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Adaptive Estimation in Multiple Time Series with Independent Component Errors

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Abstract

Multivariate time series of finite, but possibly high, dimension N are considered. A parametric form to describe autocorrelations and cross-autocorrelations is assumed, but the innovations vector has elements that have unknown, nonparametric, and possibly differing, distributions, resulting in a semiparametric model. Gaussian pseudo-maximum likelihood estimates of the parameters are $\sqrt{n}$-consistent, where n denotes series length, but asymptotically inefficient. Adaptive estimates, which can be asymptotically efficient in the presence of a nonparametric distribution, have been developed in the univariate time series case $N = 1$, but for larger N face a curse of dimensionality when extended in a general way. Similarly to independent component analysis, we model the innovations vector as a linear transformation of independent, but possibly non-identically distributed, random variables. Our semiparametric estimates employ nonparametric series estimation, and are asymptotically efficient after one Newton-type step from an initial $\sqrt{n}$-consistent parameter estimate. A Monte Carlo study of finite sample performance of the adaptive estimates is included.

AMS 2000 subject classifications. Primary 62M10, secondary 62F11, 62G10, 62J05.

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1. INTRODUCTION

Time series of multivariate observations arise in various areas of the natural, engineering and social sciences. It seems appropriate to treat observations recorded on variables that are *a priori* related simultaneously, as a multivariate time series, rather than separately as univariate time series. Whereas cross-sectional observations are often statistically independent, the likely temporal dependence in time series data raises the possibility of non-instantaneous correlations, along with the instantaneous correlations possible with multivariate cross-sectional data. The modelling of multivariate time series typically entails features common across two or more of the individual series, including common parameters, which can be more precisely estimated if information from all the time series is combined. Likewise, forecasting of multivariate time series is best carried out jointly, rather than on an individual basis.

Nevertheless the modelling and analysis of multivariate time series faces difficulties that are significantly greater than ones encountered in a univariate setting. Consider a multivariate time series x_t, $t = 1, 2, ..., n$, where x_t is an $N \times 1$ vector. We shall proceed as if the x_t are observable but our approach can be readily extended to the case that they are unobservable errors in a location or more general regression model. It will be supposed that n is large relative to N, which is treated as fixed, but nevertheless N can itself be large, and the larger it is the greater the impact on modelling and subsequent statistical inference. For stationary series, an important class of dynamic models is

$$A(B;\theta_0)\, x_t = e_t, \quad t = 0, \pm 1, ..., \tag{1}$$

where B is the lag operator, $A(B;\theta)$ is a known $N \times N$ matrix function of B and the $K \times 1$ vector θ, θ_0 is an unknown $K \times 1$ parameter vector while θ denotes any admissible value, and e_t is a sequence of unobservable $N \times 1$ vector random variables, independent across t, such that

$$\begin{aligned} E(e_t) &= 0, \\ E\left(e_t e_t^T\right) &= \Omega_0, \end{aligned}$$

where Ω_0 is an unknown $N \times N$ positive definite matrix and T denotes transposition. In particular, one supposes the existence of a possibly infinite autoregressive representation,

$$A(B;\theta) = I_N - \sum_{j=1}^{\infty} A_j(\theta)\, B^j, \tag{2}$$

where I_N is the $N \times N$ identity matrix and the $A_j(\theta)$ are given $N \times N$ matrix functions of θ. In

the finite vector autoregressive, $AR(p)$, case we have $A_j(\theta) = 0$, $j > p$, so

$$A(B;\theta) = I_N - \sum_{j=1}^{p} A_j(\theta) B^j. \tag{3}$$

However, (2) covers also vector moving averages and autoregressive moving averages, and indeed along with these short memory models it also covers ones with long memory and negative dependence, such as fractional models. The need for a finite parameterization explains the notational dependence of the $A_j(\theta)$ on θ in these latter models, where though the $A_j(\theta)$ decay as j diverges, they never actually vanish.

However the modelling of all elements of the $A_j(\theta)$ on θ is important even in the finite $AR(p)$ case (3). Here, whereas in the univariate time series case $N = 1$, where unrestricted $A_j(\theta)$, i.e. identification of each $A_j(\theta)$ with an element of θ, entails only $K = p$ parameters describing temporal dependence, when on the other hand $N > 1$ unrestricted matrices $A_j(\theta)$ give rise to $K = N^2 p$ parameters. The parameter dimension thus increases rapidly with N, presenting a 'curse of dimensionality'. For multivariate time series it is thus often important to consider parsimonious modelling of the $A_j(\theta)$, a possibility formally represented by the notational dependence of the $A_j(\theta)$ on θ. For example, the $A_j(\theta)$ can be chosen to be relatively sparse, with many *a priori* zero elements, even diagonal, for example.

