Forecasting risk with Markov–switching GARCH models: A large–scale performance study[☆]

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Abstract

We perform a large–scale empirical study to compare the forecasting performance of single–regime and Markov–switching GARCH (MSGARCH) models from a risk management perspective. We find that MSGARCH models yield more accurate Value–at–Risk and left–tail distribution forecasts than their single–regime counterpart. Also, our results indicate that accounting for parameter uncertainty improves left–tail predictions, independently of the inclusion of the Markov–switching mechanism.

Keywords: GARCH, MSGARCH, forecasting performance, large–scale study, Value–at–Risk, risk management

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1. Introduction

Under the regulation of the Basel Accords, risk managers of financial institutions need to rely on state–of–the–art methodologies for monitoring financial risks (Board of Governors of the Federal Reserve Systems, 2012). Clearly, the use of a regime–switching time–varying volatility model and Bayesian estimation methods can be considered to be state–of–the–art, but many academics and practitioners also consider the single–regime volatility model and the use of Maximum Likelihood (ML) estimation as state–of–the–art. Risk managers disagree whether the computational complexity of a regime–switching model and the Bayesian estimation method pay off in terms of a higher accuracy of their financial risk monitoring system. We study this question for monitoring the individual risks of a large number of financial assets.

Among the various building–blocks of any risk management system, the specification of the conditional volatility process is key, especially for short–term horizons (McNeil et al., 2015). Research on modeling volatility using time series models has proliferated since the creation of the original ARCH model by Engle (1982) and its generalization by Bollerslev (1986). From there, multiple extensions of the GARCH scedastic function have been proposed to capture additional stylized facts observed in financial markets, such as nonlinearities, asymmetries, and long–memory properties; see Engle (2004) for a review. These so–called GARCH–type models are today essential tools for risk managers.

An appropriate risk model should be able to accommodate the stylized facts of financial returns. Recent academic studies show that many financial assets exhibit structural breaks in their volatility dynamics and that ignoring this feature can have large effects on the precision of the volatility forecast (see, *e.g.*, Lamoureux and Lastrapes, 1990; Bauwens et al., 2014). As noted by Danielsson (2011), this shortcoming in the individual forecasting systems can have systemic consequences. He refers to these single–regime volatility models as one of the culprits of the great financial crisis: *"(...) the stochastic process governing market prices is very different during times of stress compared to normal times. We need different models during crisis and non–crisis and need to be careful in drawing conclusions from non–crisis data about what happens in crises and vice versa".*

A way to address the *switch* of model's behavior is provided by Markov–switching GARCH models (MSGARCH) whose parameters can change over time according to a discrete latent (*i.e.*, unobservable) variable. These models can quickly adapt to variations in the unconditional volatility level, which improves risk predictions (see, *e.g.*, Marcucci, 2005; Ardia, 2008).

The first contribution of our paper is to test if, indeed, MSGARCH models provide risk managers with useful tools that can improve their volatility forecasts.[1] To answer this question, we perform a large–scale empirical analysis in which we compare the risk forecasting performance of single–regime and Markov–switching GARCH models. We take the perspective of a risk manager working for a fund manager and conduct our study on the daily, weekly and ten–day log–returns of a large universe of stocks, equity indices, and foreign exchange rates. Thus, in contrast to Hansen and Lunde (2005), who compare a large number of GARCH–type models on a few series, we focus on a few GARCH and MSGARCH models and a large number of series. For single–regime and Markov–switching specifications, the scedastic specifications we consider account for different reactions of the conditional volatility to past asset returns. More precisely, we consider the symmetric GARCH model (Bollerslev, 1986) as well as the asymmetric GJR model (Glosten et al., 1993). These scedastic specifications are integrated into the MSGARCH framework with the approach of Haas et al. (2004). For the (regime–dependent) conditional distributions, we use the symmetric and the Fernández and Steel (1998) skewed versions of the Normal and Student–t distributions. Overall, this leads to sixteen models.

Our second contribution is to test the impact of the estimation method on the performance of the volatility forecasting model. GARCH and MSGARCH models are traditionally estimated by the ML technique; see Haas et al. (2004), Marcucci (2005) and Augustyniak (2014). However, several recent studies have shown the advantages of the Bayesian approach. Markov chain Monte Carlo (MCMC) procedures can explore the joint posterior distribution of the model parameters, and parameter uncertainty is naturally integrated into the risk forecasts via the predictive distribution

[1] Our study focuses exclusively on GARCH and MSGARCH models. GARCH is the workhorse model in financial econometrics and has been investigated for decades. It is widely used by practitioners and academics; see for instance Bams et al. (2017) and Herwartz (2017). MSGARCH is the most natural and straightforward extension to GARCH. Alternative conditional volatility models include stochastic volatility models (Taylor, 1994; Jacquier et al., 1994), realized measure–based conditional volatility models such as HEAVY (Shephard and Sheppard, 2010) or Realized GARCH (Hansen et al., 2011), or even combinations of these (Opschoor et al., 2017) . We leave the investigation of the gain of Markov–switching and MCMC estimation of these alternative models for further research.

(Ardia, 2008; Bauwens et al., 2010, 2014; Geweke and Amisano, 2010; Ardia et al., 2017c).

Combining the sixteen model specifications and the ML and MCMC estimation methods, we obtain 32 possible candidates for the state–of–the–art methodology for monitoring financial risk. We use a an out–of-s-ample evaluation period of 2,000 days, that ranges from (approximately) 2005 to 2016 and consists of daily log–returns. We evaluate the accuracy of the risk prediction models both in terms of estimating the Value–at–Risk (VaR) and the left–tail (*i.e.*, losses) of the conditional distribution of the assets' returns.

Our empirical results suggest a number of practical insights which can be summarized as follows. First, we find that MSGARCH models report better VaR and left–tail distribution forecasts than their single–regime counterpart. This is especially true for stock return data. Moreover, improvements are more pronounced when the Markov–switching mechanism is applied to simple specifications such as the GARCH–Normal model. Second, accounting for parameter uncertainty improves the accuracy of the left–tail predictions, independently of the inclusion of the Markov–switching mechanism. Moreover, larger improvements are observed in the case of single–regime models. Overall, we recommend risk managers to rely on more flexible models and to perform inference accounting for parameter uncertainty.

In addition to showing the good performance of MSGARCH models and MCMC estimation methods, we refer the risk manager to our R package MSGARCH (Ardia et al., 2017a,b), which implements MSGARCH models in the R statistical language with efficient C++ code.[2] We hope that this paper and the accompanying package will encourage practitioners and academics in the financial community to use MSGARCH models and MCMC estimation methods.

The paper proceeds as follows. Model specification, estimation, and forecasting are presented in Section 2. The datasets, the testing design, and the empirical results are discussed in Section 3. Section 4 concludes.

[2]Our research project was funded by the 2014 SAS/IIF forecasting research grant, to compare MSGARCH vs. GARCH models, and to develop and render publicly available the computer code for the estimation of MSGARCH models.

2. Risk forecasting with Markov–switching GARCH models

A key aspect in quantitative risk management is the modeling of the risk drivers of the securities held by the fund manager. We consider here the univariate parametric framework. First, a statistical model which describes the daily log–returns (profit and loss, P&L) dynamics is determined. Second, the model parameters are estimated for a given estimation window. Third, the one/multi–day ahead distribution of log–returns is obtained (either analytically or by simulation). Fourth, relevant risk measures, such as the Value–at–Risk (VaR) are computed from the distribution. The VaR represents a quantile of the distribution of log–returns at the desired horizon (Jorion, 2006). Risk managers can then allocate risk capital given their density or risk measure forecasts. Also, they can assess the quality of the risk model, *ex–post*, via statistical procedures referred to as *backtesting*.

