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A Technical Appendix

Here we present several details regarding the specification and estimation of MS models. In general, an autoregressive model of order p, where parameters follow a N-states Markov process, $MS(N)AR(p)$, can be written as

$$y_t = c_{St} + \phi_{1,St} y_{t-1} + ... + \phi_{p,St} y_{t-p} + \sigma_{St} \varepsilon_t$$

where $\varepsilon_t \sim \mathcal{N}(0,1)$ and $S_t = \{1, 2, ..., N\}$ is the state variable with transition probability matrix

$$P = \begin{bmatrix} p_{11} & p_{21} & \cdots & p_{N1} \\ p_{12} & p_{22} & \cdots & p_{N2} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1N} & p_{2N} & \cdots & p_{NN} \end{bmatrix}$$

where the characteristic element is defined as $p_{ij} = \Pr(s_t = j | s_{t-1} = i)$.

Let $\theta = (c_1, ..., c_N, \phi_{1,1}, ..., \phi_{p,N}, \sigma_1, ..., \sigma_N, p_{11}, ..., p_{NN})$ be the vector that groups all the parameter of the model. We can also define the probability of being in state j at time t, conditional on the parameter vector and on the data up to data t, as $\xi_{jt} = \Pr(s_t = j|\Omega_t; \theta)$. The procedure to evaluate the likelihood of the model can be summarized as follows:

1. Given θ and an initial value for ξ_{j0}, the density for period t in the state j,

$$\eta_{jt} = f(y_t/s_t = j, \Omega_{t-1}; \theta) = \frac{1}{\sqrt{2\pi}\sigma_j} \exp\left[-\frac{(y_t - c_j - \phi_{1,j} y_{t-1} - ... - \phi_{p,j} y_{t-p})^2}{2\sigma_j^2}\right]$$

2. The conditional likelihood for observation t is defined as:

$$f(y_t|\Omega_{t-1}; \theta) = \sum_{i=1}^{N} \sum_{j=1}^{N} p_{ij} \xi_{i,t-1} \eta_{jt}$$

3. Using these, the inference over the states of the model in the period t is

$$\xi_{jt} = \frac{\sum_{i=1}^{2} p_{ij} \xi_{i,t-1} \eta_{jt}}{f(y_t|\Omega_{t-1}; \theta)}$$

4. Repeat these steps for $t = 1, 2, ..., T$.

Through these iterations it is possible to calculate the whole sequence of ξ_{jt} and the conditional density $f(y_t|\Omega_{t-1}; \theta)$ for each observation. Therefore, we are able to write and evaluate the conditional log likelihood of the data given θ as

$$\log f(y_1, ..., y_T | y_0; \theta) = \sum_{t=1}^{T} \log f(y_t|\Omega_{t-1}; \theta).$$

Two alternatives can be used as the initial value of ξ_{j0}. The first one is to take an arbitrary value for it, and the second uses the unconditional probability of each state implied by the parameter vector. The latter is preferred because the initial value of ξ_{j0} changes endogenously in each iterations of the numerical algorithm. The unconditional probability vector π can be obtained by solving the system

$$\pi = (A'A)^{-1} A' e_{N+1},$$

where $A = \begin{bmatrix} I_N - P \\ \mathbf{1} \end{bmatrix}$, $\mathbf{1}$ denotes a $N \times 1$ vector of ones and e_{N+1} is the $N+1$th column of I_{N+1}.

Another relevant issue for the initialization of the maximization algorithm is the starting values for the parameters in each of the regimes. In particular, we try four different alternatives. First, we run a QLR test of structural break in the parameters and compute the different values of the coefficients before and after the break. The disadvantage of this alternative is that it detects only on break that is deterministic. As an alternative, we also try two threshold models (TAR), where the regime depends on whether the variable is above or below of, in one alternative, its mean or, in the other, its median. Finally, we also considered a SETAR model in which the threshold value is estimated.[12] To choose among these alternatives, we ran a Monte Carlo experiment were data was generated by an artificial MS model, and check which of the alternatives used to initialize the algorithm generate maximum likelihood estimates closer to the true parameters. According to the results of this experiment, we choose to use the SETAR alternative to find the initial values for the estimation of the MS model