The multivariate nature of the right hand side of the model (1) also poses a curse of dimensionality. The covariance matrix Ω_0 of the innovations e_t has potentially $N(N+1)/2$ distinct unknown elements, which quantity again increases rapidly with N. Thus, some *a priori* restrictions on Ω_0 might be imposed. Note that if e_t (and thus x_t) is Gaussian, the distribution of e_t is entirely characterized by Ω_0, and likewise the joint distribution of x_t, $t = 1, 2, ..., n$, is entirely characterized by θ_0 and Ω_0. Maximum likelihood estimation of the latter parameters has been studied, and produces asymptotically efficient estimates under additional regularity conditions. Such estimates are also of interest when Gaussianity is relaxed to milder assumptions, on moments, when they are termed pseudo-maximum likelihood estimates. In standard parameterizations, where θ_0 does not overlap with Ω_0, the (multivariate normal) limit distribution of the estimate of θ_0 is desirably the same irrespective of whether or not e_t is Gaussian. However, asymptotic efficiency is lost in the absence of Gaussianity.

There is thus interest in developing estimates of θ_0 that are asymptotically efficient in the presence of vector e_t with possibly non-Gaussian distribution. There is a relatively straightforward modification of the Gaussian maximum likelihood asymptotic theory to non-Gaussian parametric

distributions, but though obvious candidates such as multivariate-t present themselves, there is immense variety in the possible choices, even relative to the univariate case $N = 1$, and often little basis for singling out one, and moreover the consistency-robustness of Gaussian-based estimates to departures from Gaussianity generally does not extend to non-Gaussian-based estimates. Thus we develop adaptive estimates, which are asymptotically efficient in the presence of nonparametric distributional form. This goal was achieved by Stone (1975) in the context of location estimation in the setting of independent scalar observations, and then extended by Bickel (1982) to linear regression. Further, time series extensions were developed by Kreiss (1987), Drost *et al.* (1997), Koul and Schick (1997), Robinson (2005), for example, again for $N = 1$. An essential ingredient required here is essentially estimation of the nonparametric score function of the independent innovations e_t, that is, the negative of the ratio of the derivative of the probability density function of e_t to the density itself. As is well known, estimation of such functions becomes problematic in the vector case, with rapidly decreasing precision in the score function estimates, infecting the properties of the adaptive parameter estimates, certainly in moderate-sized samples.

This issue has already been recognised in the literature on independent component analysis (ICA), see e.g. Hyvarinen, Karhunen and Oja (2001), Vlassis (2001), Bach and Jordan (2002), Hastie and Tibshirani (2003), Samarov and Tsybakov (2004), Nascimento and Dias (2005), Chen and Bickel (2005, 2006), Samworth and Yuan (2012). With respect to the independent vectors e_t, this assumes the structure

$$e_t = M_0 \varepsilon_t, \tag{4}$$

where M_0 is an $N \times N$ nonsingular mixing matrix and the elements of ε_t are mutually independent zero-mean random variables. Without further restrictions M_0 is not identified, in particular unless at most one element of ε_t is Gaussian, M_0 is not identified even up to order and scaling. Some, but by no means all, of the literature, focusses on parametric distributions for ε_t. Various estimation methods, algorithms, and theoretical results, appear in the literature.

There is also a time series ICA literature, see eg Aires and Chedin (2000), Cheung and Xu (2001), Lin et al (2007), Lu et al (2009), Chen et al (2011), Garcia-Ferrer et al (2011) . This focusses not on (4) with (1) but on the structure

$$x_t = M_0 u_t,$$

where the elements of the $N \times 1$ unobservable vector u_t are mutually independent autocorrelated time series. Here, the fundamental dynamics are modelled in a univariate way, and then instantaneously mixed by the matrix M_0. The modelling and motivation here differs from combining (4) with (1),

which allows us to develop efficient semiparametric estimation without curse of dimensionality. To avoid identifiability problems we specialize (4) by fixing M_0 to be the unique positive definite square root of Ω_0, so $\Omega_0 = M_0^2$, entailing $E\varepsilon_t\varepsilon_t^T = I_N$, though there is no loss of generality in the Gaussian case.

Our adaptive estimates are described in the following section. Section 3 describes asymptotic statistical properties. Section 4 reports a Monte Carlo study of finite sample behaviour. Section 5 contains some final comments.

2. ADAPTIVE ESTIMATES

As in the bulk of the literature our basic adaptive estimate of θ_0 is an approximate Newton step from an initial $\sqrt{n}-$consistent estimate of θ_0. This requires assuming the elements of ε_t to have differentiable probability density functions and estimating their score functions. Denote by ε_{it} the ith element of ε_t and by f_i, f_i' the probability density function of ε_{it} and its derivative for $i = 1, ..., N$. Thus the score function of ε_{it} is

$$\psi_i(s) = -f_i'(s)/f_i(s),$$

$i = 1, ..., N$. Estimation of the $\psi_i(s)$ requires proxies for the unobservable ε_t. Define, for any admissible θ and any positive definite $N \times N$ matrix M,

$$\begin{aligned} \varepsilon_1(\theta, M) &= M^{-1}x_1, \\ \varepsilon_t(\theta, M) &= M^{-1}\left(x_t - \sum_{j=1}^{t-1} A_j(\theta)\, x_{t-j}\right),\ t = 2, ..., n. \end{aligned} \tag{5}$$