2.1. Model specification

We define $y_t \in \mathbb{R}$ as the (percentage point) log–return of a financial asset at time t. To simplify the exposition, we assume that the log–returns have zero mean and are not autocorrelated.[3] The general Markov–switching GARCH specification can be expressed as:

$$y_t \,|\, (s_t = k, \mathcal{I}_{t-1}) \sim \mathcal{D}(0, h_{k,t}, \boldsymbol{\xi}_k)\,, \tag{1}$$

where $\mathcal{D}(0, h_{k,t}, \boldsymbol{\xi}_k)$ is a continuous distribution with zero mean, time–varying variance $h_{k,t}$, and additional shape parameters (*e.g.*, asymmetry) gathered in the vector $\boldsymbol{\xi}_k$. Furthermore, we assume that the latent variable s_t, defined on the discrete space $\{1, \ldots, K\}$, evolves according to an unobserved first order ergodic homogeneous Markov chain with transition probability matrix $\mathbf{P} \equiv \{p_{i,j}\}_{i,j=1}^{K}$, with $p_{i,j} \equiv \mathbb{P}[s_t = j \,|\, s_{t-1} = i]$. We denote by $\mathcal{I}_{t-1}$ the information set up to time $t-1$, that is, $\mathcal{I}_{t-1} \equiv \{y_{t-i}, i > 0\}$. Given the parametrization of $\mathcal{D}(\cdot)$, we have $\mathbb{E}[y_t^2 \,|\, s_t = k, \mathcal{I}_{t-1}] = h_{k,t}$, that is, $h_{k,t}$ is the variance of y_t conditional on the realization of s_t and the information set $\mathcal{I}_{t-1}$.

[3]This is in line with empirical evidence on several markets for daily log–returns; see McNeil et al. (2015).

As in Haas et al. (2004), the conditional variance of y_t is assumed to follow a GARCH–type model.[4] Hence, conditionally on regime $s_t = k$, $h_{k,t}$ is available as a function of past returns and the additional regime–dependent vector of parameters $\boldsymbol{\theta}_k$:

$$h_{k,t} \equiv h(y_{t-1}, h_{k,t-1}, \boldsymbol{\theta}_k)\,,$$

where $h(\cdot)$ is a $\mathcal{I}_{t-1}$–measurable function, which defines the filter for the conditional variance and also ensures its positiveness. We further assume that $h_{k,1} \equiv \bar{h}_k$ $(k = 1, \ldots, K)$, where $\bar{h}_k$ is a fixed initial variance level for regime k, that we set equal to the unconditional variance in regime k. Depending on the form of $h(\cdot)$, we obtain different scedastic specifications. For instance, if:

$$h_{k,t} \equiv \omega_k + \alpha_k y_{t-1}^2 + \beta_k h_{k,t-1}\,,$$

with $\omega_k > 0$, $\alpha_k > 0$, $\beta_k \geq 0$ and $\alpha_k + \beta_k < 1$ $(k = 1, \ldots, K)$, we obtain the Markov–switching GARCH$(1,1)$ model presented in Haas et al. (2004).[5] In this case $\boldsymbol{\theta}_k \equiv (\omega_k, \alpha_k, \beta_k)'$.

Alternative definitions of the function $h(\cdot)$ can be easily incorporated in the model. For instance, to account for the well–known asymmetric reaction of volatility to the sign of past returns (often referred to as the *leverage effect*; see Black 1976), we specify a Markov–switching GJR$(1,1)$ model exploiting the volatility specification of Glosten et al. (1993):

$$h_{k,t} \equiv \omega_k + (\alpha_k + \gamma_k \mathbb{I}\{y_{t-1} < 0\})\, y_{t-1}^2 + \beta_k h_{k,t-1}\,,$$

where $\mathbb{I}\{\cdot\}$ is the indicator function, that is equal to one if the condition holds, and zero otherwise. In this case, the additional parameter $\gamma_k \geq 0$ controls the asymmetry in the conditional variance process. We have $\boldsymbol{\theta}_k \equiv (\omega_k, \alpha_k, \gamma_k, \beta_k)'$. Covariance–stationarity of the variance process conditionally on the Markovian state is achieved by imposing $\alpha_k + \beta_k + \kappa_k \gamma_k < 1$, where

[4] The specification by Haas et al. (2004) is computationally tractable as it avoids difficulties related to the past infinite history of the state variable, and allows for different GARCH behaviors in each regime to capture the difference in the variance dynamics in low and high volatility periods (Ardia, 2008, Chapter 7).

[5] We require that the conditional variance in each regime is covariance–stationary. This is a stronger condition than in Haas et al. (2004), but this allows us to ensure stationarity for various forms of conditional variance and/or conditional distributions.

$\kappa_k \equiv \mathbb{P}[y_t < 0 \,|\, s_t = k, \mathcal{I}_{t-1}]$. For symmetric distributions we have $\kappa_k = 1/2$. For skewed distributions, κ_k is obtained following the approach of Trottier and Ardia (2016).

We consider different choices for $\mathcal{D}(\cdot)$. We take the standard Normal ($\mathcal{N}$) and the Student–t ($\mathcal{S}$) distributions. To investigate the benefits of incorporating skewness in our analysis, we also consider the standardized skewed version of $\mathcal{N}$ and $\mathcal{S}$ obtained using the mechanism of Fernández and Steel (1998) and Bauwens and Laurent (2005); see Trottier and Ardia (2016) for more details. We denote the standardized skew–Normal and the skew–Student–t by sk$\mathcal{N}$ and sk$\mathcal{S}$, respectively.

Overall, our model set includes 16 different specifications recovered as combinations of:

- The number of regimes, $K \in \{1, 2\}$. When $K = 1$, we label our specification as single–regime (SR), and, when $K = 2$, as Markov–switching (MS);
- The conditional variance specification: GARCH$(1, 1)$ and GJR$(1, 1)$;
- The choice of the conditional distribution $\mathcal{D}(\cdot)$, that is, $\mathcal{D} \in \{\mathcal{N}, \mathcal{S}, \text{sk}\mathcal{N}, \text{sk}\mathcal{S}\}$.[6]

2.2. Estimation

We estimate the models either by ML or by MCMC techniques (*i.e.*, Bayesian estimation). Both approaches require the evaluation of the likelihood function.

In order to write the likelihood function corresponding to the MSGARCH model specification (1), we define the vector of log–returns $\mathbf{y} \equiv (y_1, \ldots, y_T)'$ and we regroup the model parameters into the vector $\mathbf{\Psi} \equiv (\boldsymbol{\xi}_1, \boldsymbol{\theta}_1, \ldots, \boldsymbol{\xi}_K, \boldsymbol{\theta}_K, \mathbf{P})$. The conditional density of y_t in state $s_t = k$ given $\mathbf{\Psi}$ and $\mathcal{I}_{t-1}$ is denoted by $f_{\mathcal{D}}(y_t \,|\, s_t = k, \mathbf{\Psi}, \mathcal{I}_{t-1})$.

By integrating out the state variable s_t, we obtain the density of y_t given $\mathbf{\Psi}$ and $\mathcal{I}_{t-1}$ only. The (discrete) integration is obtained as follows:

$$f(y_t \,|\, \mathbf{\Psi}, \mathcal{I}_{t-1}) \equiv \sum_{i=1}^{K} \sum_{j=1}^{K} p_{i,j}\, \eta_{i,t-1}\, f_{\mathcal{D}}(y_t \,|\, s_t = j, \mathbf{\Psi}, \mathcal{I}_{t-1})\,, \tag{2}$$

where $\eta_{i,t-1} \equiv \mathbb{P}[s_{t-1} = i \,|\, \mathbf{\Psi}, \mathcal{I}_{t-1}]$ is the filtered probability of state i at time $t-1$ and where we recall that $p_{i,j}$ denotes the transition probability of moving from state i to state j. The filtered

[6] We also tested the asymmetric EGARCH scedastic specification (Nelson, 1991) as well as alternative fat–tailed distributions, such as the Laplace and GED distributions. The performance results were qualitatively similar.

probabilities $\{\eta_{k,t}; k = 1, \ldots, K; t = 1, \ldots, T\}$ are obtained via the Hamilton filter; see Hamilton (1989) and Hamilton (1994, Chapter 22) for details.

