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

Hans Dewachter

KULeuven and RSM, EUR

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The Macro-Finance framework

Actual Law of Motion: Summary

Actual Law of Motion of observed macroeconomic dynamics follows the Evans and Honkapohja (2001) Euler approach to learning and is consistent with :

- A (semi) structural New-Keynesian model containing:
  - Long-run dynamics: the actual inflation target π_t^* and the actual equilibrium real interest rate, ρ_t.
  - Actual and perceived stochastic trends can differ due to learning: $\pi_t^* \neq \pi_t^{*P}$ and $\rho_t \neq \rho_t^P$.
  - Short-run dynamics: according to a (consumption-based) standard New-Keynesian model.
- Subjective expectations w.r.t. macroeconomic dynamics according to the Perceived Law of Motion.
- A learning rule, modeling the dynamics of the inferred stochastic endpoints, π_t^{*P} and ρ_t^P.

The Macro-Finance framework

Actual Law of Motion: Macroeconomic dynamics

Actual Law of Motion of observed macroeconomic dynamics is a VAR(I):

$$X_t = C^A + \Phi^A X_{t-1} + \Gamma^A S^A \varepsilon_t^A, \qquad X_t' = [\pi_t, y_t, i_t, \pi_t^{*P}, \rho_t^P, \pi_t^*, \rho_t]$$

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

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

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

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

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

$$\rho_t = \rho_{t-1} + \sigma_\rho \varepsilon_{\rho,t}$$

$$\pi_t^* = \pi_{t-1}^* + \sigma_{\pi^*} \varepsilon_{\pi^*,t}$$

The Macro-Finance framework

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Private expectations based on PLM:

$$E_t^P X_{t+1} = C^P + \Phi^P X_t^P.$$

The Macro-Finance framework

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Private expectations based on PLM:

$$E_t^P X_{t+1} = C^P + \Phi^P X_t^P.$$

Updating rule for perceived stochastic trends:

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

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

The Macro-Finance framework

Actual Law of Motion: Learning dynamics

- Learning dynamics (imperfect information models) 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 inferred values in function of three types of information (the weight of each source determined by w and g):
    - Actual shocks to the 'true' inflation target and/or equilibrium real rate (e.g. inflation target announcements, release of productivity data, risk perceptions..).
    - Private and exogenous belief shocks $\eta_{\pi^b,t}$, $\eta_{\rho^b,t}$ (e.g. changes in credibility,...).
    - Private and endogenous forecast errors of inflation and real interest rates, $(\pi_t - E_{t-1}^P \pi_t)$ and $(i_t - \pi_t - E_{t-1}^P (i_t - \pi_t))$.
  - The full information RE models are embedded as limiting cases ($w_\pi = w_\rho = 1$):
    - The Macro-Finance version with constant eq. real rate and time-varying inflation target: $\sigma_{\pi^*} \geq 0$, $\sigma_\rho = 0$.

The Macro-Finance framework

Actual Law of Motion: Learning dynamics

The encompassing model, although ad hoc, embeds standard expectations formation processes as limiting cases:

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

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

- Full-information rational expectations versions of the model are obtained by imposing full information, i.e. $w_\pi = w_\rho = 1$:
  - The standard New-Keynesian model with constant inflation target and eq. real rate: $\sigma_{\pi^*} = \sigma_\rho = 0$.
  - The standard Macro-Finance version with constant eq. real rate and time-varying inflation target: $\sigma_{\pi^*} \geq 0,\ \sigma_\rho = 0$.
  - The structural Macro-Finance version with consistent prices of risk, constant eq. real rate and time-varying inflation target: $\Lambda_0 = \Lambda_0^{IS}$, $\Lambda_1 = 0$, $\sigma_{\pi^*} \geq 0$, $\sigma_\rho = 0$.
- Models with pure constant gain learning rules: $w_{\pi^*} = w_\rho = 0,\ \sigma_{\rho^b} = \sigma_{\pi^{*b}} = 0$.

Econometric issues

Summary: Bayesian estimation framework

- Identification of the posterior density $p(\theta_i \mid Z^T)$of the parameter vector θ_i :

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

  with:

  - $L(Z^T \mid \theta_i)$: the likelihood of the data, Z^T, given θ_i.
  - $p(\theta_i)$: the prior density of the parameter vector, θ_i.
  - $p(Z^T)$: the marginal likelihood of the data.