Thus in general $\varepsilon_t(\theta_0, M_0)$ only approximates ε_t, due to the truncation of the infinite series in (2). In the $AR(p)$ case (3) we have, however, $\varepsilon_t(\theta_0, M_0) = \varepsilon_t$, $t \geq p+1$, and here the practitioner might prefer to take $\varepsilon_t(\theta, M) = 0$, $t \leq p$. Though ε_t has zero mean, define

$$\digamma_t(\theta, M) = \varepsilon_t(\theta, M) - n^{-1}\sum_{t=1}^{n}\varepsilon_t(\theta, M),\ t = 1, ..., n,$$

and denote the ith element of $\digamma_t(\theta, M)$ by $\digamma_{it}(\theta, M)$, then define

$$\Gamma_i(\theta, M) = (\digamma_{i1}(\theta, M), ..., \digamma_{in}(\theta, M))^T,\ i = 1, ..., N.$$

Most of the adaptive estimation literature has employed kernel estimation of the score function using the ratio of a derivative-of-density estimate to a density estimate. The consequent stochastic

denominator causes technical difficulties, and typically involves one or more forms of trimming, sometimes sample-splitting and discretization of the initial estimate, and requires strong conditions on some aspects. These problems were avoided by Beran (1976), who proposed using a series score function estimate, with respect to innovations in the scalar version of the $AR(p)$ (3), that employs integration-by-parts. His score function estimate was actually not a smoothed nonparametric one because he fixed the number of terms, L, in the series. In a cross-sectional regression model for scalar observables, Newey (1988) allowed L to increase slowly with n. Robinson (2005) employed the same approach in the context of scalar time series with parametric trend and errors that can be fractionally integrated, and stationary or nonstationary. We follow much of his notation.

Let $\phi_\ell(s)$, $\ell = 1, 2, ...$, be a sequence of given, continuously differentiable functions. For $L \geq 1$, scalar h_t, $t = 1, ..., n$, and $h = (h_1, , , h_n)^T$, define $\phi^{(L)}(h_t) = (\phi_1(h_t), ..., \phi_L(h_t))^T$, $\Phi^{(L)}(h_t) = \phi^{(L)}(h_t) - n^{-1}\sum_{s=1}^n \phi^{(L)}(h_s)$, $\phi^{'(L)}(h_t) = (\phi_1'(h_t), ..., \phi_L'(h_t))^T$ and

$$W^{(L)}(h) = n^{-1}\sum_{t=1}^n \Phi^{(L)}(h_t)\Phi^{(L)}(h_t)^T, w^{(L)}(h) = n^{-1}\sum_{t=1}^n \phi^{'(L)}(h_t),$$

$$\widehat{a}^{(L)}(h) = W^{(L)}(h)^{-1}w^{(L)}(h), \quad \psi^{(L)}(h_t; \widehat{a}^{(L)}(h)) = \widehat{a}^{(L)}(h)^T\Phi^{(L)}(h_t).$$

Then define

$$\widetilde{\psi}_{it}^{(L)}(\theta, M) = \psi^{(L)}\left(\boldsymbol{F}_{it}(\theta, M); \widehat{a}^{(L)}(\Gamma_i(\theta, M))\right), \ i = 1, ..., N, \ t = 1, ..., n.$$

Assuming the $A_j(\theta)$ are differentiable define the $K \times 1$ vectors

$$\boldsymbol{F}_{it}'(\theta, M) = \frac{\partial}{\partial\theta}\boldsymbol{F}_{it}(\theta, M), \ i = 1, ..., N, \ t = 1, ..., n.$$

Now define

$$\begin{aligned} r_L(\theta, M) &= \sum_{i=1}^N\sum_{t=1}^n \widetilde{\psi}_{it}^{(L)}(\theta, M)\boldsymbol{F}_{it}'(\theta, M), \\ J_{iL}(\theta, M) &= n^{-1}\sum_{t=1}^n \widetilde{\psi}_{it}^{(L)}(\theta, M)^2, \ i = 1, ..., N, \\ S_L(\theta, M) &= \sum_{i=1}^N J_{iL}(\theta, M)\sum_{t=1}^n \boldsymbol{F}_{it}'(\theta, M)\boldsymbol{F}_{it}'(\theta, M)^T. \end{aligned}$$

For given initial, $\sqrt{n}$ -consistent estimates $\widetilde{\theta}$, $\widetilde{M}$ define the adaptive estimate

$$\widehat{\theta} = \widetilde{\theta} - S_L\left(\widetilde{\theta}, \widetilde{M}\right)^{-1} r_L\left(\widetilde{\theta}, \widetilde{M}\right). \tag{6}$$

In the following section we establish the useful large sample approximation

$$\widehat{\theta} \underset{\cdot\ d}{\sim} \mathcal{N}\left(\theta_0, S_L\left(\widetilde{\theta}, \widetilde{M}\right)^{-1}\right), \tag{7}$$

implying that $\widehat{\theta}$ is asymptotically efficient. We might thence expect forecasts on the basis of (1) that employ $\widehat{\theta}$ to be generally more accurate than ones using $\widetilde{\theta}$, say. If desired we can iterate, applying (6) with $\widetilde{\theta}$ replaced on the right hand side by $\widehat{\theta}$, and so on, or to improve convergence (to an approximate nonparametric maximum likelihood estimate) modifying the steps, perhaps shrinking them by multiplying the correction term in (6) by a positive scalar less than 1.

