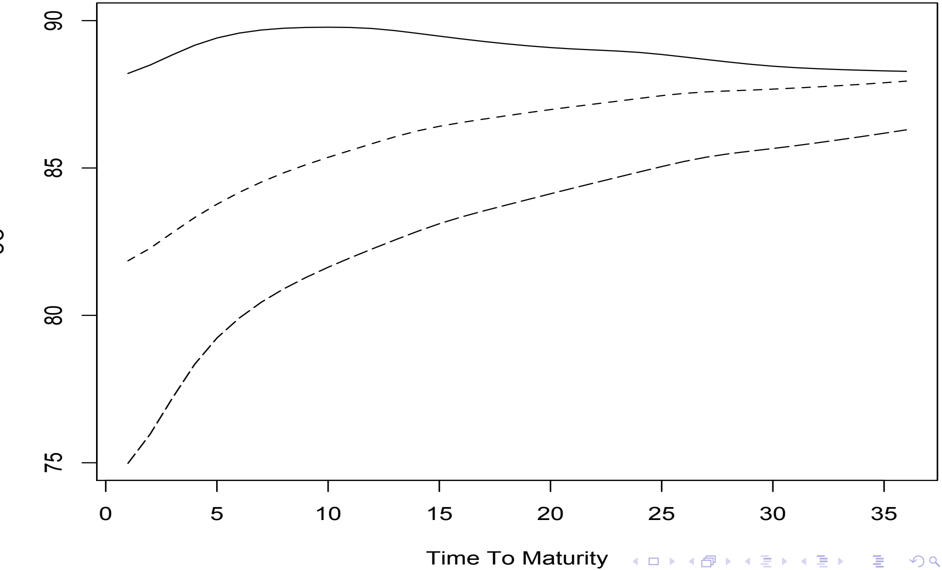
CRUDE OIL FORWARD SURFACE



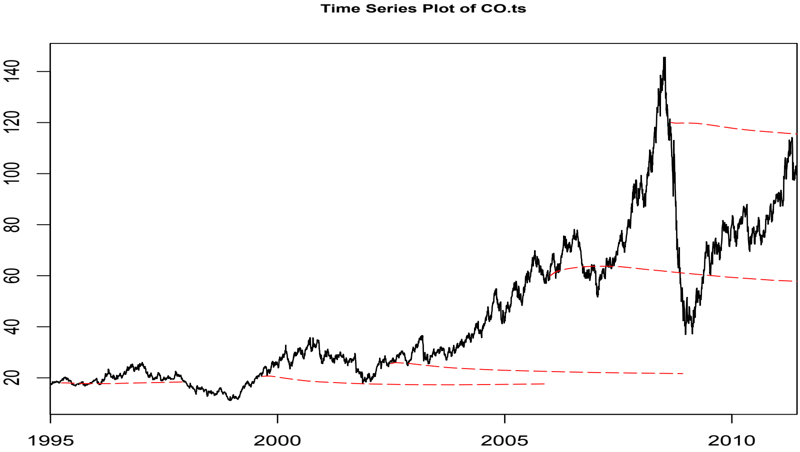
EARLY FORWARD CURVES



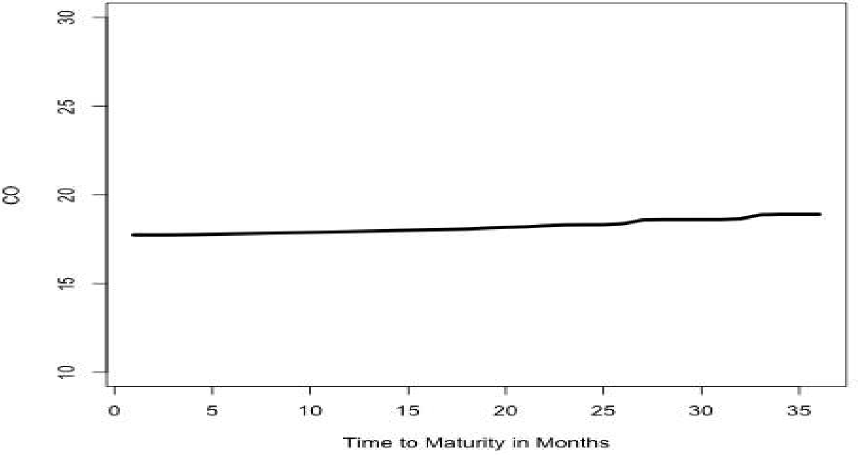
More Crude Oil Forward Curves



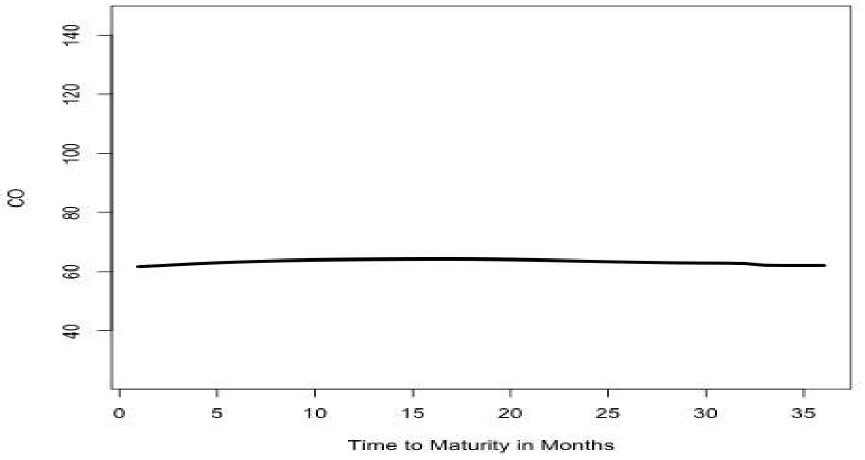
Is the Forward the Expected Value of Future Spots?



CRUDE OIL FORWARD CURVES 01/03/1995 – 12/31/1998



Crude Oil Forward Curves 01/02/2006 to 12/31/2010



Spot Forward Relationship

In financial models where one can hold positions at no cost

$$F(t,T) = S(t)e^{r(T-t)}$$

by a simple **cash & carry arbitrage** argument. In particular

$$F(t,T) = \mathbb{E}\{S(T) \,|\, \mathcal{F}_t\}$$

for risk neutral expectations.

Perfect Price Discovery

In general (theory of normal **backwardation**)

- $F(t,T)$ is a **downward biased** estimate of $S(T)$
- Spot price exceeds the forward prices

Notion of Convenience Yield

Forward Price = (risk neutral)
conditional expectation of future values of **Spot Price**

- No **cash & carry** arbitrage argument
  - Is the spot really tradable?
  - What are its dynamics?
  - How do we *risk-adjust* them?
- **Convenience Yield** for storable commodities
  - Natural Gas, Crude Oil, . . .
  - Correct interest rate to compute present values
  - Does not apply to Electricity

Spot-Forward Relationship for Commodities

For **storable** commodities (still same **cash & carry arbitrage** argument)

$$F(t, T) = S(t)e^{(r-\delta)(T-t)}$$

for $\delta \geq 0$ called **convenience yield**. (**NOT FOR ELECTRICITY !**)

Decompose $\delta = \delta_1 - c$ with

- δ_1 benefit from owning the physical commodity
- c cost of storage

Then

$$f(t, T) = e^{r(T-t)} e^{-\delta_1(T-t)} e^{-c(T-t)}$$

- $e^{r(T-t)}$ cost of **financing** the purchase
- $e^{c(T-t)}$ cost of **storage**
- $e^{-\delta_1(T-t)}$ sheer **benefit from owning** the physical commodity

Backwardation / Contango Duality

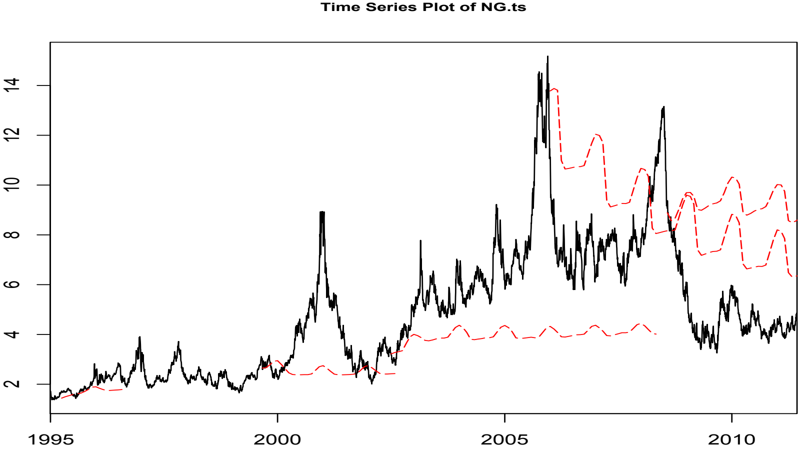
Backwardation

- $T \hookrightarrow F(t,T) = S(t)e^{(r+c-\delta_1)(T-t)}$ decreasing if $r + c < \delta_1$
  - Low cost of storage
  - Low interest rate
  - High benefit in holding the commodity