- Model evaluation is based on marginal likelihood and the BIC:

  - Marginal likelihood is obtained by integrating out θ_i :

$$p(Z^T) = \int_{\theta_i} L(Z^T \mid \theta_i)p(\theta_i)d\theta_i$$

  - Schwartz BIC criterion (independent from priors):

$$BIC = -2\ln(L(Z^T \mid \theta_i)) + p\ln(T)$$

  with p the number of parameters and T the number of observations.

Econometric issues

Summary: sets of estimated parameters

We estimate jointly six sets of parameters included in θ_i:

- Deep parameters related to the structural equations:
  - Phillips curve: inflation indexation, δ_π, inflation sensitivity to output, κ.
  - IS curve: risk aversion σ, habit persistence, h.
  - Taylor rule: inflation and output sensitivity, γ_π, γ_y and interest rate smoothing γ_i.
- Sizes (standard deviations) of the structural shocks($\sigma_\pi, \sigma_y, \sigma_i, \sigma_{\pi^*}, \sigma_\rho$).
- Learning parameters (weights $\omega_\rho, \omega_{\pi^*}$, gains g_ρ, g_{π^*} belief shocks $\sigma_{\pi^b}, , \sigma_{\rho^b}$ init. beliefs π_0^{*P}, ρ_0^P).
- Prices of risk used in bond pricing (Λ_0, Λ_1).
- Liquidity effects (mispricing $\phi(m_j), ..m_j = 1, ..n_y$).
- Measurement errors in the yields and inflation expectations $(\sigma_\eta(m))$.

Econometric issues

Summary: Prior distributions

- Structural parameters (Distr, (mean, std. dev)):
  - Phillips curve: Inflation indexation, δ_{π}, : Beta (0.7, 0.05); Output sensitivity of inflation, κ : Normal (0.12, 0.03).
  - IS curve: Risk aversion σ : Gamma (1.5, 0.34); Habit persistence, h: Beta (0.7, 0.05).
  - Taylor rule parameters. Inflation sensitivity γ_i: Normal (0.5, 0.25); Output sensitivity, γ_y: Normal (0.5, 0.5); Interest rate smoothing γ_i: Normal (0.8, 0.2).
- Learning parameters (Distr, (mean, std. dev)):
  - Bias towards full-information rational expectations. Weight public signal, w_{π^*}, w_{ρ} : Beta (0.85, 0.1).
  - Constant gain parameters, g_{π}, g_{ρ}: Uniform (0.125, 0.075).
  - Sizes of belief shocks, σ_{π^*}, σ_{ρ}: Uniform (0.01, 0.006).
- Mispricing (Distr, (mean, std. dev)):
  - Average mispricing, $\phi(m)$: Normal (0.00, 0.005).

Econometric issues

Summary: Likelihood

Likelihood based on the prediction error decomposition:

- Transition equation is based on the ALM dynamics, consistent with the learning dynamics and the structural model.
- Measurement equation includes macroeconomic variables, the yield curve and the surveys of subjective inflation expectations.
- In case of Macro-Finance models, latent variables, ρ_t and π_t^* and ρ_t^P and π_t^{*P} are filtered by means of a Kalman filter.
- For Rational Expectations and Macro-Finance models determinacy was imposed through the prior distributions on κ_π, γ_π and γ_y.
- For Learning we imposed (local) stability (in mean) of the parameters: eigenvalues ALM smaller than 1.

Econometric issues

Summary: Bayesian estimation

Parameters are estimated by simulation-based Bayesian techniques (Metropolis-Hastings):

- A first round optimization based on simulated annealing techniques.
- Metropolis-Hastings based on normal random walk dynamics.
- Acceptance ratio target 40%.
- Number of simulations 200000.
- Checks for convergence (Geweke).
- Marginal likelihood based on both Laplace transform and modified harmonic mean.