As we mentioned, our estimation approach consist in characterizing the likelihood function using MCMC methods. In particular, we proceed in two steps. First, the likelihood is maximized, using the optimization algorithm `csminwel` developed by Chris Sims.[13] The resulting mode is used as the starting value of a Random Walk Metropolis-Hastings algorithm, using a $\mathcal{N}(0, c\Sigma)$ as the proposal distribution.[14] The parameter c is calibrated to obtain an acceptance ratio close to 30% and the convergence of the chain is analyzed by checking recursive means. For each estimated alternative we generate 300K draws from the posterior, eliminating the first half of the chain to reduce the dependence from initial values.

A.1 Forecast Error Variance Decomposition

A relevant question in these models is what fraction of the total forecast uncertainty can be attributed to each of the sources described in the text. In what follows we show a theoretical decomposition of the forecast variance and suggest an implementation based on the outcome from the algorithm used to construct the confidence sets. For this, the following result would

[12] The estimation of these last three alternatives was implemented using concentration methods to minimize the sum of squared residuals.

[13] Available at http://sims.princeton.edu/yftp/optimize/.

[14] Σ is the inverse of the posterior's Hessian evaluated at the mode computed in the first step.

prove useful. Let x_t and z_t be two random vectors, then

$$V_x(x_t) = E_z\left[V_{x|z}(x_t|z_t)\right] + V_z\left[E_{x|z}(x_t|z_t)\right], \tag{2}$$

where $E_w(\cdot)$ and $V_w(\cdot)$ denote, respectively, the expectation and variance-covariance operator computed over the distribution of a generic random vector w_t.[15]

We are interested in $V_{y_{T+h}|y_T}(y_{T+h}|y_T)$. Using the previous results, we can write

$$V_{y_{T+h}|y_T}(y_{T+h}|y_T) = E_{\theta|y^T}\left[V_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right] + V_{\theta|y^T}\left[E_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right].$$

The first term $E_{\theta|y^T}\left[V_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right]$ represents the average uncertainty in the forecast when parameters are assumed to be known. The second term $V_{\theta|y^T}\left[E_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right]$ therefore represents the additional volatility that comes from parameter uncertainty. Applying again (2) to the first term we get,

$$\begin{aligned} V_{y_{T+h}|y_T}(y_{T+h}|y_T) &= E_{\theta|y^T}\left\{E_{S_T|\theta,y^T}\left[V_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\} \\ &+ E_{\theta|y^T}\left\{V_{S_T|\theta,y^T}\left[E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\} \\ &+ V_{\theta|y^T}\left[E_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right]. \end{aligned}$$

Now, the second term $E_{\theta|y^T}\left\{V_{S_T|\theta,y^T}\left[E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\}$ represents the average uncertainty brought about by not knowing the current state S_T, while the first term $E_{\theta|y^T}\{E_{S_T|\theta,y^T}[V_{y_{T+h}|S_T,\theta,y_T}(y$ can then be interpreted as the uncertainty related to the exogenous shocks.

The outcome from the algorithm proposed in section 4 can be used to compute each of these terms as follows:[16]

- Computing $E_{\theta|y^T}\left\{E_{S_T|\theta,y^T}\left[V_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\}$ (shock uncertainty):
  - $E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T) \approx N_\varepsilon^{-1}\sum_n y_{T+h}^{i,j,n} \equiv \bar{y}_{T+h}^{i,j}$, $[N_\theta \cdot N_s]$
  - $V_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T) \approx N_\varepsilon^{-1}\sum_n \left(y_{T+h}^{i,j,n} - \bar{y}_{T+h}^{i,j}\right)^2 \equiv V_{T+h}^{i,j}$, $[N_\theta \cdot N_s]$
  - $E_{S_T|\theta,y^T}\left[V_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right] \approx N_S^{-1}\sum_j V_{T+h}^{i,j} \equiv \bar{V}_{T+h}^{i}$, $[N_\theta]$
  - $E_{\theta|y^T}\left\{E_{S_T|\theta,y^T}\left[V_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\} \approx N_\theta^{-1}\sum_i \bar{V}_{T+h}^{i}$. [1]
- Computing $E_{\theta|y^T}\left\{V_{S_T|\theta,y^T}\left[E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\}$ (initial-state uncertainty):
  - $E_{S_T|\theta,y^T}\left[E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right] \approx N_S^{-1}\sum_j \bar{y}_{T+h}^{i,j} \equiv \bar{y}_{T+h}^{i}$, $[N_\theta]$

