

# Large Time-Varying Parameter VARs

Gary Koop

Dimitris Korobilis

University of Strathclyde

University of Glasgow

February 22, 2012

## Abstract

In this paper, we develop methods for estimation and forecasting in large time-varying parameter vector autoregressive models (TVP-VARs). To overcome computational constraints, we draw on ideas from the dynamic model averaging literature which achieve reductions in the computational burden through the use forgetting factors. We then extend the TVP-VAR so that its dimension can change over time. For instance, we can have a large TVP-VAR as the forecasting model at some points in time, but a smaller TVP-VAR at others. A final extension lies in the development of a new method for estimating, in a time-varying manner, the parameter(s) of the shrinkage priors commonly-used with large VARs. These extensions are operationalized through the use of forgetting factor methods and are, thus, computationally simple. An empirical application involving forecasting inflation, real output and interest rates demonstrates the feasibility and usefulness of our approach.

**Keywords:** Bayesian VAR; forecasting; time-varying coefficients; state-space model

**JEL Classification:** C11, C52, E27, E37

**Acknowledgements:** The authors are Fellows of the Rimini Centre for Economic Analysis. We would like to thank the Economic and Social Research Council for financial support under Grant RES-062-23-2646.

# 1 Introduction

Many recent papers (see, among many others, Banbura, Giannone and Reichlin, 2010; Carriero, Clark and Marcellino, 2011; Carriero, Kapetanios and Marcellino, 2009; Giannone, Lenza, Momferatou and Onorante, 2010; Koop, 2011) have found large VARs, which have dozens or even hundreds of dependent variables, to forecast well. In this literature, the researcher typically works with a single large VAR and assumes it is homoskedastic and its coefficients are constant over time. In contrast to the large VAR literature, with smaller VARs there has been much interest in extending traditional (constant coefficient, homoskedastic) VARs in two directions. First, researchers often find it empirically necessary to allow for parameter change. That is, it is common to work with time-varying parameter VARs (TVP-VARs) where the VAR coefficients evolve over time and multivariate stochastic volatility is present (see, among many others, Cogley and Sargent, 2005, Cogley, Morozov and Sargent, 2005, Primiceri, 2005 and Koop, Leon-Gonzalez and Strachan, 2009). Second, there also may be a need for model change: to allow for switches between different restricted TVP models so as to mitigate over-parametrization worries which can arise with parameter-rich unrestricted TVP-VARs (e.g. Chan, Koop, Leon-Gonzalez and Strachan, 2012). The question arises as to whether these two sorts of extensions can be done with large TVP-VARs. This paper attempts to address this question.

Unfortunately, existing TVP-VAR methods used with small dimensional models cannot easily be scaled up to handle large TVP-VARs with heteroskedastic errors. The main reason this is so is computation. With constant coefficient VARs, variants of the Minnesota prior are typically used. With this prior, the posterior and predictive densities have analytical forms and MCMC methods are not required. With TVP-VARs MCMC methods are required to do exact Bayesian inference. Even the small (trivariate) TVP-VAR recursive forecasting exercises of D'Agostino, Gambetti and Giannone (2011) and Korobilis (2012) were hugely computationally demanding. Large TVP-VARs are typically, in practice, computationally infeasible using MCMC methods.

A first contribution of this paper is to develop approximate estimation methods for large

TVP-VARs which do not involve the use of MCMC methods and are computationally feasible. To do this, we use forgetting factors. Forgetting factors (also known as discount factors), which have long been used with state space models (see, e.g., Raftery, Karny and Ettler, 2010, and the discussion and citations therein), do not require the use of MCMC methods and have been found to have desirable properties in many contexts (e.g. Dagl and Halling, 2012). Most authors simply set the forgetting factors to a constant, but we develop methods for estimating forgetting factors in a time-varying way following an approach outlined in Park, Jun and Kim (1991). This allows for the degree of variation of the VAR coefficients to be estimated from the data (without the need for MCMC).

A second contribution of this paper is to contribute to the growing literature on estimating the prior hyperparameter(s) which control shrinkage in large Bayesian VARs (see, e.g., Giannone, Lenza and Primiceri, 2012). Our approach differs from the existing literature in treating different priors (i.e. different values for the shrinkage parameter) as defining different models and using dynamic model selection (DMS) methods with a forgetting factor to select the optimal value of the shrinkage parameter at different points in time. We develop a simple recursive updating scheme for the time-varying shrinkage parameter which is computationally simple to implement.

A third contribution of this paper is to develop econometric methods for doing model selection using a model space involving the large TVP-VAR and various restricted versions of it. We define small (trivariate), medium (seven variable) and large (25 variable) TVP-VARs and develop methods for time-varying model selection over this set of models. Interest centers on forecasting the variables in the small VAR and DMS is done using the predictive densities for these variables (which are common to all the models). To be precise, the algorithm selects between small, medium and large TVP-VARs based on past predictive likelihoods for the set of variables the researcher is interested in forecasting. A potentially important advantage is that this allows for model switching. For instance, with DMS, the algorithm might select the large TVP-VAR as the forecasting model at some points in time, but at other points it might switch to a small or medium TVP-VAR, etc. Such model switching cannot be done in conventional

approaches and has been found to be useful in univariate regression applications (e.g. Koop and Korobilis, 2011). Its incorporation has the potential to be useful in improving the forecast performance of TVP-VARs of different dimensions and to provide information on which model forecasts best (and when it does so).

These methods are used in an empirical application involving a standard large US quarterly macroeconomic data set, with a focus on forecasting inflation, real output and interest rates. Our empirical results are encouraging and demonstrate the feasibility and usefulness of our approach. Relative to conventional VAR and TVP-VAR methods, our results highlight the importance of allowing for the dimension of the TVP-VAR to change over time and allowing for stochastic volatility in the errors.

## 2 Large TVP-VARs

### 2.1 Overview

In this section we describe our approach to estimating a single TVP-VAR using forgetting factors. We write the TVP-VAR as:

$$y_t = Z_t \beta_t + \varepsilon_t,$$

and

$$\beta_{t+1} = \beta_t + u_t, \tag{1}$$

where  $\varepsilon_t$  is i.i.d.  $N(0, \Sigma_t)$  and  $u_t$  is i.i.d.  $N(0, Q_t)$ .  $\varepsilon_t$  and  $u_s$  are independent of one another for all  $s$  and  $t$ .  $y_t$  for  $t = 1, \dots, T$  is an  $M \times 1$  vector containing observations on  $M$  time series variables and

$$Z_t = \begin{pmatrix} z_t' & 0 & \cdots & 0 \\ 0 & z_t' & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & z_t' \end{pmatrix},$$

where  $Z_t$  is  $M \times k$ .  $z_t$  is a vector containing an intercept and  $p$  lags of each of the  $M$  variables. Thus,  $k = M(1 + pM)$ .

Once the researcher has selected a specification for  $\Sigma_t$  and  $Q_t$ , a prior for the initial conditions (i.e.  $\beta_0$  and possibly  $\Sigma_0$  and  $Q_0$ ) and a prior for any remaining parameters of the model, then Bayesian statistical inference can proceed in a straightforward fashion (see, for instance, Koop and Korobilis, 2009 for a textbook-level treatment) using MCMC methods. The basic idea underlying these methods are that standard methods for drawing from state space models (i.e. involving the Kalman filter) can be used for drawing  $\beta_t$  for  $t = 1, \dots, T$  (conditional on  $\Sigma_t, Q_t$  and the remaining model parameters). Then  $\Sigma_t$  for  $t = 1, \dots, T$  (conditional on  $\beta_t, Q_t$  and the remaining model parameters) can be drawn. Then  $Q_t$  for  $t = 1, \dots, T$  (conditional on  $\beta_t, \Sigma_t$  and the remaining model parameters) can be drawn. Then any remaining parameters are drawn (conditional on  $\Sigma_t, Q_t$  and  $\beta_t$ ).

