Imperfect Information, Macroeconomic Dynamics and the Term Structure of Interest Rates: An Encompassing Macro-Finance Model

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Overview

- Main goals of the paper
- Motivation
- Macro-Finance framework
- Econometric issues
- Empirical findings
- Conclusions

Main goals of the paper

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The central question of this paper: Can we improve the existing empirical Macro-Finance models of the yield curve?

Methodological approach:

- Assess/estimate the empirical relevance of three types of extensions of the standard Macro-Finance framework:
  - Deviations from full information rational expectations by introducing learning dynamics (imperfect information).
  - Time variation in the equilibrium real interest rate.
  - Deviations from Gaussian no-arbitrage pricing: time invariant liquidity premiums.
- The empirical analysis is performed using Bayesian techniques combining:
  - Priors consistent with a simple New-Keynesian semi-structural framework.
  - Data on macroeconomic variables, the yield curve and survey data on inflation expectations.

Motivation

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Motivation

A need for more elaborated Macro-Finance models?

Motivation: Despite the long-standing postulate and empirical findings of a close link between the yield curve and the macroeconomic factors, no fully satisfactory macroeconomic model of the yield curve exists:

- Standard New-Keynesian models cannot replicate the variation at the long end of the yield curve:
  - Long-term yields display excessive variation relative to standard NK model, e.g. Kozicki and Tinsley (2001).
  - Excess sensitivity of long-term yields to macroeconomic shocks, e.g. Gürkaynak et al. (2005).
- Standard Macro-Finance models introduce a time-varying inflation target (long-run inflation expectations) and fit the yield curve but face an interpretation problem:
  - Excess volatility in the implied long-run inflation expectations relative to surveys or market indicators of inflation expectations (US data).
  - Implied path for the inflation target does not align with the historical record.

Motivation

A need for more elaborated Macro-Finance models?

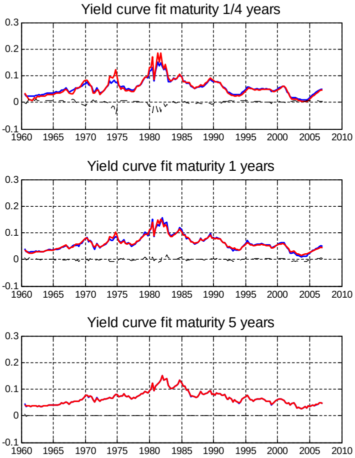
- Performance of the standard NK and Mac-Fin model (US data 1962-2007).

	Yields					**Infl. Exp. (SPF)**	
Maturity	**1/2 yr**	**1 yr**	**3yr**	**5 yr**	**10 yr**	**1yr**	**10yr**
Total variation yield (st. dev.)	**0.027**	**0.028**	**0.027**	**0.026**	**0.024**	**0.020**	**0.015**
	Standard New-Keynesian model						
Residual variation (st. dev.)	**0.009**	**0.009**	**0.013**	**0.015**	**0.018**	**0.009**	**0.013**
Resid var./total var.	0.333	0.321	0.481	0.577	0.750	0.450	0.867
	Standard Macro-Finance model						
Residual variation (st. dev)	**0.007**	**0.005**	**0.002**	**0.001**	**0.004**	**0.008**	**0.017**
Resid var/total var	0.267	0.178	0.074	0.038	0.166	0.400	1.067
	Pure finance model (3 factor Vasicek)						
Residual variation (st. dev.)	**0.002**	**0.002**	**0.000**	**0.000**	**0.002**	**n.a.**	**n.a.**

Motivation

A need for more elaborated Macro-Finance models?

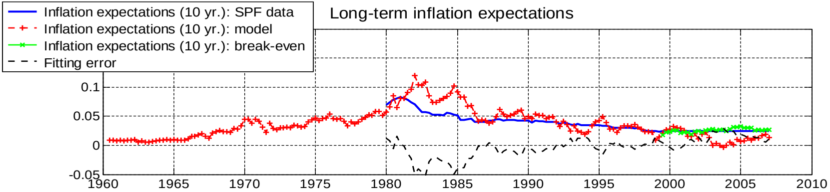
- Fit of the US yield curve: standard Mac-Fin model (1960-2007) .