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[15] A proof of this claim for the univariate case is as follows (the extension for vectors is straightforward):

$$\begin{aligned} V_x(x_t) &= E_x\left\{[x_t - E_x(x_t)]^2\right\} = E_x(x_t^2) - [E_x(x_t)]^2 = E_z\left[E_{x|z}(x_t^2|z_t)\right] - \left\{E_z\left[E_{x|z}(x_t|z_t)\right]\right\}^2, \\ &= E_z\left[E_{x|z}(x_t^2|z_t)\right] - E_z\left\{\left[E_{x|z}(x_t|z_t)\right]^2\right\} + V_z\left[E_{x|z}(x_t|z_t)\right] = E_z\left[V_{x|z}(x_t|z_t)\right] + V_z\left[E_{x|z}(x_t|z_t)\right], \end{aligned}$$

where the third equality follows from the law of iterated expectations, and the fourth and fifth use the formula for the variance $V_w(w_t) = E_w(w_t^2) - [E_w(w_t)]^2$.

[16] The number of simulations left in each case is shown in brackets at the end of each line.

- $V_{S_T|\theta,y^T}\left[E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right] \approx N_S^{-1}\sum_j \left(\bar{y}_{T+h}^{i,j} - \bar{y}_{T+h}^{i}\right)^2 \equiv V_{T+h}^i$, $[N_\theta]$
- $E_{\theta|y^T}\left\{V_{S_T|\theta,y^T}\left[E_{y_{T+h}|S_T,\theta,y_T}(y_{T+h}|S_T,\theta,y_T)\right]\right\} \approx N_\theta^{-1}\sum_i V_{T+h}^i$. [1]

- Computing $V_{\theta|y^T}\left[E_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right]$ (parameter uncertainty):
  - $E_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T) \approx (N_\varepsilon N_S)^{-1}\sum_{n,j} y_{T+h}^{i,j,n} \equiv \bar{y}_{T+h}^i$, $[N_\theta]$
  - $V_{\theta|y^T}\left[E_{y_{T+h}|\theta,y_T}(y_{T+h}|\theta,y_T)\right] \approx N_\theta^{-1}\sum_i \left(\bar{y}_{T+h}^i - N_S^{-1}\sum_\theta \bar{y}_{T+h}^i\right)^2$. [1]

- $V_{y_{T+h}|y_T}(y_{T+h}|y_T) \approx N^{-1}\sum_{n,j}\left(y_{T+h}^{i,j,n} - N^{-1}\sum_{n,j} y_{T+h}^{i,j,n}\right)^2$, [1]

B Tables and Figures

Table 1: Information Criteria

Case	Parameters changing	Number of states	AIC	HQC	BIC
1	c, ϕ, σ	2	-2.9262	-2.8881	-2.8299
2	c	2	-2.7621	-2.7354	-2.6946
3	ϕ	2	-2.8376	-2.8072	-2.7605
4	σ	2	-2.9358	-2.9091	-2.8683
5	c, ϕ	2	-2.8554	-2.8211	-2.7687
6	c, σ	2	-2.9317	-2.9012	-2.8546
7	ϕ, σ	2	-2.9272	-2.8929	-2.8404
8	c, ϕ, σ	4	-2.9369	-2.8912	-2.8213
9	c, σ	4	-2.9390	-2.9009	-2.8426
	AR(2)		-2.7632	-2.7516	-2.7338
	AR(2)-GARCH(1,1)		-2.8366	-2.8138	-2.7790

Note: See the text for the description of the cases.