This algorithm works well with small TVP-VARs, but can be computationally very demanding in larger VARs due to the fact that it is a posterior simulation algorithm. Typically, tens of thousands of draws must be taken in order to ensure proper convergence of the algorithm. And, in the context of a recursive forecasting exercise, the posterior simulation algorithm must be run repeatedly on an expanding window of data. Even with constant coefficient large VARs, Koop (2011) found the computational burden to be huge when posterior simulation algorithms were used in the context of a recursive forecasting exercise. With large TVP-VARs, the computational hurdle can simply be insurmountable.

In the next sub-section, we show how approximations using forgetting factors can be used to greatly reduce the computational burden by allowing the researcher to avoid the use of MCMC algorithms. The basic idea is to replace  $Q_t$  and  $\Sigma_t$  by estimates and, once this is done, analytical formulae exist for the posterior (for  $\beta_t$ ) and the one-step ahead predictive density.

## 2.2 Estimation of TVP-VARs Using Forgetting Factors

Forgetting factor approaches were commonly used in the past, when computing power was limited, to estimate state space models such as the TVP-VAR. See, for instance, Fagin (1964),

Jazwinsky (1970) or West and Harrison (1997) for a discussion of forgetting factors in state space models and, in the context of the TVP-VAR, see Doan, Litterman and Sims (1984). Dangl and Halling (2012) is a more recent application which also uses a forgetting factor approach. Here we explain outline the motivation for use of forgetting factor methods.

Let  $y^s = (y_1, \dots, y_s)'$  denote observations through time  $s$ . Bayesian inference for  $\beta_t$  involves the Kalman filter, formulae for which can be found in many textbook sources and will not be repeated here (see, e.g., Fruhwirth-Schnatter, 2006, Chapter 13). But key steps in Kalman filtering involve the result that

$$\beta_{t-1}|y^{t-1} \sim N\left(\beta_{t-1|t-1}, \Sigma_{t-1|t-1}\right) \quad (2)$$

where formulae for  $\beta_{t-1|t-1}$  and  $\Sigma_{t-1|t-1}$  are given in textbook sources. Kalman filtering then proceeds using:

$$\beta_t|y^{t-1} \sim N\left(\beta_{t|t-1}, \Sigma_{t|t-1}\right), \quad (3)$$

where

$$\Sigma_{t|t-1} = \Sigma_{t-1|t-1} + Q_t. \quad (4)$$

This is the only place where  $Q_t$  enters the Kalman filtering formulae and, thus, if we replace the preceding equation by:

$$\Sigma_{t|t-1} = \frac{1}{\lambda} \Sigma_{t-1|t-1} \quad (5)$$

there is no longer a need to estimate or simulate  $Q_t$ .  $\lambda$  is called a forgetting factor which is restricted to the interval  $0 < \lambda \leq 1$ . A detailed discussion of and motivation for forgetting factor approaches is given in places such as Jazwinsky (1970) and Raftery et al (2010). Equation (5) implies that observations  $j$  periods in the past have weight  $\lambda^j$  in the filtered estimate of  $\beta_t$ . Note also that (4) and (5) imply that  $Q_t = (\lambda^{-1} - 1) \Sigma_{t-1|t-1}$  from which it can be seen

that the constant coefficient case arises if  $\lambda = 1$ .

In papers such as Raftery et al (2010),  $\lambda$  is simply set to a number slightly less than one. For quarterly macroeconomic data,  $\lambda = 0.99$  implies observations five years ago receive approximately 80% as much weight as last period’s observation. This leads to a fairly stable models where coefficient change is gradual and has properties similar to what Cogley and Sargent (2005) call their “business as usual” prior. These authors use exact MCMC methods to estimate their TVP-VAR. In order to ensure that the coefficients  $\beta_t$  vary gradually they use a tight prior on their state covariance matrix  $Q$  which depends on a prior shrinkage coefficient which determines the prior mean. It can be shown that their choice for prior shrinkage coefficient allows for variation in coefficients which is roughly similar to that allowed for by  $\lambda = 0.99$ .<sup>1</sup>

A contribution of our paper is to investigate the use of forgetting factors in large TVP-VARs. However, we go beyond most of the existing literature in two ways: we investigate estimating  $\lambda$  (as opposed to simply setting it to a fixed value)<sup>2</sup> and we do so in a time varying manner. To do so, we follow a suggestion made in Park, Jun and Kim (1991) and replace  $\lambda$  by  $\lambda_t$  in (5) where

$$\lambda_t = \lambda_{\min} + (1 - \lambda_{\min}) L^{f_t} \tag{6}$$

where  $f_t = -NINT\left(\varepsilon_{t|t-1}^2\right)$  and  $\varepsilon_{t|t-1} = y_t - \beta_{t|t-1}Z_t$  is the one-step ahead prediction error produced by the Kalman filter and  $NINT$  rounds to the nearest integer. We set  $\lambda_{\min} = 0.95$  and  $L = 1.1$  (values calibrated to obtain a spread of values for the forgetting factor between 0.95 and 1.0, given our prior guess about what  $E\left(\varepsilon_{t|t-1}^2\right)$  would tend to be).

A similar approximation is used to remove the need for a posterior simulation algorithm for multivariate stochastic volatility in the measurement equation. In finance, it is common to use an Exponentially Weighted Moving Average (EWMA) to model volatility (see RiskMetrics, 1996 and Brockwell and Davis, 2009, Section 1.4). We adopt an EWMA estimator for the

---

<sup>1</sup>Note that Cogley and Sargent (2005) have a fixed state equation error covariance matrix  $Q$ , while we use a time varying one. This does not affect the interpretation of  $\lambda$  as a shrinkage factor similar to the one they use.

<sup>2</sup>An exception to this is McCormick, Raftery, Madigan and Burd (2011) which estimates forgetting factors in an application using logistic regression using dynamic model averaging.

measurement error covariance matrix:

$$\Sigma_t = \kappa \Sigma_{t-1} + (1 - \kappa) \widehat{\varepsilon}_{t-1} \widehat{\varepsilon}'_{t-1}, \quad (7)$$

where  $\widehat{\varepsilon}_{t-1} = y_{t-1} - \beta_{t-1|t-1} Z_{t-1}$  is produced by the Kalman filter. EWMA estimators also require the selection of the decay factor,  $\kappa$ . We set  $\kappa = 0.96$  which is in the region suggested in RiskMetrics (1996). This estimator requires the choice of an initial condition,  $\Sigma_0$  for which we use the sample covariance matrix of  $y^\tau$  where  $\tau + 1$  is the period in which we begin our forecast evaluation.

### 2.3 Model Selection Using Forgetting Factors

Our previous exposition applies to one model. Raftery et al (2010), in a TVP regression context, develops methods for doing dynamic model averaging (DMA) which can also be used for DMS. The reader is referred to Raftery et al (2010) or Koop and Korobilis (2011) for a complete derivation and motivation of DMA. Here we provide a general description of what it does. In subsequent sections, we use the general strategy outlined here in two ways. First, we use DMS so as to allow for the TVP-VAR to change dimension over time. Second, we use it to select optimal values for the VAR shrinkage parameter in a time-varying manner.

Suppose the researcher is working with  $j = 1, \dots, J$  models. The goal of DMA is to calculate  $\pi_{t|t-1,j}$  which is the probability that model  $j$  should be used for forecasting at time  $t$ , given information through time  $t - 1$ . Once  $\pi_{t|t-1,j}$  for  $j = 1, \dots, J$  are obtained they can either be used to do model averaging or model selection. DMS arises if, at each point in time, the model with the highest value for  $\pi_{t|t-1,j}$  is used for forecasting. Note that  $\pi_{t|t-1,j}$  will vary over time and, hence, the forecasting model can switch over time. The contribution of Raftery et al (2010) is to develop a fast recursive algorithm using a forgetting factor for obtaining  $\pi_{t|t-1,j}$ .