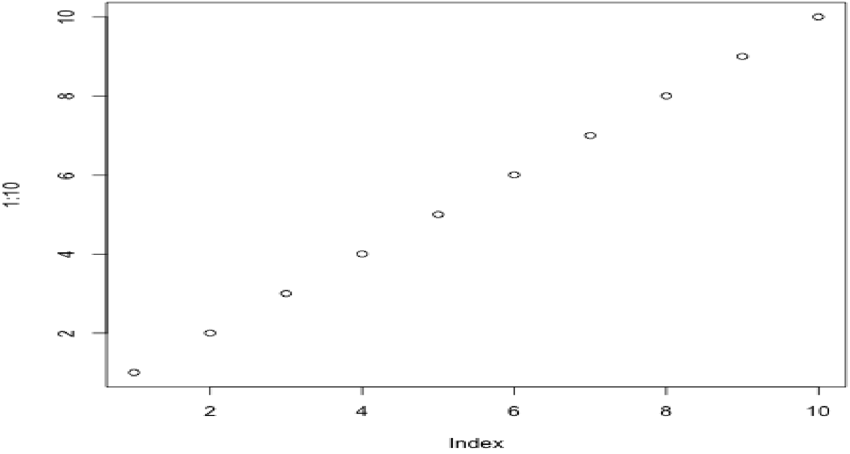
Contango

- $T \hookrightarrow F(t,T) = S(t)e^{(r+c-\delta_1)(T-t)}$ increasing if $r + c \geq \delta_1$

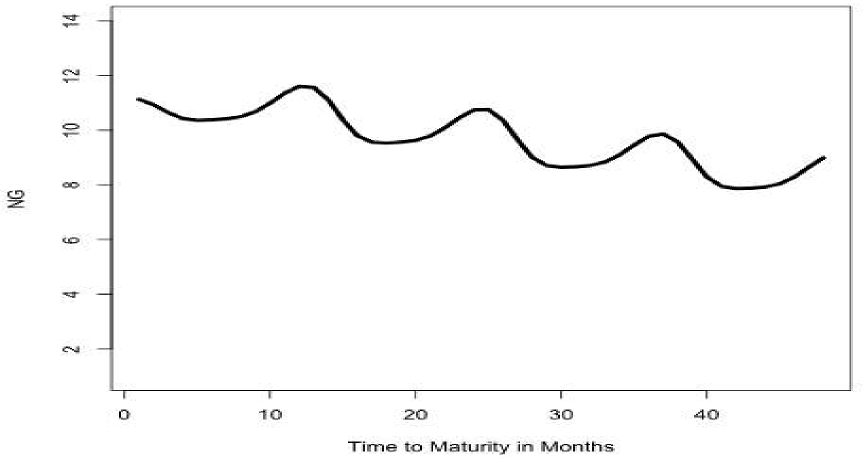
Natural Gas



NG Forward Curves 01/03/1995 – 12/31/1998



NG Forward Curves 01/02/2006 to 12/31/2010



COMMODITY CONVENIENCE YIELD MODELS

Gibson-Schwartz Two-factor model

- S_t commodity spot price
- δ_t convenience yield

Risk Neutral Dynamics

$$dS_t = (r_t - \delta_t) S_t \, dt + \sigma S_t \, dW_t^1 ,$$
$$d\delta_t = \kappa(\theta - \delta_t) dt + \sigma_\delta \, dW_t^2$$

Major Problems

- Explicit formulae (exponential affine model)
- Convenience yield implied from forward contract prices
- Unstable & Inconsistent (**R.C.-M. Ludkovski**)

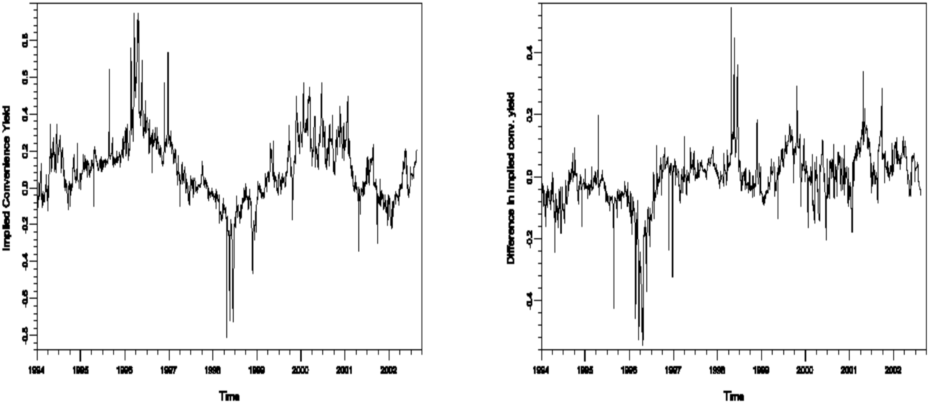
Exponential Affine Model

$$F(t,T) = S_t \mathrm{e}^{\int_t^T r_s ds} \mathrm{e}^{B(t,T)\delta_t + A(t,T)}$$

where

$$\begin{aligned} B(t,T) &= \frac{\mathrm{e}^{-\kappa(T-t)} - 1}{\kappa}, \\ A(t,T) &= \frac{\kappa\theta + \rho\sigma_s\gamma}{\kappa^2}(1 - \mathrm{e}^{-\kappa(T-t)} - \kappa(T-t)) + \\ &\quad + \frac{\gamma^2}{\kappa^3}(2\kappa(T-t) - 3 + 4\mathrm{e}^{-\kappa(T-t)} - \mathrm{e}^{-2\kappa(T-t)}). \end{aligned}$$

- For each T, one can imply δ_t from $F(t,T)$
- Inconsistency in the implied δ_t
- Ignores **Maturity Specific** effects



Crude Oil convenience yield implied by a 3 month futures contract (left)
Difference in implied convenience yields between 3 and 12 month contracts.

Convenience Yield Models Revisited

Use **forward** $F_t = F(t, T_0)$ instead of **spot** S_t (T_0 fixed maturity)

Historical Dynamics

$$\begin{aligned} dF_t &= (\mu_t - \delta_t) F_t\, dt + \sigma F_t\, dW_t^1, \\ d\delta_t &= \kappa(\theta - \delta_t) dt + \sigma_\delta\, dW_t^2 \end{aligned}$$

or more generally

$$d\delta_t = b(\delta_t, F_t) dt + \sigma_\delta(\delta_t, F_t) dW_t^2$$

We assume

- F_t is **tradable** (hence **observable**)
- (Forward) convenience yield δ_t **not observable** (**filtering**)

Different from **Bjork-Landen**'s **Risk Neutral Term Structure of Convenience Yield**

The Case of Power

Several obstructions

- Cannot store the physical commodity
- Delivery **over** a preiod $[T_1, T_2]$ (**Benth**)
- Which spot price? Real time? Day-ahead? Balance-of-the-week? month? on-peak? off-peak? etc
- Does the forward price converge as the time to maturity goes to 0?

Mathematical spot?

$$S(t) = \lim_{T \downarrow t} F(t, T)$$

Sparse Forward Data

- Lack of **transparency** (manipulated indexes)
- Poor (or lack of) **reporting** by fear of law suits
- **CCRO** white paper(s)

Dynamic Model for Forward Curves

n-factor forward curve model

$$\frac{dF(t,T)}{F(t,T)} = \mu(t,T)dt + \sum_{k=1}^{n} \sigma_k(t,T)dW_k(t) \qquad t \leq T$$

- $\boldsymbol{W} = (W_1, \ldots, W_n)$ is a n-dimensional standard Brownian motion,
- drift μ and volatilities σ_k are deterministic functions of t and time-of-maturity T
- $\mu(t,T) \equiv 0$ for pricing
- $\mu(t,T)$ calibrated to historical data for risk management

Explicit Solution

$$F(t,T) = F(0,T)\exp\left[\int_0^t \left[\mu(s,T) - \frac{1}{2}\sum_{k=1}^{n}\sigma_k(s,T)^2\right] ds + \sum_{k=1}^{n}\int_0^t \sigma_k(s,T)dW_k(s)\right]$$

Forward prices are **log-normal** (deterministic coefficients)

$$F(t,T) = \alpha e^{\beta X - \beta^2/2}$$

with $X \sim N(0,1)$ and

$$\alpha = F(0,T)\exp\left[\int_0^t \mu(s,T)ds\right], \qquad \text{and} \qquad \beta = \sqrt{\sum_{k=1}^{n}\int_0^t \sigma_k(s,T)^2 ds}$$

Dynamics of the Spot Price

Spot price left hand of forward curve

$$S(t) = F(t, t)$$

We get

$$S(t) = F(0, t) \exp\left[\int_0^t [\mu(s, t) - \frac{1}{2}\sum_{k=1}^n \sigma_k(s, t)^2] ds + \sum_{k=1}^n \int_0^t \sigma_k(s, t) dW_k(s)\right]$$

and differentiating both sides we get:

$$dS(t) = S(t)\Bigg[\Bigg(\frac{1}{F(0, t)}\frac{\partial F(0, t)}{\partial t} + \mu(t, t) + \int_0^t \frac{\partial \mu(s, t)}{\partial t} ds - \frac{1}{2}\sigma_S(t)^2$$
$$- \sum_{k=1}^n \int_0^t \sigma_k(s, t)\frac{\partial \sigma_k(s, t)}{\partial t} ds + \sum_{k=1}^n \int_0^t \frac{\partial \sigma_k(s, t)}{\partial t} dW_k(s)\Bigg) dt + \sum_{k=1}^n \sigma_k(t, t) dW_k(t)\Bigg]$$