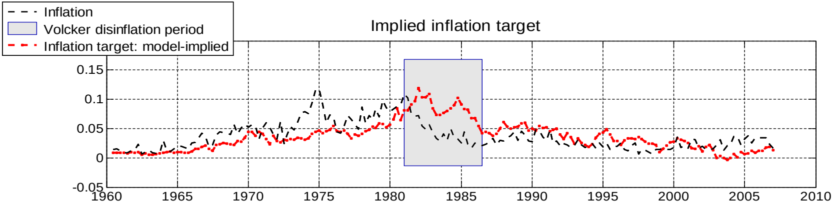


Motivation

A need for more elaborated Macro-Finance models?

- But (excessively?) volatile implied inflation expectations and target?





Macro-Finance Framework

Macro-Finance Framework

Macro-Finance Framework

Overview

- The standard Macro-Finance model
- The encompassing model
- Affine yield curve representation
- Perceived Law of Motion
- Learning

Macro-Finance Framework

The standard Macro-Finance model

Standard Macro-Finance models (Hordahl et al. (2006), Bekaert et al. (2006), Doh (2006), Dewachter and Lyrio (2006), De Graeve et al. (2007), Rudebusch and Wu (2004)...)

- Extended expectations hypothesis relates the long-term yield, $y_t(m)$, to expectations of short-term interest rates, $E_t(i_{t+j})$, and maturity-specific risk premiums, $\varkappa(m)$:

$$y_t(m) = \frac{1}{m}\sum_{j=0}^{m-1} E_t\left[i_{t+j}\right] + \varkappa(m)$$

- Benchmark NK macro model relates interest rate expectations to macroeconomic variables, i.e. inflation, output gap, the policy rate and the inflation target:

$$E_t\left[i_{t+j}\right] = f(y_t,\ (\pi_t - \pi_t^*),\ i_t,\ \pi_t^*,\ j)$$

$$\lim_{j\to\infty} E_t\left[i_{t+j}\right] = \bar{\rho} + \pi_t^*$$

- The yield curve implied by the standard Macro-Finance model is:

$$y_t(m) = \frac{1}{m}\sum_{j=0}^{m-1} f(y_t,\ (\pi_t - \pi_t^*),\ i_t,\ \pi_t^*,\ j) + \varkappa(m)$$

Macro-Finance Framework

The standard Macro-Finance model

Encompassing/extended Macro-Finance model:

- Extended expectations hypothesis under the Perceived Law of Motion (E^P PLM):

$$y_t(m) = \frac{1}{m}\sum_{j=0}^{m-1} E_t^P\left[i_{t+j}\right] + rp_t$$

- Extended NK macro model including perceived (time-varying) equilibrium real rate, ρ_t^P:

$$E_t^P\left[i_{t+j}\right] = f(y_t,\ (\pi_t - \pi_t^{*P}),\ i_t,\ \pi_t^{*P}, \rho_t^P, j)$$

$$\lim_{j\to\infty} E_t^P\left[i_{t+j}\right] = \pi_t^{*P} + \rho_t^P$$

- The yield curve implied by the extended model (allowing for liquidity effects and time-varying premiums):

$$y_t(m) = \frac{1}{m}\sum_{j=0}^{m-1} f(y_t,\ (\pi_t - \pi_t^{*P}),\ i_t,\ \pi_t^{*P}, \rho_t^P, j) + \varkappa_t(m) + \phi(m)$$

The Macro-Finance framework

Affine yield curve representation

We obtain an affine yield curve representation in the (perceived) state, X_t^P by assuming log-normal pricing (Ang and Piazzesi (2003)):

$$y_t(m) = \underbrace{-a(m)/m - (b(m)/m)\, X_t^P}_{\text{No-Arbitrage}} + \underbrace{\phi(m)}_{\text{Liq. effect}} + \underbrace{\eta_t(m)}_{\text{meas. err.}}$$

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No-Arbitrage:

PLM dynamics:

$$X_t^P = C^P + \Phi^P X_{t-1}^P + \Gamma^P S^P \varepsilon_t^P$$

No-arbitrage conditions:

$$P_t(m) = E_t^P\left[M_{t,t+1} P_{t+1}(m-1)\right]$$

$$M_{t,t+1} = \exp(-i_t - c_m - \Lambda_t' \varepsilon_t^P)$$

$$\Lambda_t = \Lambda_0 + \Lambda_1 X_t^P$$

The Macro-Finance framework

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$$\Lambda_t = \Lambda_0 + \Lambda_1 X_t^P$$