Econometric issues

Summary: Likelihood

Transition equation (ALM) models observed macroeconomic dynamics:

$$X_t = C^A + \Phi^A X_{t-1} + \Gamma^A S^A \varepsilon_t^A, \quad X_t' = [\pi_t, y_t, i_t, \pi_t^{*P}, \rho_t^P, \pi_t^*, \rho_t]$$

- Structural model (conditioned on true stochastic endpoints, π_t^* and ρ_t):

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

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

$$i_t = (1-\gamma_i)(\rho_t + E_t^P \pi_{t+1} + \gamma_\pi(\pi_t - \pi_t^*) + \gamma_y y_t) + \gamma_i i_{t-1} + \sigma_i \varepsilon_{i,t}$$

$$\rho_t = \rho_{t-1} + \sigma_\rho \varepsilon_{\rho,t}$$

$$\pi_t^* = \pi_{t-1}^* + \sigma_{\pi^*} \varepsilon_{\pi^*,t}$$

- The subjective beliefs of agents summarized in the PLM and the learning rule:

$$E_t^P X_{t+1}^P = C^P + \Phi^P X_t^P$$

Econometric issues

Summary: Likelihood

- The measurement equation incorporates three types of information: macroeconomic variables, X_t^o, the yield curve, Y_t, and survey data on inflation expectations, S_t:

$$\begin{bmatrix} X_t^o \\ Y_t \\ S_t \end{bmatrix} = \begin{bmatrix} 0 \\ A_y \\ A_S \end{bmatrix} + \begin{bmatrix} I_o \\ B_y \\ B_S \end{bmatrix} X_t + \begin{bmatrix} 0 \\ \phi_y \\ 0 \end{bmatrix} + \begin{bmatrix} 0 \\ \eta_{y,t} \\ \eta_{S,t} \end{bmatrix}$$

- This measurement equation summarizes three relations:
  - Observable macroeconomic variables are included in X_t: $X_t^o = I_o X_t$.
  - No-arbitrage and liquidity terms link the yields to the (perceived) macroeconomic state: $Y_t = A_y + B_y X_t + \phi_y + \eta_{y,t}$.
  - The PLM determines subjective beliefs: $S_t = A_S + B_S X_t$.

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	$\longleftarrow$ Stand. NK mod
MF1	NK model (1)	Consistent Λ_0^{IS}	Full-info RE	Yes	$\longleftarrow$ Stand. MF mod
MFS	NK model (2)	Consistent: Λ_0^{IS}	Full-info RE	No	$\longleftarrow$ Struct. MF mod
MFM	NK model (2)	Consistent: Λ_0^{IS}	Full-info RE	Yes	
MFF	NK model (2)	Free: Λ_0, Λ_1	Full-info RE	No	
MFE	NK model (2)	Free: Λ_0, Λ_1	Learning	Yes	$\longleftarrow$ Encompass.mod

Econometric issues

Data

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

- Quarter-by-quarter inflation (GDP deflator) rate (p.a. terms) are used. Source: Federal Reserve Economic Data archive (FRED).
- CBO output gap measure is used (no- real time data). Source: Congressional Budget Office.
- Fed fund rate is used as policy rate. 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 horizon. Source: Survey of Professional Forecasters, FED Philadelphia.

Results for the encompassing model

Yield curve fit: posterior moments

Table: POSTERIOR DENSITY ESTIMATES I: ENCOMPASSING MODEL MFLA

Param.	Mean	Std. Dev	Mode	Crit.val. 5%	Crit. val. 95%
	Average mispricing yields				
$\phi(1/2)$	-0.0034	0.0016	-0.0032	-0.0054	-0.0001
$\phi(1)$	-0.0001	0.0019	0.0003	-0.0023	0.0038
$\phi(3)$	0.0010	0.0021	0.0017	-0.0010	0.0058
$\phi(5)$	0.0011	0.0022	0.0018	-0.0008	0.0063
$\phi(10)$	0.0010	0.0038	0.0013	-0.0023	0.0095
	Standard deviation measurement errors yield curve				
$\sigma_{\eta,y}(1/4)$	0.0103	0.0005	0.0101	0.0094	0.0111
$\sigma_{\eta,y}(1/2)$	0.0044	0.0003	0.0044	0.0040	0.0049
$\sigma_{\eta,y}(1)$	0.0040	0.0002	0.0040	0.0037	0.0043
$\sigma_{\eta,y}(3)$	0.0020	0.0001	0.0019	0.0018	0.0022
$\sigma_{\eta,y}(5)$	0.0008	0.0001	0.0008	0.0006	0.0010
$\sigma_{\eta,y}(10)$	0.0035	0.0002	0.0034	0.0032	0.0039
	Standard deviation measurement errors inflation expectations				
$\sigma_{\eta,\pi}(1)$	0.0052	0.0004	0.0051	0.0046	0.0058
$\sigma_{\eta,\pi}(10)$	0.0010	0.0001	0.0010	0.0008	0.0012