To do DMA or DMS we must first specify the set of models under consideration. In papers such as Raftery et al (2010) or Koop and Korobilis (2011) the models are TVP regressions with different sets of explanatory variables. In the present paper, our model space is of a different nature, including TVP-VARs of differing dimensions, but the basic algorithm still holds.



DMS is a recursive algorithm where the necessary recursions are analogous to the prediction and updating equations of the Kalman filter. Given an initial condition,  $\pi_{0|0,j}$  for  $j = 1, \dots, J$ , Raftery et al (2010) derive a model prediction equation using a forgetting factor  $\alpha$ :

$$\pi_{t|t-1,j} = \frac{\pi_{t-1|t-1,j}^\alpha}{\sum_{l=1}^J \pi_{t-1|t-1,l}^\alpha}, \quad (8)$$

and a model updating equation of:

$$\pi_{t|t,j} = \frac{\pi_{t|t-1,j} p_j(y_t|y^{t-1})}{\sum_{l=1}^J \pi_{t|t-1,l} p_l(y_t|y^{t-1})}, \quad (9)$$

where  $p_j(y_t|y^{t-1})$  is the predictive likelihood (i.e. the predictive density for model  $j$  evaluated at  $y_t$ ). Note that this predictive density is produced by the Kalman filter and has a standard, textbook, formula (e.g. Fruhwirth-Schnatter, 2006, page 405). The predictive likelihood is a measure of forecast performance.

We refer the reader to Raftery et al (2010) for additional details (e.g. the relationship of this approach to the marginal likelihood), but note here that the calculation of  $\pi_{t|t,j}$  and  $\pi_{t|t-1,j}$  is simple and fast, not involving using of simulation methods. To help understand the implication of the forgetting factor approach, note that  $\pi_{t|t-1,j}$  (the key probability used to select models), can be written as:

$$\pi_{t|t-1,j} \propto \prod_{i=1}^{t-1} [p_j(y_{t-i}|y^{t-i-1})]^\alpha.$$

Thus, model  $j$  will receive more weight at time  $t$  if it has forecast well in the recent past (where forecast performance is measured by the predictive density,  $p_j(y_{t-i}|y^{t-i-1})$ ). The interpretation of “recent past” is controlled by the forgetting factor,  $\alpha$  and we have the same exponential decay as we do for the forgetting factor  $\lambda$ . For instance, if  $\alpha = 0.99$ , forecast performance five years ago receives 80% as much weight as forecast performance last period. If  $\alpha = 0.95$ , then forecast performance five years ago receives only about 35% as much weight. These considerations suggest that, as with  $\lambda$  (or  $\lambda_t$ ) we focus on the interval  $\alpha \in (0.95, 0.99)$ .

## 2.4 Model Selection Among Priors

Given that we use a forgetting factor approach which negates the need to estimate  $Q_t$  and use an EWMA estimate for  $\Sigma_t$ , prior information is required only for  $\beta_0$ . But this source of prior information is likely to be important. That is, papers such as Banbura et al (2010) are working with large VARs with many more parameters than observations and prior information is crucial in obtaining reasonable results. With TVP-VARs this need is even greater. Accordingly, we use a tight Minnesota prior for  $\beta_0$ . In the case where the time-variation in parameters is removed (i.e. when  $\Sigma_t = \Sigma$  and  $\lambda_t = 1$  for all  $t$ ), this Minnesota prior on  $\beta_0$  becomes a Minnesota prior in a constant coefficient VAR and, thus, this important special case is included as part of our approach.

With large VARs and TVP-VARs it is common to use training sample priors (e.g. Primiceri, 2005 and Banbura et al, 2010) to elicit hyperparameters which control the degree of shrinkage. In training sample approaches, the same prior is used as each point in time in a recursive forecasting exercise. However, in this paper we adopt a different approach which allows for the estimation of the shrinkage hyperparameter in a time-varying fashion. The algorithm we develop allows for the shrinkage hyperparameter to be updated automatically (in a similar fashion to the way the Kalman filter updates coefficient estimates). In the context of a recursive forecasting exercise, an alternative strategy for having time-varying shrinkage would be to re-estimate the shrinkage priors at each point in time and re-estimate the model at each point in time (such an approach is used in Giannone, Lenza and Primiceri, 2012). This can be computationally demanding (particularly if the shrinkage parameter is estimated at a grid of values). Our automatic updating procedure avoids this problem and is computationally much less demanding.

For a TVP-VAR of a specific dimension, we use a Normal prior for  $\beta_0$  which is similar to the Minnesota prior (see, e.g., Doan, Litterman and Sims, 1984). Our empirical section uses a data set where all variables have been transformed to stationarity and, thus, we choose the prior mean to be  $E(\beta_0) = 0$ . A Minnesota prior for a VAR using untransformed levels variables would set appropriate elements of  $E(\beta_0)$  to 1 so as to shrink towards a random walk

and this can be trivially accommodated in the approach set out below.

The Minnesota prior covariance matrix for  $\beta_0$  is typically assumed to be diagonal and we follow this practice. If we let  $\text{var}(\beta_0) = \underline{V}$  and  $\underline{V}_i$  denote its diagonal elements, then our prior covariance matrix is defined through:

$$\underline{V}_i = \begin{cases} \frac{\gamma}{r^2} & \text{for coefficients on lag } r \text{ for } r = 1, \dots, p \\ \underline{a} & \text{for the intercepts} \end{cases}, \quad (10)$$

where  $p$  is lag length. The key hyperparameter in  $\underline{V}$  is  $\gamma$  which controls the degree of shrinkage on the VAR coefficients. We will estimate  $\gamma$  from the data. Note that this differs from the Minnesota prior in that the latter contains two shrinkage parameters (corresponding to own lags and other lags) and these are set to fixed values. Theoretically, allowing for two shrinkage parameters in our approach is straightforward. To simplify computation we only have one shrinkage parameter (as does Banbura et al, 2010). Finally, we set  $\underline{a} = 10^3$  for the intercepts so as to be noninformative.

In large VARs and TVP-VARs, a large degree of shrinkage is necessary to produce reasonable forecast performance. We achieve this by estimating  $\gamma$  at each point in time using the following strategy. Define a grid of values for  $\gamma$ :  $\gamma^{(1)}, \dots, \gamma^{(G)}$ . We use the following very wide grid for  $\gamma$ :  $[10^{-10}, 10^{-5}, 0.001, 0.005, 0.01, 0.05, 0.1]$ . For a Bayesian, a model contains a likelihood and a prior. Different values for  $\gamma$  can be thought of as defining different priors and, thus, different models. We can use the DMS methods described in the preceding sub-section to find the optimal value for  $\gamma$ . However, before we do this, we further augment the model space to allow for TVP-VARs of different dimensions.

## 2.5 Model Selection Among TVP-VARs of Different Dimension

DMA and DMS have previously been used in time-varying regression contexts where each model is defined by the set of included explanatory variables. In the previous sub-section, we described how DMS can be used where the models are defined by different priors. We can also augment the model space with models of different dimensions. In particular, we can do

DMS over three models: a small, medium and large TVP-VAR. Definitions of the variables contained in each TVP-VAR are given in the Data Appendix.