Affine yield curve representation (No-Arbitr.):

$$y_t(m) = -a(m)/m - (b(m)/m)\,X_t^P$$

No-arbitrage restrictions:

$$a(m) = a(m-1) + b(m-1)(C^P - \Gamma^P S^P S^{P\prime} \Lambda_0) + JIT$$

$$b(m) = b(m-1)(\Phi^P - \Gamma^P S^P S^{P\prime} \Lambda_1) - \delta_1'.$$

The Macro-Finance framework

Perceived Law of Motion: Macroeconomic dynamics

The Perceived Law of Motion is a VAR(I) in the perceived state, X_t^P :

$$X_t^P = C^P + \Phi^P X_{t-1}^P + \Gamma^P S^P \varepsilon_t^P, \qquad X_t^P = [\pi_t, y_t, i_t, \pi_t^{*P}, \rho_t^P]$$

The Macro-Finance framework

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New-Keynesian model with stoch. trends π_t^{*P} and ρ_t^P:

$$\pi_t = \mu_\pi E_t^P \pi_{t+1} + (1-\mu_\pi)\pi_{t-1} + \kappa y_t + \sigma_\pi \varepsilon_{\pi,t}$$

$$y_t = \mu_y E_t^P y_{t+1} + (1-\mu_y) y_{t-1} - \phi(i_t - E_t^P \pi_{t+1} - \rho_t^P) + \sigma_y \varepsilon_{y,t}$$

$$i_t = (1-\gamma_i) i_t^T + \gamma_i i_{t-1} + \sigma_i \varepsilon_{i,t}$$

$$i_t^T = \rho_t^P + E_t^P \pi_{t+1} + \gamma_\pi (\pi_t - \pi_t^{*P}) + \gamma_y y_t$$

$$\pi_t^{*P} = \lim_{s\to\infty} E_t^P [\pi_{t+s}]$$

$$\rho_t^P = \lim_{s\to\infty} E_t^P [i_{t+s} - \pi_{t+s}]$$

The Macro-Finance framework

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$$i_t = (1-\gamma_i) i_t^T + \gamma_i i_{t-1} + \sigma_i \varepsilon_{i,t}$$

$$i_t^T = \rho_t^P + E_t^P \pi_{t+1} + \gamma_\pi (\pi_t - \pi_t^{*P}) + \gamma_y y_t$$

$$\pi_t^{*P} = \lim_{s\to\infty} E_t^P [\pi_{t+s}]$$

$$\rho_t^P = \lim_{s\to\infty} E_t^P [i_{t+s} - \pi_{t+s}]$$

Updating the perceived stochastic trends:

$$\pi_t^{*P} = \pi_{t-1}^{*P} + f(X_t, \ldots, X_{t-n})$$

$$\rho_t^P = \rho_{t-1}^P + f(X_t, \ldots, X_{t-n})$$

$$X_t = [\pi_t,\ y_t,\ i_t, \pi_t^{*P}, \rho_t^P, \pi_t^*, \rho_t]$$

The Macro-Finance framework

Learning dynamics

- Learning dynamics are modeled along the lines of Kozicki and Tinsley (2005):

$$\pi_t^{*P} = \pi_{t-1}^{*P} + w_\pi \sigma_{\pi^*} \varepsilon_{\pi^*,t} + (1 - w_\pi) \left[\sigma_{\pi^b} \eta_{\pi,t} + g_\pi (\pi_t - E_{t-1}^P \pi_t) \right]$$

$$\rho_t^P = \rho_{t-1}^P + w_\rho \sigma_\rho \varepsilon_{\rho,t} + (1 - w_\rho) \left[\sigma_{\rho^b} \eta_{\rho,t} + g_\rho (i_t - \pi_t - E_{t-1}^P (i_t - \pi_t)) \right]$$

  - The learning rule updates perceived trends in function of three types of information:
    - Actual shocks to the 'true' inflation target and/or equilibrium real rate (e.g. inflation target announcements, release of productivity data, risk perceptions...).
    - Subjective and exogenous belief shocks $\eta_{\pi^b,t}$, $\eta_{\rho^b,t}$ (e.g. changes in credibility,...).
    - Subjective and endogenous forecast errors of inflation and real interest rates, $(\pi_t - E_{t-1}^P \pi_t)$ and $(i_t - \pi_t - E_{t-1}^P (i_t - \pi_t))$.
  - Although ad hoc, the learning rule embeds as limiting cases:
    - The full info. RE models ($w_\pi = w_\rho = 1$): e.g. stand; Mac-Fin $\sigma_{\pi^*} \geq 0$, $\sigma_\rho = 0$.
    - Constant gain learning rule ($w_\pi = w_\rho = 0$, $\sigma_{\rho^b} = \sigma_{\pi^b} = 0$, $g_\pi > 0$ $g_\rho > 0$).