Spot volatility

$$\sigma_S(t)^2 = \sum_{k=1}^n \sigma_k(t, t)^2. \qquad (1)$$

Clewlow - Strickland

Hence

$$\frac{dS(t)}{S(t)} = \left[\frac{\partial \log F(0,t)}{\partial t} + D(t)\right] dt + \sum_{k=1}^{n} \sigma_k(t,t) dW_k(t)$$

with drift

$$D(t) = \mu(t,t) - \frac{1}{2}\sigma_S(t)^2 + \int_0^t \frac{\partial \mu(s,t)}{\partial t} ds - \sum_{k=1}^{n} \int_0^t \sigma_k(s,t) \frac{\partial \sigma_k(s,t)}{\partial t} ds$$
$$+ \sum_{k=1}^{n} \int_0^t \frac{\partial \sigma_k(s,t)}{\partial t} dW_k(s)$$

REMARKS

Still **Clewlow - Strickland**

- Interpretation of drift (in a risk-neutral setting)
  - logarithmic derivative of the forward can be interpreted as a discount rate (*i.e.*, the running interest rate)
  - $D(t)$ can be interpreted as a convenience yield
- Drift generally **not Markovian**
- Particular case $n = 1$, $\mu(t, T) \equiv 0$, $\sigma_1(t, T) = \sigma e^{-\lambda(T-t)}$

$$D(t) = \lambda[\log F(0, t) - \log S(t)] + \frac{\sigma^2}{4}(1 - e^{-2\lambda t})$$

$$\frac{dS(t)}{S(t)} = [\mu(t) - \lambda \log S(t)]dt + \sigma dW(t)$$

exponential OU

Changing Variables

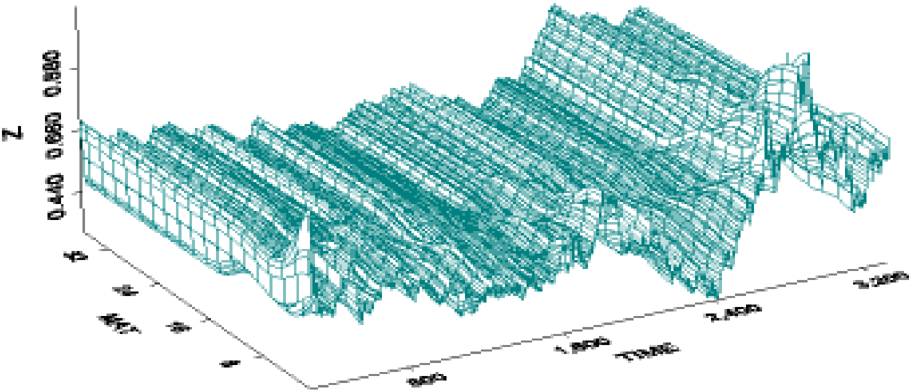
time-of-maturity $T \quad \rightrightarrows \quad$ **time-to-maturity** τ

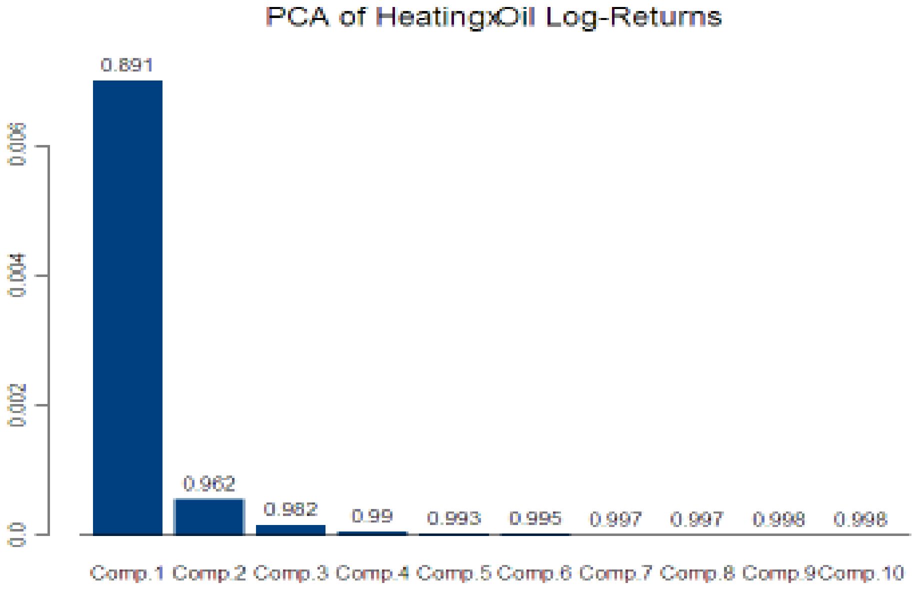
changes dependence upon t

$$t \hookrightarrow F(t, T) = F(t, t + \tau) = \tilde{F}(t, \tau)$$

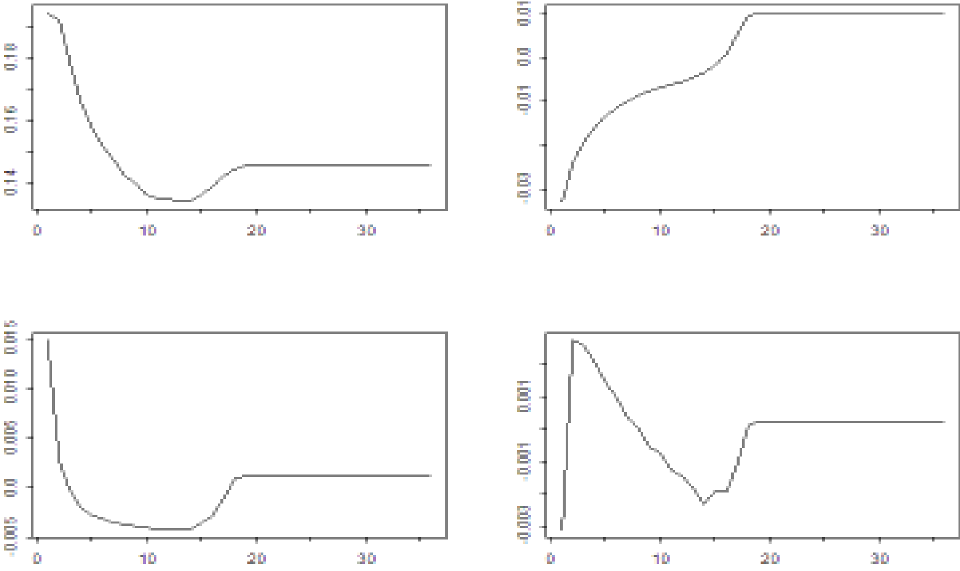
Fixed Domain $[0, \infty)$ for $\tau \hookrightarrow \tilde{F}(t(\tau)$