Thus, in this paper, the model space is defined by a value for  $\gamma$  and a TVP-VAR dimensionality. With seven values for  $\gamma$  and three TVP-VAR sizes, we have 21 different models. Remember that our goal is to calculate  $\pi_{t|t-1,j}$  for  $j = 1, \dots, J$  which is the probability that model  $j$  is the forecasting model at time  $t$ , given information through time  $t - 1$ . When forecasting at time  $t$ , we evaluate  $\pi_{t|t-1,j}$  for every  $j$  and use the value of  $\gamma$  and TVP-VAR dimension which maximizes it. The recursive algorithm given in (8) and (9) can be used to evaluate  $\pi_{t|t-1,j}$ . This algorithm begins with an initial condition:  $\pi_{0|0,j} = \frac{1}{J}$  with  $J = 21$ , which expresses a view that all possible models are equally likely.

The predictive density,  $p_j(y_{t-i}|y^{t-i-1})$ , plays the key role in DMS. When working with TVP-VARs of different dimension,  $y_t$ , will be of different dimension and, hence, predictive densities will not be comparable. To get around this problem, we use the predictive densities for the small TVP-VAR (i.e. these are the variables which are common to all models). In our empirical work, this means the dynamic model selection is determined by the joint predictive likelihood for inflation, output and the interest rate.

We refer to this approach, which allows for TVP-VARs of different dimension to be selected at different points in time, as dynamic dimension selection or DDS. Thus, we use notation TVP-VAR-DDS as notation for forecasting approaches which include this aspect.

### 3 Empirical Results

#### 3.1 Data

Our data set comprises 25 major quarterly US macroeconomic variables and runs from 1959:Q1 to 2010:Q2. We work with a small TVP-VAR with three variables, a medium TVP-VAR with seven and a large TVP-VAR with 25. Following, e.g., Stock and Watson (2008) and recommendations in Carriero, Clark and Marcellino (2011) we transform all variables to stationarity. The choice of which variables are included in which TVP-VAR is motivated by the choices of

Banbura et al (2010). The Data Appendix provides a complete listing of the variables, their transformation codes and which variables belong in which TVP-VAR.

We investigate the performance of our approach in forecasting CPI, real GDP and the Fed funds rate (which we refer to as inflation, GDP and the interest rate below). These are the variables in our small TVP-VAR. The transformation codes are such that the dependent variables are the percentage change in inflation (the second log difference of CPI), GDP growth (the log difference of real GDP) and the change in the interest rate (the difference of the Fed funds rate). We also standardize all variables by subtracting off a mean and dividing by a standard deviation. We calculate this mean and standard deviation for each variable using data from 1959Q1 through 1969Q4 (i.e. data before our forecast evaluation period).

### 3.2 Other Modelling Choices and Models for Comparison

We use a lag length of 4. This is consistent with quarterly data. Worries about over-parameterization with this relatively long lag length are lessened by the use of the Minnesota prior variance, (10), which increases shrinkage as lag length increases. All of our remaining modelling choices are stated above. To remind the reader of the important choices in our TVP-VAR-DDS approach:

- We have a forgetting factor which controls the degree of time-variation in the VAR coefficients which we set to  $\lambda = 0.99$ .
- We have a forgetting factor,  $\alpha$ , which controls the amount of model switching of the prior shrinkage parameter and over TVP-VAR dimensions. Consistent with Raftery et al (2010), we set  $\alpha = 0.99$ .
- We have a decay factor which controls the volatility,  $\kappa$ . Following RiskMetrics (1996) we set  $\kappa = 0.96$ .

We compare the performance of TVP-VAR-DDS as outlined above to many special cases. Unless otherwise noted, these special cases are restricted versions of TVP-VAR-DDS and, thus

(where relevant) have exactly the same modelling choices, priors and select the prior shrinkage parameter in the same way. They include:

- TVP-VARs of each dimension, with no DDS being done.
- Time-varying forgetting factor versions of the TVP-VARs. In this case,  $\lambda_t$  is constrained to be in the interval  $[0.95, 1]$ . We label such cases  $\lambda = \lambda_t$  in the tables.
- VARs of each dimension, obtained by setting  $\lambda_t = 1$  for  $t = 1, \dots, T$ .
- Homoskedastic versions of each VAR.<sup>3</sup>

We also present random walk forecasts (labelled RW) and forecasts from a homoskedastic small VAR estimated using OLS methods (labelled Small VAR OLS).

### 3.3 Estimation Results

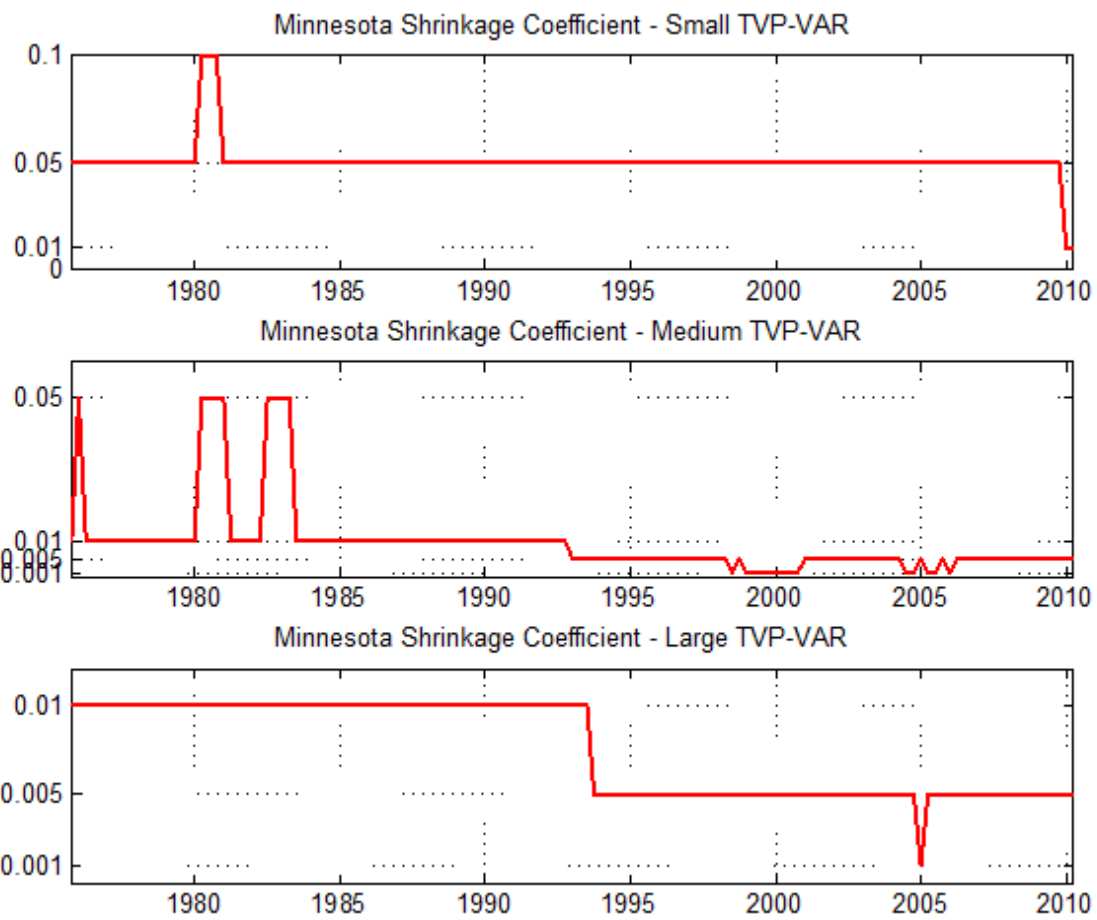
The main focus of this paper is on forecasting, but it is useful to briefly present some empirical evidence on other aspects of our approach. Figure 1 plots the selected value of  $\gamma$ , the shrinkage parameter in the Minnesota prior, at each point in time for TVP-VARs of different dimension. Note that, as expected, we are finding that the necessary degree of shrinkage increases as the dimension of the TVP-VAR increases.