Econometric issues

Econometric issues

Econometric issues

Overview

- Data
- Summary of Bayesian estimation procedure
  - Sets of estimated parameters
  - Prior distributions
  - Likelihood
- Alternative model versions

Econometric issues

Data

Model is estimated on US data: 1960Q2 till 2006Q4.

- Inflation: quarter-by-quarter GDP deflator (p.a. terms) is used. Source: Federal Reserve Economic Data archive (FRED).
- Output gap: CBO output gap measure is used (no- real time data). Source: Congressional Budget Office.
- Policy rate: Fed fund effective rate is used. Source: FRED.
- Yield curve: 1/4, 1/2, 1, 3, 5, 10 yr. maturities. Sources: Gürkaynak et al. (2006) and FRED.
- Inflation expectations: average inflation expectations over 1 and 10 year horizons. Source: Survey of Professional Forecasters, FED Philadelphia.

Econometric issues

Summary: Bayesian estimation framework

MCMC (Metropolis-Hastings) identification of the posterior density $p(\theta_i \mid Z^T)$:

$$p(\theta_i \mid Z^T) = L(Z^T \mid \theta_i)p(\theta_i)/p(Z^T)$$

- Parameters θ_i: structural parameters related to the NK model, learning, prices of risk , mispricing and measurement errors.
- Priors of the parameters, $p(\theta_i)$:
  - Priors related to structural parameters are in line with macro literature.
  - The priors of the learning model are biased towards rational expectations $(E(w) = 0.85,\ \sigma(w) = 0.10)$.
- Likelihood function, $L(Z^T \mid \theta_i)$, generated by the prediction error decomposition (Kalman filter):
  - Transition equation is based on the Actual Law of Motion.
  - Measurement equation combines macroeconomic information (π_t, y_t, i_t), yield curve variables and inflation expectations surveys.

Econometric issues

Versions of the model

Table: PROPERTIES OF ALTERNATIVE VERSIONS OF THE MODEL

Model	Macro (# stoch. trends)	Prices of Risk	Expectations	Mispricing	
NK0	NK model (0)	Consistent Λ_0^{IS}	Full-info RE	Yes	⟵ Stand. NK mod
MF1	NK model (1)	Consistent Λ_0^{IS}	Full-info RE	Yes	⟵ **Stand. MF mod**
MFS	NK model (2)	Consistent: Λ_0^{IS}	Full-info RE	No	⟵ Struct. MF mod
MFM	NK model (2)	Consistent: Λ_0^{IS}	Full-info RE	Yes	⟵ Liq. MF mod
MFF	NK model (2)	Free: Λ_0, Λ_1	Full-info RE	No	⟵ Flex. MF mod
MFE	NK model (2)	Free: Λ_0, Λ_1	Learning	Yes	⟵ **Encompass.mod**

Empirical findings

Empirical findings

Empirical findings

- Improving standard Macro-Finance models?
    - Comparing model versions
- Estimation results of the MFE model
    - Parameter estimates
    - Implied macroeconomic factors
- Macro factors and the yield curve implied by the MFE model
    - Fit of the yield curve
    - Liquidity effects

Improving standard Macro-Finance models?

Comparing model versions

Conclusion 1: The encompassing model, incorporating time-varying equilibrium real rates, imperfect information and liquidity effects, is strongly favored by the data.