Table 2: Estimated Parameters

	Case 1				Case 4		
	AR	$S_t=1$	$S_t=2$	C.S.	$S_t=1$	$S_t=2$	C.S.
c	0.037	0.008	0.155	[-0.37;0.05]	0.021		
	(0.03)	(0.03)	(0.13)		(0.03)		
ϕ_1	1.370	1.321	1.397	[-0.32;0.16]	1.345		
	(0.00)	(0.06)	(0.13)		(0.05)		
ϕ_2	-0.378	-0.323	-0.431	[-0.13;0.35]	-0.349		
	(0.01)	(0.06)	(0.13)		(0.05)		
σ^2	0.004	0.002	0.013	[-0.02;-0.01]	0.002	0.012	[-0.02;-0.01]
	(0.00)	(0.00)	(0.00)		(0.00)	(0.00)	
$p_{1,1}$		0.953		[0.91;0.98]	0.955		[0.91;0.98]
$p_{2,1}$		0.220		[0.08;0.45]	0.182		[0.07;0.36]

Note: Standard errors in parenthesis. For the parameters c, ϕ, σ^2 the column C.S. reports the confidence set of the difference of the coefficient between both states (e.g. $c_{S_t=1} - c_{S_t=2}$). For the probabilities, the column C.S. reports the confidence set of the estimated probability. The rest of the entries are the mean of the distribution. All these where obtained using the MCMC procedure described in the appendix, using 150K draws from the distribution.

Table 3: Estimated Parameters, Cont.

	Case 6			Case 8			Case 9		
	$S_t=1$	$S_t=2$	C.S.	$S_t=1$	$S_t=2$	C.S.	$S_t=1$	$S_t=2$	C.S.
c	0.026	0.033	[-0.03;0.02]	0.001	1.345	[-1.38;-1.32]	0.025	0.020	[-0.05;0.07]
	(0.03)	(0.04)		(0.01)	(0.02)		(0.04)	(0.04)	
ϕ_1	1.343			-0.342	0.195	[-1.59;-1.44]	1.337		
	(0.05)			(0.02)	(0.04)		(0.05)		
ϕ_2	-0.349			1.203	-0.262	[0.34;0.55]	-0.342		
	(0.05)			(0.03)	(0.04)		(0.05)		
σ^2	0.002	0.012	[-0.02;-0.01]	0.001	0.010	[-0.01;0.00]	0.002	0.011	[-0.02;-0.01]
	(0.00)	(0.00)		(0.00)	(0.00)		(0.00)	(0.00)	
$p_{1,1}$	0.955		[0.91;0.98]	0.946		[0.9;0.98]	0.955		[0.91;0.98]
$p_{2,1}$	0.189		[0.07;0.37]	0.233		[0.08;0.48]	0.183		[0.07;0.37]
$p^2_{1,1}$				0.813		[0.71;0.9]	0.589		[0.07;0.99]
$p^2_{2,1}$				0.621		[0.43;0.8]	0.454		[0.02;0.93]

Note: See Table 2. $p^2_{1,1}$ and $p^2_{2,1}$ are the transition probabilities associated with the process that governs parameters other than the variance.

Table 4: Confidence Set for difference in the Unconditional Mean Across Regimes.

	95% Confidence Set
Case 6	[-9.54;7.36]
Case 8	[-28.31;-18.09]
Case 9	[-30.03;30.03]

Note: These were computed from the outcome of the MCMC procedure.

Table 5: Information Criteria in Sub-Sample

	1975.01 - 2004.12			1975.01 - 2007.12		
Case	AIC	HQC	BIC	AIC	HQC	BIC
1	-3.098	-3.055	-2.990	-3.001	-2.961	-2.900
2	-2.999	-2.969	-2.923	-2.304	-2.276	-2.234
3	-3.066	-3.032	-2.980	-2.925	-2.893	-2.844
4	-3.104	-3.073	-3.028	-3.013	-2.985	-2.942
5	-2.970	-2.931	-2.872	-2.942	-2.906	-2.851
6	-3.100	-3.066	-3.013	-3.009	-2.977	-2.928
7	-3.094	-3.055	-2.997	-3.005	-2.969	-2.914

Note: See the text for the description of the cases.

Table 6: Parameter Estimates Case 4, Different Samples.