Finally, the likelihood function is obtained from (2) as follows:

$$\mathcal{L}(\mathbf{\Psi} \mid \mathbf{y}) \equiv \prod_{t=1}^{T} f(y_t \mid \mathbf{\Psi}, \mathcal{I}_{t-1}) \,. \tag{3}$$

The ML estimator $\widehat{\mathbf{\Psi}}$ is obtained by maximizing the logarithm of (3).[7] In the case of MCMC estimation, the likelihood function is combined with a diffuse (truncated) prior $f(\mathbf{\Psi})$ to build the kernel of the posterior distribution $f(\mathbf{\Psi} \mid \mathbf{y})$. As the posterior is of an unknown form (the normalizing constant is numerically intractable), it must be approximated by simulation techniques. In our case, draws from the posterior are generated with the adaptive random–walk Metropolis sampler of Vihola (2012). We use 50,000 burn–in draws and build the posterior sample of size 1,000 with the next 50,000 draws keeping only every 50th draw to diminish the autocorrelation in the chain.[8] For both ML and MCMC estimations, we ensure positivity and stationarity of the conditional variance in each regime during the estimation. Model parameters are updated every ten observations.[9]

2.3. Density and VaR forecasting

Generating one–step ahead density and VaR forecasts with MSGARCH models is straightforward. First, note that the one–step ahead conditional probability density function (PDF) of y_{T+1} is a mixture of K regime–dependent distributions:

$$f(y_{T+1} \mid \mathbf{\Psi}, \mathcal{I}_T) \equiv \sum_{k=1}^{K} \pi_{k,T+1} f_{\mathcal{D}}(y_{T+1}; 0, h_{k,T+1}, \boldsymbol{\xi}_k) \,, \tag{4}$$

[7] Positivity and covariance–stationarity constraints are guaranteed through specific parameter mapping. All details are provided in Ardia et al. (2017a).

[8] We performed several sensitivity analyses to assess the impact of the estimation's setup. First, we changed the hyper–parameter values. Second, we ran longer MCMC chains. Third, we used 10,000 posterior draws instead of 1,000. Finally, we tested an alternative MCMC sampler based on adaptive mixtures of Student–t distribution (Ardia et al., 2009). In all cases, the conclusions remained qualitatively similar.

[9] We selected this frequency to speed up the computations. Similar results for a subset of stocks were obtained when updating the parameters every day. This is also in line with the observation of Ardia and Hoogerheide (2014), who show, in the context of GARCH models, that the performance of VaR forecasts is not significantly affected when moving from a daily updating frequency to a weekly or monthly updating frequency.

with mixing weights $\pi_{k,T+1} \equiv \sum_{i=1}^{K} p_{i,k}\eta_{i,T}$ where $\eta_{i,T} \equiv \mathbb{P}[s_T = i \,|\, \boldsymbol{\Psi}, \mathcal{I}_T]$ $(i = 1, \ldots, K)$ are the filtered probabilities at time T. The cumulative density function (CDF) is obtained from (4) as follows:

$$F(y_{T+1} \,|\, \boldsymbol{\Psi}, \mathcal{I}_T) \equiv \int_{-\infty}^{y_{T+1}} f(z \,|\, \boldsymbol{\Psi}, \mathcal{I}_T) \mathrm{d}z \,. \tag{5}$$

Within the ML framework, the predictive PDF and CDF are simply computed by replacing $\boldsymbol{\Psi}$ by the ML estimator $\widehat{\boldsymbol{\Psi}}$ in (4) and (5). Within the MCMC framework, we proceed differently, and integrate out the parameter uncertainty. Given a posterior sample $\{\boldsymbol{\Psi}^{[m]}, m = 1, \ldots, M\}$, the predictive PDF is obtained as:

$$f(y_{T+1} \,|\, \mathcal{I}_T) \equiv \int_{\boldsymbol{\Psi}} f(y_{T+1} \,|\, \boldsymbol{\Psi}, \mathcal{I}_T) \mathrm{d}\boldsymbol{\Psi} \approx \frac{1}{M} \sum_{m=1}^{M} f(y_{T+1} \,|\, \boldsymbol{\Psi}^{[m]}, \mathcal{I}_T) \,. \tag{6}$$

The predictive CDF is given by:

$$F(y_{T+1} \,|\, \mathcal{I}_T) \equiv \int_{-\infty}^{y_{T+1}} f(z \,|\, \mathcal{I}_T) \mathrm{d}z \,. \tag{7}$$

For both ML and MCMC estimation, the VaR is estimated as a quantile of the predictive density, by numerically inverting the predictive CDF. For instance, in the MCMC framework, the VaR at the α risk level is estimated as:

$$\mathrm{VaR}_{T+1}^{\alpha} \equiv \inf \left\{ y_{T+1} \in \mathbb{R} \,|\, F(y_{T+1} \,|\, \mathcal{I}_T) = \alpha \right\} \,.$$

In our empirical application, we consider the VaR at the 1% and 5% risk levels.

For evaluating the risk at an h–period horizon, we must rely on simulation techniques to obtain the conditional density and VaR forecasts, as described, for instance, in Blasques et al. (2016). More specifically, given a MSGARCH model parameter $\boldsymbol{\Psi}$, we generate 25,000 paths of daily log–returns over a horizon of h days.[10] The simulated distribution and the obtained α–quantile then serve as estimates of the density and VaR forecasts of the h–day cumulative log–return.

[10]In the case of ML estimation, we generate 25,000 paths with parameter $\widehat{\boldsymbol{\Psi}}$, while in the case of MCMC estimation, we generate 25 paths for each of the 1,000 value $\boldsymbol{\Psi}^{[m]}$ in the posterior sample. Increasing the number of simulations had no impact on the results.

3. Large–scale empirical study

We use 1,500 log–returns (in percent) for the estimation and run the backtest over 2,000 out–of–sample log-returns for a period ranging from October 10, 2008, to November 17, 2016 (the full dataset starts on December 26, 2002). Each model is estimated on a rolling window basis, and one–step ahead as well as multi–step cumulative log–returns density forecasts are obtained. From the density, we compute the VaR at the 1% and 5% risk levels.

3.1. Datasets

We test the performance of the various models on several universes of securities typically traded by fund managers:

- A set of 426 stocks, selected by taking the S&P 500 universe index as of November 2016, and omitting the stocks for which more than 5% of the daily returns are zero, and stocks for which there are less than 3,500 daily return observations.
- A set of eleven stock market indices: (1) S&P 500 (US; SPX), (2) FTSE 100 (UK; FTSE), (3) CAC 40 (France; FCHI), (4) DAX 30 (Germany; GDAXI), (5) Nikkei 225 (Japan; N225), (6) Hang Seng (China, HSI), (7) Dow Jones Industrial Average (US; DJI), (8) Euro Stoxx 50 (Europe; STOXX50), (9) KOSPI (South Korea; KS11), (10) S&P/TSX Composite (Canada; GSPTSE), and (11) Swiss Market Index (Switzerland; SSMI);
- A set of eight foreign exchange rates: USD against CAD, DKK, NOK, AUD, CHF, GBP, JPY, and EUR.

Data are retrieved from Datastream. Each price series is expressed in local currency. We compute the daily percentage log–return series defined by $x_t \equiv 100 \times \log(P_t/P_{t-1})$, where P_t is the adjusted closing price (value) on day t. We then de–mean the returns x_t using an AR(1)–filter, and use those filtered returns, y_t, to estimate and evaluate the precision of the financial risk monitoring systems.

In Table 1, we report the summary statistics on the out–of–sample daily, five–day, and ten–day cumulative log–returns for the three asset classes. We report the standard deviation (Std), the skewness (Skew) and kurtosis (Kurt) coefficients evaluated over the full sample as well as the historical 5% and 1% VaR levels. We note the higher volatility in all periods for the universe of stocks, followed by indices and exchange rates. All securities exhibit negative skewness, with larger values for indices and stocks, while exchange rates seem to behave more symmetrically. Interestingly, the negative skewness tends to be more pronounced for indices as the horizon grows. Finally, at the daily horizon, we observe a significant kurtosis for stocks. Fat tails are also present for indices and exchange rates, but less pronounced than for stocks. However, as the horizon grows, the kurtosis of all asset classes tends to diminish.