A general strategy for choosing $\widetilde{\theta}$, $\widetilde{M}$ is exact or approximate Gaussian pseudo-maximum likelihood estimation, possibly the conditional-sum-of squares estimate (as in Box and Jenkins (1971)), which also uses directly the residual functions (5), see also Robinson (2005).

Given its popularity and computational convenience, especially in forecasting, the implications for the $AR(p)$ process (3) are worth discussing. As discussed in the Introduction, we may wish to impose a parsimonious parameterization on $A_1(\theta), ..., A_p(\theta)$, especially when N is large. Many of these are covered by the linear restrictions $v(\theta) = vec(A_1(\theta), ..., A_p(\theta)) = Q\theta + q$ for given $pN^2 \times K$ rank K matrix Q and $pN^2 \times 1$ vector q (often $q = 0$). Thus $\left(\partial/\partial\theta^T\right) v(\theta) = Q$. As mentioned above, in the $AR(p)$ case we might modify (5) by taking $\varepsilon_t(\theta, M) = 0$, $t \leq p$, and correspondingly dropping summands for $t = 1, ..., p$ from calculations. Thus write for $t > p$, $X_t = \left(x_{t-1}^T, ..., x_{t-p}^T\right)^T$ and $x_t - \sum_{j=1}^{p} A_j(\theta) x_{t-j} = x_t - \left(X_t^T \otimes I_N\right)(Q\theta + q)$. We thence take $\widetilde{\theta}$ to be the least squares estimate

$$\widetilde{\theta} = \left(\sum_{t=p+1}^{n} Q^T \left(X_t X_t^T \otimes I_N\right) Q\right)^{-1} \sum_{t=p+1}^{n} \left(Q^T \left(X_t \otimes I_N\right) x_t - Q^T \left(X_t X_t^T \otimes I_N\right) q\right) \tag{8}$$

and likewise

$$\widetilde{\Omega}(\theta) = (n-p)^{-1} \sum_{t=p+1}^{n} \left(x_t - \sum_{j=1}^{p} A_j(\theta) x_{t-j}\right)\left(x_t - \sum_{j=1}^{p} A_j(\theta) x_{t-j}\right)^T, \tag{9}$$

$$\widetilde{M} \text{ positive definite, } \widetilde{\Omega}\left(\widetilde{\theta}\right) = \widetilde{M}^2.$$

In connection with calculating the $F'_{it}(\theta, M)$ note that for $t > p$,

$$\frac{\partial}{\partial\theta^T}\varepsilon_t(\theta, M) = -\frac{\partial}{\partial\theta^T} M^{-1}(A_1(\theta), ..., A_p(\theta)) X_t = -\left(X_t' \otimes M^{-1}\right) Q.$$

3. ASYMPTOTIC NORMALITY

As in the scalar time series case of Robinson (2005) some trade-offs between conditions on the model and on the implementation are possible, but for simplicity we focus below on a single set

of regularity conditions, and generally we attempt to present these in such a way as to minimise introduction of additional notation. For example, in Assumption 5 below we employ the fact that the limiting covariance matrix of an asymptotically efficient estimate is a scalar multiple of that of the Gaussian pseudo likelihood estimate, and primitive conditions for the finiteness and non-singularity of the latter are available. Also, as in Robinson (2005) the conditions can be extended to cover stationary and nonstationary fractional behaviour. Relevant discussion of our conditions can be found in Robinson (2005).

Assumption 1 *The sequence x_t is generated by (1), (2) and (4), where the ε_t are independent and identically distributed with elements that are independent and have zero means and unit variances, and M_0 is the unique positive definite square root of the finite, positive definite matrix Ω_0.*

Assumption 2 $E\varepsilon_{i0}^4 < \infty, \;\; i = 1, ..., N.$

Assumption 3 *For $i = 1, ..., N$, ε_{i0} has density, $f_i(s)$, that is absolutely continuous, and*

$$0 < \mathcal{J}_i < \infty,$$

where $\mathcal{J}_i = \int \psi_i(s)^2 f_i(s)\, ds$.

Assumption 4 *Let $\mathcal{N}$ be a sufficiently small neighbourhood $\mathcal{N}$ of θ_0. Then on $\mathcal{N}$, $A(s;\theta)$ is thrice continuously differentiable in θ for $|s| = 1$, $B(s;\theta) = A(s;\theta)^{-1} = I_N + \sum_{j=1}^{\infty} B_j(\theta) s^j$ exists for $|s| = 1$, and denoting by γ_j the modulus of any element of $B_j(\theta)$ or the supremum over $\mathcal{N}$ of the modulus of any element of $A_j(\theta)$ or of its first, second or third derivatives, with respect to any element of θ, we have $\sum_{j=1}^{\infty} j^3 \gamma_j < \infty$.*

Assumption 5 *Denoting by $\overline{\theta}$ the Gaussian pseudo likelihood estimate of θ_0, the limiting covariance matrix of $n^{1/2}\left(\overline{\theta} - \theta_0\right)$ is finite and positive definite.*