	Full Sample	1975.01 to 2004.12	1975.01 to 2007.12
c	0.021	0.084	0.018
ϕ_1	1.345	1.313	1.324
ϕ_2	-0.349	-0.335	-0.328
$\sigma^2_{S_t=2}$	0.002	0.002	0.002
$\sigma^2_{S_t=1}$	0.012	0.009	0.009
$p_{1,1}$	0.955	0.967	0.966
$p_{2,1}$	0.818	0.804	0.860

Note: See Table 2

Table 7: Information Criteria, Log-Difference of Copper Price.

Case	AIC	HQC	BIC
1	6.289	6.328	6.386
2	6.449	6.475	6.516
3	6.396	6.427	6.473
4	6.278	6.305	6.346
5	6.395	6.430	6.482
6	6.282	6.312	6.359
7	6.286	6.321	6.373

Table 8: Root-Mean-Squared Forecast Error and Tests

				Test Statistic vs. Case 4			
Months				AR		GARCH	
Ahead	AR	GARCH	Case 4	DM	HLN	DM	HLN
1	0.099	0.100	0.098	2.00**	1.98*	1.50	1.49
2	0.182	0.182	0.178	2.01**	1.95*	1.79*	1.74*
3	0.257	0.257	0.250	2.39**	2.27**	1.75*	1.66*
6	0.425	0.424	0.412	2.61**	2.29**	1.16	1.02
12	0.465	0.458	0.445	2.06**	1.45	0.53	0.37

Note: The column DM reports the Diebold and Mariano (1995) test statistic of the null that both models have the same Root-Mean-Squared Forecast Error, while the column HLM reports the modification to the DM test suggested by Harvey et al. (1997). ** denotes rejection at 5% significance level and * at 10%.

Table 9: Forecast Coverage of a 90% Confidence Interval and Tests

Months				Test P-val vs. Case 4	
Ahead	AR	GARCH	Case 4	AR	GARCH
1	50.0	36.1	51.4	0.49	0.35
2	64.8	60.6	64.8	0.50	0.47
3	68.6	72.9	80.0	0.43	0.46
6	85.1	85.1	91.0	0.47	0.47
12	95.1	96.7	95.1	0.50	0.49

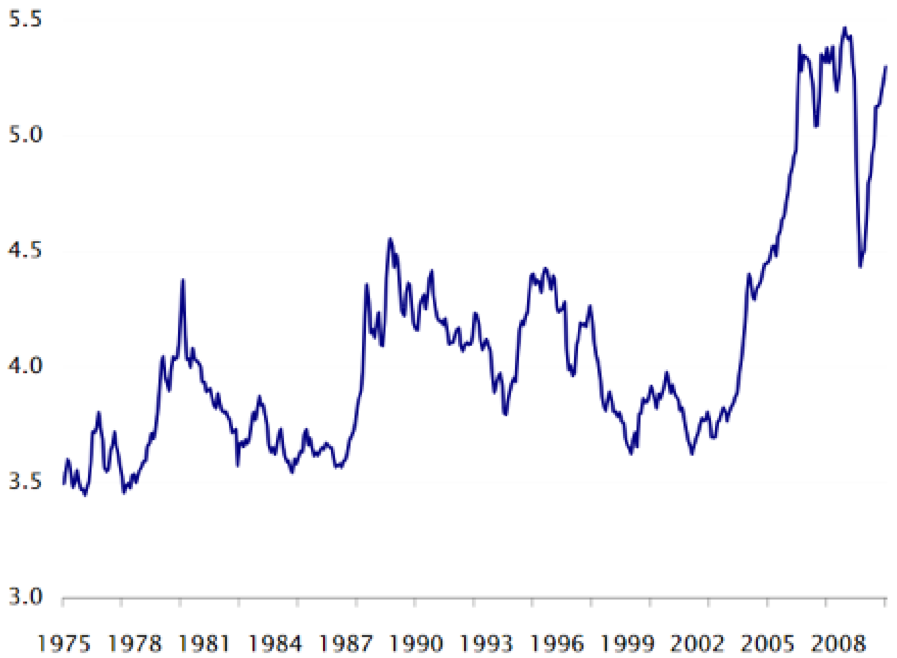
Note: The second to fourth column denote the coverage (in percentage) of the simulated forecast confidence bands of 90%. The last two columns show the p-value of the Giacomini and White (2006) test of predictive ability, using a cuadratic coverage accuracy loss function, of the null that both models provide the same coverage.