Macro factors and the yield curve

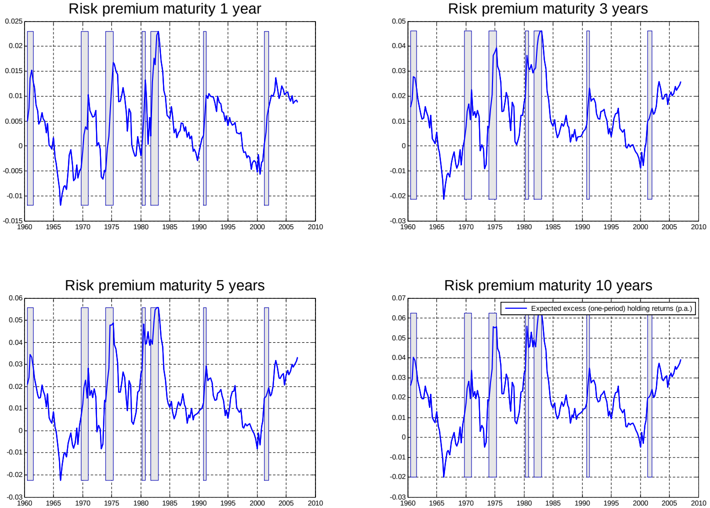
Risk premiums: expected excess holding returns

Conclusion 6: The encompassing model implies significant and time-varying risk premiums, covarying with the output and interest rate gaps.

- The encompassing Macro-Finance model explains unconditional risk premiums relatively well.
- The encompassing model implies significant and countercyclical time variation in the risk premiums. Risk premiums tend to be high/increase during recessions and be low/decrease during booms.
- This feature of the model derives from the time variation in the risk premiums for supply and policy rate shocks:
  - Supply shock risk premium: correlates positively with interest rate gap and negatively with output (gap).
  - Policy rate shock risk premium: correlates negatively with the interest rate gap.

Macro factors and the yield curve

Risk premiums: expected excess holding returns



Macro factors and the yield curve

Risk premiums: expected excess holding returns

Table: POSTERIOR DENSITY ESTIMATES III: ENCOMPASSING MODEL MFL

Param	Mean	Std. Dev	Mode	Crit.val. 5%	Crit. val. 95%
	Price of risk: $\Lambda_0 (\times 10^{-2})$				
$\Lambda_{0,\pi}$	-0.0700	0.1379	-0.1257	-0.3218	0.1365
$\Lambda_{0,y}$	-0.0675	0.1359	0.0432	-0.2558	0.1843
$\Lambda_{0,i}$	-0.0844	0.1456	-0.0193	-0.3322	0.1576
$\Lambda_{0,\pi*}$	-0.0576	0.1680	-0.0559	-0.2970	0.2323
$\Lambda_{0,\rho}$	-0.1026	0.0796	-0.1144	-0.2128	0.0385
	Price of risk: $\Lambda_1 (\times 10^{-4})$				
$\Lambda_{1,\pi\pi}$	0.0728	0.0779	-0.0030	-0.0456	0.1973
$\Lambda_{1,\pi y}$	0.3139	0.0944	0.2782	0.1737	0.4842
$\Lambda_{1,\pi i}$	-1.1067	0.2303	-0.9401	-1.5123	-0.7743
$\Lambda_{1,y\pi}$	-0.1302	0.3327	-0.0016	-0.8500	0.2734
$\Lambda_{1,yy}$	0.1051	0.1363	0.0575	-0.1463	0.3112
$\Lambda_{1,yi}$	-0.4329	0.4250	-0.5493	-1.0148	0.3596
$\Lambda_{1,i\pi}$	-0.0445	0.0469	-0.0382	-0.1268	0.0337
$\Lambda_{1,iy}$	-0.0274	0.0363	-0.0198	-0.0887	0.0326
$\Lambda_{1,ii}$	0.5592	0.0718	0.5353	0.4471	0.6808