Assumption 6 *As $n \to \infty$,*

$$n^{\frac{1}{2}}\left(\tilde{\theta} - \theta_0\right) = O_p(1), \quad n^{\frac{1}{2}}(\widetilde{M} - M_0) = O_p(1).$$

Assumption 7 *$\phi_\ell(s)$ satisfies*

$$\phi_\ell(s) = \phi(s)^\ell, \tag{10}$$

where $\phi(s)$ is strictly increasing and thrice continuously differentiable and is such that, for some $\kappa \geq 0$, $C < \infty$,

$$|\phi(s)| \leq 1(|s| \leq 1) + |s|^\kappa 1(|s| > 1), \;\; \left|\phi'(s)\right| + \left|\phi''(s)\right| + \left|\phi'''(s)\right| \leq C(1 + |\phi(s)|^C).$$

Assumption 8 *$L \to \infty$ as $n \to \infty$ and*

$$\underline{\lim}_{n\to\infty} \left(\frac{\log n}{L} \right) > 8 \left\{ \log \eta + \max(\log \varphi, 0) \right\} \simeq 7.05 + 8 \max(\log \varphi, 0);$$

where $\eta = 1 + 2^{\frac{1}{2}} \simeq 2.414$, $\varphi = (1 + |\phi(s_1)|) / (\phi(s_2) - \phi(s_1))$, $[s_1, s_2]$ being an interval on which the $f_i(s)$ are bounded away from zero.

Theorem *Let Assumptions 1-8 hold. Then as $n \to \infty$, $S_L \left(\widetilde{\theta}, \widetilde{M} \right)^{1/2} (\hat{\theta} - \theta_0) \ \to_d \mathcal{N}(0, I_K)$.*

The theorem is proved by a straightforward extension of the proof of Theorem 1 of Robinson (2005), so the details are omitted.

4. FINITE SAMPLE PERFORMANCE

A Monte Carlo study was carried out to investigate finite-sample performance. The main features of interest are perhaps the impact of various choices of dimension N, the degree of mixing afforded by the matrix M_0, and heterogeneity in the elements of ε_t. We used M_0 of form

$$M_0 = (1 - c) I_N + c 1_N 1_N^T,$$

where 1_N is the $N \times 1$ vector of 1's. M_0 is positive definite for $c < 1$, and Ω_0 has similar structure, $\Omega_0 = (1 - c)^2 I_N + (Nc + 2c(1 - c)) 1_N 1_N^T$. We took $c = 0.5$ and 0.9. We focussed on the $AR(1)$ case of (3), subjecting $A_1(\theta)$ to linear restrictions as discussed in Section 2, in particular

$$A_1(\theta) = diag(\theta_1, ..., \theta_N), \text{ so } K = N, \tag{11}$$

denoting by θ_i the ith element of θ, and

$$A_1(\theta) = \theta I_N, \quad \text{so } K = 1. \tag{12}$$

In (11) we took elements of θ_0 within the interval $[0.5, 0.9]$, for example $\theta_0 = (0.50, 0.57, 0.63, 0.7, 0.77, 0.83, 0.90)^T$ when $N = 7$, while in (12) we took θ_{0i} as 0.5 and 0.9. We chose $N = 2$, and 7, along with $n = 50$ and 100, and also a high-dimensional case $N = 56$, with $n = 560$. The candidate distributions for ε_t are in Table 1.

Table 1: Source distributions.

0	$\mathcal{N}(0,1)$
1	$0.5\mathcal{N}(-3,1)+0.5\mathcal{N}(3,1)$
2	$0.05\mathcal{N}(0,1)+0.95\mathcal{N}(0,1)$
3	Laplace
4	$t(5)$
5	Laplace+$\mathcal{N}(0,1)$
6	$t(5)+U[0,1]$

The methods were implemented using (8) and (9) for $\widetilde{\theta}$ and $\widetilde{M}$, and with either $\phi(s)=s$ or $\phi(s)=s(1+s)^{-\frac{1}{2}}$ in (10), with $L=1,2,3$ and 4. As well as computing the one-step estimate (6), we went on to compute an iterative estimate, defined as

$$\widehat{\theta}_{j+1}=\widehat{\theta}_j-0.2S_L\left(\widehat{\theta}_j,\widetilde{M}\right)^{-1}r_L\left(\widehat{\theta}_j,\widetilde{M}\right),\quad j=1,2,..., \tag{13}$$

where $\widehat{\theta}_1=\widehat{\theta}$, stopping when $\left|\hat{\theta}_{j+1}-\hat{\theta}_j\right|<0.001$.

The results are based on $R=1000$ replications, except for the $N=56$ case, where $R=100$. For the purpose of the immediately following definitions only, for convenience we take $\hat{\theta}$ either to denote (6) or the iterative estimate obtained from (13). We report relative mean squared error, RMSE =MSE($\hat{\theta}$)/MSE($\tilde{\theta}$), where MSE(θ) $=R^{-1}\sum_{i=1}^{R}\left(\theta^{(i)}-\theta_0\right)^2$, $\theta^{(i)}$ referring in each case to the ith replicate. We also report the relative out-of-sample 5 steps ahead forecast MSE, RFMSE=FMSE($\hat{\theta}$)/FMSE($\tilde{\theta}$), where FMSE(θ) $=R^{-1}\sum_{i=1}^{R}(\hat{x}_{n+5}^{(i)}(\theta)-x_{n+5}^{(i)})^2$ with $\hat{x}_{n+5}(\theta)=\theta^5 x_n$. We report results only for $\theta_0=0.5$ (results for other values of θ_0 were similar).

