

Schwaab, Bernd; Lucas, Andre; Koopman, Siem Jan

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## Systemic Risk Diagnostics

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Duisenberg school of finance – Tinbergen Institute Discussion Paper

**TI 10–104 / DSF 2**

## **Systemic Risk Diagnostics**

*Bernd Schwaab<sup>1</sup>*

*André Lucas<sup>2,3,4</sup>*

*Siem Jan Koopman<sup>2,3</sup>*

<sup>1</sup> *European Central Bank, Financial Markets Research;*

<sup>2</sup> *VU University Amsterdam;*

<sup>3</sup> *Tinbergen Institute;*

<sup>4</sup> *Duisenberg school of finance.*

# Systemic risk diagnostics: coincident indicators and early warning signals\*

*Bernd Schwaab,<sup>(a)</sup> Siem Jan Koopman,<sup>(b,c)</sup> André Lucas<sup>(c,d)</sup>*

<sup>(a)</sup> European Central Bank, Financial Markets Research

<sup>(b)</sup> Department of Econometrics, VU University Amsterdam

<sup>(c)</sup> Tinbergen Institute

<sup>(d)</sup> Department of Finance, VU University Amsterdam, and Duisenberg school of finance

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## Abstract

A macro-prudential policy maker can manage risks to financial stability only if current and future risks can be reliably assessed. We propose a novel framework to assess financial system risk. Using a dynamic factor framework based on state-space methods, we model latent macro-financial and credit risk components for a large data set comprising the U.S., the EU-27 area, and the rest of the world. Controlling for global, region-specific, and industry effects, we construct coincident measures ('thermometers') and forward looking indicators of financial distress and the likelihood of financial melt-down. We find that credit risk conditions can significantly and persistently de-couple from macro-financial fundamentals. Such decoupling can serve as an early warning signal for macro-prudential policy.

**Keywords:** financial crisis; systemic risk; credit portfolio models; frailty-correlated defaults; state space methods.

JEL classification: *G21, C33*

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\*Corresponding author: Bernd Schwaab, European Central Bank, Kaiserstrasse 29, 60311 Frankfurt, Germany. Tel. +49 69 1344 7216. Email: Bernd.Schwaab@ecb.int. We thank Christian Brownlees, Robert Engle, Philipp Hartmann, Martin Scheicher, and Michel van der Wel for comments. We thank Thomas Kostka and Silviu Oprica for excellent research assistance. The views expressed in this paper are those of the authors and they do not necessarily reflect the views or policies of the European Central Bank or the European System of Central Banks.

*"One of the greatest challenges ... at this time is to restore financial and economic stability. ... The academic research community can make a significant contribution in supporting policy-makers to meet these challenges. It can help to improve analytical frameworks for the early identification and assessment of systemic risks."* Jean-Claude Trichet, President of the ECB, Clare Distinguished Lecture in Economics and Public Policy, University of Cambridge, December 2009.

# 1 Introduction

Macro-prudential oversight seeks to focus on safeguarding the financial system as a whole. This has proven to be a major issue in the wake of the recent financial crisis. The debate on macro-prudential policies and potential warning signals ignited by the crisis is currently under full swing. Many of the models constructed before the crisis have fallen short in this respect. For example, regulators have learned the hard way that cross-sectional correlations between asset and credit exposures can have severe consequences, even though each of these exposures might be qualified as safe when considered in isolation. Cross-sectional dependence undermines the benefits of diversification and may lead to a ‘fallacy of composition’ at the systemic level, see for example Brunnermeier, Crocket, Goodhart, Persaud, and Shin (2009). In particular, traditional risk-based capital regulation at the individual institution level may significantly underestimate systemic risk by neglecting the macro impact of a joint reaction of financial intermediaries to a common shock.

There is widespread agreement that financial systemic risk is characterized by both cross-sectional and time-related dimensions; see, for example, Hartmann, de Bandt, and Alcalde (2009). The cross-sectional dimension concerns how risks are correlated across financial institutions at a given point in time due to, for example, direct and indirect linkages across institutions and prevailing default conditions. The time series dimension concerns the evolution of systemic risk over time due to, for example, changes in the default cycle, changes in financial market conditions, and the potential buildup of financial imbalances such as asset and credit market bubbles.

In contrast to the broad consensus on the set of models, indicators, and analytical tools for macroeconomic and monetary policy analysis, such agreement is absent for macro-prudential policy analysis. The current paper makes a step in filling this gap. In particular, we make two contributions to the existing literature on systemic risk assessment.

First, we propose a unified econometric framework for the measurement of global macro-financial and credit risk conditions based on state space methods. The framework follows the mixed-measurement dynamic factor model (MM-DFM) approach as introduced by Koopman, Lucas, and Schwaab (2010). Our model provides a diagnostic tool that tracks the evolution of macro-financial developments and point in time risk conditions, as well as their joint

impact on system stability. Such a diagnostic tool for systemic risk measurement is definitely needed as a first step to start assessing and communicating this risk. Second, we develop a set of coincident and forward looking indicators for financial distress based on the empirical output of our analysis. We distinguish ‘thermometers’ and ‘crystal balls’. Thermometers are coincident risk indicators that, metaphorically, a policy maker can plug into the financial system to read off its ‘heat’. Crystal balls are forward looking early warning indicators that - to some extent - permit a glimpse into the future of financial stability conditions. Early warning indicators may be based on estimated deviations from fundamentals that accrue in the present. Obviously, constructing a useful early warning signal is substantially harder than an assessment of current risk conditions.

We use our framework to study systemic risk conditions across three broad geographical regions, i.e., (i) the U.S., (ii) current EU-27 countries, and (iii) all remaining countries. In this way, our perspective departs substantially from most earlier studies that typically focus on one region only, in particular the U.S. Several people have stressed the importance of such an international perspective, see e.g. de Larosiere (2009), and Brunnermeier et al. (2009). It requires one to look beyond domestic developments for detecting financial stability risk. In the context of the recent crisis. For example, the saving behavior of Asian countries has been cited as a contributing factor to low interest rates and easy credit access in the U.S., see e.g. Brunnermeier (2009). Similarly, developments in the U.S. housing market have triggered distress for European financial institutions. In our MM-DFM model, we allow for the differential impact of world business cycle conditions on regional default rates, unobserved regional risk factors, as well as world-wide industry sector dynamics.

Our empirical study is based on worldwide credit data for more than 12.000 firms. We differentiate between the impact of macro and financial market conditions on defaults versus autonomous default dynamics, and industry effects. We refer to the autonomous default dynamics as frailty effects, see also Duffie, Eckner, Horel, and Saita (2009). Our empirical findings show that the magnitude of frailty effects can serve as a warning signal for macro-prudential policy makers. Latent residual effects are highest when aggregate default conditions (the ‘default cycle’) diverge significantly from what is implied by aggregate macroeconomic conditions (the ‘business cycle’), e.g. due to unobserved shifts in credit supply. Historically, frailty effects have been pronounced during bad times, such as the savings and loan crisis in the U.S. leading up to the 1991 recession, or exceptionally good times, such as the years 2005-07 leading up to the recent financial crisis. In the latter years, default conditions are much too benign compared to observed macro and financial data. In either case, a macro-prudential policy maker should be aware of a possible decoupling of systematic default risk conditions from their macro-financial fundamentals. The flexible tool of mixed measurement dynamic factor models provides the necessary sophisticated and flexible measurement tool needed for a timely detection of this decoupling.

Our work is related to two lines of literature. First, we relate to the work on accurately measuring point-in-time credit risk conditions. In general, this is a complicated task since not all processes that determine corporate default and financial distress are easily observed. Recent research indicates that readily available macro-financial variables and firm-level information may not be sufficient to capture the large degree of default clustering present in corporate default data, see e.g. Das, Duffie, Kapadia, and Saita (2007). In particular, there is substantial evidence for an additional dynamic unobserved ‘frailty’ risk factor as well as contagion dynamics, see McNeil and Wendin (2007), Koopman, Lucas, and Monteiro (2008), Koopman and Lucas (2008), Lando and Nielsen (2008), and Duffie, Eckner, Horel, and Saita (2009), and Azizpour, Giesecke, and Schwenkler (2010). ‘Frailty’ and contagion risk cause default dependence above and beyond what is implied by observed covariates alone. Compared to these earlier papers, our current paper takes an explicit international perspective. In addition, it allows for both macro, frailty, and industry effects. Finally, it provides a unified framework to integrate systemic risk signals from different sources, whether macroeconomic and financial market conditions, equity markets and balance sheet information (via expected default frequencies, EDFs), or actual defaults.

Another line of literature relates to our second contribution, the construction of systemic risk measures. Segoviano and Goodhart (2009) adopt a copula perspective to link together the failure of several financial institutions. Their approach is partly non-parametric, whereas our framework is parametric. However, our parametric framework lends itself more easily to extensions to high dimensions, i.e., a large number of individual financial institutions. This is practically impossible in the Segoviano and Goodhart (2009) approach due to the non-parametric characteristics. Extensions to higher dimensions is a relevant issue in our current study, as we take a, literally, global perspective of the financial system. Another paper related to ours is Giesecke and Kim (2010). These authors take a hazard rate approach with contagion and observed macro-financial factors (no frailty). In contrast to their model, our mixed-measurements framework allows us to model the macro developments and default dynamics in a joint factor structure. Giesecke and Kim, by contrast, take the macro data as exogenous regressors in their analysis. Also, our study explicitly incorporates the global dimension and distinguishes between global and regional factors.

The remainder of this paper is set up as follows. In Section 2, we briefly review the literature on systemic risk measurement and discuss the desirable properties of a good systemic risk measure. Section 3 discusses our econometric framework that is based on a mixed-measurement dynamic factor model. Some details of parameter and factor estimation are given as well. Section 4 presents the data. Section 5 discusses the main empirical results and presents coincident and forward-looking measures of financial distress. Section 6 concludes.