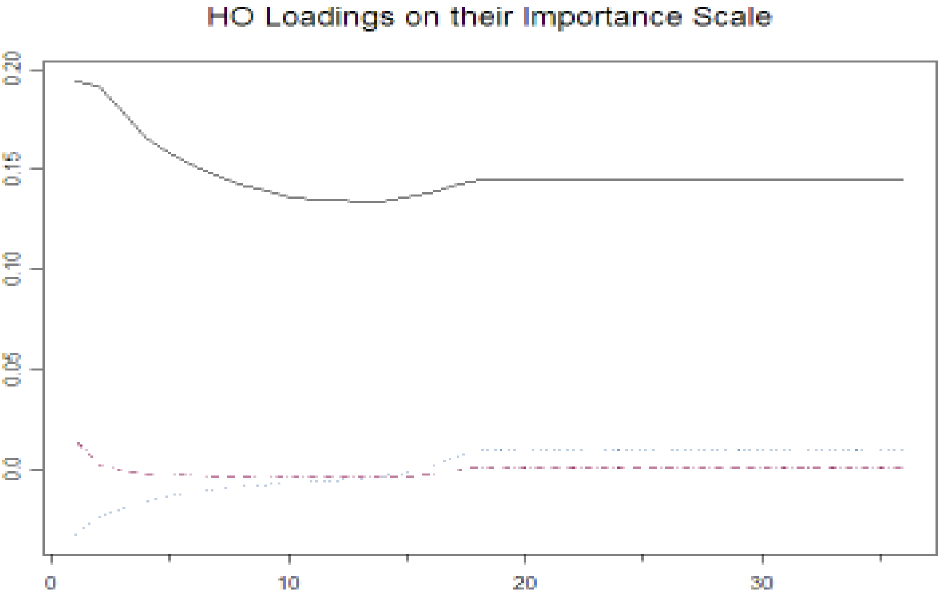
Heating Oil Forward Surface

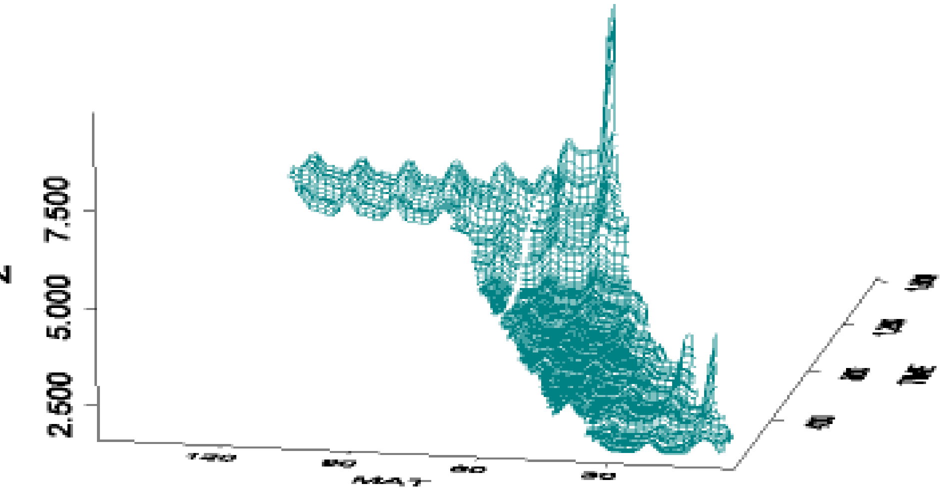


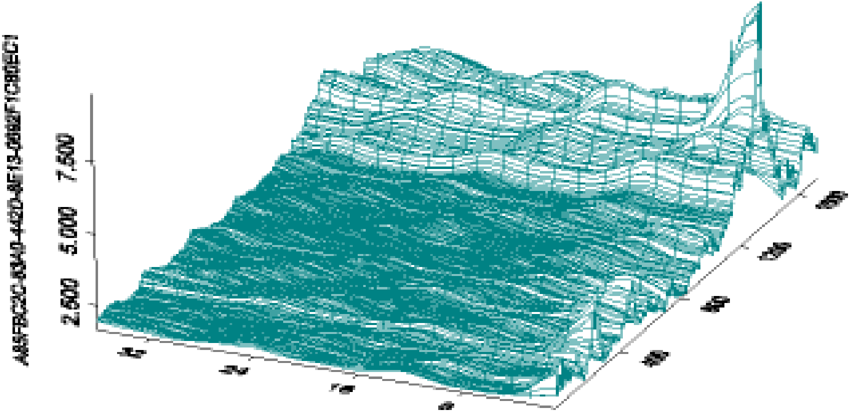

PCA of HeatingxOil Log-Returns
0.891
0.962
0.982
0.99
0.993
0.995
0.997
0.997
0.998
0.998
0.0
0.002
0.004
0.006
Comp.1
Comp.2
Comp.3
Comp.4
Comp.5
Comp.6
Comp.7
Comp.8
Comp.9
Comp.10

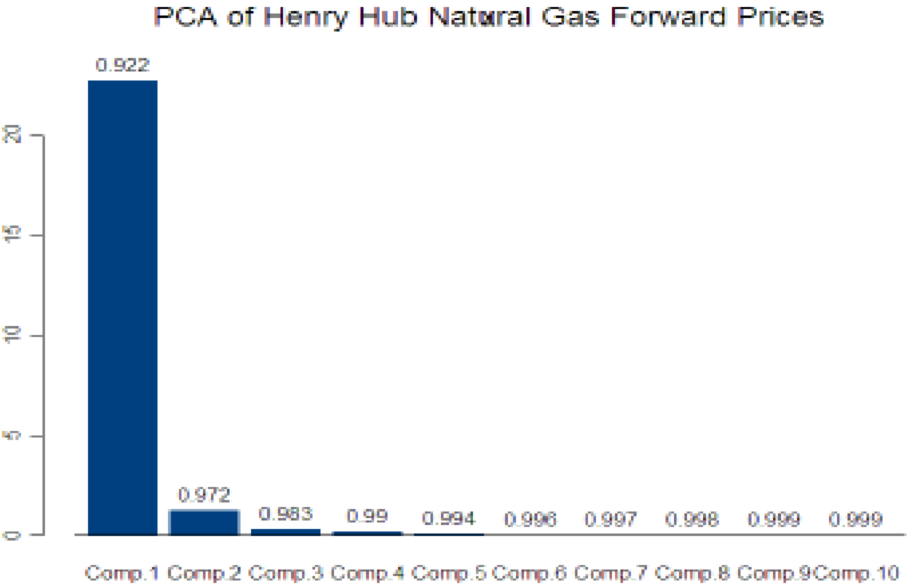
HO PCA Loadings



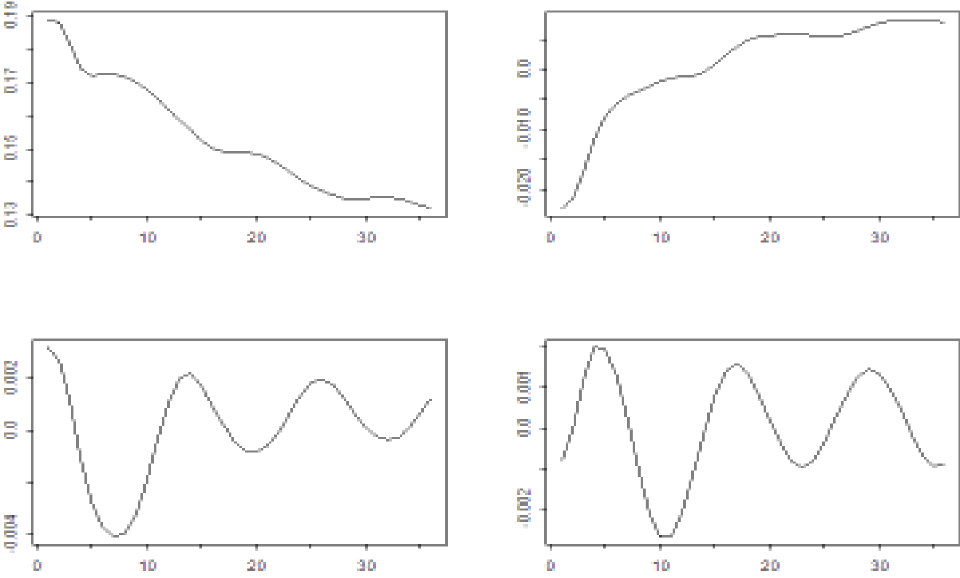

HO Loadings on their Importance Scale
0.20
0.15
0.10
0.05
0.0
0
10
20
30


7.500
5.000
2.500
Z

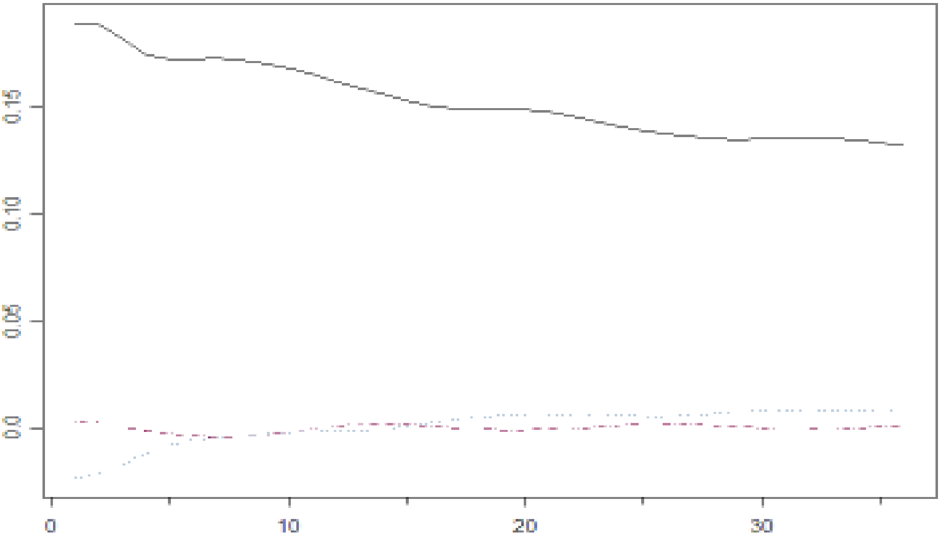

2,500
5,000
7,500


PCA of Henry Hub Natural Gas Forward Prices
0.922
0.972
0.983
0.99
0.994
0.996
0.997
0.998
0.999
0.999
0
5
10
15
20
Comp.1 Comp.2 Comp.3 Comp.4 Comp.5 Comp.6 Comp.7 Comp.8 Comp.9 Comp.10

HH PCA Loadings



HH Loadings on their Absolute Importance Scale



Changing Variables

$$\textbf{time-of-maturity } T \quad \rightrightarrows \quad \textbf{time-to-maturity } \tau$$

changes dependence upon t

$$t \hookrightarrow F(t, T) = F(t, t + \tau) = \tilde{F}(t, \tau)$$

For **pricing purposes**

- For T fixed, $\{F(t, T)\}_{0 \le t \le T}$ **is a martingale**
- For τ fixed, $\{\tilde{F}(t, \tau)\}_{0 \le t}$ **is NOT a martingale**

$\tilde{F}(t, \tau) = F(t, t+\tau)$, $\quad \tilde{\mu}(t, \tau) = \mu(t, t+\tau)$, $\quad$ and $\quad \tilde{\sigma}_k(t, \tau) = \sigma_k(t, t+\tau)$,

In general dynamics become

$$d\tilde{F}(t, \tau) = \tilde{F}(t, \tau) \left[\left(\tilde{\mu}(t, \tau) + \frac{\partial}{\partial \tau} \log \tilde{F}(t, \tau) \right) dt + \sum_{k=1}^{n} \tilde{\sigma}_k(t, \tau) dW_k(t) \right],$$