[Insert Table 1 about here.]

3.2. Forecasting performance tests

We compare the adequacy of the 32 models in terms of providing accurate forecasts of the left tail of the conditional distribution and the VaR levels.

3.2.1. Accuracy of VaR predictions

For testing the accuracy of the VaR predictions, we use the so–called *hit* variable, which is a dummy variable indicating a loss that exceeds the VaR level:

$$I_t^\alpha \equiv \mathbb{I}\{y_t \leq \mathrm{VaR}_t^\alpha\}\,,$$

where VaR_t^α denotes the VaR prediction at risk level α for time t, and $\mathbb{I}\{\cdot\}$ is the indicator function equal to one if the condition holds, and zero otherwise. If the VaR is correctly specified, then the hit variable has a mean value of α and is independently distributed over time. We test this for the $\alpha = 1\%$ and $\alpha = 5\%$ risk levels using the unconditional coverage (UC) test by Kupiec (1995), and the dynamic quantile (DQ) test by Engle and Manganelli (2004).

The UC test by Kupiec (1995) uses the likelihood ratio to test that the violations have a Binomial distribution with $\mathbb{E}[I_t^\alpha] = \alpha$. Denote by $x \equiv \sum_{t=1}^T I_t^\alpha$ the number of observed rejections on a total of T observations, then, under the null of correct coverage, we have that the test statistic:

$$\mathrm{UC}_\alpha \equiv -2\ln\left[(1-\alpha)^{T-x}\alpha^x\right] + 2\ln\left[\left(1-\frac{x}{T}\right)^{T-x}\left(\frac{x}{T}\right)^x\right]\,,$$

is asymptotically chi–square distributed with one degree–of–freedom.

The DQ test by Engle and Manganelli (2004) is a test of the joint hypothesis that $\mathbb{E}[I_t^\alpha] = \alpha$ and that the hit ratios are independently distributed. The implementation of the test involves the de–meaned process $\text{Hit}_t^\alpha \equiv I_t^\alpha - \alpha$. Under correct model specification, conditionally and unconditionally, Hit_t^α has zero mean and is serially uncorrelated. The DQ test is then the traditional Wald test of the joint nullity of all coefficients in the following linear regression:

$$\text{Hit}_t^\alpha = \delta_0 + \sum_{l=1}^{L} \delta_l \text{Hit}_{t-l}^\alpha + \delta_{L+1} \text{VaR}_{t-1}^\alpha + \epsilon_t \,.$$

If we denote the OLS parameter estimates as $\widehat{\boldsymbol{\delta}} \equiv (\widehat{\delta}_0, \ldots, \widehat{\delta}_{L+1})'$ and $\mathbf{Z}$ as the corresponding data matrix with, in column, the observations for the $L+2$ explanatory variables, then the DQ test statistic of the null hypothesis of correct unconditional and conditional coverage is:

$$\text{DQ}_\alpha \equiv \frac{\widehat{\boldsymbol{\delta}}' \mathbf{Z}' \mathbf{Z} \widehat{\boldsymbol{\delta}}}{\alpha(1-\alpha)} \,.$$

As in Engle and Manganelli (2004), we choose $L = 4$ lags. Under the null hypothesis of correct unconditional and conditional coverage, we have that DQ_α is asymptotically chi–square distributed with $L + 2$ degrees of freedom.[11]

3.2.2. Accuracy of the left–tail distribution

Risk managers care not only about the accuracy of the VaR forecast but also about the accuracy of the complete left–tail region of the log–return distribution. This broader view of all losses is central in modern risk management, and, consistent with the regulatory shift to using Expected Shortfall as the risk measure for determining capital requirements starting in 2018 (Basel Committee on Banking Supervision, 2013).

A first approach is to compute the weighted average difference of the observed returns with respect to the VaR value, and give higher weight to losses that violate the VaR level. This corre-

[11] As in Bams et al. (2017), it is possible to add more explanatory variable such as lagged returns and lagged squared returns and jointly test the new coefficients. In our case, results obtained by adding lagged returns or lagged squared returns are qualitatively similar to the simpler specification.

sponds to the quantile loss assessment of González-Rivera et al. (2004) and McAleer and Da Veiga (2008). Formally, given a VaR prediction at risk level α for time t, the associated quantile loss (QL) is defined as:

$$\mathrm{QL}_t^\alpha \equiv (\alpha - I_t^\alpha)(y_t - \mathrm{VaR}_t^\alpha)\,.$$

A second approach that we consider is to compare the empirical distribution with the predicted conditional distribution through the weighed Continuous Ranked Probability Score (wCRPS), introduced by Gneiting and Ranjan (2011) as a generalization of the CRPS scoring rule (Matheson and Winkler, 1976). Following the notation introduced in Section 2, the wCRPS for a forecast at time t is defined as:

$$\mathrm{wCRPS}_t \equiv \int_{\mathbb{R}} \omega(z)\,(F(z\,|\,\mathcal{I}_{t-1}) - \mathbb{I}\{y_t \leq z\})^2\,\mathrm{d}z\,,$$

where F is the predictive CDF and $\omega\colon \mathbb{R} \to \mathbb{R}^+$ is a continuous weight function, which emphasizes regions of interest of the predictive distribution, such as the tails or the center. Since our focus is on predicting losses, we follow Gneiting and Ranjan (2011) and use the decreasing weight function $\omega(z) \equiv 1 - \Phi(z)$, where Φ is the CDF of a standard Gaussian distribution. This way, discrepancies between the left tail of the returns distribution are weighed more than those on the right tail.[12]

For both the quantile loss and the wCRPS approach, we test the statistical significance of the differences in the forecasting performance of two competing models, say models i and j. We do this by first computing, for each out–of–sample date t, the average performance statistics across all securities in the same asset class. Denote this difference as $\Delta_t^{i-j} \equiv L_t^i - L_t^j$, where L_t^i is the average value of the performance measure (quantile loss or wCRPS) of all assets within the same asset class. We then test $H_0 : \mathbb{E}[\Delta_t^{i-j}] = 0$ using the standard Diebold and Mariano (1995) (DM) test statistic, implemented with the heteroscedasticity and autocorrelation robust (HAC) standard error estimators of Andrews (1991) and Andrews and Monahan (1992). If the null hypothesis is

[12]We compute wCRPS with the following approximation:

$$\mathrm{wCRPS}_t \approx \frac{z_u - z_l}{M-1} \sum_{m=1}^{M} w(z_m)\,(F(z_m\,|\,\mathcal{I}_{t-1}) - \mathbb{I}\{y_t \leq z_m\})^2\,,$$

where $z_m \equiv z_l + m \times (z_u - z_l)/M$ and z_u and z_l are the upper and lower values, which defines the range of integration. The accuracy of the approximation can be increased to any desired level by M. Setting $z_l = -100$, $z_u = 100$ and $M = 1{,}000$ provides an accurate approximation when working with returns in percentage points.

rejected, the sign of the test statistics indicates which model is, on average, preferred for a particular loss measure.

3.3. Results

We now summarize our results regarding our main research question: *Does the additional complexity of Markov–switching and the use of Bayesian estimation methods lead to more accurate out–of–sample downside risk predictions?* We first present our results regarding the accuracy of the VaR predictions and then use the quantile loss and wCRPS approach to evaluate the gains in terms of left–tail predictions.