## 2 Quantitative measures of systemic risk

### 2.1 A post-crisis literature review

We briefly review a selection of quantitative measures of systemic risk that have recently been proposed in the literature. In that literature, systemic risk is understood in two different but related ways. First, the ‘systemic risk contribution’ associated with a large and complex financial institution corresponds to a negative externality its risk taking has on other firms. It is the extent to which a firm ‘pollutes the public good’ of financial stability. Given accurate measures of risk contribution, such an externality may be internalized e.g. through Pigouvian taxation. Conversely, however, systemic risk is often understood as financial system risk. We follow this second convention. This notion is analogous to assessing the total size of the (risk) pie (rather than its composition). It may be operationalized as the time varying probability of experiencing a systemic event, e.g., the simultaneous failure of a large number of financial intermediaries.

The literature on financial system risk can be usefully structured by making a distinction between the different sources of systemic risk. First, financial sector contagion risk is caused by an initially idiosyncratic problem that sequentially becomes widespread in the cross-section. Second, shared exposure to financial market shocks and macroeconomic developments may cause simultaneous problems for financial intermediaries. Third, financial imbalances such as credit and asset market bubbles that build up gradually over time may unravel suddenly, with detrimental effects for the system. We review the literature based on this distinction that is also used in the ECB (2009) report and the lecture of Trichet (2009).

**Systemic risk contribution:** Acharya, Pedersen, Philippon, and Richardson (2010) show how each financial institution’s contribution to overall systemic risk can be measured. The extent to which an institution imposes a negative externality on the system is called *Systemic Expected Shortfall* (SES). An institution’s SES increases in its leverage and MES, *Marginal Expected Shortfall*. Brownlees and Engle (2010) propose ways to estimate the MES. Huang, Zhou, and Zhu (2009, 2010) propose a systemic risk measure called the *distress insurance premium*, or DIP, which represents a hypothetical insurance premium against systemic financial distress. Adrian and Brunnermeier (2009) suggest *CoVaR*, the Value at Risk of the financial system conditional on an individual institution being under stress. These methods are targeted more towards the identification of systemically important institutions. Their prime source of information is taken from equity markets via equity return data.

**Contagion/Cross-sectional perspective:** Contagion risk refers to an initially idiosyncratic problem that becomes more widespread in the cross-section. Segoviano and Goodhart (2009) define banking stability measures based on an entropy-based copula approach that matches marginal default probability constraints from CDS markets or other sources. Billo, Getmansky, Lo, and Pelizzon (2010) capture dependence between intermediaries through

principal components analysis and predictive causality tests. Some measures allow to infer systemic risk contribution as well. Similarly, Hartmann, Straetmans, and de Vries (2005) derive indicators of the severity of banking system risk from banks' equity returns using multivariate extreme value theory. This literature recognizes system risk as largely resulting from multivariate (tail) dependence.

**Macro-financial stress:** Macroeconomic shocks matter for financial stability because they tend to affect all firms in an economy. A macro shock causes an increase in correlated default losses, with detrimental effects on intermediaries and thus financial stability. Aikman et al. (2009) propose a 'Risk Assessment Model for Systemic Institutions' (RAMSI) to assess the impact of macroeconomic and financial shocks on both individual banks as well as the banking system. Giesecke and Kim (2010) define systemic risk as the conditional (time-varying) probability of failure of a large number of financial institutions, based on a dynamic hazard rate model with macroeconomic covariates. A related study using a large number of macroeconomic and financial covariates is Koopman, Lucas, and Schwaab (2008).

**Financial imbalances:** Financial imbalances such as credit and asset market bubbles may build up gradually over time. However, they may unravel quite suddenly and abruptly with detrimental effects on financial markets and intermediaries. Financial imbalances are not easily characterized and difficult to quantify. Inference on financial misalignments can be based on observed covariates, such as the private-credit-to-GDP ratio, total-lending-growth, valuation ratios, changes in property and asset prices, financial system leverage and capital adequacy, etc., see e.g. Borio and Lowe (2002), Misina and Tkacz (2008), and Barrell, Davis, Karim, and Liadze (2010). Despite recent progress, these models still display large errors when predicting financial stress.

## 2.2 What is needed for measuring systemic risk ?

We identify five core features for an appropriate indicator of systemic risk. We refer to these features in the next sections where we discuss our econometric framework.

**A broader definition of systemic risk:** Current tools for financial risk measurement rely on relatively narrow definitions of a systemic event. A more comprehensive framework could be based on e.g. the theoretical work of Goodhart, Sunirand, and Tsomocos (2006) who argue that systemic risk arises from (i) spillover dynamics at the financial industry level, (ii) shocks to the macroeconomic and financial markets environment, and implicitly (iii) the potential unraveling of widespread financial imbalances. These sources of risk act on observed data simultaneously, and should therefore all be part of a diagnostic framework. Otherwise, incorrect risk attributions may arise. For example, allowing for interconnectedness through business links but not for shared exposure to common risk factors may spuriously attribute dependence to links that do not exist.

**International or inter-regional focus:** Several studies have stressed the importance



of an international perspective, see e.g. Brunnermeier et al. (2009), de Larosiere (2009) and Volcker et al. (2009). As argued in the introduction, an exclusive focus on domestic conditions is inefficient at best and most likely severely misleading. Consequently, a diagnostic tool for systemic risk should incorporate information from various regions and industries.

**Macroeconomic/financial conditions:** The main source of risk in the banking book is default clustering. Adverse changes in macroeconomic and financial conditions affect the solvency of all, financial and non-financial, firms in the economy. Observed macro-financial risk factors are therefore systematic and a source of cross-sectional dependence between defaults. The resulting default clusters have a first-order impact on intermediaries' profitability and solvency, and therefore on financial stability. As a result, proxies for time-varying macro-financial and credit risk conditions should be at the core of a systemic risk assessment exercise.

**Expected default frequencies:** Financial institutions rarely default. This is particularly the case in Europe, where we count 12 financial defaults in the period from 1984Q1 to 2010Q2. Data scarcity poses obvious problems for the modeling of shared financial distress and financial default dependence. As a consequence, models based on actual default experience may only give a partial picture of current stress. Other measures of credit risk can complement historical default information. Such information can be obtained from asset markets (equities, bonds, credit default swaps) and possibly be augmented with accounting data. One candidate that integrates information from accounting data (via debt levels) and forward-looking equity markets (via prices and volatilities) are expected default frequencies (EDF) which are based on structural models for credit risk. We include this measure in our empirical analysis. Other information can be added in the form of credit default swaps (CDS) spreads. However, the short length of time series of liquid CDS for individual firms is typically a problem.

**Unobserved factors:** Financial distress, systemic risk, and the time-varying probability of a systemic event are inherently unobserved processes. Their main drivers are also unobserved: contagion risk at the financial sector level, changes in shared macro-financial conditions, and financial imbalances such as unobserved large shifts in credit supply. Many of these unobserved conditions, however, can be inferred (reverse-engineered) from different sets of observed data. The appropriate econometric tools for extracting unobserved factors from observed data are collectively known as state space methods.

## 3 The diagnostic framework

### 3.1 Mixed-measurement dynamic factor models

We use the mixed-measurement dynamic factor model (MM-DFM) approach as introduced in Koopman, Lucas, and Schwaab (2010). The approach is based on a state space framework and incorporates all desired features as stated in Section 2.2. The main idea is to estimate the composite factors of unobserved systemic risk using a panel of time series observations. Once the unobserved (or latent) risk factors are estimated, we can construct an accurate coincident and forward looking measures of systemic risk.

Credit risk is the main risk in the banking book and time-varying credit conditions are therefore central to systemic risk assessment. Our data sources for assessing credit risk consist of  $N$  macroeconomic and financial market variables  $x_t$ , default counts  $y_t$  obtained from historical information across  $R$  regions, and expected default frequencies (EDFs)  $z_t$  for  $S_r$  financial firms in the  $r$ th region for  $r = 1, \dots, R$  and for time index  $t = 1, \dots, T$ . The data is denoted by

$$x_t = (x_{1t}, \dots, x_{Nt})', \quad (1)$$

$$y_t = (y_{1,1t}, \dots, y_{1,Jt}, \dots, y_{R,1t}, \dots, y_{R,Jt})', \quad (2)$$

$$z_t = (z_{1,1t}, \dots, z_{1,S_{1,t}}, \dots, z_{R,1t}, \dots, z_{R,S_{R,t}})', \quad (3)$$

for  $t = 1, \dots, T$ , where  $x_{nt}$  represents the value of the  $n$ th macroeconomic variable at time period  $t$ ,  $y_{r,jt}$  is the number of defaults for economic region  $r$ , cross-section  $j$  and time period  $t$ , and  $z_{r,st}$  is the EDF in economic region  $r$  of financial  $s$  in time period  $t$ , for  $n = 1, \dots, N$ ,  $t = 1, \dots, T$ ,  $r = 1, \dots, R$ ,  $j = 1, \dots, J$  and  $s = 1, \dots, S_r$ . Cross-section  $j$  can represent different categories of firms. For example,  $j$  can represent industry sector, rating category, firm age cohort, or a combination of these. We assume that all variables  $x_t$ ,  $y_t$ , and  $z_t$  are driven by a vector of common dynamic factors, that is  $f_t$ . However, our panel data may be unbalanced, such that all variables may not be observed at all time periods.

The model combines normally and non-normally distributed variables. We adopt a standard conditional independence assumption: conditional on latent factors  $f_t$ , the measurements  $(x_t, y_t, z_t)$  are independent over time and within the cross-section. In our specific case and conditional on  $f_t$ , we assume that the elements of  $x_t$  are normally distributed with their means as functions of  $f_t$ . The default counts  $y_{r,jt}$  have a binomial distribution with  $k_{r,jt}$  trials and with a probability  $\pi_{r,jt}$  that is a function of  $f_t$ . The number of trials  $k_{r,jt}$  refers to the number of firms and  $\pi_{r,jt}$  is the probability of default for a specific cross-section  $j$  in region  $r$  at time  $t$ . The EDFs  $z_t$  are transformed to represent a frequency for a quarterly horizon. The corresponding log-odds ratio is defined as  $\bar{z}_{r,st} = \log(z_{r,st}/(1 - z_{r,st}))$ . We effectively model the log-odds as being a normal variable (conditional on  $f_t$ ). The factor

structure distinguishes macro, regional frailty, and industry-specific effects, denoted by  $f_t^m$ ,  $f_t^d$ ,  $f_t^i$ , respectively. We therefore have  $f_t' = (f_t^{m'}, f_t^{d'}, f_t^{i'})$ . The latent factors are the main input for our systemic risk measures which we discuss below.