Finally, for the case (12) we report coverage of nominal 95% and 99% confidence intervals based on (7). Again, we report results only for $\theta_0=0.5$. In cases where there was a substantial difference between the one-step estimate (6) and the iterative one obtained from we report results for both. The first column in each of the following tables corresponds to the value of the mixing parameter c, the second indicates the value of n, and the third the value of θ_0.

Table 2											
$A_1(\theta) = diag(\theta_1, ..., \theta_N)$, $K = N = 2$ elements of ε_t each distributed according to 0 in Table 1.											
				$\phi(s) = s$				$\phi(s) = s(1+s)^{-\frac{1}{2}}$			
c	n	θ_0	L	1	2	3	4	1	2	3	4
One-step											
0.5	50	0.5	RMSE	0.96	0.92	0.99	1.05	1.05	1.00	1.01	1.05
		0.9	RMSE	1.75	1.69	1.56	1.40	1.71	1.67	1.80	1.58
		0.5	RFMSE	0.52	0.54	0.66	0.66	0.58	0.64	0.60	0.71
	100	0.5	RMSE	0.70	0.74	0.81	0.84	0.78	0.79	0.74	0.84
		0.9	RMSE	1.05	1.12	1.23	1.33	1.27	1.36	1.24	1.14
		0.5	RFMSE	0.75	0.76	0.78	0.78	0.73	0.75	0.79	0.78
0.9	50	0.5	RMSE	0.51	0.48	0.63	0.62	0.65	0.63	0.60	0.69
		0.9	RMSE	1.41	1.48	1.73	1.51	1.92	1.45	1.56	1.69
		0.5	RFMSE	0.62	0.65	0.73	0.75	0.81	0.67	0.72	0.85
	100	0.5	RMSE	0.66	0.73	0.57	0.57	0.81	0.78	0.58	0.67
		0.9	RMSE	3.30	3.37	2.66	2.53	3.71	3.39	2.87	2.96
		0.5	RFMSE	0.93	1.01	0.96	0.99	1.00	1.00	0.93	0.97
Iterative											
0.9	50	0.5	RMSE	0.23	0.23	0.32	0.33	0.26	0.25	0.31	0.33
		0.9	RMSE	0.34	0.34	0.53	0.54	0.38	0.36	0.43	0.45
		0.5	RFMSE	0.68	0.67	0.66	0.58	0.66	0.65	0.64	0.65
	100	0.5	RMSE	0.12	0.13	0.13	0.15	0.14	0.15	0.15	0.17
		0.9	RMSE	0.16	0.17	0.17	0.21	0.19	0.21	0.21	0.31
		0.5	RFMSE	0.81	0.89	0.85	0.83	0.83	0.86	0.86	0.79

Table 3											
$A_1(\theta) = diag(\theta_1, ..., \theta_N)$, $K = N = 7$ elements of ε_t distributed according to $(0-6)$ in Table 1 with each distribution used only once.											
				$\phi(s) = s$				$\phi(s) = s(1+s)^{-\frac{1}{2}}$			
c	n	θ_0	L	1	2	3	4	1	2	3	4
One-step											
0.5	50	0.5	RMSE	0.56	0.60	0.74	0.69	0.62	0.57	0.68	0.74
		0.9	RMSE	1.38	1.30	1.24	1.09	1.26	1.06	1.21	1.14
		0.5	RFMSE	0.41	0.51	0.52	0.56	0.45	0.48	0.55	0.50
	100	0.5	RMSE	0.38	0.37	0.40	0.41	0.40	0.42	0.36	0.43
		0.9	RMSE	0.94	0.96	1.10	0.88	1.00	1.06	0.94	0.84
		0.5	RFMSE	0.70	0.70	0.70	0.72	0.67	0.72	0.73	0.69
0.9	50	0.5	RMSE	0.55	0.52	0.56	0.57	0.66	0.64	0.58	0.57
		0.9	RMSE	1.59	1.46	1.64	1.45	2.01	1.72	1.62	1.42
		0.5	RFMSE	0.62	0.68	0.67	0.59	0.64	0.70	0.66	0.66
	100	0.5	RMSE	0.83	0.78	0.75	0.69	0.96	0.94	0.76	0.70
		0.9	RMSE	3.54	3.65	3.65	3.47	3.95	4.01	3.65	3.23
		0.5	RFMSE	0.98	0.97	1.09	1.06	1.33	1.09	1.05	1.00
Iterative											
0.9	50	0.5	RMSE	0.17	0.19	0.19	0.27	0.14	0.17	0.20	0.26
		0.9	RMSE	0.23	0.26	0.23	0.37	0.20	0.22	0.24	0.31
		0.5	RFMSE	0.65	0.65	0.64	0.63	0.69	0.66	0.71	0.68
	100	0.5	RMSE	0.08	0.08	0.08	0.08	0.07	0.08	0.08	0.08
		0.9	RMSE	0.12	0.09	0.10	0.10	0.10	0.09	0.11	0.11
		0.5	RFMSE	0.83	0.84	0.86	0.84	0.83	0.88	0.81	0.78

Table 4

$A_1(\theta) = diag(\theta_1, ..., \theta_N)$, $K = N = 56$ elements of ε_t distributed according to $(0-6)$ in Table 1 with each distribution used eight times.