3.3.1. Effect of model and estimator choice on the accuracy of VaR predictions

We first use the UC test of Kupiec (1995) and the DQ test of Engle and Manganelli (2004) to evaluate the accuracy of each of the 32 methods considered in terms of predicting the VaR at the 5% and 1% level for the daily returns on the 426 stocks, 11 stock indices and 8 exchange rates. For each asset, we obtain the p–value corresponding to the UC and DQ test computed using 2,000 out–of–sample observations. In Table 2, we aggregate the results per asset class by presenting the percentage of assets for which the null hypothesis of correct unconditional and conditional coverage is rejected at the 5% level, by the UC and DQ test, respectively.[13]

[Insert Table 2 about here.]

Consider in Panels A and B of Table 2 the results for the UC test. At both VaR risk levels, we find that the validity of the VaR predictions based on the GARCH and GJR skewed Student–t risk model is never rejected, whatever the use of SR or MS models, or ML or MCMC estimation methods. The result changes drastically when we consider the more powerful DQ test of correct conditional coverage in Panels C and D. Here, we find clear evidence that the use of MS GJR

[13] In the case of stocks, as the universe is large and therefore prone to false positives, the p–values are corrected for Type I error using the false discovery rate (FDR) approach of Benjamini and Hochberg (1995). The FDR correction for a confidence level q proceeds as follows. For a set of m ordered p–values $p_1 \leq p_2 \leq \ldots \leq p_m$ and corresponding null hypotheses $H_1, H_2, \ldots, H_m$, define v as the largest value of i for which $p_i \leq \frac{i}{m}q$, and the reject all hypotheses H_i for $i = 1, \ldots, v$.

models leads to a lower percentage of rejections of the validity of the VaR prediction for all asset classes. At the 1% risk level, these differences are most often significant.

Overall, the one–day ahead backtest results indicate outperformance of MS over SR models, especially for VaR prediction on equities. Moreover, a GJR specification leads to a substantial reduction in the rejection frequencies. Both for MS and SR specifications, a fat–tailed conditional distribution is of primary importance and delivers excellent results at both risk levels.

Finally, for this analysis, the frequency of rejections are similar between the MCMC and ML estimation methods. More precisely, a t–test for equal average rejections indicates that differences are insignificant. We thus conclude that, based on the analysis of VaR forecast accuracy, it is hard to discriminate between MCMC and ML estimation methods.

3.3.2. Effect of model choice on accuracy of left–tail predictions

A further question is how model simplification affects the accuracy of the left–tail return prediction. In Table 3, we report the standardized difference between the average QL and wCRPS values of the assets belonging to the same asset class, when we switch from a MS specification to a SR specification. The standardization corresponds to the Diebold and Mariano (1995) (DM) test statistic, and negative values indicate out–of–sample evidence of a deterioration in the prediction accuracy. When the standardized value exceeds 2.57 (*i.e.*, 1% significance level for a bilateral test) in absolute value, the statistical significance is highlighted with a gray shading. We report results obtained with the MCMC framework only, as the performance obtained with MCMC estimation is better for both MS and SR models (especially for SR specifications) compared with ML estimation, as discussed below.[14]

[Insert Table 3 about here.]

One–step ahead results for wCRPS favor MS models with negative values observed for almost all asset classes and model specifications. QL and wCRPS results are consistent with the backtest results: They exhibit the superior performance of the MS specification for the universe of stocks,

[14]Hence, our discussion based on MCMC results is more conservative in the sense that it gives an advantage to the SR specifications.

while outperformance is less clear for indices and exchange rates. Indeed, for indices, MS is required only when a non fat–tailed conditional distribution is assumed, while for exchange rates, MS is generally not required. Note that, for all assets, the improvements tend to be more pronounced when the Markov–switching mechanism is applied to simple specifications such as the GARCH–Normal model.

For stocks, the MS specification significantly outperforms in terms of the wCRPS measure at the five–day horizon. For the wCRPS measure at the ten–day horizon, and for the QL measure at the five– and ten–day horizons, results are mostly non–significant. MS and SR models perform similarly for the five– and ten–day returns on stocks. Finally, for exchange rate returns, SR models outperform MS models at the five– and ten–day horizons according to the QL 1% measure, while the differences in QL 5% and wCRPS are insignificant.

We now consider in Table 4 a complete comparison of the wCRPS performance of all MS models (in row) versus all SR models (in column). The elements in the diagonal correspond to the wCRPS values reported in Table 3. They are informative about the change in wCRPS when switching from a MS model to a SR model, keeping the same specification for the conditional variance and distribution. The analysis of the extra–diagonal elements is informative about the changes in wCRPS when switching from a MS model to a SR model, and changing the specification of the volatility model or the density function. In this table, an outperforming MS risk model is a model for which all standardized gains when changing the specification are negative. For almost all comparisons, this is the case for the MS GJR model with skewed Student–t innovations. The only exception is for modeling the returns of stock market indices, where it performs similarly as its SR counterpart.

[Insert Table 4 about here.]

3.3.3. Effect of estimator choice on accuracy of left–tail predictions

In Table 5, we report the results for the MCMC versus ML estimation methods in the case of one–step ahead QL and wCRPS measures. Panel A (Panel B) shows the results for MS (SR) models, where a negative (positive) value indicates outperformance (underperformance) of MCMC against ML estimation. In light gray, we emphasize cases of significant outperformance of MCMC estimation over ML. For stocks, the QL 1% and 5% comparisons indicate that MCMC is preferred over ML, and it is significant in the majority of the specifications. The same observation can be made for wCRPS. For equity indices and exchange rates, QL and wCRPS results are in favor of MCMC for both MS and SR models but results are less significant than for stocks. Overall, we recommend to account for parameter uncertainty especially for stocks data, and when the interest is on the left tail of the log–returns distribution. The performance gain is especially large for SR models.

[Insert Table 5 about here.]

3.3.4. Constrained Markov–switching specifications

So far, our empirical results have highlighted the need for a MS mechanism in GARCH–type models in the case of stocks. We now refine the analysis by examining whether the same gains are achieved when constraining that the conditional distribution of the MS specifications has the same shape parameter across the regimes. Hence, we apply the MS mechanism only to the conditional variance. The objective is to determine whether, in the context of MS models, the switches in the variance dynamics are the dominant contributor to the gains in risk forecasting accuracy.

In Table 6, we report the performance measures obtained with the constrained MS models for the various horizons, when models are estimated by MCMC.[15] Results are in line with the non–constrained case of Table 3, but less significant. Hence, accounting for structural breaks in only the variance dynamics improves the risk forecasts at the daily, weekly and ten–day horizons. If we let the shape parameters depend upon the regime, we further improve the performance.

[Insert Table 6 about here.]

4. Conclusion

In this paper, we investigate if MSGARCH models provide risk managers with useful tools for improving the risk forecasts of securities typically hold by fund managers. Moreover, we investi-

[15]Forecasting results obtained via ML estimation are qualitatively similar and available from the authors upon request.

gate if integrating the model's parameter uncertainty within the forecasts, via MCMC methods, improves predictions. Our results and practical advice can be summarized as follows.

First, risk managers should extend their GARCH–type models with a Markov–switching specification. Indeed, we find that Markov–switching GARCH models report better Value–at–Risk and left–tail distribution forecasts than their single–regime counterpart. This is especially true for stock return data. Moreover, improvements are more pronounced when the Markov–switching mechanism is applied to simple specifications such as the GARCH–Normal model.

Second, accounting for parameter uncertainty helps for left–tail predictions independently of the inclusion of the Markov–switching mechanism. Moreover, larger improvements are observed when parameter uncertainty is included in single–regime models.

Overall, we recommend risk managers to rely on more flexible models and to perform inference accounting for parameter uncertainty. To help them implementing these in practice, we have released the open–source R package MSGARCH; see Ardia et al. (2017a,b).

Our research could be extended in several ways. First, our study considered single–regime versus two–state Markov–switching specifications. Hence, it would be of interest to see if a third regime leads to superior performance, and if the optimal number of regimes (according to penalized likelihood information criteria) changes over time and is different across data sets. Second, additional universes could be considered, such as emerging markets and commodities. Third, one could extend the set of models and compare the performance of MSGARCH with realized volatility models such as the HEAVY model of Shephard and Sheppard (2010). Finally, our analysis only considered financial risk monitoring systems for individual financial assets. The new standard for capital requirements for market risk (Basel Committee on Banking Supervision, 2016) calls for backtesting at the individual desk level and the aggregate level. For this reason, it would be interesting to consider also the impact of choices in modeling dependence. Including these extensions in our current research setup increases further the (already large) number of models included in the comparison. We leave them as a topic for future work.