Table 10: Forecast Error Variance Decomposition

Months	AR		GARCH		Case 4		
Ahead	Param.	Shock	Param.	Shock	Param.	State	Shock
1	2.6	97.4	5.2	94.8	0.04	3.2	96.7
2	4.4	95.6	8.7	91.3	0.04	4.6	95.4
3	5.6	94.4	11.2	88.8	0.04	5.5	94.4
6	7.9	92.1	16.9	83.1	0.04	7.9	92.1
12	12.2	87.8	21.1	78.9	0.04	12.6	87.4

Note: Each entrance is the percentage of the forecast error variance due to each of the possible sources of uncertainty.

Figure 1: Copper Price (in logs)



Note: The series is the log of the monthly spot price of copper (in dollars) at the London Market, from January 1975 to January 2010. The source is the International Financial Statistics database from the IMF.

Figure 2: Smoothed (two-sided) Probabilities of the Low-Variance State

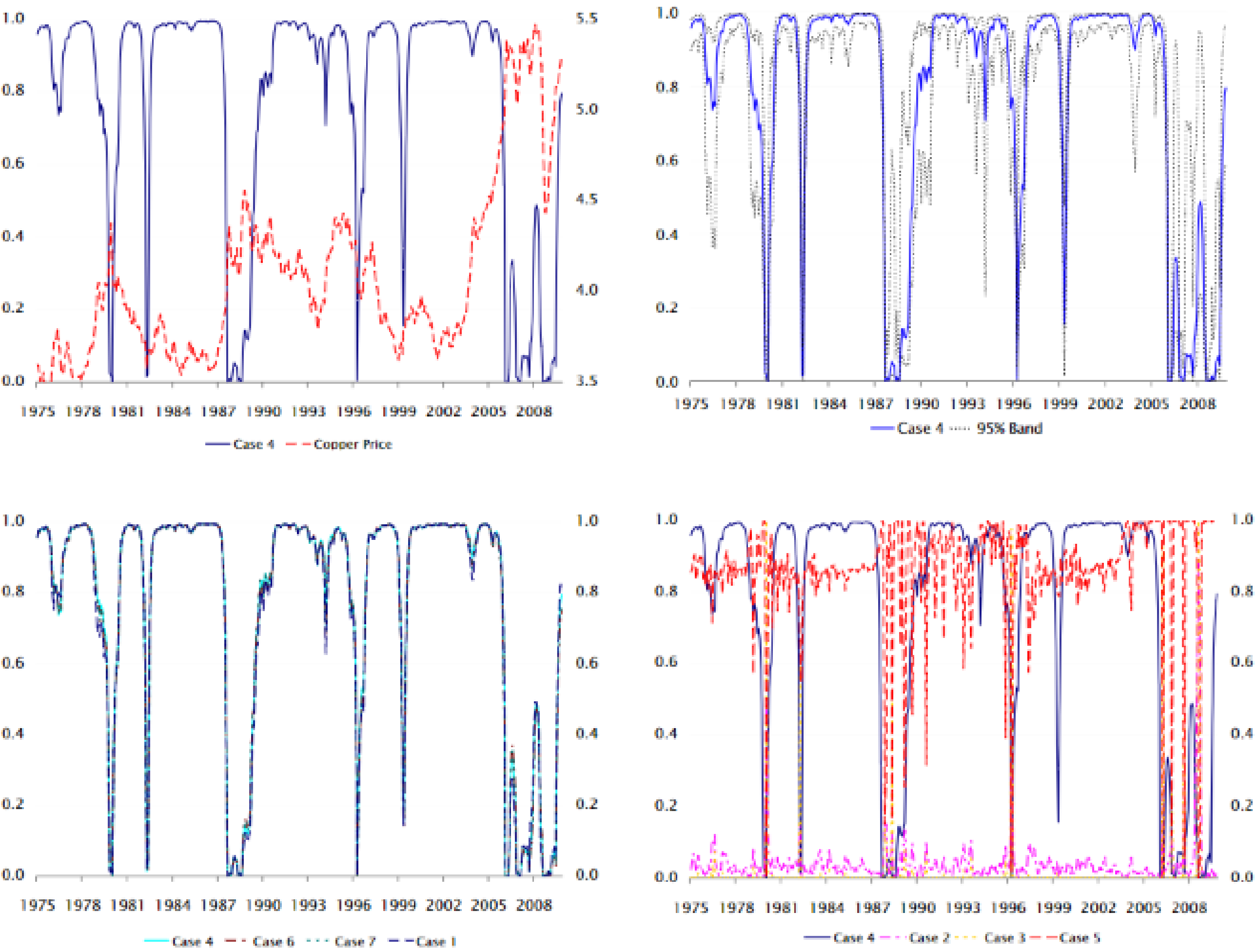


Figure 3: Smoothed (two-sided) Probabilities

Constant and Lags | Variance

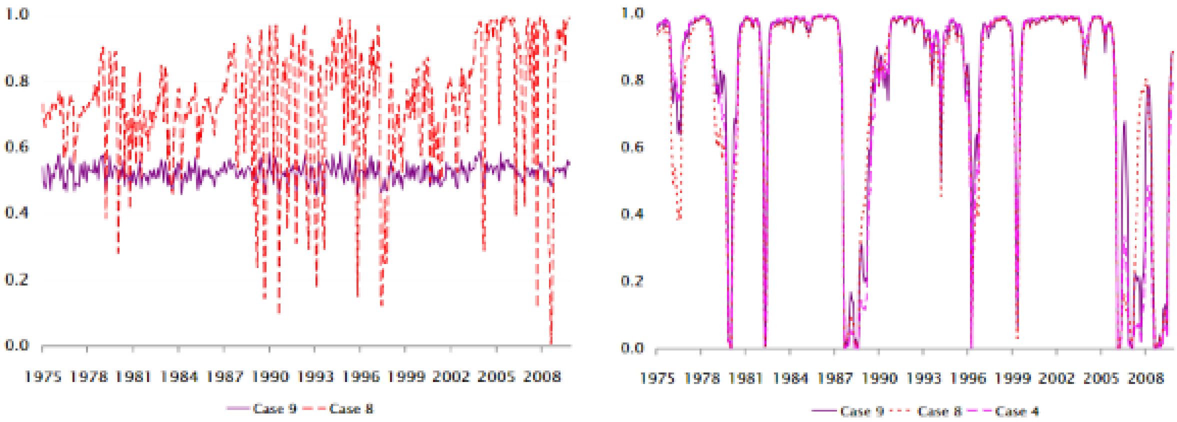


Figure 4: Smoothed (two-sided) Probabilities of the Low-Variance State, Case 4, Different Samples

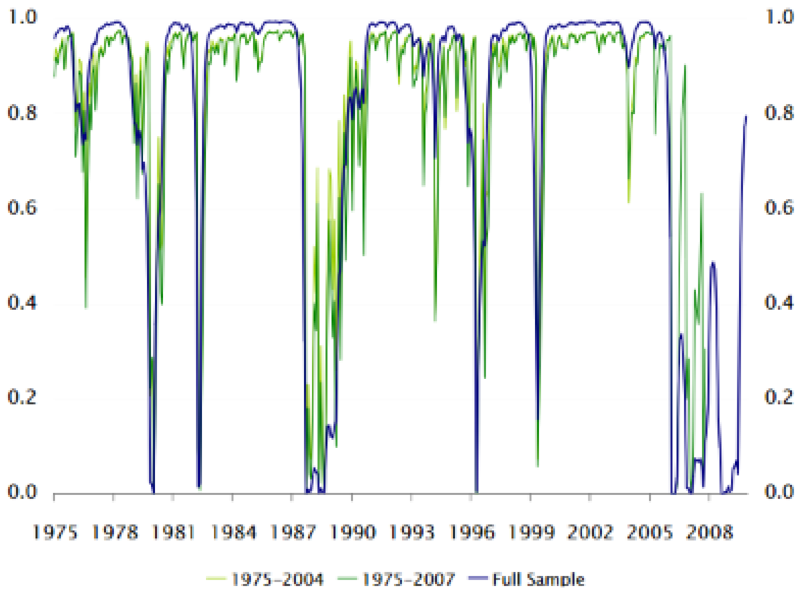
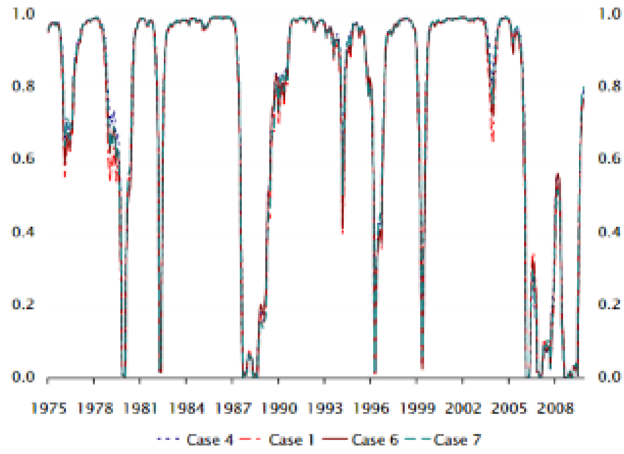