				$\phi(s) = s$				$\phi(s) = s(1+s)^{-\frac{1}{2}}$			
c	n	θ_0	L	1	2	3	4	1	2	3	4
One-step											
0.5	560	0.5	RMSE	3.44	4.02	4.07	3.89	4.26	3.57	4.06	3.65
		0.9	RMSE	19.2	22.1	15.0	20.7	32.0	16.8	25.1	18.1
		0.5	RFMSE	2.03	1.28	1.24	1.50	1.73	1.36	1.26	1.43
Iterative											
0.5	560	0.5	RMSE	0.07	0.07	0.08	0.07	0.08	0.08	0.08	0.07
		0.9	RMSE	0.19	0.20	0.14	0.22	0.21	0.19	0.22	0.15
		0.5	RFMSE	0.95	0.98	0.98	0.92	0.98	0.99	0.97	0.98
One-step											
0.9	100	0.5	RMSE	12.8	12.5	12.5	14.6	14.4	11.1	14.3	10.1
		0.9	RMSE	55.5	60.2	43.0	64.9	87.3	45.7	75.1	44.8
		0.5	RFMSE	3.44	2.33	2.04	2.71	3.51	2.33	1.88	2.23
Iterative											
0.9	50	0.5	RMSE	0.09	0.11	0.06	0.06	0.08	0.09	0.09	0.11
		0.9	RMSE	0.53	0.61	0.40	0.30	0.55	0.56	0.61	0.62
		RFMSE		0.99	1.00	0.98	0.96	1.00	1.01	0.99	1.00

Table 5											
$A_1(\theta) = \theta I_N,\ K = 1,\ N = 2$ elements of ε_t each distributed according to 0 in Table 1.											
				$\phi(s) = s$				$\phi(s) = s(1+s)^{-\frac{1}{2}}$			
c	n	θ_0	L	1	2	3	4	1	2	3	4
One-step											
0.5	50	0.5	RMSE	0.93	0.90	0.93	0.94	0.96	0.95	0.95	0.96
		0.9	RMSE	1.33	1.33	1.26	1.24	1.33	1.33	1.29	1.18
		0.5	RFMSE	0.44	0.44	0.58	0.56	0.45	0.50	0.50	0.55
			95%	0.94	0.92	0.86	0.86	0.92	0.92	0.89	0.85
			99%	0.98	0.97	0.94	0.94	0.98	0.97	0.96	0.93
	100	0.5	RMSE	0.84	0.84	0.84	0.87	0.88	0.84	0.87	0.92
		0.9	RMSE	1.15	1.07	1.07	1.09	1.14	1.15	1.09	1.06
		0.5	RFMSE	0.54	0.55	0.60	0.67	0.71	0.60	0.63	0.67
			95%	0.94	0.94	0.93	0.90	0.94	0.93	0.92	0.90
			99%	0.99	0.99	0.98	0.97	0.99	0.99	0.98	0.97
0.9	50	0.5	RMSE	0.84	0.81	0.85	0.86	0.86	0.86	0.86	0.89
		0.9	RMSE	1.11	1.10	1.07	1.07	1.11	1.11	1.09	1.00
		0.5	RFMSE	0.36	0.35	0.48	0.48	0.35	0.38	0.41	0.46
			95%	0.94	0.91	0.86	0.86	0.92	0.92	0.88	0.84
			99%	0.98	0.97	0.94	0.93	0.98	0.97	0.96	0.93
	100	0.5	RMSE	0.75	0.75	0.76	0.79	0.80	0.75	0.79	0.83
		0.9	RMSE	0.99	0.90	0.92	0.95	0.99	0.99	0.91	0.90
		0.5	RFMSE	0.47	0.48	0.52	0.61	0.64	0.53	0.56	0.59
			95%	0.94	0.94	0.92	0.90	0.94	0.93	0.92	0.90
			99%	0.99	0.99	0.98	0.97	0.99	0.98	0.98	0.97