PCA WITH SEASONALITY

Fundamental Assumption

$$\sigma_k(t,T) = \sigma(t)\sigma_k(T-t) = \sigma(t)\sigma_k(\tau)$$

for some function $t \hookrightarrow \sigma(t)$

Notice

$$\sigma_S(t) = \tilde{\sigma}(0)\sigma(t)$$

provided we set:

$$\tilde{\sigma}(\tau) = \sqrt{\sum_{k=1}^{n} \sigma_k(\tau)^2}.$$

Conclusion

$t \hookrightarrow \sigma(t)$ is (up to a constant) the **instantaneous spot volatility**

Rationale for a New PCA

- Fix times-to-maturity $\tau_1, \tau_2, \ldots, \tau_N$
- Assume on each day t, quotes for the forward prices with times-of-maturity $T_1 = t + \tau_1$, $T_2 = t + \tau_2$, ..., $T_N = t + \tau_N$ are available

$$\frac{d\tilde{F}(t,\tau_i)}{\tilde{F}(t,\tau_i)} = \left(\tilde{\mu}(t,\tau_i) + \frac{\partial}{\partial \tau}\log \tilde{F}(t,\tau_i)\right) dt + \sigma(t)\sum_{k=1}^{n}\sigma_k(\tau_i)dW_k(t) \qquad i = 1,\ldots,N$$

Define $\mathbf{F} = [\sigma_k(\tau_i)]_{i=1,\ldots,N,\ k=1,\ldots,n}$.

$$d\log \tilde{F}(t,\tau_i) = \left(\tilde{\mu}(t,\tau_i) + \frac{\partial}{\partial \tau_i}\log \tilde{F}(t,\tau_i) - \frac{1}{2}\sigma(t)^2\tilde{\sigma}(\tau_i)^2\right) dt + \sigma(t)\sum_{k=1}^{n}\sigma_k(\tau_i)dW_k(t),$$

Instantaneous variance/covariance matrix $\{M(t); t \geq 0\}$ defined by:

$$d[\log \tilde{F}(\,\cdot\,,\tau_i), \log \tilde{F}(\,\cdot\,,\tau_j)]_t = M_{i,j}(t)dt$$

satisfies

$$M(t) = \sigma(t)^2\left(\sum_{k=1}^{n}\sigma_k(\tau_i)\sigma_k(\tau_j)\right)$$

or equivalently

$$M(t) = \sigma(t)^2\mathbf{F}\mathbf{F}^*$$

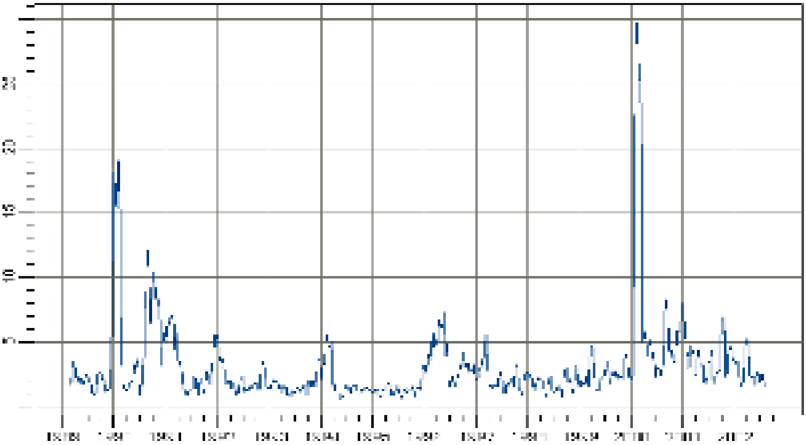
Strategy Summary

- Estimate instantaneous spot volatility $\sigma(t)$ (in a rolling window)
- Estimate $\mathbf{FF}^*$ from historical data as the empirical auto-covariance of $\ln(F(t, \cdot)) - \ln(F(t-1, \cdot))$ after normalization by $\sigma(t)$
- Instantaneous auto-covariance structure of the entire forward curve becomes time independent
- Do SVD of auto-covariance matrix and get

$$\tau \hookrightarrow \sigma_k(\tau)$$

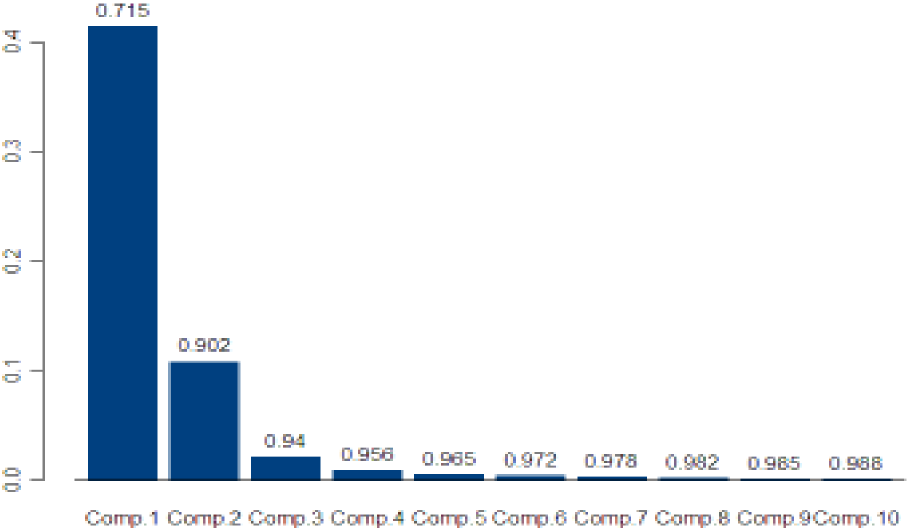
- Choose order n of the model from their relative sizes

THE CASE OF NATURAL GAS

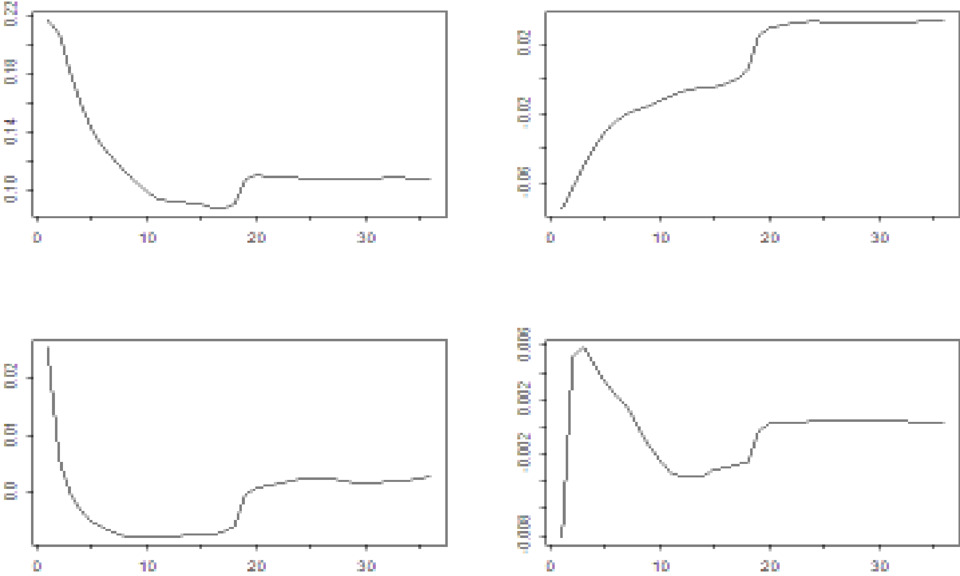


Instantaneous standard deviation of the Henry Hub natural gas spot price computed in a sliding window of length 30 days.

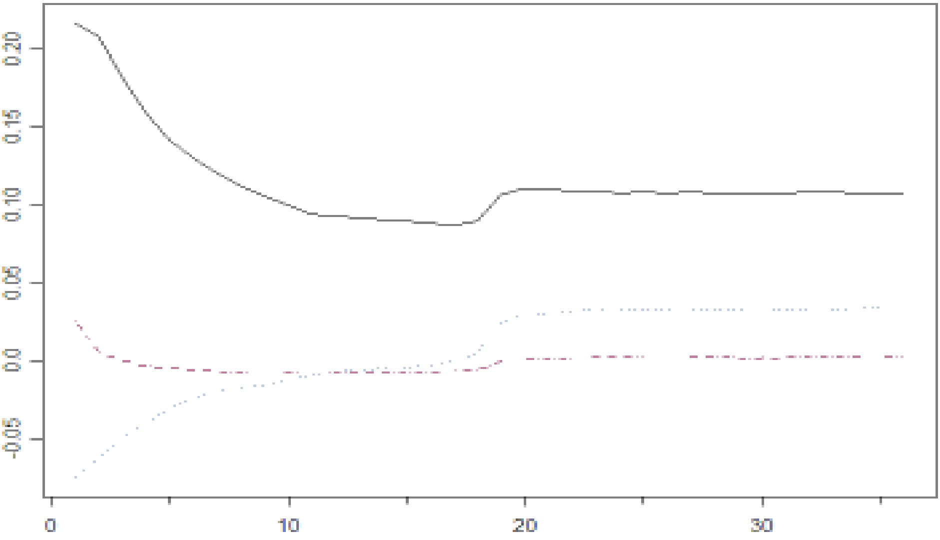
PCA of Henry Hub Natural Gas De-Seasonalized Forward Prices



HH De-Seasonalized PCA Loadings



HH De-Seasonalized Loadings on their Absolute Importance Scale



Supply/Demand & Price Formation

Mean Reversion toward the cost of production

The example of the power prices

- **Reduced Form Models**
  - Nonlinear effects (exponential OU^2)