In the factor model structure we assume that the macroeconomic and financial variables in  $x_t$  are only determined by the macro factors while the other observed variables in  $y_t$  and  $\bar{z}_t$  are determined by all factors,

$$x_{nt}|f_t^m \sim \text{Gaussian}(\mu_{nt}, \sigma_n^2), \quad (4)$$

$$y_{r,jt}|f_t^m, f_t^d, f_t^i \sim \text{Binomial}(k_{r,jt}, \pi_{r,jt}), \quad (5)$$

$$\bar{z}_{r,st}|f_t^m, f_t^d, f_t^i \sim \text{Gaussian}(\bar{\mu}_{st}, \bar{\sigma}_s^2). \quad (6)$$

where the means  $\mu_{nt}$  and  $\bar{\mu}_{st}$ , and probability  $\pi_{r,jt}$  are functions of  $f_t$  and where the variances  $\sigma_n^2$  and  $\bar{\sigma}_s^2$  are treated as unknown coefficients. The number of firms at risk  $k_{r,jt}$  is known since it is observed from the dataset. The factors in  $f_t^m$  capture shared business cycle dynamics in both macro and credit risk data, and are therefore common to  $x_t$ ,  $y_t$ , and  $\bar{z}_t$ . The frailty factors in  $f_t^d$  are region-specific; they only load on the realized defaults,  $y_{r,t}$ , and the log-odds of EDFs,  $\bar{z}_{s,t}$ , from a given region. The frailty and industry factors are independent of observed macroeconomic and financial data. They capture variation due to default risk, above and beyond what is already implied by the macro factors  $f_t^m$ . The latent factors in  $f_t^i$  affect firms in the same industry. Such factors may arise as a result of default dependence through up- and downstream business links, and may capture the industry-specific propagation of aggregate shocks. Both  $f_t^d$  and  $f_t^i$  help capture a deviation of default activity from what is implied by macro-financial fundamentals as summarized by  $f_t^m$ .

The point-in-time default probabilities  $\pi_{r,jt}$  in (5) vary over time due to the shared exposure to the underlying risk factors in  $x_t$ , as summarized by  $f_t^m$ , to the frailty effects  $f_t^d$ , and to the latent industry specific effects  $f_t^i$ . We model  $\pi_{r,jt}$  as the logistic transform of an index function  $\theta_{r,jt}$ ,

$$\pi_{r,jt} = (1 + e^{-\theta_{r,jt}})^{-1}, \quad (7)$$

where  $\theta_{r,jt}$  may be interpreted as the log-odds or logit transform of  $\pi_{r,jt}$ . This transform ensures that time-varying probabilities  $\pi_{r,jt}$  are in the unit interval.

The panel data dynamics in (1) to (3) are captured by time-varying parameters or unobserved signals which are modeled as functions of the dynamic factors in  $f_t$ . In particular, we have

$$\mu_{nt} = c_n + \beta_n' f_t^m, \quad (8)$$

$$\theta_{r,jt} = \lambda_{r,j} + \beta_{r,j}' f_t^m + \gamma_{r,j}' f_t^d + \delta_{r,j}' f_t^i, \quad (9)$$

$$\bar{\mu}_{r,st} = \bar{c}_{r,s} + \bar{\beta}_{r,s}' f_t^m + \bar{\gamma}_{r,s}' f_t^d + \bar{\delta}_{r,s}' f_t^i, \quad (10)$$

where  $\lambda_{r,j}$ ,  $c_n$ , and  $\bar{c}_{r,s}$  are fixed effects, and risk factor sensitivities  $\beta$ ,  $\gamma$ , and  $\delta$  refer to the loadings on macro factors, frailty factors, and industry-specific factors, respectively. Fixed effects and factor loadings may differ across firms and regions. Since the cross-section is high-dimensional, we follow Koopman and Lucas (2008) in reducing the number of parameters by imposing the following additive structure,

$$\bar{\chi}_{r,j} = \chi_0 + \chi_{1,d_j} + \chi_{2,s_j} + \chi_{3,r_j}, \quad \text{for } \bar{\chi} = \lambda, \beta, \gamma, \delta, \bar{\beta}, \bar{\gamma}, \bar{\delta} \quad (11)$$

where  $\chi_0$  represents the baseline effect,  $\chi_{1,d}$  is the industry-specific deviation,  $\chi_{2,s}$  is the deviation related to rating group, and  $\chi_{3,r}$  is the deviation related to regional effects. Since we assume that the baseline effect  $\chi_0$  is nonzero, some of the other coefficients need to be subject to zero constraints to ensure identification. The specification in (11) is parsimonious yet sufficiently flexible to accommodate heterogeneity across regions and industries.

The latent factors are stacked into the vector  $f_t = (f_t^m, f_t^d, f_t^i)'$ . We assume that the elements of  $f_t$  follow independent autoregressive dynamics. In our study, we have

$$f_t = \Phi f_{t-1} + \eta_t, \quad \eta_t \sim \text{NID}(0, \Sigma_\eta). \quad (12)$$

where the coefficient matrix  $\Phi$  and covariance matrix  $\Sigma_\eta$  are assumed diagonal. Extensions to more complex dynamic structures are straightforward exercises. The autoregressive structure in (12), however, already allows sufficient stickiness in the components of  $f_t$ . For example, it allows the macroeconomic factors  $f_t^m$  to evolve slowly over time and to capture business cycle dynamics in macro and default data. Similarly, the credit climate and industry default conditions are modeled as persistent processes for  $f_t^d$  and  $f_t^i$ , respectively. The  $m \times 1$  disturbance vector  $\eta_t$  is serially uncorrelated. To ensure the identification of the factor loadings, we impose  $\Sigma_\eta = I - \Phi\Phi'$ . It implies that  $E[f_t] = 0$ ,  $\text{Var}[f_t] = I$ , and  $\text{Cov}[f_t, f_{t-h}] = \Phi^h$ , for  $h = 1, 2, \dots$ . As a result, the loading coefficients  $\beta_{r,j}$ ,  $\gamma_{r,j}$ , and  $\delta_{r,j}$  in (9) can be interpreted as risk factor volatilities (standard deviations) for the firms in cross section  $(r, j)$ . It also leads us to the initial condition  $f_1 \sim N(0, \Sigma_0)$  and completes the specification of the factor process.

### 3.2 Parameter and risk factor estimation

The mixed measurement dynamic factor model presented in the previous section is an extension of the non-Gaussian measurement state space models as discussed in Shephard and Pitt (1997) and Durbin and Koopman (1997) to modeling observations from different families of parametric distributions. The model relies on a parameter vector that contains the coefficients in  $\Phi$ ,  $\lambda$ ,  $\beta$ ,  $\gamma$ ,  $\delta$ ,  $\bar{\beta}$ ,  $\bar{\gamma}$ , and  $\bar{\delta}$ . This parameter vector is estimated by the method of simulated maximum likelihood. Since our dynamic factor model partly relies on the binomial

density, the likelihood function is not available in a convenient analytical form. We therefore need to evaluate the high-dimensional integral of the likelihood function directly. Numerical integration is not computationally feasible for such high-dimensional cases and therefore we rely on Monte Carlo simulation methods for evaluating the likelihood function. As the same random numbers can be used for likelihood evaluations for different parameter vectors, the likelihood is a smooth function of the parameter vector. Hence we can maximize the Monte Carlo likelihood function directly by means of a numerical optimization method. We refer to the Appendix A1 for details on our simulation based estimation procedure for mixed measurement data.

An advantage of using state space methods is the convenient treatment of missing values in the dataset. Missing values can have a strong presence in the panels (1) to (3). For example, some macroeconomic variables in  $x_t$  may not be available at the beginning of the sample. Also, default data  $y_{r,jt}$  is not available (missing) if there are no corresponding firms at risk, that is  $k_{r,jt} = 0$ . We refer to the Appendix A2 for the treatment of the many missing values in our setup. Clearly, state space methods provide a natural framework to account for missing entries in the data without any adjustments to the model.

The cross-sectional dimension in the panels (1) to (3) can become very large. High-dimensional measurements can lead to computational problems for any method of estimation. Jungbacker and Koopman (2008) show that state space methods for dynamic factor models with high-dimensional measurements and a low-dimensional state vector become computationally feasible when we transform the panel dataset to a time series of observation vectors that have the same dimension as the factors. The transformation results are only justified for the linear Gaussian measurement model. However, many importance sampling computations as detailed in Appendix A1 rely on an approximating linear Gaussian measurement equation. Appendix A3 demonstrates that we can adapt the results of Jungbacker and Koopman (2008) to nonlinear models for partly non-Gaussian data. These methods are helpful regarding the feasibility of the analyses in our empirical study.

### 3.3 Thermometers and crystal balls

Using the mixed measurement model set-up, we can construct indicators of financial distress for a specific region or combination of regions. Being based on (8) to (10), such indicators automatically integrate the effects of macro, frailty, and industry effects. We consider five indicators, four coincident measures ('thermometers'), and one forward-looking early warning indicator ('crystal ball'). Thermometers are designed to display the current 'heat' in the financial system. A crystal ball is an early warning indicator that captures imbalances that are currently building up and may pose a risk to the system at a later stage. Both thermometers and crystal balls are essential tools to monitor system risk in a forward looking macro-prudential policy context.

The first thermometer is the model-implied financial sector failure rate. The time-varying default probability  $\pi_{r,jt}$  in (7) can be interpreted as the fraction of financial intermediaries that are expected to fail over the next three months. We estimate this quantity by aggregating implied rates from the bottom up across banks and financial non-banks. Naturally, high failure rates imply high levels of common financial distress, and thus a higher risk of adverse real economy effects through financial failure.