Table 6											
$A_1(\theta) = \theta I_N,\ K = 1,\ N = 7$ elements of ε_t each distributed according to $(0-6)$ in Table 1 with each distribution used only once.											
				$\phi(s) = s$				$\phi(s) = s(1+s)^{-\frac{1}{2}}$			
c	n	θ_0	L	1	2	3	4	1	2	3	4
One-step											
0.5	50	0.5	RMSE	0.55	0.57	0.60	0.63	0.54	0.54	0.60	0.63
		0.9	RMSE	0.98	0.90	0.91	0.86	0.90	0.89	0.82	0.83
		0.5	RFMSE	0.20	0.22	0.27	0.28	0.20	0.19	0.25	0.29
			95%	0.86	0.84	0.80	0.76	0.87	0.84	0.78	0.73
			99%	0.97	0.91	0.91	0.88	0.95	0.93	0.89	0.85
	100	0.5	RMSE	0.49	0.48	0.47	0.49	0.46	0.48	0.47	0.52
		0.9	RMSE	0.71	0.69	0.69	0.63	0.66	0.68	0.66	0.67
		0.5	RFMSE	0.34	0.35	0.38	0.38	0.40	0.44	0.40	0.44
			95%	0.91	0.91	0.91	0.89	0.91	0.91	0.88	0.83
			99%	0.98	0.97	0.98	0.96	0.98	0.97	0.96	0.94
0.9	50	0.5	RMSE	0.50	0.52	0.53	0.58	0.51	0.51	0.55	0.59
		0.9	RMSE	0.82	0.77	0.76	0.77	0.77	0.80	0.73	0.79
		0.5	RFMSE	0.15	0.16	0.13	0.20	0.15	0.16	0.23	0.30
			95%	0.85	0.84	0.79	0.74	0.86	0.84	0.78	0.73
			99%	0.96	0.94	0.90	0.87	0.95	0.95	0.90	0.83
	100	0.5	RMSE	0.45	0.45	0.45	0.45	0.41	0.42	0.44	0.49
		0.9	RMSE	0.63	0.61	0.57	0.60	0.55	0.58	0.57	0.61
		0.5	RFMSE	0.34	0.37	0.29	0.34	0.31	0.37	0.37	0.36
			95%	0.91	0.89	0.89	0.88	0.92	0.90	0.88	0.84
			99%	0.98	0.96	0.97	0.95	0.98	0.97	0.96	0.93

The models relating to Tables 2 and 5, $N = 2$, are regarded as the baseline cases, with $K = 2$ and $K = 1$ respectively, where we take ε_t to be Gaussian. For $A_1(\theta) = I_N\theta$, (12), there is little difference between the two estimates for $c = 0.5$, as is to be expected since there is relatively little mixing and least squares (8) is efficient under Gaussianity. For $c = 0.9$ we see a slight improvement of the adaptive estimates' relative performance, again as expected since we now have a more even mixture of Gaussian innovations.

However, for $A_1(\theta) = \text{diag}(\theta_1, \ldots, \theta_N)$, (11), we find some strange results for $c = 0.9$. The performance of the one-step adaptive estimate (6) is worse than least squares (8), and, moreover the relative performance of the former falls as we increase sample size. From inspection of additional results (not presented for the sake of brevity) we found that both estimates improve significantly with increasing sample size, but least squares sees a far more dramatic gain. On the other hand the iterative adaptive estimates dominate least squares and we see an improvement in this relative superiority with increasing sample size. This pattern continues and becomes more evident as we increase the dimension N, in Tables 3, 4 and 6, where also non-Gaussian distributions are introduced. For $A_1(\theta) = I_n\theta$, with increasng N the relative performance of the adaptive estimates increases across all parameter values, reflecting the inefficiency of least squares as we move further from the Gaussian benchmark. It seems that when there is a high degree of mixing, $c = 0.9$, in order for the adaptive estimates to achieve efficiency improvements over least squares in small samples the iterative estimator is required.

Irrespective of the sample size and the value of the mixing parameter, c, the relative performance of the adaptive estimates is poorer for $\theta_0 = 0.9$ compared to $\theta_0 = 0.5$. Thus it appears that their relative superiority is mitigated somewhat near the unit root.

The choice of L does not seem to make a large difference in terms of RMSE. For $\theta_0 = 0.5$, a larger L tends to reduce relative performance of the adaptive estimates, whereas for $\theta_0 = 0.9$ a larger L improves it. There does not seem to be a clear pattern in the results for the different forms of $\phi(s)$.

The forecast performance of the adaptive estimates looks encouraging. In nearly all situations they outperform least squares; only in the high dimensional case, $N = 56$, is the one-step estimate inferior. Here it appears that the simplest form of estimate, taking $L = 1$ and $\phi(s) = s$, provides the best results.

Outcomes for confidence interval coverage are also fairly encouraging. It appears that for smaller sample sizes coverage rates are fairly anti-conservative, but as n increases to 100 these rates return fairly closely to the nominal level. For smaller values of L the coverage tracks the nominal level very

closely, but becomes quite anti-conservative as L increases. The different forms of $\phi(s)$, as well as the distinction between one-step and iterative estimates, appear to have little effect on the coverage rates.

5. FINAL COMMENTS

We have presented adaptive estimates of the parameters in models for stationary multiple time series of possibly high dimension, avoiding a curse of dimensionality by modelling the innovations vector as a linear transformation of independent but possibly non-identically distributed random variables, having nonparametric distributions. A variety of extensions are possible. As in the scalar time series case of Robinson (2005), regression models can be considered, with x_t in (1) instead representing unobservable errors, whence adaptive estimates of the regression parameters as well as θ_0 can be constructed. Again, as in the latter reference, a more general class of dynamics can also be considered, including stationary and nonstationary fractional behaviour. A more challenging prospect, in part suggested by the second model employed in the Monte Carlo of the previous section, is to develop asymptotic theory with the number K of parameters remaining fixed but the number N of time series increasing with n.

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