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Table 1: Summary statistics of the return data

The table presents the summary statistics of the (de–meaned) h–day cumulative log–returns for securities in the three asset classes used in our study. We report the standard deviation (Std), the skewness (Skew), the kurtosis (Kurt), 5% historical VaR, and 1% historical VaR on an unconditional basis for the 2,000 out–of–sample observations. For each statistic, we compute the 25th, 50th and 75th percentiles over the whole universe of assets.

h	Percentile	Std	Skew	Kurt	5% VaR	1% VaR
Panel A: Stocks (426 series)						
	25th	1.48	−0.39	6.89	−3.44	−6.55
1	50th	1.89	−0.13	9.24	−2.85	−5.23
	75th	2.33	0.12	14.10	−2.25	−4.10
	25th	3.29	−0.42	4.93	−7.94	−14.60
5	50th	4.21	−0.20	5.87	−6.55	−11.59
	75th	5.19	0.01	7.53	−5.17	−9.15
	25th	4.54	−0.49	4.47	−10.92	−19.99
10	50th	5.76	−0.27	5.30	−9.02	−15.74
	75th	6.98	−0.05	6.92	−7.16	−12.43
Panel B: Stock market indices (11 series)						
	25th	1.07	−0.40	6.07	−2.37	−3.70
1	50th	1.15	−0.23	7.29	−1.85	−3.39
	75th	1.39	−0.17	10.29	−1.77	−3.05
	25th	2.42	−0.55	5.04	−5.09	−8.38
5	50th	2.54	−0.47	6.18	−4.22	−7.60
	75th	3.09	−0.29	8.22	−3.86	−6.91
	25th	3.29	−0.79	5.47	−7.13	−12.32
10	50th	3.43	−0.62	6.31	−5.70	−10.83
	75th	4.19	−0.55	7.04	−5.19	−9.99
Panel C: Exchange rates (8 series)						
	25th	0.61	−0.53	4.36	−1.07	−1.73
1	50th	0.62	−0.08	4.51	−1.01	−1.62
	75th	0.77	0.05	11.60	−0.95	−1.56
	25th	1.32	−0.36	3.65	−2.39	−3.72
5	50th	1.39	−0.05	4.05	−2.26	−3.48
	75th	1.66	0.08	5.91	−2.06	−3.07
	25th	1.85	−0.31	3.36	−3.43	−5.00
10	50th	1.93	−0.10	3.52	−3.04	−4.78
	75th	2.29	0.13	5.12	−2.93	−4.64

Table 2: Percentage of assets for which the validity of the VaR predictions is rejected
The table presents the percentage of assets for which the unconditional coverage test (UC, Panels A and B) by Kupiec (1995) and the Dynamic Quantile test (DQ, Panels C and D) by Engle and Manganelli (2004) reject the null hypothesis of correct unconditional coverage (UC, DQ) and independence of violations (DQ) for the one–step ahead 1%–VaR (Panels A and C) and 5%–VaR (Panels B and D) at the 5% significance level. The VaR forecasts are obtained for Markov–switching (MS) and single–regime (SR) models for the various universes (426 stocks, 11 indices, and 8 exchange rates) and estimated via MCMC or ML techniques. We highlight in gray the best performing method for the cases in which, for a given asset class and model specification, the percentages of rejections between MS and SR models are significantly different at the 5% level. In the case of stocks, rejections frequencies are corrected for Type I error using the FDR approach of Benjamini and Hochberg (1995).

	Stocks				Stock market indices				Exchange rates			
	MCMC		ML		MCMC		ML		MCMC		ML	
Model	MS	SR	MS	SR	MS	SR	MS	SR	MS	SR	MS	SR
Panel A: UC 1%–VaR												
GARCH $\mathcal{N}$	0.00	26.76	0.23	29.34	72.73	90.91	72.73	90.91	25.00	25.00	25.00	25.00
GARCH sk$\mathcal{N}$	0.00	8.92	0.23	9.62	9.09	63.64	0.00	63.64	0.00	12.50	0.00	12.50
GARCH $\mathcal{S}$	0.00	0.00	0.00	0.00	54.55	45.45	27.27	27.27	25.00	25.00	25.00	12.50
GARCH sk$\mathcal{S}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GJR $\mathcal{N}$	0.00	16.43	0.00	19.48	54.55	90.91	63.64	90.91	25.00	25.00	25.00	37.50
GJR sk$\mathcal{N}$	0.00	3.52	0.00	5.16	0.00	54.55	0.00	45.45	0.00	12.50	0.00	25.00
GJR $\mathcal{S}$	0.00	0.00	0.00	0.00	18.18	36.36	18.18	36.36	12.50	12.50	12.50	12.50
GJR sk$\mathcal{S}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Panel B: UC 5%–VaR												
GARCH $\mathcal{N}$	0.70	39.20	0.70	38.73	36.36	36.36	27.27	36.36	25.00	50.00	25.00	50.00
GARCH sk$\mathcal{N}$	0.00	41.31	0.00	40.38	0.00	0.00	0.00	0.00	12.50	25.00	0.00	25.00
GARCH $\mathcal{S}$	0.94	1.17	0.70	0.70	54.55	54.55	36.36	54.55	25.00	12.50	25.00	12.50
GARCH sk$\mathcal{S}$	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GJR $\mathcal{N}$	0.47	38.73	0.47	36.15	18.18	18.18	36.36	27.27	25.00	37.50	25.00	37.50
GJR sk$\mathcal{N}$	0.00	40.38	0.00	39.91	0.00	0.00	0.00	0.00	12.50	12.50	0.00	12.50
GJR $\mathcal{S}$	1.64	1.64	0.70	0.47	18.18	27.27	18.18	27.27	37.50	37.50	37.50	37.50
GJR sk$\mathcal{S}$	0.00	0.00	0.00	0.00	0.00	18.18	0.00	18.18	0.00	0.00	0.00	0.00
Panel C: DQ 1%–VaR												
GARCH $\mathcal{N}$	14.08	53.52	14.32	54.69	63.64	90.91	72.73	90.91	25.00	37.50	12.50	37.50
GARCH sk$\mathcal{N}$	14.08	48.36	15.49	50.00	45.45	63.64	45.45	63.64	12.50	37.50	12.50	37.50
GARCH $\mathcal{S}$	19.95	28.64	16.90	29.34	54.55	63.64	63.64	54.55	25.00	25.00	25.00	25.00
GARCH sk$\mathcal{S}$	18.31	23.94	17.37	24.18	45.45	45.45	36.36	36.36	12.50	25.00	12.50	25.00
GJR $\mathcal{N}$	5.87	32.39	6.10	34.74	18.18	90.91	36.36	90.91	12.50	37.50	12.50	37.50
GJR sk$\mathcal{N}$	5.87	27.00	6.10	28.17	9.09	27.27	9.09	45.45	12.50	25.00	0.00	25.00
GJR $\mathcal{S}$	7.04	10.33	4.46	9.86	18.18	27.27	18.18	18.18	12.50	25.00	12.50	25.00
GJR sk$\mathcal{S}$	5.16	10.33	6.57	11.27	0.00	0.00	0.00	0.00	12.50	12.50	12.50	12.50
Panel D: DQ 5%–VaR												
GARCH $\mathcal{N}$	3.52	26.29	3.52	25.82	18.18	9.09	36.36	9.09	0.00	0.00	0.00	0.00
GARCH sk$\mathcal{N}$	3.52	29.81	2.82	30.05	9.09	9.09	9.09	9.09	0.00	0.00	0.00	0.00
GARCH $\mathcal{S}$	1.64	7.75	1.64	8.92	45.45	54.55	36.36	54.55	0.00	0.00	0.00	0.00
GARCH sk$\mathcal{S}$	2.11	6.57	2.82	7.98	9.09	9.09	9.09	9.09	0.00	0.00	0.00	0.00
GJR $\mathcal{N}$	0.00	14.32	0.00	14.55	9.09	9.09	9.09	0.00	0.00	0.00	0.00	0.00
GJR sk$\mathcal{N}$	0.00	15.02	0.00	13.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
GJR $\mathcal{S}$	0.00	0.00	0.00	1.17	9.09	0.00	9.09	9.09	12.50	12.50	12.50	12.50
GJR sk$\mathcal{S}$	0.00	0.70	0.00	0.70	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 3: Standardized gain in average performance when switching from MS to SR models This table presents the Diebold and Mariano (1995) test statistic of equal average loss function between the MS and SR models for forecasting the distribution of h–day cumulative log–returns ($h \in \{1, 5, 10\}$). As loss functions, we consider the QL measure (at $\alpha = 1\%$ and $\alpha = 5\%$) and wCRPS measure. Negative values indicate outperformance of the Markov–switching specification compared with the single–regime models. In light (dark) gray, we report statistics which are significantly negative (positive) at the 1% level (bilateral test). The multi–step cumulative log–returns forecasts are generated using 25,000 simulated paths of daily log–returns. Models are estimated by MCMC.