A second thermometer is the time-varying probability of simultaneous failure of a large number of financial intermediaries, as suggested in Giesecke and Kim (2010). Such intermediaries may be depository institutions, but also insurers, re-insurers, and broker/dealers that provide intermediation services. The latter three categories are part of the ‘shadow’ banking system. Due to the conditional independence assumption, the joint probability of failure can easily be constructed from the binomial cumulative distribution function and the time-varying financial sector failure rates.

A third indicator is based on the default signals  $\theta_{r,jt}$  in (9). The signals  $\theta_{r,jt}$  consist of two terms,  $\theta_{r,jt} = [\lambda_{r,j}] + [\beta'_{r,j}f_t^m + \gamma'_{r,j}f_t^d + \delta'_{r,j}f_t^i]$ , where the fixed effects  $\lambda_{r,j}$  pin down the *through-the-cycle* log-odds of the default rate, and the systematic factors  $f_t^m$ ,  $f_t^d$ , and  $f_t^i$  jointly determine the *point-in-time* default conditions. The signals  $\theta_{r,jt}$  are Gaussian since all risk factors in  $f_t$  are Gaussian. We can therefore standardize these signals to unconditionally standard normally distributed values  $z_{r,jt}^\theta$ ,

$$z_{r,jt}^\theta = (\theta_{r,jt} - \lambda_{r,j}) / \sqrt{\text{Var}(\theta_{r,jt})},$$

where  $\text{Var}(\theta_{r,jt}) = \beta'_{r,j}\beta_{r,j} + \gamma'_{r,j}\gamma_{r,j} + \delta'_{r,j}\delta_{r,j} \geq 0$  is the unconditional variance of  $\theta_{r,jt}$ . Our systematic credit risk indicator (SRI) for firms of type  $j$  in region  $r$  at time  $t$  is given by

$$\text{SRI}_{r,jt} = \bar{\Phi}(z_{r,jt}^\theta), \quad (13)$$

where  $\bar{\Phi}(z)$  is the standard normal cumulative distribution function. Values of  $\text{SRI}_{r,jt}$  lie between 0 and 1 by construction with uniform (unconditional) probability. Values below 0.5 indicate less-than-average common default stress, while values above this value suggest above-average stress. Values below 20%, say, are exceptionally benign, and values above 80% are indicative of substantial systematic stress. Our measure of financial system risk is obtained when (13) is applied to model-implied failure rates for *financial* firms in a given region.

A fourth indicator of financial system risk is the expected number of financial defaults over the next year conditional of at least one financial default occurring,

$$\text{BSI}_{r,j} = k_{r,jt}\pi_{r,jt} / (1 - \text{Binomial}(0; k_{r,jt}, \pi_{r,jt})). \quad (14)$$

This Banking Stability Index has been proposed by Huang (1992), and subsequently used by e.g. Hartmann et al. (2005) and Segoviano and Goodhart (2009). Naturally, a high expected number of financial defaults indicates adverse financial conditions.

Finally, the indicator (13) can be modified to only capture frailty and industry effects. This yields a signal whether local default experience in a particular industry and region is unexpectedly different from what would be expected based on macro fundamentals  $f_t^m$ . This indicator is our ‘credit risk bubble’ early warning indicator,

$$\text{CBI}_{r,j} = |(\gamma'_{r,j} f_t^d + \delta'_{r,j} f_t^i) / \sqrt{\gamma'_{r,j} \gamma_{r,j} + \delta'_{r,j} \delta_{r,j}}|. \quad (15)$$

Section 5 below reports and discusses the indicator values from this section. In particular, we demonstrate that major deviations of credit risk conditions from what is implied by standard macro-financial fundamentals have in the past preceded financial and macroeconomic distress.

## 4 Data

We use data from three main sources in the empirical study below. First, a panel of macroeconomic and financial time series data is taken from Datastream with the aim to capture international business cycle and financial market conditions. Macroeconomic data is obtained for different economic regions, including the U.S. and the EU-27 countries. Table 1 provides a listing. The macro variables enter the analysis as annual growth rates from 1984Q1 to 2010Q1.

A second dataset is constructed from default data from Moody’s. The database contains rating transition histories and default dates for all rated firms (worldwide) from 1984Q1 to 2010Q1. From this data, we construct quarterly values for  $y_{r,jt}$  and  $k_{r,jt}$  in (5). When counting exposures  $k_{r,jt}$  and corresponding defaults  $y_{r,jt}$ , a previous rating withdrawal is ignored if it is followed by a later default. If there are multiple defaults per firm, we consider only the first event. In addition, defaults that are due to a parent-subsidiary relationship are excluded. Such defaults typically share the same default date, resolution date, and legal bankruptcy date in the database. Inspection of the default history (text) and parent number confirms the exclusion of these cases. The database distinguishes 12 industry sectors which we pool into seven industry groups, see the first column of Table 2 for a listing. We consider four broad rating groups, investment grade  $Aaa - Baa$ , and three speculative grade groups  $Ba$ ,  $B$ , and  $Caa - C$ .

Table 2 provides an overview of the international exposure and default count data. Corporate data is most abundant for the U.S., with E.U. countries second. Most firms are either from the industrial or financial sector. The bottom of Table 2 suggests that about 60% of

**Table 1: International macroeconomic time series data**

We list the variables contained in the macroeconomic panel. The time series data enters the analysis as yearly (yoy) growth rates. The sample is from 1984Q1 to 2010Q1.

Region	Summary of time series in category	Total no
(i) U.S.	Real GDP Industrial Production Index Inflation (implicit GDP price deflator) Dow Jones Industrials Share Price Index Unemployment Rate, 16 years and older US Treasury Bond Yield, 20 years US T-Bill Yield, 3 months ISM Purchasing Managers Index	8
(ii) EU-27	Euro Area (EA16) Real GDP Euro Area (EA16) Industrial Production Index Euro Area (EA16) Inflation (Harmonized CPP) Euro Share Price Index, Datastream Euro Area (EA16) Unemployment Rate Euro Area (EA16) Gov't Bond Yield, 10 years Euro Interbank Offered Rate (Euribor), 3 months Euro Area (EA16) Industrial Confidence Indicator	8
(iii) Other	Japan: Real GDP Japan: Unemployment Rate Japan: Tokyo Stock Exchange Index (Topix) China: Real GDP China: Shanghai Composite Share Price Index Russia: Real GDP Russia: Unemployment Rate India: Industrial Production Brazil: Industrial Production Brazil: Unemployment Rate (Metropolitan Areas) Canada: Industrial Production Canada: Unemployment Rate	12

28



**Table 2: International default and exposure counts**

The top panel presents default counts disaggregated across industry sectors and economic region. The middle panel presents the total number of firms counted from 1981Q1 to 2010Q1. The bottom panel presents the cross section of firms at risk ('exposures') at point-in-time 2008Q1 according to rating group and economic region.

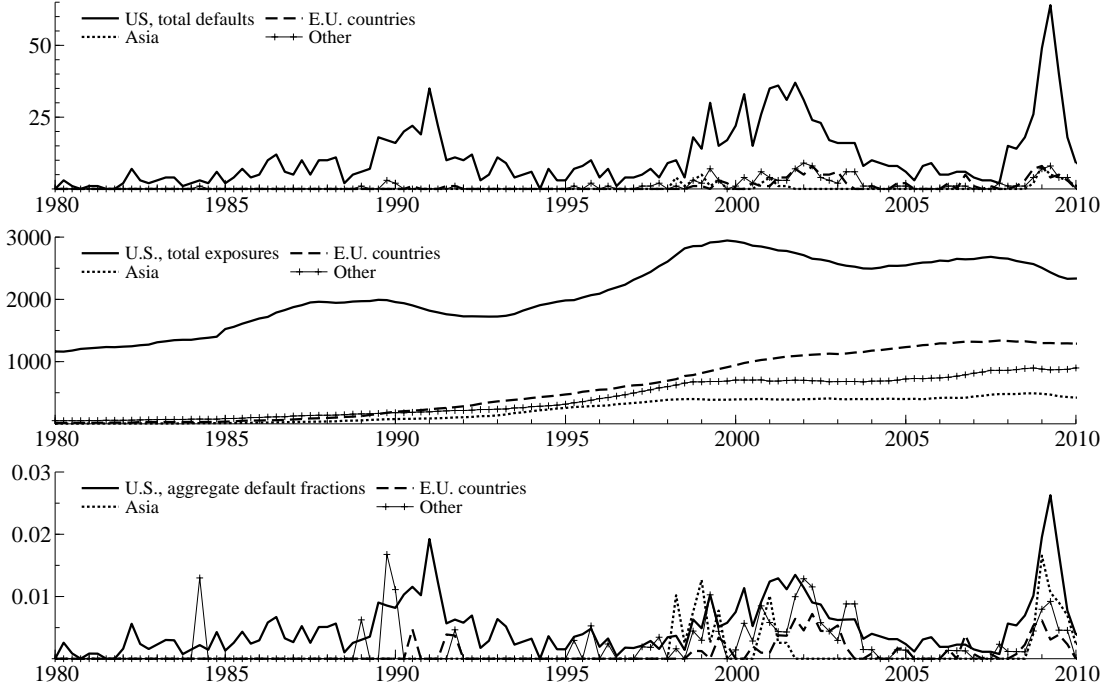
Defaults	U.S.	Europe	Asia	Remainder	Sum
Bank	41	8	9	13	71
Fin non-Bank	84	4	8	6	102
Transport	90	17	1	7	115
Media	127	2	0	2	131
Leisure	97	9	1	14	121
Utilities	24	2	0	5	31
Energy	79	0	1	6	86
Industrial	435	16	16	37	504
Technology	177	38	3	21	239
Retail	94	1	2	2	99
Cons Goods	120	8	3	14	145
Misc	31	0	4	12	47
Sum	1399	105	48	139	1691

Firms	U.S.	Europe	Asia	Remainder	Sum
Bank	478	603	238	353	1672
Fin non-Bank	966	371	130	370	1837
Transport	336	70	29	43	478
Media	460	33	5	29	527
Leisure	434	73	5	54	566
Utilities	597	149	41	97	884
Energy	512	84	31	121	748
Industrial	1920	419	180	317	2836
Technology	941	204	86	134	1365
Retail	311	32	21	25	389
Cons Goods	591	110	34	78	813
Misc	250	151	66	192	659
Sum	7796	2299	866	1813	12774

Firms, 2008Q1	U.S.	Europe	Asia	Remainder	Sum
Aaa	50	84	26	43	203
Aa	141	355	85	165	746
A	415	403	161	176	1155
Baa	575	229	91	200	1095
Ba	278	72	51	126	527
B	673	96	62	121	952
Ca-C	379	58	7	49	493
Sum	2511	1297	483	880	5171

**Figure 1: Actual default experience**

We present time series plots of (a) the total default counts  $\sum_j y_{r,jt}$  aggregated to a univariate series, (b) the total number of firms  $\sum_j k_{r,jt}$  in the database, and (c) aggregate default fractions  $\sum_j y_{r,jt} / \sum_j k_{r,jt}$  over time. We distinguish different economic regions: the U.S., the EU-27 area, and other countries.