Table: MODEL PERFORMANCE: MARGINAL LIKELIHOOD AND BIC

Log Marginal likelihood and BIC						
Model	NK0	**MF1**	MFS	MFM	MFF	**MFE**
Marg. Lik	6124	**7240**	7381	7628	7638	**7741**
BIC	12387	**-14591**	-14815	-15333	-15384	**-15442**
Decomposition of BIC						
Model	NK0	**MF1**	MFS	MFM	MFF	**MFE**
Macro (-2lnlik)	-3414	**-3495**	-3760	-3711	-3745	**-3772**
Yields (-2lnlik)	-7413	**-9187**	-9037	-9392	-9504	**-9538**
Infl. exp.(-2lnlik)	-1683	**-1447**	-2227	-2197	-2182	**-2256**
Penalty	131	**136**	131	157	194	**272**

Estimation results

Parameter estimates of the encompassing model

Conclusion 2: The structural parameters of the encompassing model are plausible and aligned to the empirical macro literature.

- The behavioral parameters of the (semi-) structural NK model are in line with empirical macro literature:
  - Relative to benchmark Mac-Fin models, we find stronger forward looking components ($\mu_\pi = 0.66$, $\mu_y = 0.69$). e.g. Galí et al (2005)
    - Phillips curve: low but significant inflation indexation ($\delta_\pi = 0.53$) and output sensitivity ($\kappa = 0.012$).
    - IS-curve: significant habit persistence ($h = 0.75$) and risk aversion in line with macro lit. ($\sigma = 2.5$).
  - Taylor rule parameters in line with the literature. Relatively low interest rate smoothing : ($\gamma_\pi = 0.4$, $\gamma_y = 0.63$ and $\gamma_i = 0.69$). e.g. Rudebusch (2002).
- Actual stochastic trends:
  - Inflation target displays only small time variation ($\sigma_{\pi^*} = 0.04\%$) but imprecisely estimated.
  - Significant volatility in the equilibrium real rate ($\sigma_\rho = 0.7\%$) but imprecisely estimated. (e.g. Trehan and Wu (2007), Bjornland et al (2006, 2007), Bekaert et al. (2005), Laubach and Williams (2003)...)

Estimation results

Parameter estimates of the encompassing model

	Param.	Mean	Std. Dev.	Mode	Crit.val. 5%	Crit. val. 95%
		Phillips curve				
Inflation indexation ⟶	δ_π	0.5337	0.0327	**0.5288**	0.4829	0.5891
Output sensitivity ⟶	κ	0.0137	0.0042	**0.0117**	0.0078	0.0212
		IS curve				
Habit persistence ⟶	h	0.7512	0.0445	**0.7566**	0.6741	0.8179
Risk aversion ⟶	σ	2.6779	0.4004	**2.5551**	1.9344	3.2328
		Monetary policy rule				
Inflation gap ⟶	γ_π	0.3707	0.1081	**0.4389**	0.2296	0.5824
Output gap ⟶	γ_y	0.6673	0.1638	**0.6341**	0.4931	1.0214
Interest smoothing ⟶	γ_i	0.6827	0.0406	**0.6896**	0.6462	0.7849
		Shocks				
Supply shock	σ_π	0.0118	0.0010	0.0120	0.0101	0.0136
Demand shock	σ_y	0.0032	0.0003	0.0031	0.0027	0.0038
Policy rate shock	σ_i	0.0117	0.0007	0.0119	0.0110	0.0131
Inflation target shock ⟶	σ_{π^*}	0.0015	0.0010	**0.0004**	0.0001	0.0034
Eq. real rate shock ⟶	σ_ρ	0.0074	0.0014	**0.0073**	0.0039	0.0083

Estimation results

Parameter estimates of the encompassing model

Conclusion 3: Imperfect information and learning effects dominate long-run inflation expectations. The parameter estimates imply only weak anchoring of subjective inflation expectations.

- Inflation belief shocks and adaptive learning effects dominate subjective inflation expectations (at the mode $w_{\pi^*} = 0.65$):
  - Inflation target shocks: **0.03%** ($w_\pi \sigma_{\pi^*} = 0.65 \times 0.04\% = 0.03\%$).
  - Inflation belief shocks: **0.20%** ($(1 - w_\pi)\sigma_{\pi^{*b}} = 0.35 \times 0.58\% = 0.20\%$).
  - Inflation forecast errors (gain= 0.08) : **0.12%**.
- No strong learning effects observed for the equilibrium real interest rate (at the mode $w_\rho = 0.97$):
  - Real rate (target) shocks: **0.71%** ($w_\rho \sigma_{\pi^*} = 0.97 \times 0.73\% = 0.71\%$).
  - Real rate belief shocks: **0.04%** ($(1 - w_\rho)\sigma_{\pi^{*b}} = 0.03 \times 1.2\% = 0.04\%$).
  - Real rate forecast errors (gain 0.01): **0.01%**.