Figure 5: Smoothed (two-sided) Probabilities of the Low-Variance State, Log-Difference of Copper Price



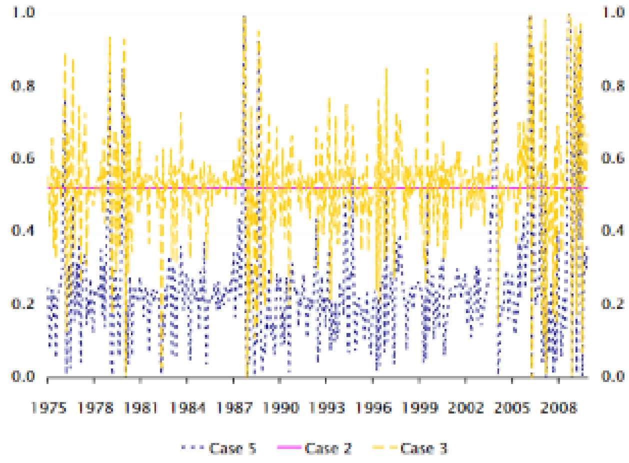
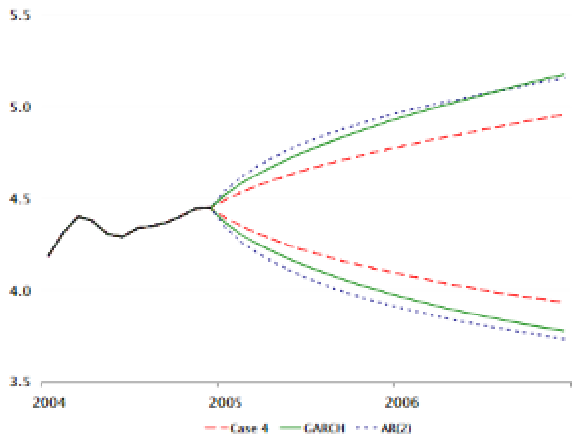
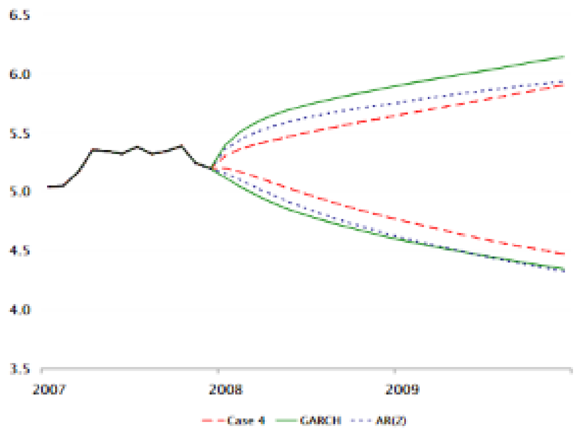


Figure 6: Forecast 90% Confidence Bands Examples

Low Variance State



High Variance State



Pontificia Universidad Católica Argentina

"Santa María de los Buenos Aires"

Facultad de Ciencias Económicas

Escuela de Economía "Francisco Valsecchi"

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