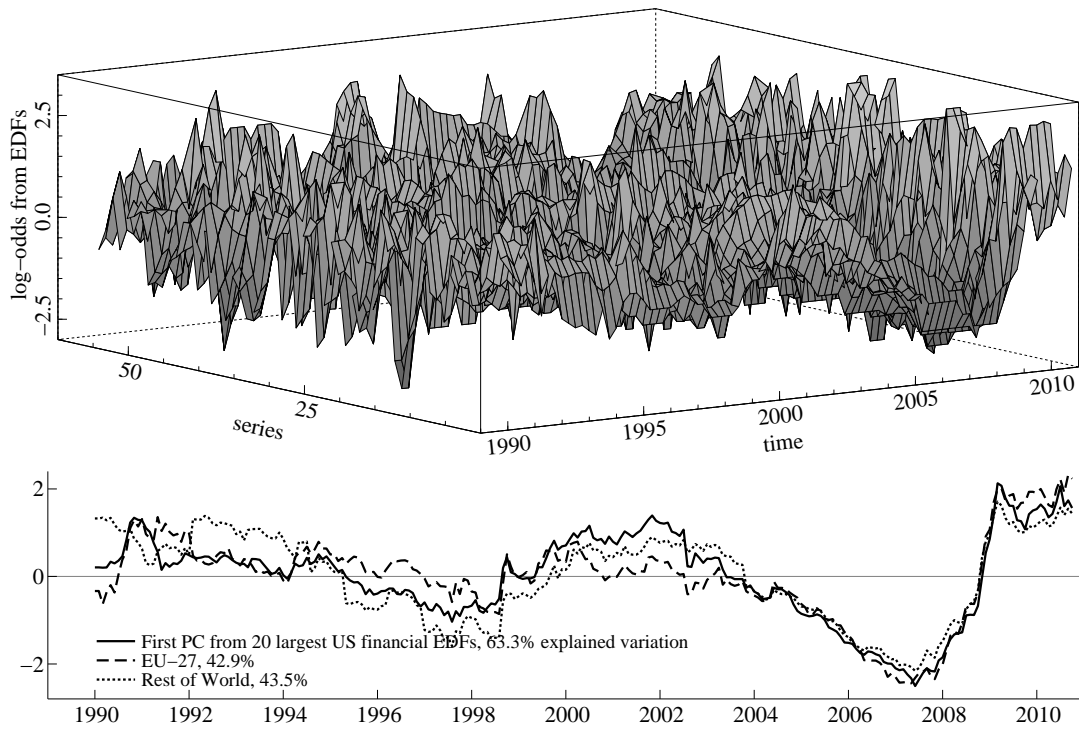


all worldwide ratings are investment grade. European and Asian firms are more likely to be rated investment grade, with shares of 83% and 75%, respectively. Figure 1 plots aggregate default counts, exposures, and observed fractions over time for each economic region.

Table 2 reveals that financial intermediaries rarely default, in particular in Europe. This is an obvious problem for inference on time-varying risk conditions. For financials, we therefore add data from a third dataset. Data on expected default frequencies for the 20 largest (based on 2008Q4 market cap) financial firms in the US, EU-27, and Rest of the World, is taken from Moody's KMV CreditEdge. These  $3 \times 20 = 60$  expected default frequencies are based on a firm value model that takes equity values and balance sheet information as inputs. We use it to augment our relatively sparse data on actual defaults for financial firms. Figure 2 plots the panel of EDF data, after transformation to a quarterly scale and log-odds ratio. The principal components and reported eigenvalues in the bottom panel indicate substantial common variation across institutions and regions that can be summarized in a factor structure.

**Figure 2: Expected default frequencies of 60 global financials**

The top panel reports the standardized log-odds from EDF data for the largest 60 global financial firms (banks and financial non-banks). The sample consists of the largest 20 U.S., EU-27, and Rest of the world financial firms, respectively. The raw data sample is from 1990Q1 to 2010Q3, and contains missing values. Missing values are inferred using the EM algorithm of Stock and Watson (2002). The bottom graph plots the respective first principal components from the US, EU-27, and the Rest of the world sub-sample.



## 5 Empirical results on system risk

This section presents the main empirical findings. Section 5.1 comments briefly on the main sources of financial default clustering. Sections 5.2 and 5.3 present our thermometers and crystal balls for systemic risk assessment.

### 5.1 Why do financial defaults cluster?

Observed credit risk data reveals that aggregate financial sector failure rates are up to ten times higher in bad times than in good times. This is striking. Why do financial failures cluster so dramatically over time? Which sources of risk are important, and to what extent? The answer to these questions is important for constructing effective coincident and forward looking risk indicators.

Table 3 presents the parameter estimates for model specification (1) to (12). The fixed effects and factor loadings in the signal equation (9) satisfy the additive structure (11). Coefficients  $\lambda$  in the left column combine to the baseline failure rates. The middle and right-hand columns present estimates for loadings  $\beta$ ,  $\gamma$ , and  $\delta$  that pertain to macro, frailty, and industry factors, respectively.

The parameter estimates indicate that macro, frailty, and industry effects are all important for international credit risk conditions. Defaults from all regions and industries load significantly on common factors from global macro-financial data. This by itself already implies a considerable degree of default clustering. In general, however, common variation with macro data is not sufficient. Frailty effects are pronounced in particular for U.S. firms. The industry-specific factors load significantly on default data from all regions, which indicates shared dynamics across regions.

Table 4 attributes the variation in the (Gaussian) log-odds of financial sector failure rates to three primary risk drivers, i.e., changes in macro-financial conditions, excess default clustering for all firms (financial and non-financial), and financial sector-specific dynamics. These drivers are associated with the vectors of latent factors  $f_t^m$ ,  $f_t^d$ , and  $f_t^i$ , respectively. The relative importance of each source of variation can be inferred from the estimated risk factor loadings. Given that each risk factor is unconditional standard normal, the factor loading is the estimated risk factor volatility (standard deviation) by construction.

Table 4 indicates that shocks to joint macro-financial and default conditions are the dominant driver of financial distress. Times of financial sector stress and business cycle downturns have tended to coincide. This is intuitive, since financial stress may have negative real consequences, and vice versa, with significant feedback and amplification effects. Timing effects are only captured indirectly, as current estimates of  $f_t^m$  capture a rotated version of current and lagged structural driving forces, see Stock and Watson (2002) for a discussion and intuition from the linear Gaussian context. Industry and frailty dynamics are important

**Table 3: Parameter estimates**

We report the maximum likelihood estimates of selected coefficients in the specification of the log-odds ratio (9) with parameterization (11) for  $\lambda$  and  $\beta$ . Coefficients  $\lambda$  combine to fixed effects, or baseline failure rates. Factor loadings  $\beta$ ,  $\gamma$ , and  $\delta$  refer to macro, frailty, and industry risk factors, respectively. The estimation sample is from 1984Q1 to 2010Q1.

Intercepts $\lambda_j$			Loadings $f_t^m$			Loadings $f_t^d, f_t^i, c_t$		
par	val	t-val	par	val	t-val	par	val	t-val
$\lambda_0$	-2.67	11.56	$\beta_{1,0}$	0.34	3.60	$\gamma_{US}$	0.52	6.81
			$\beta_{1,1,fin}$	0.04	0.11	$\gamma_{EU}$	0.07	0.20
$\lambda_{1,fin}$	0.14	0.54	$\beta_{1,2,IG}$	0.78	2.18	$\gamma_{RoW}$	0.53	2.59
$\lambda_{1,tra}$	-0.29	0.73	$\beta_{1,3,EU}$	0.26	0.92			
$\lambda_{1,lei}$	-0.04	0.24	$\beta_{1,3,RoW}$	0.38	1.45	$\delta_{fin}$	0.43	2.35
$\lambda_{1,utl}$	-0.27	0.84				$\delta_{tra}$	0.71	2.84
$\lambda_{1,tec}$	-0.04	0.23	$\beta_{2,0}$	0.21	1.75	$\delta_{lei}$	0.37	1.54
$\lambda_{1,ret}$	-0.40	2.49	$\beta_{2,1,fin}$	0.08	0.53	$\delta_{utl}$	0.99	2.34
			$\beta_{2,2,IG}$	-0.11	0.39	$\delta_{ind}$	-	-
$\lambda_{2,IG}$	-6.48	12.24	$\beta_{2,3,EU}$	0.10	0.37	$\delta_{tec}$	0.60	1.77
$\lambda_{2,BB}$	-3.78	10.03	$\beta_{2,3,RoW}$	0.01	0.01	$\delta_{ret}$	0.47	2.28
$\lambda_{2,B}$	-2.27	14.19						
			$\beta_{3,0}$	-0.05	0.44	$\delta_{3,EU}$	0.72	3.34
$\lambda_{3,EU}$	-1.13	5.11	$\beta_{3,1,fin}$	-0.09	0.62	$\delta_{3,RoW}$	0.10	0.71
$\lambda_{3,RoW}$	-0.42	2.02	$\beta_{3,2,IG}$	0.33	1.24			
			$\beta_{3,3,EU}$	-0.34	1.04			
			$\beta_{3,3,RoW}$	0.13	0.18			
			$\beta_{4,0}$	-0.11	1.44			
			$\beta_{4,1,fin}$	-0.05	0.36			
			$\beta_{4,2,IG}$	0.92	3.65			
			$\beta_{4,3,EU}$	-0.01	0.62			
			$\beta_{4,3,RoW}$	-0.57	1.12			