		Stocks			Stock market indices			Exchange rates		
Horizon	Model	QL 1%	QL 5%	wCRPS	QL 1%	QL 5%	wCRPS	QL 1%	QL 5%	wCRPS
$h = 1$	GARCH $\mathcal{N}$	-0.60	-4.94	-9.32	-3.84	0.50	-4.04	-0.09	0.39	-2.65
	GARCH sk$\mathcal{N}$	-0.25	-4.90	-9.25	-2.64	0.10	-3.26	0.95	-0.25	-3.41
	GARCH $\mathcal{S}$	-4.00	-3.55	-3.41	-1.50	-0.90	-0.17	1.12	-1.26	-2.17
	GARCH sk$\mathcal{S}$	-4.52	-4.20	-2.79	-2.21	-0.87	0.22	2.18	-0.56	-1.45
	GJR $\mathcal{N}$	-0.63	-6.02	-9.96	-3.58	0.53	-4.30	0.64	0.58	-1.64
	GJR sk$\mathcal{N}$	-0.22	-5.95	-9.94	-2.04	-0.31	-3.00	0.79	0.07	-1.88
	GJR $\mathcal{S}$	-3.88	-4.44	-5.00	-1.80	0.49	0.11	0.36	-1.03	-2.35
	GJR sk$\mathcal{S}$	-3.64	-4.17	-3.44	-0.93	0.61	0.47	0.92	-0.68	-1.66
$h = 5$	GARCH $\mathcal{N}$	-0.66	-1.70	-2.72	-2.11	-1.47	-1.19	2.69	1.69	0.73
	GARCH sk$\mathcal{N}$	-0.52	-1.67	-2.65	-2.14	-1.61	-0.88	2.59	1.17	0.46
	GARCH $\mathcal{S}$	-1.78	-2.27	-2.68	-0.77	-1.61	-0.89	2.00	1.53	-1.26
	GARCH sk$\mathcal{S}$	-1.70	-2.37	-2.39	-1.55	-2.72	-0.32	3.67	0.85	-0.93
	GJR $\mathcal{N}$	-0.53	-2.38	-2.77	0.10	-0.10	-0.51	3.27	1.15	0.30
	GJR sk$\mathcal{N}$	-0.30	-2.37	-2.74	0.62	-1.10	-0.30	3.70	1.54	1.15
	GJR $\mathcal{S}$	-1.32	-2.63	-4.52	-0.21	-1.76	-0.49	4.08	0.04	-2.07
	GJR sk$\mathcal{S}$	-1.14	-1.61	-3.37	0.26	-0.65	-0.04	4.60	1.05	-1.09
$h = 10$	GARCH $\mathcal{N}$	-0.18	-0.82	-1.93	-1.23	-0.66	-1.91	1.55	1.18	0.89
	GARCH sk$\mathcal{N}$	-0.14	-0.71	-1.96	-1.76	-0.80	-1.35	1.23	1.58	0.86
	GARCH $\mathcal{S}$	-0.83	-1.01	-1.25	-1.05	-0.79	-1.95	1.12	1.63	-0.59
	GARCH sk$\mathcal{S}$	-0.93	-1.22	-1.02	-1.19	-0.99	-1.22	2.78	2.12	-0.46
	GJR $\mathcal{N}$	-0.15	-1.24	-1.91	0.48	-1.08	-0.92	1.16	1.11	0.62
	GJR sk$\mathcal{N}$	0.02	-1.22	-1.71	0.21	-1.44	-0.87	2.47	1.15	1.03
	GJR $\mathcal{S}$	-0.53	-1.46	-4.04	1.16	-1.43	-1.13	2.92	0.34	-1.71
	GJR sk$\mathcal{S}$	-0.48	-1.15	-2.80	0.72	-2.19	-1.31	4.55	1.12	-1.09

Table 4: Standardized gain in average performance when switching from MS to SR and changing the specification

This table presents the Diebold and Mariano (1995) test statistic of equal average wCRPS between a MS implementation (in rows) and a SR implementation (in column), for all considered specifications, when forecasting the distribution of one–day ahead log–returns. We report test statistics computed with robust HAC standard errors. Negative values indicate outperformance of the Markov–switching specification compared with single–regime models. In light (dark) gray, we report statistics which are significantly negative (positive) at the 1% level (bilateral test). Models are estimated by MCMC.

		SR GARCH				SR GJR			
		$\mathcal{N}$	sk$\mathcal{N}$	$\mathcal{S}$	sk$\mathcal{S}$	$\mathcal{N}$	sk$\mathcal{N}$	$\mathcal{S}$	sk$\mathcal{S}$
Panel A: Stocks									
MS GARCH	$\mathcal{N}$	-9.32	-9.56	3.29	3.30	-6.80	-6.85	3.29	3.38
	sk$\mathcal{N}$	-9.00	-9.25	3.60	3.67	-6.60	-6.65	3.42	3.54
	$\mathcal{S}$	-9.01	-9.20	-3.41	-2.99	-7.29	-7.36	-0.14	-0.13
	sk$\mathcal{S}$	-8.86	-9.07	-2.92	-2.79	-7.15	-7.22	0.01	0.04
MS GJR	$\mathcal{N}$	-10.11	-10.26	0.88	0.93	-9.96	-10.25	3.20	3.18
	sk$\mathcal{N}$	-9.88	-10.06	0.88	0.95	-9.64	-9.94	3.33	3.38
	$\mathcal{S}$	-9.73	-9.88	-2.92	-2.76	-9.48	-9.68	-5.00	-4.79
	sk$\mathcal{S}$	-9.57	-9.74	-2.46	-2.34	-9.24	-9.46	-3.19	-3.44
Panel B: Stock market indices									
MS GARCH	$\mathcal{N}$	-4.04	-0.67	3.09	6.00	4.80	7.15	8.15	9.76
	sk$\mathcal{N}$	-5.25	-3.26	-1.04	3.29	3.06	5.46	6.18	8.55
	$\mathcal{S}$	-5.66	-2.90	-0.17	5.09	3.68	6.13	7.17	9.20
	sk$\mathcal{S}$	-6.08	-4.83	-3.52	0.22	2.00	4.39	4.98	7.71
MS GJR	$\mathcal{N}$	-9.65	-7.81	-6.19	-4.26	-4.30	0.33	2.19	4.76
	sk$\mathcal{N}$	-10.39	-9.41	-7.75	-6.35	-5.21	-3.00	-1.80	1.82
	$\mathcal{S}$	-9.79	-8.28	-6.91	-5.11	-4.66	-1.15	0.11	3.92
	sk$\mathcal{S}$	-10.20	-9.53	-8.29	-7.19	-5.34	-3.80	-2.83	0.47
Panel C: Exchange rates									
MS GARCH	$\mathcal{N}$	-2.65	-3.49	5.38	3.95	-2.06	-2.74	3.52	2.81
	sk$\mathcal{N}$	-2.00	-3.41	4.86	5.74	-1.53	-2.45	3.44	3.78
	$\mathcal{S}$	-6.84	-6.53	-2.17	-2.36	-6.09	-6.03	-2.31	-2.45
	sk$\mathcal{S}$	-5.45	-6.29	-0.99	-1.45	-4.81	-5.61	-1.32	-1.73
MS GJR	$\mathcal{N}$	-1.71	-2.33	4.40	3.59	-1.64	-2.35	5.32	3.89
	sk$\mathcal{N}$	-1.13	-1.95	4.26	4.53	-1.02	-1.88	4.53	5.14
	$\mathcal{S}$	-6.02	-6.03	-1.56	-1.68	-6.38	-6.38	-2.35	-2.46
	sk$\mathcal{S}$	-5.05	-5.49	-0.84	-1.21	-5.21	-5.74	-1.35	-1.66