Macro factors and the yield curve

Variance decomposition: Interpretation of the yield curve: level, slope and curvature factors

Conclusion 7: A variance decomposition of the level, slope and curvature factor identifies the following interpretations:

- Level factor. Unlike standard Mac-Fin models, this model identifies three main factors impacting on the level:
  - Target real rate shocks (68% at 1yr hor.).
  - Belief shock for inflation (5% at 1yr hor.).
  - Supply, demand and policy rate shocks due to the adaptive learning component (respectively 8%, 7% and 12% at 1yr hor.).
- Slope factor. Standard findings are recovered:
  - Most important is the independent policy rate factor (65% at 1yr hor.)
  - Supply and demand factors play a role on the intermediate frequencies, due to interest rate smoothing (5% and 24% at 1yr hor).
- Curvature factor. In line with Bekaert et al. (2005):
  - Curvature primarily related to the policy rate factor (62% at 1yr hor.).
  - Curvature with supply and demand shocks (13% and 23% at 1yr hor.).

Macro factors and the yield curve

Variance decomposition: Interpretation of the yield curve: level, slope and curvature factors

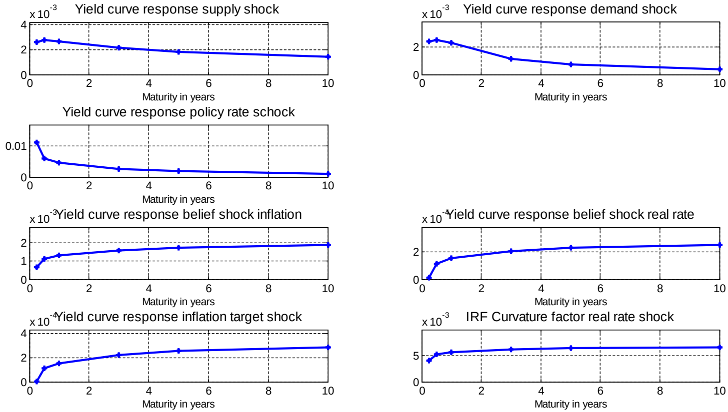
Table: VARIANCE DECOMPOSTION: ENCOMPASSING MODEL MFL

Type of shock	Fed fund rate	Level	Slope	Curvature	Infl exp 1y	Infl exp 10y
	Frequency: 1 quarter					
Supply (ε_π)	0.04	0.08	0.01	0.13	0.90	0.35
Demand (ε_y)	0.04	0.04	0.03	0.22	0.02	0.00
Policy rate(ε_i)	0.81	0.33	0.88	0.63	0.00	0.00
Belief inflat.(η_π)	0.00	0.03	0.01	0.00	0.08	0.64
Belief real rate(η_ρ)	0.00	0.00	0.00	0.00	0.00	0.00
Infl. target ($\varepsilon_{\pi*}$)	0.00	0.00	0.00	0.00	0.00	0.00
Neutral real rate(ε_ρ)	0.11	0.52	0.06	0.02	0.00	0.00
	Frequency: 20 quarters					
Supply (ε_π)	0.06	0.04	0.06	0.13	0.42	0.21
Demand (ε_y)	0.07	0.02	0.32	0.24	0.03	0.00
Policy rate(ε_i)	0.12	0.03	0.55	0.60	0.00	0.00
Belief inflat.(η_π)	0.09	0.09	0.03	0.01	0.57	0.79
Belief real rate(η_ρ)	0.00	0.00	0.00	0.00	0.00	0.00
Infl. target ($\varepsilon_{\pi*}$)	0.00	0.00	0.00	0.00	0.00	0.00
Neutral real rate(ε_ρ)	0.66	0.82	0.04	0.02	0.00	0.00

Macro factors and the yield curve

Variance decomposition: Instantaneous impulse-response analysis (deviation from baseline)