**Table 4: Why do financial defaults cluster?**

We report the results of a variance decomposition of transformed (Gaussian, log-odds) failure rates for financial firms in three economic regions. The unconditional variation is attributed to three latent sources of financial distress. Each source of distress is captured by a corresponding set of latent factors and associated risk factor standard deviations. Specifically,  $s_{r,j}^m = \beta'_{r,j}\beta_{r,j}/\text{Var}(\theta_{r,jt})$ ,  $s_{r,j}^d = \gamma'_{r,j}\gamma_{r,j}/\text{Var}(\theta_{r,jt})$ , and  $s_{r,j}^i = \delta'_{r,j}\delta_{r,j}/\text{Var}(\theta_{r,jt})$ , where  $\text{Var}(\theta_{r,jt}) = \beta'_{r,j}\beta_{r,j} + \gamma'_{r,j}\gamma_{r,j} + \delta'_{r,j}\delta_{r,j} \geq 0$ , and  $j$  refers to financial firms. The estimation sample is from 1984Q1 to 2010Q1.

	Changes in observed macro-financial conditions	Latent default- specific dynamics	Latent financial sector dynamics
	$s_{r,fin}^m$	$s_{r,fin}^d$	$s_{r,fin}^i$
U.S.	67.9%	19.0%	13.1%
EU-27	51.5%	0.2%	48.3%
Rest of world	69.5%	15.1%	15.4%

secondary sources of joint financial failure. As a result, all three sources of risk should all be accounted for. In particular, an exclusive focus on contagion linkages in a network (e.g. through ‘heat maps’ and ‘spider web’ plots) without properly taking into account the dependence due to common risk factors will likely yield a wrong attribution of cross-sectional dependence to links that do not exist.

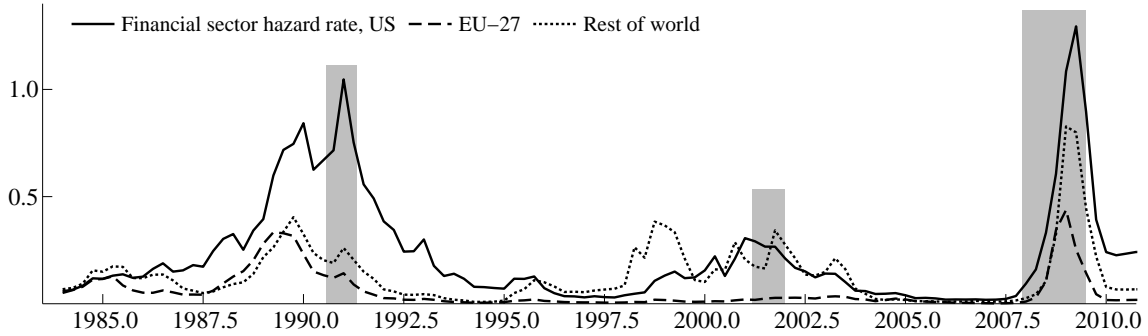
## 5.2 Thermometers: coincident indicators of financial distress

This section presents the thermometers that are constructed from the estimated risk factors and loading parameters. Figure 3 plots the estimated quarterly financial sector failure rate. This rate is obtained by aggregating from the bottom up across individual banks and financial non-banks. For U.S. financials, the values range from slightly above zero in good times to more than 1% in crisis times. This means that about 4-5% of the currently active financial intermediaries are expected to default over the course of one year. Shaded areas in Figure 3 represent U.S. recession periods according to the NBER. Each recession implies common (systematic) stress on financials. The 1991 and 2008-09 recessions have been harder on U.S. financials than the relatively more benign 2001 recession. We also find that a recession is not necessary for systemic stress of financial firms. An example is the period in the late 1980s in the U.S., when common stress is pronounced while the economy is not in recession. Model-implied stress for European and Rest of the world intermediaries is lower than for U.S. financials. This is due to their higher credit quality on average, see Table 2.

Figure 4 plots the time-varying probability of at least  $k$  banking failures,  $k = 1, \dots, 20$ . This joint probability is based on 1000 assumed exposures, and plotted over time 1984Q1

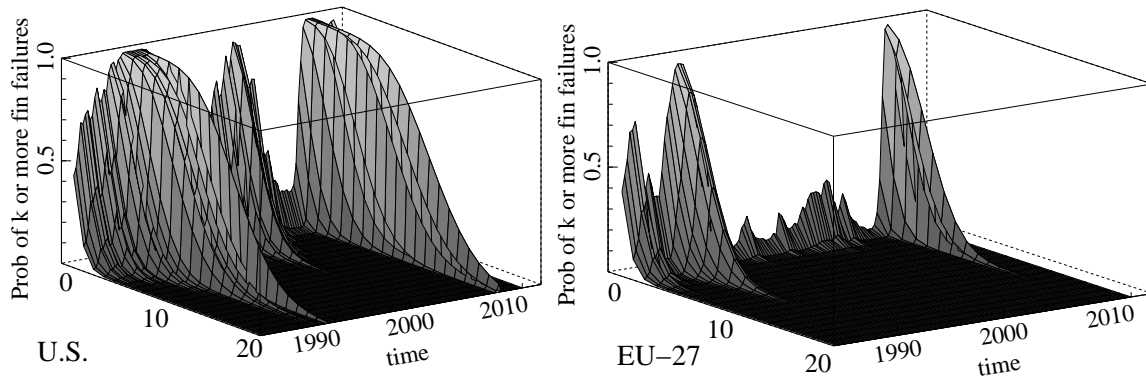
**Figure 3: Implied financial sector failure rate**

We plot the model-implied default failure rate for financial sector firms. The sector failure rate is obtained by aggregating across banks and financial non-banks from the bottom up. Shaded areas represent NBER US recession times. Estimation sample is 1984Q1 to 2010Q1.



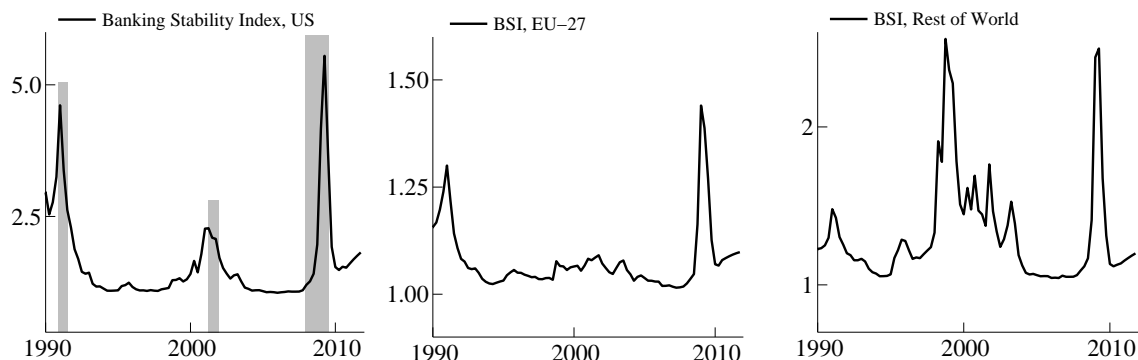
**Figure 4: Probability of simultaneous financial failures**

We report the probability of a systemic event, defined as the simultaneous failure of  $k$  or more rated financial firms. Financial firms are banks and financial non-banks. The threshold  $k$  can be read off the y-axis. Exposures are held fixed at 1000, such that  $k = 10$  implies a quarterly failure rate of 1% or more. The left and right panels refer to the U.S. and the EU-27 areas, respectively.



### Figure 5: Banking Stability Index

We plot indicator (14), i.e., the expected number of financial defaults over a one year horizon conditional on at least one default occurring. Firms at risk are held fixed at 100. Shaded areas correspond to US NBER recession periods. Financial firms are banks and financial non-banks.



to 2010Q4. In general, the model-implied likelihood of losing more than 1% (i.e., 10) of financial firms over the next three months is negligible during most times. However, this probability can be substantial during times of crisis. The estimated failure probabilities are at best coincident indicators. For example, the model-implied risk of financial meltdown is at a minimum as of mid-2007, at the begin of the financial crisis, despite the use of market data and forward looking EDFs to assess system risk. It underscores the point that the financial system may be most at risk exactly when it in fact looks the safest. This is referred to as the ‘paradox of systemic risk’, see Borio (2010).