To illustrate the estimation of the time-varying forgetting factors, Figure 2 plots  $\lambda_t$  against time for the small TVP-VARs (the medium and large TVP-VARs show similar patterns). Note that  $\lambda_t$  does vary over the allowed interval of  $(0.95, 1.0)$  and, hence, sometimes the VAR coefficients are changing very little, but at other times much more change is allowed for. Typically, we find little change in stable times such as the 1960s and 1990s, but more rapid change in unstable times.

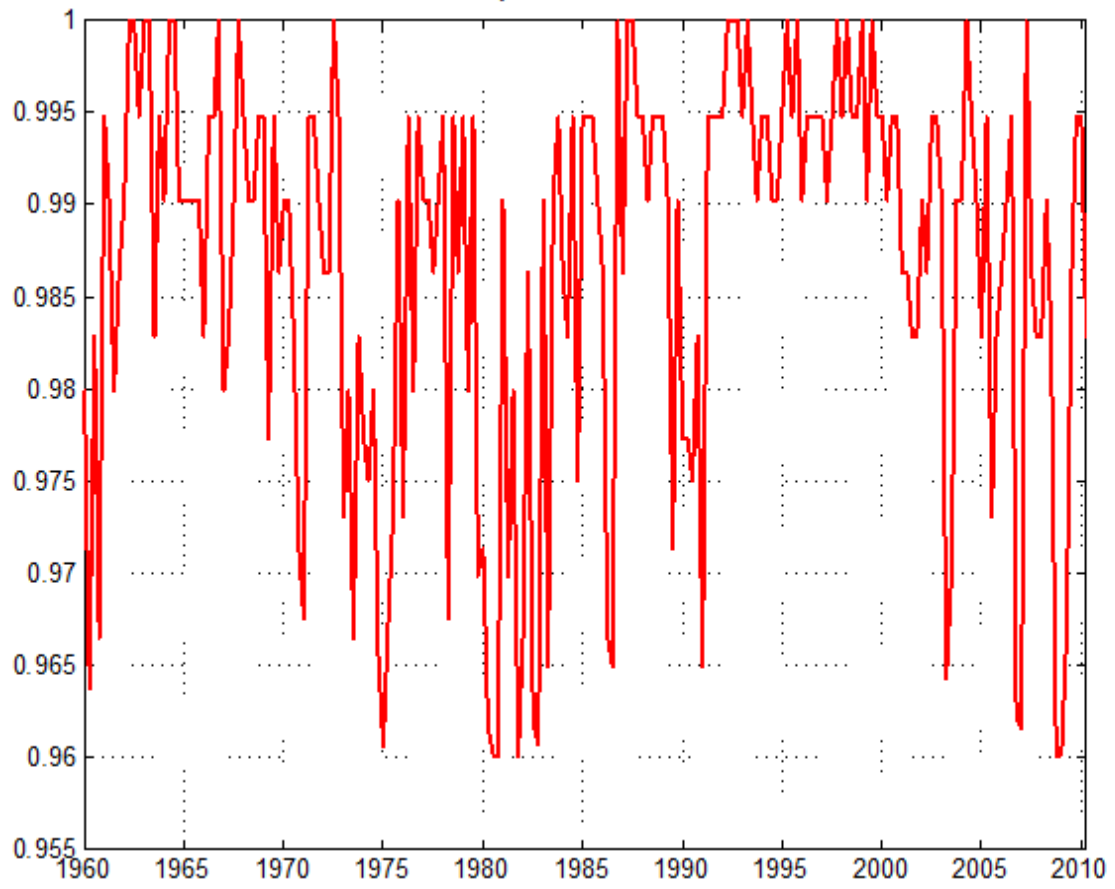
Figure 3 plots the time-varying probabilities associated with the TVP-VAR of each dimension. Note that, for each dimension of TVP-VAR, the optimum value for the Minnesota

---

<sup>3</sup>When forecasting  $y_t$  given information through  $t - 1$ ,  $\Sigma$  is estimated as  $\frac{1}{t-1} \sum_{i=1}^{t-1} \widehat{\varepsilon}_i \widehat{\varepsilon}_i'$ .



Estimated  $\lambda_t$  values - Small TVP-VAR





prior shrinkage parameter,  $\gamma$ , is chosen and the probability plotted in Figure 3 is for this optimum value. Remember that TVP-VAR-DDS will forecast with the TVP-VAR of dimension with highest probability. It can be seen that there is a great deal of switching between TVP-VARs of different dimension. In the relatively stable period from 1990 through 2007, the small TVP-VAR is being used to forecast. For most of the remaining time DDS selects the large TVP-VAR, although there are some exceptions to this (e.g. the medium TVP-VAR is selected for most of the 1967-1973 period).

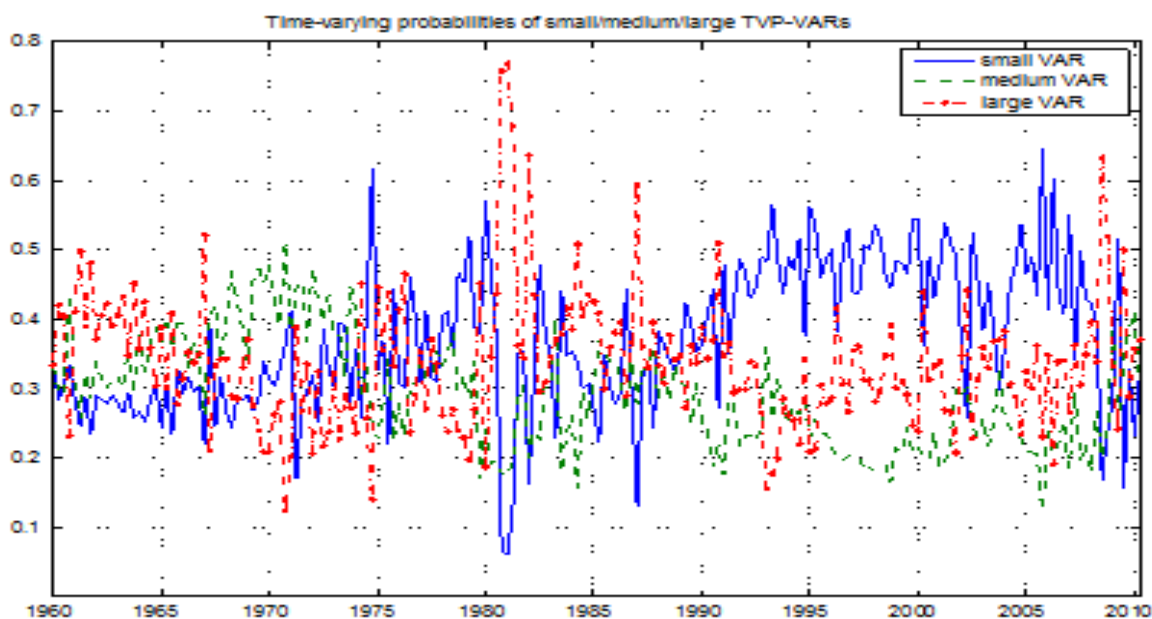


Figure 2

### 3.4 Forecast Comparison

We present iterated forecasts for horizons of up to two years ( $h = 1, \dots, 8$ ) with a forecast evaluation period of 1970Q1 through 2010Q2. The use of iterated forecasts does increase the computational burden since predictive simulation is required (i.e. when  $h > 1$  an analytical formula for the predictive density does not exist). We do predictive simulation in two different ways. The first (simpler) way uses the VAR coefficients which hold at time  $T$  to forecast variables at time  $T + h$ . This is labelled  $\beta_{T+h} = \beta_T$  in the tables below and assumes no

VAR coefficient change between  $T$  and  $T + h$ . The second way, labelled  $\beta_{T+h} \sim RW$  in the tables, does allow for coefficient change out-of-sample and simulates from the random walk state equation (1) to produce draws of  $\beta_{T+h}$ . Both ways provide us with  $\beta_{T+h}$  and we simulate draws of  $y_{\tau+h}$  conditional on  $\beta_{T+h}$  to approximate the predictive density.<sup>4</sup>

The alternative would be to use direct forecasting, but recent papers such as Marcellino, Stock and Watson (2006) tend to find that iterated forecasts are better. Direct forecasting would also require re-estimating the model for different choices of  $h$  and would not necessarily remove the need for predictive simulation since the researcher may need to simulate  $\beta_{T+h}$  from (1) when  $h > 1$ .