Supply/Demand & Price Formation

Mean Reversion toward the cost of production
The example of the power prices

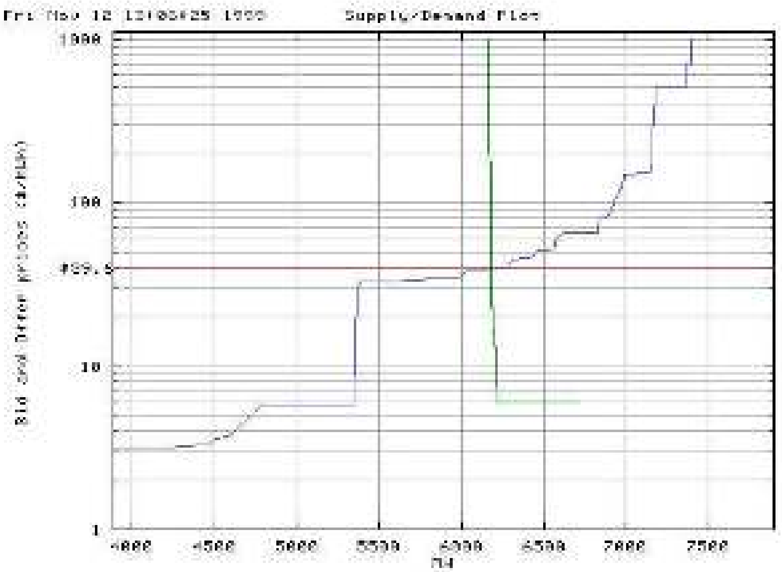
- **Reduced Form Models**
  - Nonlinear effects (exponential OU^2)
  - Jumps (**Geman-Roncoroni**, textbfBenth, textbfCartea,textbfMeyer-Brandis, . . .)
- **Structural Models**
  - Inelastic Demand
  - The Supply Stack

Barlow (based on **merit** order graph)

- $s_t(x)$ supply at time t when power price is x
- $d_t(x)$ demand at time t when power price is x

Power price at time t is number S_t such that

$$s(S_t) = d_t(S_t)$$



Example of a merit graph (Alberta Power Pool, courtesy M. Barlow)

Barlow's Proposal

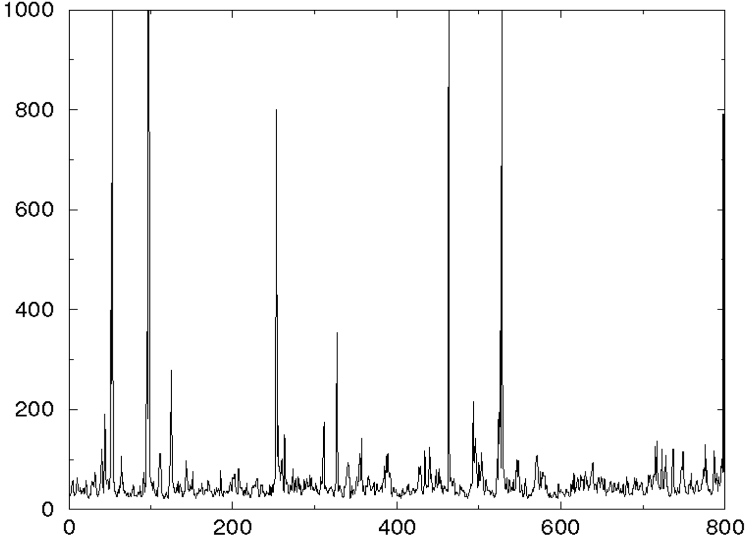
$$S(t) = \begin{cases} f_\alpha(X_t) & 1+\alpha X_t > \epsilon_0 \\ \epsilon_0^{1/\alpha} & 1+\alpha X_t \le \epsilon_0 \end{cases}$$

for the **non-linear** function

$$f_\alpha(x) = \begin{cases} (1+\alpha x)^{1/\alpha}, & \alpha \neq 0 \\ e^x & \alpha = 0 \end{cases}$$

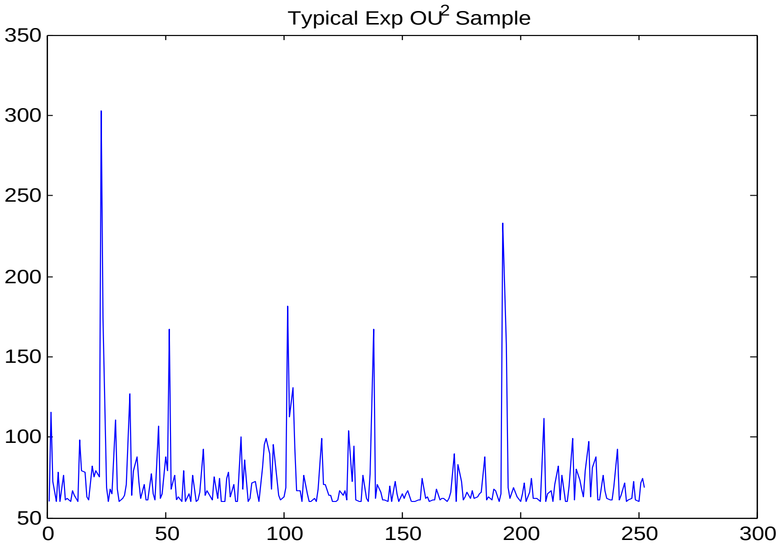
of an **OU** diffusion

$$dX_t = -\lambda(X_t - \overline{x})dt + \sigma dW_t$$



Monte Carlo Sample from Barlow's Spot Model (courtesy M. Barlow)

Cheap Alternative



Example of a Monte Carlo Sample from the Exponential of an OU^2

Negative Prices

Consider the case of **PJM**
(Pennsylvania - New Jersey - Maryland)

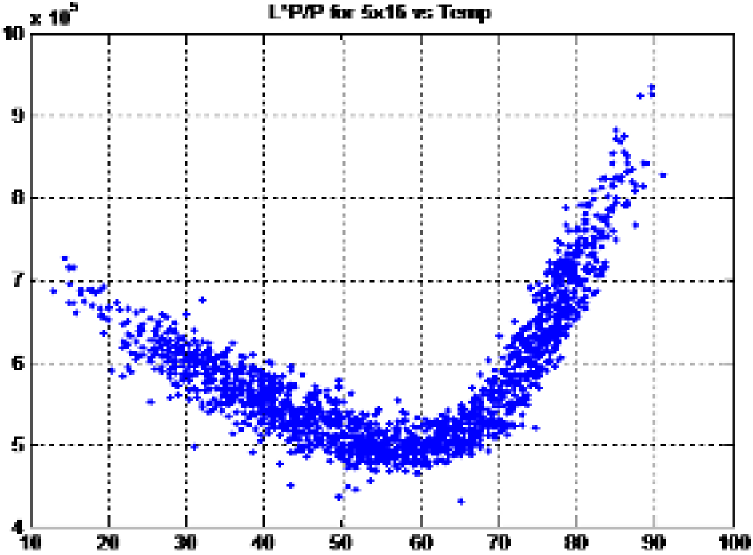
- Over $3,000$ nodes in the transmission network
- Each day, and for each node
  - Real time prices
  - Day-ahead prices
  - Hour by hour load prediction for the following day
- **Historical prices**
- In 2003 over $100,000$ instances of **NEGATIVE PRICES**
  - Geographic clusters
  - Time of the year (**shoulder months**)
  - Time of the day (**night**)
- **Possible Explanations**
  - Load miss-predicted
  - High temperature volatility

Other Statistical Issues: Modelling Demand

For many contracts, delivery needs to match demand

- **Demand** for energy highly correlated with **temperature**
  - Heating Season (winter) HDD
  - Cooling Season (summer) CDD
- **Stylized Facts** and **First (naive) Models**
  - Electricity demand = β * weather + α

Load / Temperature



Daily Load versus Daily Temperature (PJM)

Other Statistical Issues: Modelling Demand

For many contracts, delivery needs to match demand

- **Demand** for energy highly correlated with **temperature**
  - Heating Season (winter) HDD
  - Cooling Season (summer) CDD
- **Stylized Facts** and **First (naive) Models**
  - Electricity demand = β * weather + α
    - Not true all the time
    - Time dependent β by filtering !
  - From the stack: Correlation (Gas,Power) = f(weather)
    - No significance, too unstable
    - Could it be because of heavy tails?
- **Weather dynamics** need to be included
  - **Another Source of Incompleteness**

Risk Management Example

In 2001, PU budget for electricity was 2.8 M $ in the red! (PU is small)

- Never Again such a Short Fall !!!
- Student (Greg Larkin) Senior Thesis
- **Hedging Volume Risk**
  - Protection against the Weather Exposure
  - **Temperature Options** on CDDs (Extreme Load)
- **Hedging Volume & Basis Risk**
  - Protection against Gas & Electricity Price Spikes
  - Gas purchase with **Swing Options**

Mitigating Volume Risk with Swing Options

Exposure to spikes in prices of

- Natural Gas (used to fuel the plant)
- Electricity Spot (in case of overload)

Proposed Solution

- Forward Contracts
- Swing Options

Pretty standard

Mitigating Volume Risk

- Use **Swing Options**
- Multiple Rights to deviate (within bounds) from base load contract level
- **Pricing & Hedging** quite involved!
  - Tree/Forest Based Methods
    - Direct Backward Dynamic Programing Induction (à la Jaillet-Ronn-Tompaidis)
  - **New Monte Carlo Methods**
    - Nonparametric Regression (à la Longstaff-Schwarz) Backward Dynamic Programing Induction