Figure 5 plots the expected number of financial defaults over a one year horizon given that at least one firm is going down over that time period, see (14). We hold the number of exposures fixed at 100. During the peak of the financial crisis, about five U.S. financials are expected to fail over the next year conditional on one firm going down. No data on financial sector counterparty exposures is used for this estimate. This is an advantage, since such data will likely take years to be available.<sup>1</sup>

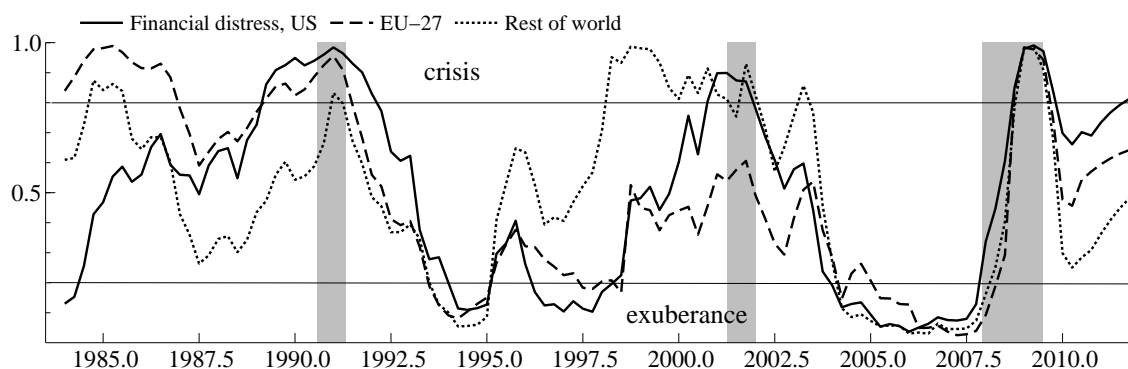
Figure 6 plots financial distress based on the indicator (13). The probability integral transformation in (13) maps common financial distress into a uniform variable, such that its percentiles can be read off the transformed y-axis. We refer to the best and worst 20% of times as relative ‘exuberance’ and ‘crisis’, respectively. Financial distress is virtually absent during the mid/late-1990s and mid-2000s. The mid-1990s are associated with the Clinton-Greenspan policy mix of low interest rates and low budget deficits, and corresponding

<sup>1</sup>The newly founded U.S. Office of Financial Research (OFR) is mandated to make an important step in this regard, and has a strong backing through the Dodd Frank act. The OFR sets data standards and has legal subpoena power to obtain information from financial institutions. As of now and the near future, however, counterparty exposures are simply not observed.



**Figure 6: Scaled financial distress**

The figure plots the risk indicator (13) based on the model-implied financial sector failure rates. A percentile-to-percentile transformation implies that relative levels of implied distress can be read off the y-axis. The best and worst 20% of times are referred to as times of exuberance and crisis, respectively.



favorable macroeconomic conditions. The mid-2000s are characterized by exceptionally low interest rates and easy credit access for U.S. firms. We note that bubbles started to build during either of these times (the dot.com and lending bubble, respectively). The role of a macro-prudential policy maker is then to consider taking away the punch bowl from the ‘party’ once it starts to heat up. Conversely, support measures may be required during times of crisis. The indicator (13) helps in making assessments of relative historical, current, and (possibly) predicted future stress.

### 5.3 Early warning signals

We argue that large frailty effects at a given time can serve as a warning signal for a macro-prudential policy maker. Roughly speaking, frailty effects capture the difference between current point-in-time default conditions vis-a-vis their benchmark values based on observable macro-financial covariates. Such differences can arise due to e.g. unobserved shifts in credit supply, changes in (soft) lending standards, and financial imbalances that are difficult to quantify. The main idea is that a comparison of credit and macro-financial conditions yields a useful early warning indicator for financial stability. It can be seen as related to the private credit to GDP ratio, which is in line with the relevant early warning literature, see for example Borio and Lowe (2002), Misina and Tkacz (2008), Alessi and Detken (2009), and Barrell, Davis, Karim, and Liadze (2010). The main difference is that we look at credit *risk* instead of credit *quantity* relative to macro-financial conditions.

Past experiences of financial fragility, financial booms and financial crises, suggests that problems rarely appear at the same place in the financial system twice in a row. The

main commonality between the different events that turned into a fully fledged financial crisis is that they were not expected by market participants and regulators. Goodhart and Persaud (2008) point out that if market prices for assets or credit were good at predicting crashes, crises would not happen. Similarly, Abreu and Brunnermeier (2003) explain how asset market bubbles can build up over time despite the presence of rational arbitrageurs. Mispricing can persist in particular during late stages of an asset or lending bubble. These findings suggest that (i) building early warning signals based solely based on market prices has obvious drawbacks, and that (ii) it may be useful to look for structure in the ‘unexpected’, or leftover variation.

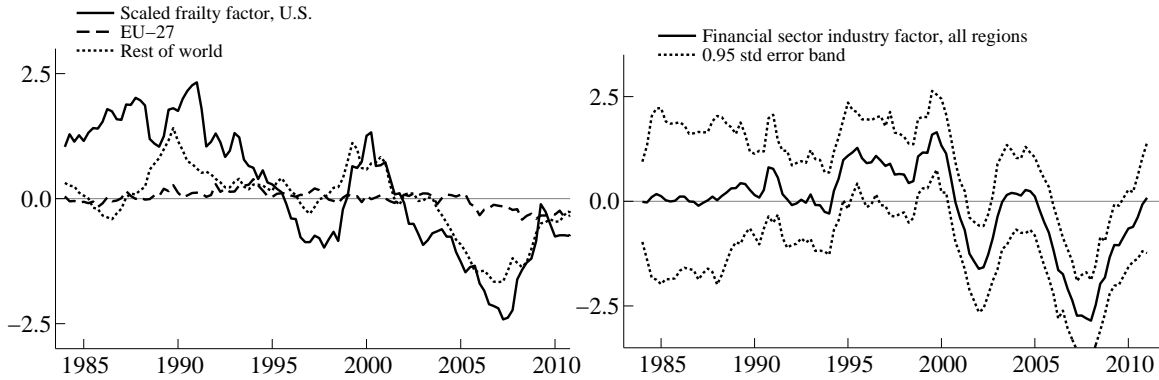
Our warning signals build on Koopman, Lucas, and Schwaab (2008), Duffie, Eckner, Horel, and Saita (2009), and Azizpour, Giesecke, and Schwenkler (2010) who find substantial evidence for a dynamic unobserved risk factor driving default for U.S. firms above and beyond what is implied by observed macro-financial covariates and other information. We interpret the frailty factor as largely capturing unobserved variation in credit supply, or changes in the ease of credit access. We rely on two pieces of evidence for interpretation, as reported in Koopman, Lucas, and Schwaab (2008). First, frailty tends to load more heavily on financially weaker - and thus more credit constrained - firms. This appears to hold in general, and in particular during the years leading up to the financial crisis. Second, our frailty estimates are highly correlated with ex post reported lending standards, such as the ones obtained from the Senior Loan Officer Survey (SLO), as e.g. reported in Maddaloni and Peydro (2010). These findings suggests that frailty, among other effects, captures outward shifts in (unobserved) credit supply. Changes in the ease of credit access affect credit risk conditions: it is hard to default if one is drowning in credit. As a result, systematic default risk (‘the default cycle’) can decouple from what is implied by macro-financial conditions (‘the business cycle’).

The left panel of Figure 7 presents the estimated frailty factors for the U.S., EU-27, and the rest of the world, scaled by their standard deviations. For the U.S., frailty effects have been pronounced during bad times, such as the savings and loan crisis in the U.S. in the late 1980s, leading up to the 1991 recession. They have also been pronounced in exceptionally good times, such as the years 2005-07 leading up to the recent financial crisis. In these years, default conditions are much more benign than would be expected from observed macro and financial data. At these times, frailty effects are large in absolute value, and significantly different from zero.

Our ‘credit risk bubble’ indicator (15) combines estimated frailty and financial sector industry effects into an early warning signal. By construction, the indicator is the absolute value of a standard normal variable. As a result, values above 1.96 can be seen as extreme, and values around 3 are very extreme. Shaded areas correspond to NBER recession times. Focusing on the U.S., deviations from macro-financial fundamentals are high during the 1986-91 savings and loan crisis, which contributed to the later 1991 recession. U.S. risk

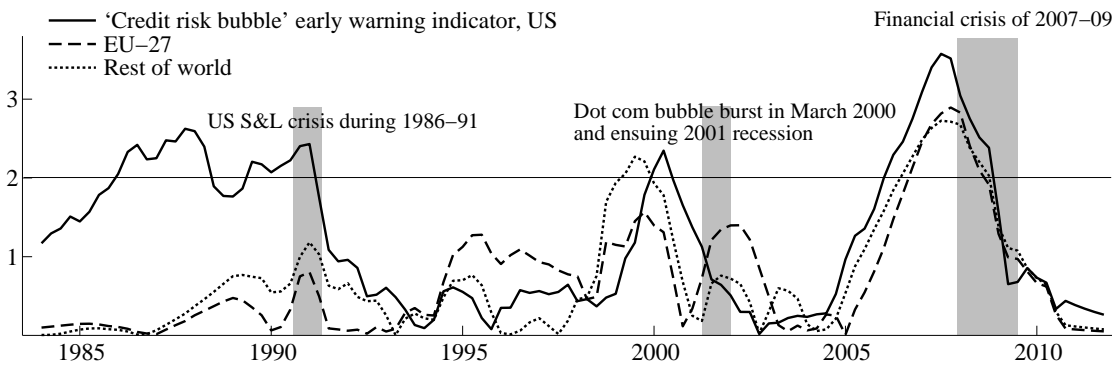
**Figure 7: Latent factor estimates**

The left panel reports the conditional mean estimates of three region-specific frailty factors. The right panel plots the financial sector industry factor that is common to financial firms in all regions. The approximate standard error bands in the right panel are at a 95% confidence level.



**Figure 8: ‘Credit risk bubble’ early warning indicator**

We plot deviations of credit risk conditions (here for financial firms) from macro-financial fundamentals as captured by the indicator (15). Shaded areas correspond to NBER US recession periods. The indicator is constructed as the absolute value of a standard normal variable. Values above 1.96 are ‘exceptional’. The horizontal line is at 2.



indicator values are again elevated leading up to the March 2000 dot.com asset bubble burst and the ensuing 2001 recession. Finally, during the years leading up to the financial crisis, risk conditions have visibly completely decoupled from macro-financial fundamentals. We conclude that a monitoring of time-varying credit risk and macro-fundamental conditions is of key importance for making macro-prudential policy. Our mixed-measurement dynamic factor model is a versatile tool to make financial stability assessments operational.

## 6 Conclusion

We proposed a novel diagnostic framework for financial systemic risk assessment based on mixed-measurement dynamic factor models and state space methods. We found a large degree of commonality in the default climate for large corporate firms across the globe. This holds in particular for financial firms, underlining the global nature of systemic stress events. We combined the factor estimates into new and straightforward indicators of coincident and future financial system risk, and found that a decoupling of credit from macro-financial conditions may serve as an early warning signal for a macro-prudential policy maker.