As measures of forecast performance, we use mean squared forecast errors (MSFEs) and predictive likelihoods. The latter are popular with many Bayesians since they evaluate the forecast performance of the entire predictive density (as opposed to merely the point forecast). It is natural to use the joint predictive density for our three variables of interest (i.e. inflation, GDP and the interest rate) as an overall measure of forecast performance. Thus, Tables 1 through 3 present MSFEs for each of our three variables of interest separately. Table 4 presents sums of log predictive likelihoods using the joint predictive likelihood for these three variables.

MSFEs are presented relative to the TVP-VAR-DDS approach which simulates  $\beta_{T+h}$  from the random walk state equation. Tables 1 through 3 are mostly filled with numbers greater than one, indicating TVP-VAR-DDS is forecasting better than other forecasting approaches. This is particularly true for inflation and GDP. For the interest rate, TVP-VAR-DDS forecasts best at several forecast horizons but there are some forecast horizons (especially  $h = 7, 8$ ) where large TVP-VARs are forecasting best. Nevertheless, overall MSFEs indicate TVP-VAR-DDS is the best forecasting approach among the comparators we consider. Note, too, that TVP-VAR-DDS is forecasting much better than our most simple benchmarks: random walk forecasts and forecasts from a small VAR estimated using OLS methods.

---

<sup>4</sup>For longer-term forecasting, this has the slight drawback that our approach is based on the model updating equation (see equation 9) which uses one-step ahead predictive likelihoods (which may not be ideal when forecasting  $h > 1$  periods ahead).

If we consider results for TVP-VARs of a fixed dimension, it can be seen that our different implementations (i.e. different treatments of forgetting factors or methods of predictive simulation) lead to similar MSFEs. Overall, we are finding that large TVP-VARs tend to forecast better than small or medium ones, although there are many exceptions to this. For instance, large TVP-VARs tend to do well when forecasting interest rates and inflation, but when forecasting GDP the small TVP-VAR tends to do better. Such findings highlight that there may often be uncertainty about TVP-VAR dimensionality suggesting the usefulness of TVP-VAR-DDS. In general, though, MSFEs indicate that heteroskedastic VARs tend to forecast about as well as TVP-VARs suggesting that, with this data set, allowing for time-variation in VAR coefficients is less important than allowing for DDS.

With regards to predictive simulation, MSFEs suggest that simulating  $\beta_{T+h}$  from the random walk state equation yields only modest forecast improvements over the simpler strategy of assuming no change in VAR coefficients over the horizon that the forecast is being made.

Table 1: Relative Mean Squared Forecast Errors, GDP equation

	$h = 1$	$h = 2$	$h = 3$	$h = 4$	$h = 5$	$h = 6$	$h = 7$	$h = 8$
FULL MODEL								
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.00	1.02	1.02	1.03	1.02	1.00	1.01	0.99
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SMALL VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.04	0.95	1.08	1.00	1.04	1.08	1.01	1.02
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.03	0.92	1.08	1.03	1.04	1.08	1.01	1.04
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.05	0.95	1.08	1.03	1.03	1.06	0.99	1.02
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.04	0.95	1.06	1.02	1.02	1.06	1.01	1.01
VAR, heteroskedastic	1.04	0.94	1.06	1.03	1.04	1.06	1.02	1.04
VAR, homoskedastic	1.09	1.01	1.04	1.01	1.06	1.08	1.02	1.04
MEDIUM VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.09	0.99	1.04	1.04	1.06	1.05	1.02	1.07
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.09	0.99	1.03	1.04	1.07	1.05	1.02	1.06
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.10	1.00	1.04	1.07	1.06	1.05	1.03	1.05
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.05	1.00	1.04	1.04	1.06	1.05	1.01	1.10
VAR, heteroskedastic	1.10	1.00	1.02	1.05	1.09	1.02	1.02	1.10
VAR, homoskedastic	1.08	1.02	1.04	1.08	1.09	1.03	1.00	1.08
LARGE VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.03	1.04	1.02	1.06	1.07	1.07	1.06	1.10
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.04	1.06	1.05	1.10	1.08	1.08	1.08	1.11
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.02	1.05	1.03	1.06	1.06	1.08	1.07	1.09
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.05	1.10	1.03	1.05	1.07	1.07	1.09	1.11
VAR, heteroskedastic	1.09	1.12	1.08	1.11	1.09	1.10	1.10	1.13
VAR, homoskedastic	1.02	1.05	1.04	1.04	1.03	1.03	1.03	1.05
BENCHMARK MODELS								
RW	1.59	1.71	1.81	1.97	1.96	1.88	1.96	2.22
Small VAR OLS	1.19	1.13	1.53	1.29	1.31	1.36	1.27	1.29

Table 2: Relative Mean Squared Forecast Errors, Inflation equation

	$h = 1$	$h = 2$	$h = 3$	$h = 4$	$h = 5$	$h = 6$	$h = 7$	$h = 8$
FULL MODEL								
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.02	0.99	1.00	1.00	1.00	1.01	0.99	1.00
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SMALL VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.04	1.05	1.07	1.06	1.06	1.06	1.00	1.04
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.04	1.06	1.09	1.06	1.04	1.04	1.01	1.03
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.03	1.06	1.07	1.06	1.05	1.04	1.01	1.04
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.03	1.07	1.05	1.03	1.04	1.03	0.99	1.06
VAR, heteroskedastic	1.02	1.04	1.03	1.01	1.02	1.02	0.98	1.05
VAR, homoskedastic	1.05	1.08	1.05	1.02	1.02	1.03	0.98	1.06
MEDIUM VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.08	1.06	1.07	1.01	1.00	1.04	0.99	1.05
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.12	1.07	1.09	0.99	1.01	1.03	0.98	1.07
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.08	1.05	1.05	1.01	1.00	1.05	0.99	1.04
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.07	1.05	1.06	1.02	1.02	1.02	0.97	1.07
VAR, heteroskedastic	1.07	1.06	1.02	1.00	1.02	1.02	0.96	1.07
VAR, homoskedastic	1.11	1.10	1.11	1.03	1.03	1.04	0.96	1.09
LARGE VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.01	1.02	1.02	0.95	0.99	1.04	0.97	1.04
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.01	1.04	1.03	0.95	1.00	1.02	0.97	1.04
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.01	1.03	1.03	0.95	1.01	1.04	0.97	1.02
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.03	1.01	1.03	0.96	1.00	1.04	0.97	1.05
VAR, heteroskedastic	1.05	1.03	1.03	0.95	1.01	1.03	0.96	1.04
VAR, homoskedastic	1.05	1.05	1.04	0.96	1.01	1.05	0.97	1.07
BENCHMARK MODELS								
RW	3.26	2.71	1.69	2.07	2.11	1.73	1.65	1.74
Small VAR OLS	1.09	1.23	1.12	1.14	1.16	1.05	1.02	1.18