Estimation results

Parameter estimates of the encompassing model

Table: Posterior density estimates Ib: Learning parameters

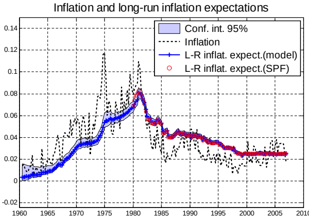
	Param.	Mean	Std. Dev.	Mode	Crit.val. 5%	Crit. val. 95%
		Learning parameters: Long-run inflation expectations: π_t^{*P}				
Weight RE $\longrightarrow$	w_π	0.6083	0.0645	**0.6550**	0.4897	0.6907
Gain $\longrightarrow$	g_π	0.2191	0.0255	**0.2190**	0.1668	0.2479
Belief shock $\longrightarrow$	$\sigma_{\pi^{*b}}$	0.0045	0.0014	**0.0058**	0.0015	0.0067
Target shock $\longrightarrow$	σ_{π^*}	0.0015	0.0010	**0.0004**	0.0001	0.0034
		Learning parameters: perceived eq. real rate: ρ_t^P				
Weight RE $\longrightarrow$	w_ρ	0.7789	0.1441	**0.9746**	0.5858	0.9872
Gain $\longrightarrow$	g_ρ	0.1200	0.0746	**0.0443**	0.0117	0.2392
Belief shock $\longrightarrow$	σ_{ρ^b}	0.0121	0.0058	**0.0050**	0.0017	0.0194
Eq. real shock $\longrightarrow$	σ_ρ	0.0074	0.0014	**0.0073**	0.0039	0.0083

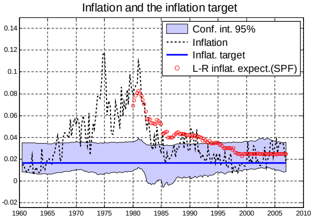
$$\pi_t^{*P} = \pi_{t-1}^{*P} + w_\pi \sigma_{\pi^*} \varepsilon_{\pi^*,t} + (1 - w_\pi)\left[\sigma_{\pi^b}\eta_{\pi,t} + g_\pi(\pi_t - E_{t-1}^P \pi_t)\right]$$

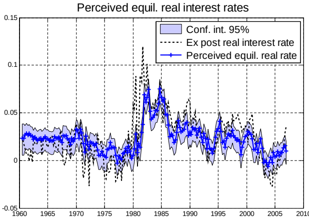
$$\rho_t^P = \rho_{t-1}^P + w_\rho \sigma_\rho \varepsilon_{\rho,t} + (1 - w_\rho)\left[\sigma_{\rho^b}\eta_{\rho,t} + g_\rho(i_t - \pi_t - E_{t-1}^P(i_t - \pi_t))\right]$$

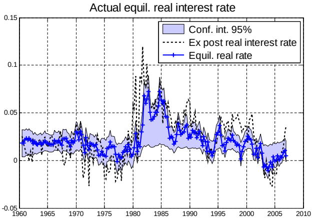
Estimation results

Implied factors









Macro factors and the yield curve

Yield curve fit

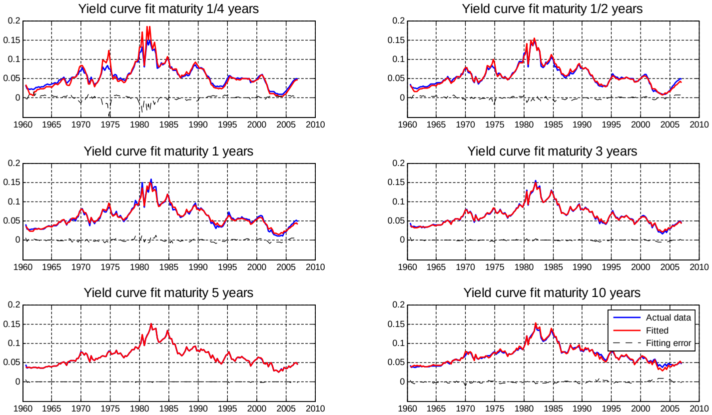
Conclusion 4: The encompassing Macro-Finance model captures a substantial part of the time variation of the yield curve and aligns inflation expectations to survey data SPF (unlike standard Mac-Fin models).