## Appendix A1: estimation via importance sampling

The observation density function of  $y = (y'_1, x'_1, \dots, y'_T, x'_T)'$  can be expressed by the joint density of  $y$  and  $f = (f'_1, \dots, f'_T)'$  where  $f$  is integrated out, that is

$$p(y; \psi) = \int p(y, f; \psi) df = \int p(y|f; \psi)p(f; \psi)df, \quad (\text{A.16})$$

where  $p(y|f; \psi)$  is the density of  $y$  conditional on  $f$  and  $p(f; \psi)$  is the density of  $f$ . Importance sampling refers to the Monte Carlo estimation of  $p(y; \psi)$  by sampling  $f$  from a Gaussian importance density  $g(f|y; \psi)$ . We can express the observation density function  $p(y; \psi)$  by

$$p(y; \psi) = \int \frac{p(y, f; \psi)}{g(f|y; \psi)} g(f|y; \psi) df = g(y; \psi) \int \frac{p(y|f; \psi)}{g(y|f; \psi)} g(f|y; \psi) df. \quad (\text{A.17})$$

Since  $f$  is from a Gaussian density, we have  $g(f; \psi) = p(f; \psi)$  and  $g(y; \psi) = g(y, f; \psi) / g(f|y; \psi)$ . In case  $g(f|y; \psi)$  is close to  $p(f|y; \psi)$  and in case simulation from  $g(f|y; \psi)$  is feasible, the Monte Carlo estimator

$$\tilde{p}(y; \psi) = g(y; \psi) M^{-1} \sum_{k=1}^M \frac{p(y|f^{(k)}; \psi)}{g(y|f^{(k)}; \psi)}, \quad f^{(k)} \sim g(f|y; \psi), \quad (\text{A.18})$$

is numerically efficient, see Kloek and van Dijk (1978), Geweke (1989) and Durbin and Koopman (2001).

For a practical implementation, the importance density  $g(f|y; \psi)$  can be based on the linear Gaussian approximating model

$$y_{jt} = \mu_{jt} + \theta_{jt} + \varepsilon_{jt}, \quad \varepsilon_{jt} \sim N(0, \sigma_{jt}^2), \quad (\text{A.19})$$

where mean correction  $\mu_{jt}$  and variance  $\sigma_{jt}^2$  are determined in such a way that  $g(f|y; \psi)$  is sufficiently close to  $p(f|y; \psi)$ . It is argued by Shephard and Pitt (1997) and Durbin and Koopman (1997) that  $\mu_{jt}$  and  $\sigma_{jt}$

can be uniquely chosen such that the modes of  $p(f|y; \psi)$  and  $g(f|y; \psi)$  with respect to  $f$  are equal, for a given value of  $\psi$ .

To simulate values from the importance density  $g(f|y; \psi)$ , the simulation smoothing method of Durbin and Koopman (2002) can be applied to the approximating model (A.19). For a set of  $M$  draws of  $g(f|y; \psi)$ , the evaluation of (A.18) relies on the computation of  $p(y|f; \psi)$ ,  $g(y|f; \psi)$  and  $g(y; \psi)$ . Density  $p(y|f; \psi)$  is based on (5) and (4), density  $g(y|f; \psi)$  is based on the Gaussian density for  $y_{jt} - \mu_{jt} - \theta_{jt} \sim N(0, \sigma_{jt}^2)$ , that is (A.19), and  $g(y; \psi)$  can be computed by the Kalman filter applied to (A.19), see Durbin and Koopman (2001).

The likelihood function can be evaluated for any value of  $\psi$ . By keeping the random numbers fixed, we maximize the likelihood estimator (A.18) with respect to  $\psi$  by a numerical optimisation method. Furthermore, we can estimate the latent factors  $f_t$  via importance sampling. It can be shown that

$$E(f|y; \psi) = \int f \cdot p(f|y; \psi) df = \frac{\int f \cdot w(y, f; \psi) g(f|y; \psi) df}{\int w(y, f; \psi) g(f|y; \psi) df},$$

where  $w(y, f; \psi) = p(y|f; \psi)/g(y|f; \psi)$ . The estimation of  $\tilde{f}_t = E(f|y; \psi)$  and its standard error  $s_t$  via importance sampling can be achieved by

$$\tilde{f} = \sum_{k=1}^M w_k \cdot f^{(k)} \Big/ \sum_{k=1}^M w_k, \quad s_t^2 = \left( \sum_{k=1}^M w_k \cdot (f_t^{(k)})^2 \Big/ \sum_{k=1}^M w_k \right) - \tilde{f}_t^2,$$

with  $w_k = p(y|f^{(k)}; \psi)/g(y|f^{(k)}; \psi)$ ,  $f^{(k)} \sim g(f|y; \psi)$ , and  $\tilde{f}_t$  is the  $t$ th element of  $\tilde{f}$ .

## Appendix A2: treatment of missing values

When missing values are present in the data vector  $y = (y'_1, \dots, y'_T)'$ , some care must be taken when computing the importance sample weights  $w_k = p(y|f^{(k)}; \psi)/g(y|f^{(k)}; \psi)$ ,  $f^{(k)} \sim g(f|y; \psi)$ . The mode estimates of the corresponding signals  $\theta = (\theta'_1, \dots, \theta'_T)'$  and factors  $f = (f'_1, \dots, f'_T)'$  are available even when we have missings. Some bookkeeping is required to evaluate  $p(y|f; \psi)$  and  $g(\tilde{y}|f; \psi)$  at the corresponding values of  $f$ , or  $\theta$ . Forecasts  $\tilde{f}_{T+h}$ , for  $h = 1, 2, \dots, H$ , can be obtained by treating future observations  $y_{T+1}, \dots, y_{T+H}$  as missing, and by applying the estimation and signal extraction techniques of Section 6 to data  $(y_0, \dots, y_{T+H})$ .

## Appendix A3: collapsing observations

A recent result in Jungbacker and Koopman (2008) states that it is possible to collapse a  $[N \times 1]$  vector of (Gaussian) observations  $y_t$  into a vector of transformed observations  $y_t^l$  of lower dimension  $m < N$  without compromising the information required to estimate factors  $f_t$  via the Kalman Filter and Smoother. We here adapt their argument to a nonlinear mixed-measurement setting. We focus on collapsing the artificial Gaussian data  $\tilde{y}_t$  with associated covariance matrices  $\tilde{H}_t$ , see (A.19) and (12).

Consider a linear approximating model for transformed data  $\tilde{y}_t^* = A_t \tilde{y}_t$ , for a sequence of invertible matrices  $A_t$ , for  $t = 1, \dots, T$ . The transformed observations are given by

$$\tilde{y}_t^* = \begin{pmatrix} \tilde{y}_t^l \\ \tilde{y}_t^h \end{pmatrix}, \quad \text{with } \tilde{y}_t^l = A_t^l \tilde{y}_t \text{ and } \tilde{y}_t^h = A_t^h \tilde{y}_t,$$

where time-varying projection matrices are partitioned as  $A_t = [A_t^l : A_t^h]'$ . We require (i) matrices  $A_t$  to be of full rank to prevent the loss of information in each rotation, (ii)  $A_t^h \tilde{H}_t A_t^{l'} = 0$  to ensure that observations  $\tilde{y}_t^l$  and  $\tilde{y}_t^h$  are independent, and (iii)  $A_t^h Z_t = 0$  to ensure that  $y_t^h$  does not depend on  $f$ . Several such matrices  $A_t^l$  that fulfill these conditions can be found. A convenient choice is presented below. Matrices  $A_t^h$  can be constructed from  $A_t^l$ , but are not necessary for computing smoothed signal and factor estimates.

Given matrices  $A_t$ , a convenient model for transformed observations  $\tilde{y}_t^*$  is of the form

$$\begin{aligned} \tilde{y}_t^l &= A_t^l \theta_t + e_t^l, \\ \tilde{y}_t^h &= e_t^h \end{aligned} \quad , \quad \begin{pmatrix} e_t^l \\ e_t^h \end{pmatrix} \sim NIID \left( 0, \begin{bmatrix} \tilde{H}_t^l & 0 \\ 0 & \tilde{H}_t^h \end{bmatrix} \right),$$

where  $\tilde{H}_t^l = A_t^l \tilde{H}_t A_t^{l'}$ ,  $\tilde{H}_t^h = A_t^h \tilde{H}_t A_t^{h'}$ ,  $\theta_t = Z f_t$ , and  $Z$  contains the factor loadings. Clearly, the  $[N - m]$  dimensional vector  $\tilde{y}_t^h$  contains no information about  $f_t$ . We can speed up computations involving the KFS recursions as follows.

**Algorithm** : Consider (approximating) Gaussian data  $\tilde{y}_t$  with time-varying covariance matrices  $\tilde{H}_t$ , and  $N > m$ . To compute smoothed factors  $f_t$  and signals  $\theta_t$ ,

1. construct, at each time  $t = 1, \dots, T$ , a matrix  $A_t^l = C_t Z' \tilde{H}_t^{-1}$ , with  $C_t$  such that  $C_t' C_t = \left( Z' \tilde{H}_t^{-1} Z \right)^{-1}$  and  $C_t$  upper triangular. Collapse observations as  $\tilde{y}_t^l = A_t^l \tilde{y}_t$ .
2. apply the Kalman Filter and Smoother (KFS) to the  $[m \times 1]$  low-dimensional vector  $\tilde{y}_t^l$  with time-varying factor loadings  $C_t^{-1'}$  and  $\tilde{H}_t^l = I_m$ .

This approach gives the same factor and signal estimates as when the KFS recursions are applied to the  $[N \times 1]$  dimensional system for  $\tilde{y}_t$  with factor loadings  $Z$  and covariances  $\tilde{H}_t$ .

A derivation is provided in Jungbacker and Koopman (2008, Illustration 4).

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