Mathematics of Swing Contracts: a Crash Course

Review: **Classical Optimal Stopping Problem: American Option**

- $X_0, X_1, X_2, \cdots, X_n, \cdots$ rewards
- Right to ONE Exercise
- Mathematical Problem

$$\sup_{0 \le \tau \le T} \mathbb{E}\{X_\tau\}$$

Mathematical Solution

- Snell's Envelop
- Backward Dynamic Programming Induction in Markovian Case

Standard, Well Understood

New Mathematical Challenges

In its simplest form the problem of **Swing/Recall** option pricing is an

Optimal Multiple Stopping Problem

- $X_0, X_1, X_2, \cdots, X_n, \cdots$ rewards
- Right to N Exercises
- Mathematical Problem

$$\sup_{0 \le \tau_1 < \tau_2 < \cdots < \tau_N \le T} \mathbb{E}\{X_{\tau_1} + X_{\tau_2} + \cdots + X_{\tau_N}\}$$

- **Refraction** period θ

$$\tau_1 + \theta < \tau_2 < \tau_2 + \theta < \tau_3 < \cdots < \tau_{N-1} + \theta < \tau_N$$

Part of recall contracts & crucial for continuous time models

Instruments with Multiple American Exercises

- **Ubiquitous in Energy Sector**
  - Swing / Recall contracts
  - End user contracts (EDF)
- **Present in other contexts**
  - Fixed income markets (e.g. chooser swaps)
  - Executive option programs
    Reload $\rightarrow$ Multiple exercise, Vesting $\rightarrow$ Refraction, $\cdots$
  - Fleet Purchase (airplanes, cars, $\cdots$)
- **Challenges**
  - Valuation
  - Optimal exercise policies
  - Hedging

SOME MATHEMATICAL PROBLEMS

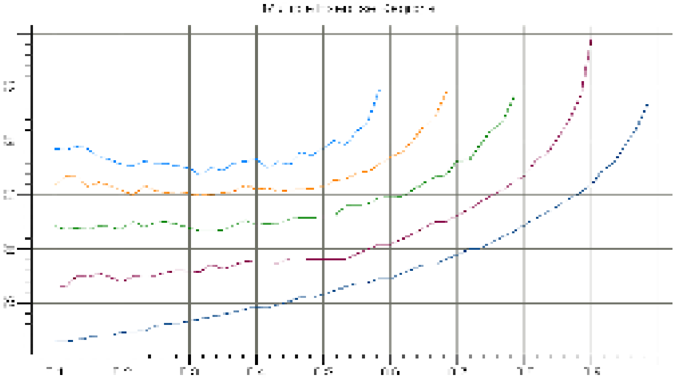
Recursive re-formulation into a hierarchy of classical optimal stopping problems

- Development of a theory of *Generalized Snell's Envelop* in continuous time setting
- Find a form of Backward Dynamic Programing Induction in Markovian Case
- Design & implement efficient numerical algorithms for finite horizon case

Results

- Perpetual case: abstract nonsense & characterization of the optimal policies
  R.C.& **S.Dayanik** (diffusion), **R.C.**& **N.Touzi** (GBM)
- Finite horizon case
  Jaillet - **Ronn** - **Tomapidis** (Tree) **R.C. N.Touzi** (GBM) **B.Hambly** (chooser swap)

R.C.-TOUZI, (BOUCHARD)



Exercise regions for $N = 5$ rights and finite maturity computed by Malliavin-Monte-Carlo.

Mitigation of Volume Risk with Temperature Options

- Rigorous Analysis of the Dependence between the **Budget Shortfall** and **Temperature** in Princeton
- Use of Historical Data (**sparse**) & Define of a **Temperature Protection**
  - Period of the Coverage
  - Form of the Coverage
- Search for the **Nearest Weather Stations** with HDD/CDD Trades
  - La Guardia Airport (LGA)
  - Philadelphia (PHL)
- Define a Portfolio of LGA & PHL forward / option Contracts
- Construct a **LGA / PHL basket**

Pricing: How Much is it Worth to PU?

- **Actuarial / Historical Approach**
  - Burn Analysis
  - Temperature Modeling & Monte Carlo VaR Computations
  - Not Enough Reliable Load Data
- **Expected (Exponential) Utility Maximization** (**A. Danilova**)
  - Use Gas & Power Contracts
  - Hedging in Incomplete Models
  - Indifference Pricing
  - Very Difficult Numerics (whether PDE's or Monte Carlo)

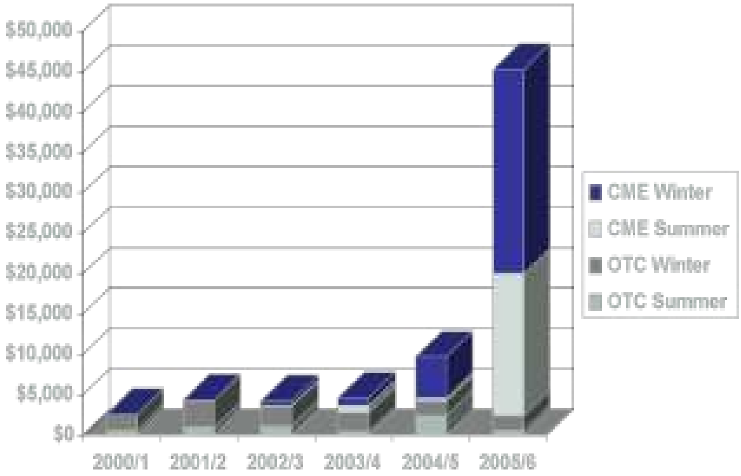
The Weather Markets

Weather is an essential economic factor

- *'Weather is not just an environmental issue; it is a major economic factor. At least 1 trillion USD of our economy is weather-sensitive'* (William Daley, 1998, US Commerce Secretary)
- **20% of the world economy** is estimated to be affected by weather
- Energy and other industrial sectors, Entertainment and Tourism Industry, ...
- **WRMA**

Weather Derivatives as a **Risk Transfer** Mechanism (**El Karoui - Barrieu**)

Size of the Weather Market



Total Notional Value of weather contracts: (in million USD) Price Waterhouse Coopers market survey).

Weather Derivatives

- **OTC** Customer tailored transactions
  - Temperature, Precipitation, Wind, Snow Fall, ...
- **CME** ($\approx$ 50%) (Tempreature - Launched in 1999)
  - 18 American cities
  - 9 European cities (London, Paris, Amsterdam, Berlin, Essen, Stockholm, Rome, Madrid and Barcelona)
  - 2 Japanese cities (Tokyo and Osaka)

AN EXAMPLE OF PRECIPITATION CONTRACT

- Physical Underlying Daily Index:
  - Precipitation in Paris
  - A day is a rainy day if precipitation exceeds 2mm
- Season
  - 2000: April thru August + September weekends
  - 2001: April thru August + September weekends
  - 2002: April thru August + September weekends
- Aggregate Index
  - Total Number of Rainy Days in the Season
- Pay- Off
  - Strike, Cap, Rate

RainFall Option Continued

- **Who Wanted this Deal?**
  - A Natural Trying to Hedge RainFall Exposure (Asterix Amusement Park)
- **Who was willing to take the other side?**
  - Speculators
  - Insurance Companies
  - Re-insurance Companies
  - Statistical Arbitrageurs
  - Investment Banks
  - Hedge Funds
  - Endowment Funds
  - ....

Other Example: Precipitation / Snow Pack

- **City of Sacramento**
  - HydroPower Electricity
- Who was on the other side?
  - Large Energy Companies (**Aquila, Enron**)

Who is covering for them?

Jargon of Temperature Options

For a given **location**, on any given day t

$$CDD_t = \max\{T_t - 65, 0\} \qquad HDD_t = \max\{65 - T_t, 0\}$$

Season

- One Month (CME Contracts)
- May 1st September 30 (CDD season)
- November 1st March 31st (HDD season)

Index

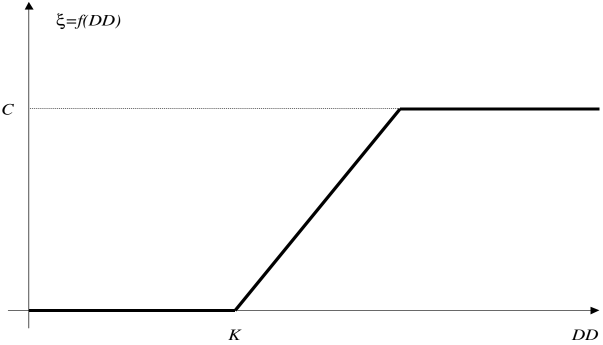
- Aggregate number of DD in the season

$$I = \sum_{t \in \text{Season}} CDD_t \quad \text{or} \quad I = \sum_{t \in \text{Season}} HDD_t$$