Figure: INSTANTANEOUS IMPULSE RESPONSE FUNCTIONS OF THE YIELD CURVE MFL MODEL



Inflation scares

Inflation scares

Inflation scares

Historical decomposition of the 'Great Inflation and Disinflation' episodes

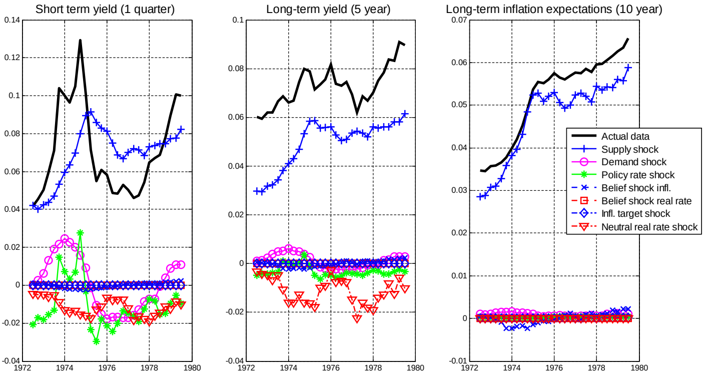
Conclusion 8: The estimation results establish the empirical relevance of the "Inflation Scares" argument for both inflation expectations and the yield curve.

- Inflation Scares: " ... Significant and persistent deviations of inflation expectations from those implied by rational expectations [by the inflation target], even at long horizons...." (Orphanides and Williams, 2005)
- Inflation Scares arise as a consequence learning dynamics amplifying and lengthening the impact of correlated supply shocks (Orphanides and williams, 2005) or inflation belief shocks (Kozicki and Tinsley, 2005).
- A historical decomposition of the ' Great Inflation and Disinflation' episodes:
  - The 'Great Inflation' episode (1972-1980): the un-anchoring of inflation expectations and long-term yields is primarily attributed to (correlated) supply shocks.
  - The 'Great Disinflation' episode (1980-1988): both correlated supply shocks and belief shocks contribute to the re-anchoring of inflation expectations and long-term yields.

Inflation scares

Historical decomposition of the 'Great Inflation' episode

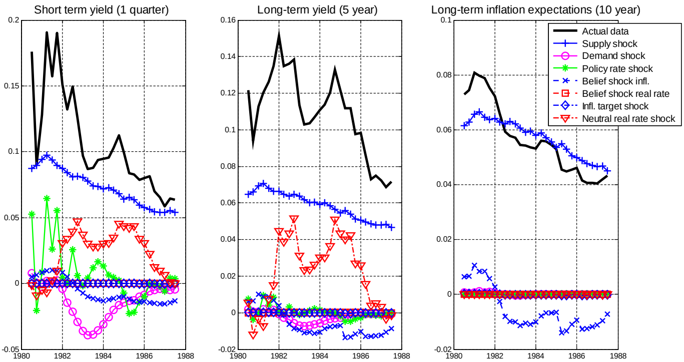
Figure: HISTORICAL DECOMPOSITION BASED ON THE MFL-MODEL OF THE GREAT INFLATION PERIOD



Inflation scares

Historical decomposition of the 'Great Disinflation' episode

Figure: HISTORICAL DECOMPOSITION BASED ON THE MFL-MODEL OF THE GREAT DISINFLATION PERIOD



Time variation eq. real rate

Trehan Wu (JME, 2007)