	Yields					**Infl. Exp. (SPF)**	
Maturity	**1/2 yr**	**1 yr**	**3yr**	**5 yr**	**10 yr**	**1yr**	**10yr**
Total variation yield (st. dev.)	**0.027**	**0.028**	**0.027**	**0.026**	**0.024**	**0.020**	**0.015**
	Encompassing Macro-Finance model						
Residual variation (st. dev.)	**0.005**	**0.004**	**0.002**	**0.001**	**0.003**	**0.005**	**0.001**
R-square	0.963	0.979	0.994	0.999	0.978	0.927	0.995
	Standard Macro-Finance model						
Residual variation (st. dev)	**0.007**	**0.005**	**0.002**	**0.001**	**0.004**	**0.008**	**0.017**
	Pure finance model (3 factor Vasicek)						
Residual variation (st. dev.)	**0.002**	**0.002**	**0.000**	**0.000**	**0.002**	**n.a.**	**n.a.**

Macro factors and the yield curve

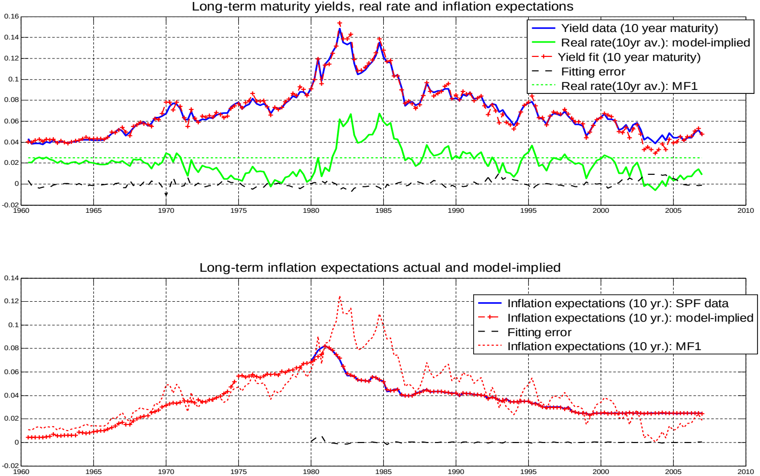
Yield curve fit

Figure: OBSERVED AND FITTED YIELD CURVE OF THE MFE MODEL



Macro factors and the yield curve

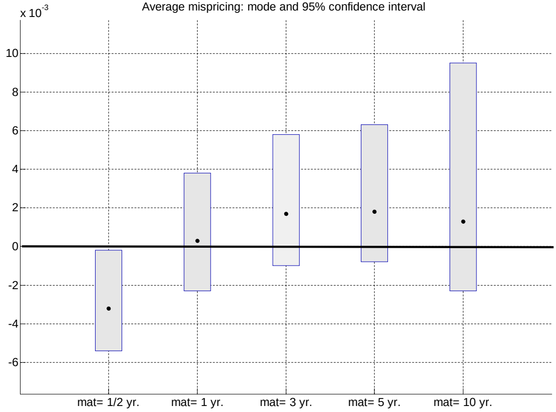
Yield curve fit



Macro factors and the yield curve

Mispricing or liquidity effects

Conclusion 5: There is evidence of significant mispricing (liquidity preference effects), especially at the short end of the yield curve.



Conclusions

- In this paper the standard (empirical) Macro-Finance models are extended by introducing (i) time variation in the equilibrium real interest rate (ii) liquidity effects and (iii) learning.
- The encompassing model outperforms all existing Macro-Finance models. The model 'explains' more than 95% of yield curve dynamics.
- The encompassing model, unlike standard Macro-Finance models, reconciles yield curve dynamics, inflation expectations and the inflation target. The results suggest that:
  - Learning dynamics generate significant differences between long-run inflation expectations and the inflation target. Important drivers of subjective inflation expectations are inflation forecasts errors and belief shocks.
  - Perceived eq. real rate dynamics explain a substantial share of the variation in long-term yields.
  - Significant liquidity and risk premium effects at the short end of the yield curve.
- Open issues:
  - Sources of dynamics in perceived and/or actual equilibrium real interest rate?