Pay-Off

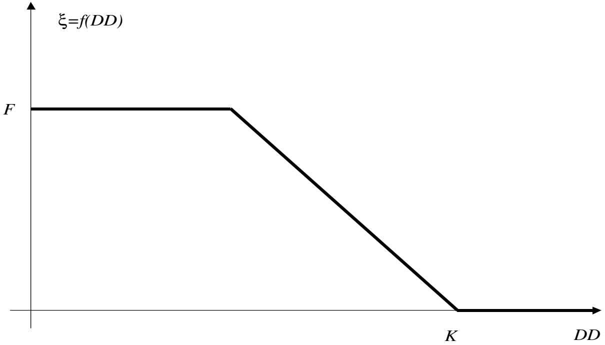
- Strike K, Cap C, Rate α

Call with Cap



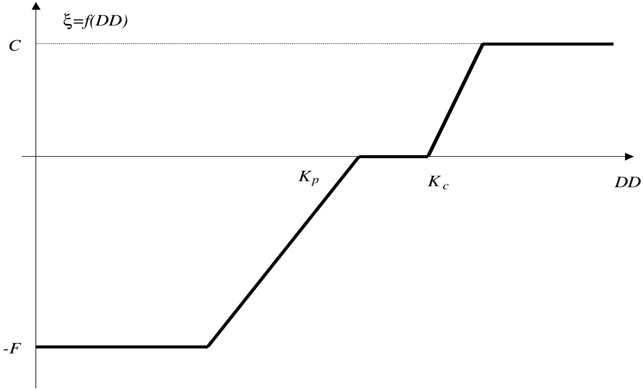
Pay-off $= \min\{\max\{\alpha * (I - K), 0\}, C\}$

Put with a Floor

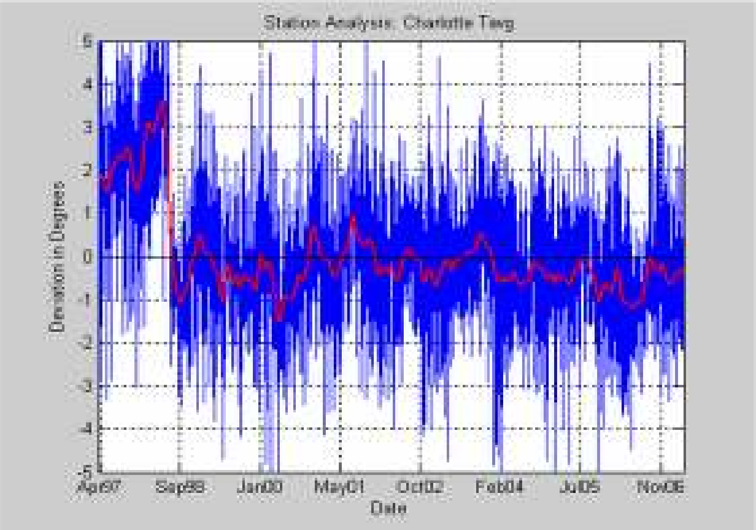


Pay-off $= \min\{\max\{\alpha * (K - I), 0\}, C\}$

Collar



Folklore of Data Reliability



Famous Example of Weather Station Change in Charlotte (NC).

Stylized Spreadsheet of a Basket Option

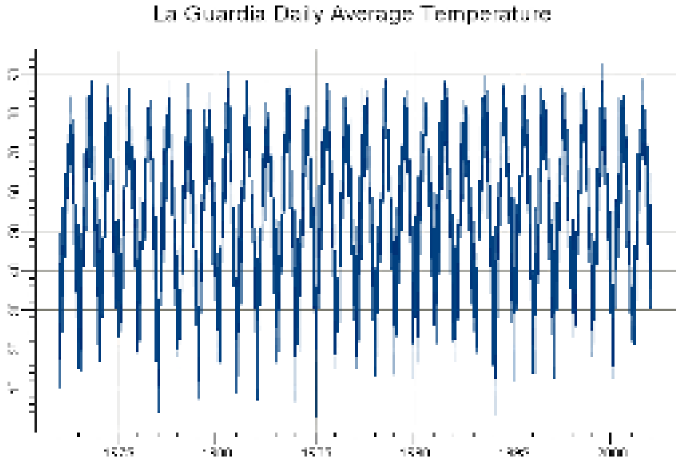
- **Structure**: Heating Degree Day (HDD) Floor (Put)
- **Index**: Cumulative HDDs
- **Term**: November 1, 2007 February 28, 2008
- **Stations**:
  - New York, LaGuardia 57.20%
  - Boston, MA 24.5%
  - Philadelphia, PA 12.00%
  - Baltimore, MD 6.30%
- **Floor Strike**: 3130 HDDs
- **Payout**: USD 35,000/HDD
- **Limit**: USD 12,500,000
- **Premium**: USD 2,925,000

Weather and Commodity

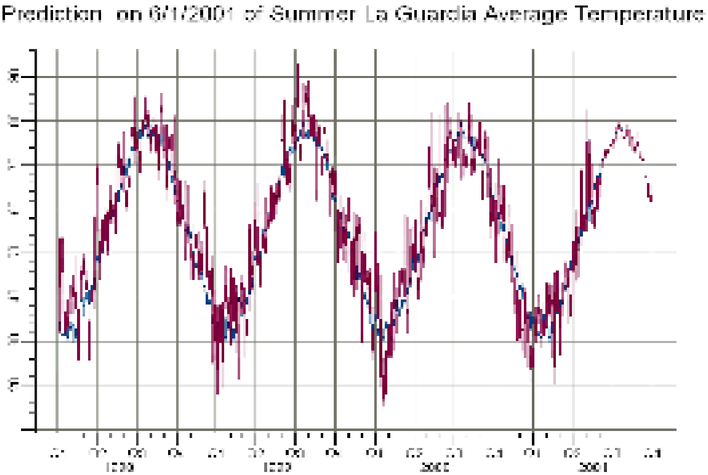
- **Stand-alone**
  - temperature ($\approx$ 80%)
  - precipitation ($\approx$ 10%)
  - wind ($\approx$ 5%)
  - snow fall ($\approx$ 5%)
- **In-Combination**
  - natural gas
  - power
  - heating oil
  - propane
- Agricultural risk (yield, revenue, input hedges and trading)
- Power outage - contingent power price options

WEATHER (TEMPERATURES) DERIVATIVES

- Still Extremely **Illiquid** Markets (except for **front month**)
- **Misconception**: Weather Derivative = Insurance Contract
  - No secondary market (Except on **Enron-on-Line**!!!)
- **Mark-to-Market** (or Model)
  - Essentially never changes
  - At least, Not Until Meteorology kicks in (10-15 days before maturity)
  - Then Mark-to-Market (or Model) changes every day
  - Contracts change hands
  - That's when major losses occur and money is made
- This *hot period* is not considered in academic studies
  - Need for updates: new information coming in (temperatures, forecasts, ...)
  - Filtering is (again) the solution



Daily Average Temperature at La Guardia.



Prediction on 6/1/2001 of daily temperature over the next four months.

The Future of the Weather Markets

- **Social function** of the weather market
  - Existence of a Market of Professionals (for weather risk transfer)
- **Under attack** from
  - (Re-)Insurance industry (but *high freuency / low cost*)
  - Utilities (trying to pass weather risk to end-customer)
    - EDF program in France
    - Weather Normalization Agreements in US
- **Cross Commodity Products**
  - Gas & Power contracts with **weather triggers/contingencies**
  - New (major) players: **Hedge Funds** provide liquidity
- **World Bank**
  - Use weather derivatives instead of insurance contracts

The Weather Market Today

- **Insurance Companies**: Swiss Re, XL, Munich Re, Ren Re
- **Financial Houses**: Goldman Sachs, Deutsche Bank, Merrill Lynch, SocGen, ABN AMRO
- **Hedge funds**: D. E. Shaw, Tudor, Susquehanna, Centaurus, Wolverine

Where is Trading Taking Place?

- Exchange: **CME** (Chicago Mercantile Exchange) 29 cites globally traded, monthly / seasonal contracts
- **OTC**
- Strong end-user demand within the **energy sector**

Incomplete Market Model & Indifference Pricing

- Temperature Options: Actuarial/Statistical Approach
- Temperature Options: Diffusion Models (**Danilova**)
- Precipitation Options: Markov Models (**Diko**)
  - *Problem:* Pricing in an Incomplete Market
  - *Solution:* Indifference Pricing à la Davis

$$
\begin{aligned}
d\theta_t &= p(t,\theta)dt + q(t,\theta)dW_t^{(\theta)} + r(t,\theta)dQ_t^{(\theta)} \\
dS_t &= S_t[\mu(t,\theta)dt + \sigma(t,\theta)dW_t^{(S)}]
\end{aligned}
$$

  - θ_t **non-tradable**
  - S_t **tradable**

Example: **Exponential Utility Function**

$$\tilde{p}_t = \frac{\mathbb{E}\{\tilde{\phi}(Y_T)e^{-\int_t^T V(s,Y_s)ds}\}}{\mathbb{E}\{e^{-\int_t^T V(s,Y_s)ds}\}}$$

where

- $\tilde{\phi} = e^{-\gamma(1-\rho^2)f}$
  where $f(\theta_T)$ is the pay-off function of the European call on the temperature
- $\tilde{p}_t = e^{-\gamma(1-\rho^2)p_t}$
  where p_t is price of the option at time t
- Y_t is the diffusion:

$$dY_t = [g(t, Y_t) - \frac{\mu(t, Y_t) - r}{\sigma(t, Y_t)} h(t, Y_t)]dt + h(t, Y_t)d\tilde{W}_t$$

  starting from $Y_0 = y$
- V is the time dependent potential function:

$$V(t, y) = -\frac{1-\rho^2}{2}\frac{(\mu(t, y) - r)^2}{\sigma(t, y)^2}$$

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