Table 3: Relative Mean Squared Forecast Errors, Interest Rate equation

	$h = 1$	$h = 2$	$h = 3$	$h = 4$	$h = 5$	$h = 6$	$h = 7$	$h = 8$
FULL MODEL								
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.03	1.00	1.02	1.00	0.99	0.99	1.00	0.99
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
SMALL VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.16	1.02	1.14	1.19	1.01	0.99	1.16	1.11
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.18	0.99	1.13	1.12	1.02	0.99	1.08	1.07
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.16	1.00	1.16	1.20	1.02	1.01	1.14	1.11
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.19	1.01	1.14	1.16	1.02	0.96	1.11	1.08
VAR, heteroskedastic	1.19	1.00	1.12	1.09	1.00	0.96	1.05	1.01
VAR, homoskedastic	1.25	1.10	1.15	1.11	0.99	0.96	1.04	1.03
MEDIUM VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.18	1.01	1.10	1.06	0.98	0.99	0.98	0.97
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.19	1.03	1.10	1.06	0.98	1.03	0.98	0.98
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.20	1.01	1.12	1.06	0.97	1.00	0.98	0.98
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.19	0.98	1.07	1.04	1.00	1.00	0.96	0.98
VAR, heteroskedastic	1.17	0.97	1.05	1.02	0.97	1.00	0.98	0.96
VAR, homoskedastic	1.25	1.06	1.11	1.03	1.00	1.01	0.96	0.98
LARGE VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	1.07	0.94	1.06	0.96	0.98	1.00	0.91	0.92
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	1.06	0.97	1.09	0.98	1.00	1.02	0.91	0.92
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	1.05	0.94	1.05	0.97	0.98	1.00	0.92	0.91
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	1.07	0.93	1.07	0.97	0.97	1.01	0.91	0.91
VAR, heteroskedastic	1.07	0.95	1.06	0.97	0.99	0.99	0.92	0.91
VAR, homoskedastic	1.13	0.98	1.06	0.99	1.01	1.02	0.92	0.92
BENCHMARK MODELS								
RW	1.91	2.16	1.92	1.87	1.64	1.98	2.37	1.93
Small VAR OLS	1.76	1.47	1.59	2.11	1.78	1.69	2.23	2.03

Predictive likelihoods are presented in Table 4, relative to TVP-VAR-DDS. To be precise, the numbers in Table 4 are the sum of log predictive likelihoods for a specific model minus the

sum of log predictive likelihoods for TVP-VAR-DDS. The fact that almost all of these numbers are negative supports the main story told by the MSFEs: TVP-VAR-DDS is forecasting well at most forecast horizons. At  $h = 1$ , TVP-VAR-DDS forecasts best by a considerable margin and at other forecast horizons it beats other TVP-VAR approaches. However, there are some important differences between predictive likelihood and MSFE results that are worth noting.

The importance of allowing for heteroskedastic errors in getting the shape of the predictive density correct is clearly shown by the poor performance of homoskedastic models in Table 4. In fact, the heteroskedastic VAR exhibits the best forecast performance at many horizons. However, the dimensionality of this best forecasting model differs across horizons. For instance, at  $h = 2$  the small model forecasts best, but at  $h = 3$  the medium model wins and at  $h = 4$  it is the large heteroskedastic VAR. This suggests, even when the researcher is using a VAR (instead of a TVP-VAR), DDS still might be a useful as a conservative forecasting device which can forecast well in a context where there is uncertainty over the dimension of the VAR.

Table 4: Relative Predictive Likelihoods, Total (all 3 variables)

	$h = 1$	$h = 2$	$h = 3$	$h = 4$	$h = 5$	$h = 6$	$h = 7$	$h = 8$
FULL MODEL								
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} = \beta_T$	0.84	0.91	2.47	4.03	4.76	3.30	6.69	4.11
TVP-VAR-DDS, $\lambda = 0.99, \beta_{T+h} \sim RW$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SMALL VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	-6.71	4.62	-3.70	-2.72	2.73	1.93	-0.32	0.68
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	-7.47	2.15	-5.24	-3.72	-0.41	-2.67	-2.68	-3.63
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	-5.95	4.84	-1.95	-2.56	2.20	-0.92	-1.04	-3.32
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	-4.77	3.70	0.13	-0.68	2.39	2.84	3.47	3.36
VAR, heteroskedastic	-6.18	6.86	-1.39	1.57	12.00	6.24	5.87	9.11
VAR, homoskedastic	-47.44	-29.97	-27.74	-22.87	-15.96	-18.50	-18.92	-15.93
MEDIUM VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	-23.55	0.79	-1.58	2.84	11.31	5.85	7.69	9.27
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	-30.24	-6.10	-3.53	0.05	9.61	3.93	3.16	10.68
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	-23.22	-0.09	-3.16	-0.54	11.33	5.07	8.13	9.80
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	-20.69	0.68	-1.95	1.62	8.20	2.49	8.78	4.87
VAR, heteroskedastic	-20.89	1.08	5.07	8.39	15.12	14.02	14.79	14.52
VAR, homoskedastic	-58.28	-31.86	-29.35	-21.09	-10.14	-13.94	-7.38	-10.65
LARGE VAR								
TVP-VAR, $\lambda = 0.99, \beta_{T+h} = \beta_T$	-18.16	-7.81	-6.85	-1.32	3.03	-3.69	1.46	8.33
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} = \beta_T$	-21.96	-12.99	-16.46	-10.61	-5.42	-17.35	-5.08	-2.82
TVP-VAR, $\lambda = 0.99, \beta_{T+h} \sim RW$	-16.14	-8.25	-9.70	-2.45	-0.24	-7.56	-1.48	2.93
TVP-VAR, $\lambda = \lambda_t, \beta_{T+h} \sim RW$	-16.24	-5.20	-6.70	-0.41	2.83	-5.90	1.56	1.82
VAR, heteroskedastic	-17.30	-1.63	-1.76	8.46	12.46	6.03	10.36	13.24
VAR, homoskedastic	-50.33	-37.35	-35.31	-28.60	-17.52	-29.13	-22.05	-20.50
BENCHMARK MODELS								
RW	-	-	-	-	-	-	-	-
Small VAR OLS	-52.94	-40.42	-49.99	-52.48	-45.69	-36.48	-37.92	-49.35



## 4 Conclusions

In this paper, we have developed computationally feasible methods for forecasting with large TVP-VARs through the use of forgetting factors. We use forgetting factors in several ways. First, they allow for simple forecasting within a single TVP-VAR model. However, inspired by the literature on dynamic model averaging and selection (see Raftery et al, 2010), we also use forgetting factors so as to allow for fast and simple dynamic model selection. That is, we develop methods so that the forecasting model can change at every point in time.

DMS can be used with any type of model. We have found it useful to define our models in terms of the priors that they use and their dimension. The former allows us to estimate the shrinkage parameter of the Minnesota prior in a time-varying fashion using a simple recursive updating scheme. The latter allows the TVP-VAR dimension to change over time. In our empirical exercise, we have found our approach to offer moderate improvements in forecast performance over other VAR or TVP-VAR approaches.

It would be simple to extend the general modelling framework presented here in several ways. For instance, instead of using model selection methods to select prior hyperparameters or TVP-VAR dimension, it would have been straightforward to use model averaging. It would also have been possible to use our methods with VARs instead of TVP-VARs (and, in our forecasting exercise, we do this as a special case). Another extension would be to use this approach for variable selection in a TVP-VAR. Suppose, for instance, that a researcher was interested in forecast a particular variable (e.g. inflation) and had 9 potential predictors. We could define a model space which includes the 10 dimensional TVP-VAR, all 9 dimensional TVP-VARs which included inflation as one of the variables, all 8 dimensional TVP-VARs, etc. Doing DMS using the approach outlined over this large model space would be computationally demanding, but would allow the researcher to select the appropriate predictors for inflation (and allow the set of predictors to change over time). In sum, we would argue that doing DMS using forgetting factors is a potentially powerful tool in a wide variety of macroeconomic forecasting exercises.