Table 1
Model parameter estimates

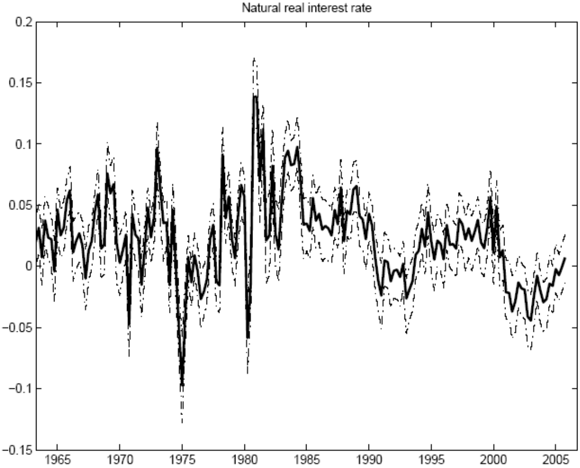
Parameter	Baseline specifications	Stationary z_t~AR(1)	$d = 0$
a_{y1}	1.16 (9.42)	1.13 (7.74)	1.12 (8.47)
a_{y2}	−0.24 (−2.03)	−0.26 (−1.87)	−0.27 (−1.79)
a_r	−0.13 (−5.37)	−0.13 (−2.99)	−0.08 (−4.08)
$b_{\pi1}$	0.49 (8.25)	0.47 (7.00)	0.47 (8.62)
$b_{\pi2}$	0.37 (4.94)	0.35 (4.93)	0.35 (5.53)
b_y	0.26 (4.31)	0.17 (3.22)	0.13 (2.18)
b_{x1}	0.004 (3.91)	0.005 (5.05)	0.004 (4.04)
b_{x2}	0.05 (4.16)	0.02 (0.99)	0.05 (4.20)
c	0.80 (2.28)	0.81 (2.52)	0.81 (2.14)
d	−0.05 (−0.84)	−0.05 (−0.06)	0
ρ_z	1.00	0.97 (3.40)	1.00
$\sigma_1(y)$	0.57 (6.10)	0.73 (5.96)	0.70 (3.21)
$\sigma_2(\pi)$	0.80 (16.74)	0.81 (16.77)	0.81 (10.02)
$\sigma_3(z)$	0.22 (5.48)	0.25 (2.20)	0.17 (2.74)
$\sigma_4(y^*)$	0.46 (4.23)	0.43 (2.38)	0.53 (2.15)
$\sigma_5(g)$	0.20 (4.23)	0.19 (2.38)	0.24 (2.15)
Log likelihood	−415.56	−414.16	−415.83

Note: MLE estimation results. t-statistics are reported in parenthesis.

Time variation eq. real rate

Bjorland et al (2006)

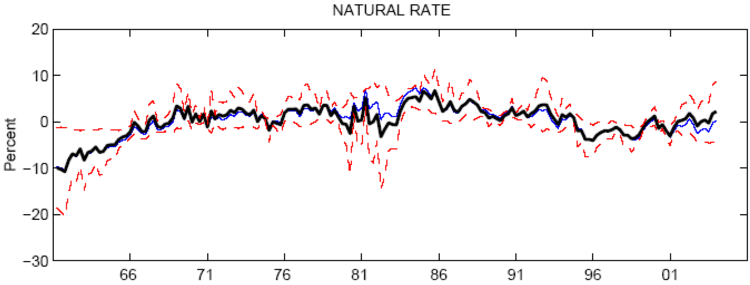
Figure 2: The natural real interest rate



The figure shows the smoothed estimate of the natural real interest rate with a 95 percent confidence band.

Time variation eq. real rate

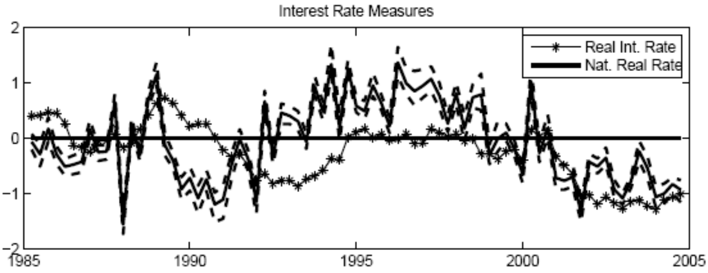
Bekaert et al (2005)



The top Panel shows the average output gap across the 7 models we estimate (thick line) and the model CR,EI,N output gap (thin line) for our sample period: 1961:1Q-2003:4Q. The bottom Panel shows the average natural rate across the 7 models we estimate (thick line) and the model CR,EI,N natural rate (thin line). Both panels also graph confidence bands in dashed lines. The confidence bands were constructed adding and subtracting 2 cross-sectional standard deviations to the average values.

Time variation eq. real rate

Edge et al (FED Working Paper)



Notes:

1. The real interest rate and natural real rate are shown relative to their steady-state level.
2. The solid lines are the median estimates of the output gap and natural real rate.
3. The dotted lines are the 90 percent credible set around the output gap and natural real rate.