## References

- Banbura, M., Giannone, D. and Reichlin, L. (2010). “Large Bayesian vector auto regressions,” *Journal of Applied Econometrics*, 25, 71-92.
- Brockwell, R. and Davis, P. (2009). *Time series: Theory and methods* (second edition). New York: Springer.
- Carriero, A., Clark, T. and Marcellino, M. (2011). “Bayesian VARs: Specification choices and forecast accuracy,” Federal Reserve Bank of Cleveland, working paper 11-12.
- Carriero, A., Kapetanios, G. and Marcellino, M. (2009). “Forecasting exchange rates with a large Bayesian VAR,” *International Journal of Forecasting*, 25, 400-417.
- Chan, J., Koop, G., Leon-Gonzalez, R. and Strachan, R. (2012). “Time varying dimension models,” *Journal of Business and Economic Statistics*, forthcoming.
- Cogley, T., Morozov, S. and Sargent, T. (2005). “Bayesian fan charts for U.K. inflation: Forecasting and sources of uncertainty in an evolving monetary system,” *Journal of Economic Dynamics and Control*, 29, 1893-1925.
- Cogley, T. and Sargent, T. (2001). “Evolving post World War II inflation dynamics,” *NBER Macroeconomics Annual*, 16, 331-373.
- Cogley, T. and Sargent, T. (2005). “Drifts and volatilities: Monetary policies and outcomes in the post WWII U.S.,” *Review of Economic Dynamics*, 8, 262-302.
- D’Agostino, A., Gambetti, L. and Giannone, D. (2009). “Macroeconomic forecasting and structural change,” *Journal of Applied Econometrics*, forthcoming.
- Dangl, T. and Halling, M. (2012). “Predictive regressions with time varying coefficients,” *Journal of Financial Economics*, forthcoming.
- Doan, T., Litterman, R. and Sims, C. (1984). “Forecasting and conditional projections using a realistic prior distribution”, *Econometric Reviews*, 3, 1-100.
- Fagin, S. (1964). “Recursive linear regression theory, optimal filter theory, and error analyses of optimal systems,” *IEEE International Convention Record Part i*, pages 216-240.
- Fruhwirth-Schnatter, S., (2006). *Finite Mixture and Markov Switching Models*. New York: Springer.

Giannone, D., Lenza, M., Momferatou, D. and Onorante, L. (2010). “Short-term inflation projections: a Bayesian vector autoregressive approach,” ECARES working paper 2010-011, Universite Libre de Bruxelles.

Giannone, D., Lenza, M. and Primiceri, G. (2012). “Prior selection for vector autoregressions,” *Centre for Economic Policy Research*, working paper 8755.

Jazwinsky, A. (1970). *Stochastic Processes and Filtering Theory*. New York: Academic Pres.

Koop, G. (2011). “Forecasting with medium and large Bayesian VARs,” *Journal of Applied Econometrics*, forthcoming.

Koop, G. and Korobilis, D. (2009). “Bayesian multivariate time series methods for empirical macroeconomics,” *Foundations and Trends in Econometrics*, 3, 267-358.

Koop, G. and Korobilis, D. (2011). “Forecasting inflation using dynamic model averaging,” *International Economic Review*, forthcoming.

Koop, G., Leon-Gonzalez, R. and Strachan, R. (2009). “On the evolution of the monetary policy transmission mechanism,” *Journal of Economic Dynamics and Control*, 33, 997-1017.

Korobilis, D. (2012). “VAR forecasting using Bayesian variable selection”, *Journal of Applied Econometrics*, forthcoming.

Marcellino, M., Stock, J. and Watson, M. (2006). “A comparison of direct and iterated AR methods for forecasting macroeconomic series h-steps ahead,” *Journal of Econometrics*, 135, 499-526.

McCormick, T., Raftery, A. Madigan, D. and Burd, R. (2011). “Dynamic logistic regression and dynamic model averaging for binary classification,” *Biometrics*, forthcoming.

Park, D., Jun, B. and Kim, J. (1991). “Fast tracking RLS algorithm using novel variable forgetting factor with unity zone,” *Electronics Letters*, 27, 2150-2151.

Primiceri, G. (2005). “Time varying structural vector autoregressions and monetary policy,” *Review of Economic Studies*, 72, 821-852.

Raftery, A., Karny, M. and Ettlter, P. (2010). “Online prediction under model uncertainty via dynamic model averaging: Application to a cold rolling mill,” *Technometrics*, 52, 52-66.

RiskMetrics (1996). *Technical Document* (Fourth Edition). Available at <http://www.riskmetrics.com/system/files/private/td4e.pdf>.

Stock, J. and Watson, M. (2008). “Forecasting in dynamic factor models subject to structural instability,” in *The Methodology and Practice of Econometrics, A Festschrift in Honour of Professor David F. Hendry*, edited by J. Castle and N. Shephard, Oxford: Oxford University Press.

West, M. and Harrison, J. (1997). *Bayesian Forecasting and Dynamic Models*, second edition, New York: Springer.

## A Data Appendix

All series were downloaded from St. Louis' FRED database and cover the quarters 1959:Q1 to 2010:Q2. Some series in the database were observed only on a monthly basis and quarterly values were computed by averaging the monthly values over the quarter. All variables are transformed to be approximately stationary following Stock and Watson (2008). In particular, if  $z_{i,t}$  is the original untransformed series, the transformation codes are (column Tcode below): 1 - no transformation (levels),  $x_{i,t} = z_{i,t}$ ; 2 - first difference,  $x_{i,t} = z_{i,t} - z_{i,t-1}$ ; 3 - second difference,  $x_{i,t} = z_{i,t} - z_{i,t-2}$ ; 4 - logarithm,  $x_{i,t} = \log z_{i,t}$ ; 5 - first difference of logarithm,  $x_{i,t} = \ln z_{i,t} - \ln z_{i,t-1}$ ; 6 - second difference of logarithm,  $x_{i,t} = \ln z_{i,t} - \ln z_{i,t-2}$ .

Table A1: Series used in the Small VAR with  $n = 3$

Series ID	Tcode	Description
GDPC96	5	Real Gross Domestic Product
CPIAUCSL	6	Consumer Price Index: All Items
FEDFUNDS	2	Effective Federal Funds Rate

Table A2: Additional series used in the Medium VAR with  $n = 7$

Series ID	Tcode	Description
PMCP	1	NAPM Commodity Prices Index
BORROW	6	Borrowings of Depository Institutions from the Fed
SP500	5	S&P 500 Index
M2SL	6	M2 Money Stock

Table A3: Additional Series used in the Large VAR with  $n = 25$ 

Series ID	Tcode	Description
PINCOME	6	Personal Income
PCECC96	5	Real Personal Consumption Expenditures
INDPRO	5	Industrial Production Index
UTL11	1	Capacity Utilization: Manufacturing
UNRATE	2	Civilian Unemployment Rate
HOUST	4	Housing Starts: Total: New Privately Owned Housing Units
PPIFCG	6	Producer Price Index: All Commodities
PCECTPI	5	Personal Consumption Expenditures: Chain-type Price Index
AHEMAN	6	Average Hourly Earnings: Manufacturing
M1SL	6	M1 Money Stock
OILPRICE	5	Spot Oil Price: West Texas Intermediate
GS10	2	10-Year Treasury Constant Maturity Rate
EXUSUK	5	U.S. / U.K Foreign Exchange Rate
GPDIC96	5	Real Gross Private Domestic Investment
PAYEMS	5	Total Nonfarm Payrolls: All Employees
PMI	1	ISM Manufacturing: PMI Composite Index
NAPMNOI	1	ISM Manufacturing: New Orders Index
OPHPBS	5	Business Sector: Output Per Hour of All Persons