Table 5: Standardized gain in average performance when switching from MCMC to ML estimation
This table presents the Diebold and Mariano (1995) test statistic of equal average loss function between MCMC and ML models for forecasting the distribution of one–day ahead log–returns. As loss functions, we consider the QL measure (at $\alpha = 1\%$ and $\alpha = 5\%$) and wCRPS measure. Panels A and B report the test statistics when comparing MCMC against ML estimation for SR and MS specifications, respectively. Negative values indicate outperformance of the MCMC estimation method. In light (dark) gray, we report statistics which are significantly negative (positive) at the 1% level (bilateral test).

	Stocks			Indices			Exchange rates		
	QL 1%	QL 5%	wCRPS	QL 1%	QL 5%	wCRPS	QL 1%	QL 5%	wCRPS
Panel A: Markov–switching GARCH models									
GARCH $\mathcal{N}$	-3.65	-3.26	-2.24	-0.33	-0.58	-0.25	-1.33	0.99	-2.02
GARCH sk$\mathcal{N}$	-3.58	-2.93	-0.60	-1.56	-2.33	-1.04	-0.82	-1.24	-1.04
GARCH $\mathcal{S}$	-2.20	-5.78	-5.55	0.77	-0.17	-0.85	-0.78	0.29	0.35
GARCH sk$\mathcal{S}$	-5.04	-6.88	-7.04	1.13	-0.52	-0.58	-1.54	-1.64	-2.98
GJR $\mathcal{N}$	-1.91	-2.66	-3.22	-1.21	-2.95	-2.08	-1.09	-1.38	-3.61
GJR sk$\mathcal{N}$	-1.83	-3.12	-2.06	-1.11	-0.84	-1.40	0.06	-0.32	-1.17
GJR $\mathcal{S}$	-1.07	-3.11	-4.48	-1.29	-1.56	-4.11	-1.75	-2.40	-4.19
GJR sk$\mathcal{S}$	-3.10	-3.90	-5.28	-2.95	-2.02	-3.48	-1.59	-0.38	-2.50
Panel B: Single–regime GARCH models									
GARCH $\mathcal{N}$	-5.05	-4.23	-7.84	-2.99	-0.23	-5.63	-1.59	-0.42	-3.20
GARCH sk$\mathcal{N}$	-4.77	-3.36	-6.64	-2.55	-1.05	-4.48	-1.33	-0.86	-4.14
GARCH $\mathcal{S}$	-5.13	-5.08	-4.93	-1.27	-0.60	-3.39	-1.41	-1.12	-3.76
GARCH sk$\mathcal{S}$	-5.72	-5.40	-5.18	-2.74	-1.51	-3.87	-2.83	-2.47	-4.46
GJR $\mathcal{N}$	-5.11	-2.80	-6.90	-3.65	-2.43	-5.92	-1.67	-2.70	-4.14
GJR sk$\mathcal{N}$	-4.55	-2.30	-5.65	-2.26	-2.03	-3.94	-0.13	-2.62	-4.61
GJR $\mathcal{S}$	-3.78	-4.23	-5.23	-4.13	-2.52	-4.17	-1.61	-1.96	-4.71
GJR sk$\mathcal{S}$	-3.93	-4.06	-5.03	-3.82	-1.64	-3.16	-1.46	-2.24	-4.66

Table 6: Standardized average gain in performance when switching from constrained MS to SR models

This table presents the Diebold and Mariano (1995) test statistic of equal average loss function between the constrained MS and SR models for forecasting the distribution of h–day cumulative log–returns ($h \in \{1, 5, 10\}$). As loss functions, we consider the QL measure (at $\alpha = 1\%$ and $\alpha = 5\%$) and wCRPS measure. We report the test statistics computed with robust HAC standard errors, for the time series in the various universes. Negative values indicate outperformance of the shape–parameter constrained Markov–switching specification compared with its single–regime counterpart. In light (dark) gray, we report statistics which are significantly negative (positive) at the 1% level (bilateral test). The multi–step cumulative log–returns forecasts are generated using 25,000 simulated paths of daily log–returns. Models are estimated by MCMC.

		Stocks			Stock market indices			Exchange rates		
Horizon	Model	QL 1%	QL 5%	wCRPS	QL 1%	QL 5%	wCRPS	QL 1%	QL 5%	wCRPS
$h = 1$	GARCH sk$\mathcal{N}$	-0.44	-5.19	-9.34	-2.68	0.66	-3.26	0.27	-0.93	-3.70
	GARCH $\mathcal{S}$	-2.43	-2.32	-2.97	-1.53	-1.54	-1.02	0.73	0.10	-0.53
	GARCH sk$\mathcal{S}$	-2.70	-2.69	-2.62	-1.70	-0.98	-1.40	1.62	0.31	-0.23
	GJR sk$\mathcal{N}$	-0.37	-6.39	-9.92	-1.95	-1.59	-5.07	0.16	-0.91	-2.77
	GJR $\mathcal{S}$	-2.64	-2.99	-4.33	-2.25	-0.48	-0.64	0.30	-0.60	-1.04
	GJR sk$\mathcal{S}$	-2.90	-3.20	-4.10	-1.34	-0.93	-0.71	0.72	-0.40	-0.97
$h = 5$	GARCH sk$\mathcal{N}$	-0.62	-1.79	-2.76	-2.05	-0.55	-0.73	2.75	0.63	0.18
	GARCH $\mathcal{S}$	-0.48	-0.98	-1.44	-0.92	-2.23	-1.72	1.96	0.28	-0.58
	GARCH sk$\mathcal{S}$	-0.81	-1.06	-1.08	-1.58	-2.34	-1.45	1.25	1.56	0.46
	GJR sk$\mathcal{N}$	-0.44	-2.46	-2.60	-0.48	-1.49	-0.49	1.94	0.55	0.41
	GJR $\mathcal{S}$	-0.41	-1.26	-3.19	-0.19	-1.03	-0.87	3.19	1.40	-0.56
	GJR sk$\mathcal{S}$	-0.21	-0.83	-2.86	0.80	-0.33	0.02	3.02	1.54	-0.92
$h = 10$	GARCH sk$\mathcal{N}$	-0.25	-0.84	-2.06	-1.92	0.03	-1.71	1.44	1.55	0.73
	GARCH $\mathcal{S}$	-0.29	-0.25	-0.23	-1.74	-1.46	-2.11	0.17	1.76	0.10
	GARCH sk$\mathcal{S}$	-0.27	0.09	0.42	-0.40	-1.94	-2.30	1.20	1.30	0.92
	GJR sk$\mathcal{N}$	-0.10	-1.28	-1.80	-0.74	-1.92	-1.90	0.66	0.61	0.58
	GJR $\mathcal{S}$	-0.18	-0.41	-1.74	-0.53	-1.24	-1.79	2.36	1.27	-0.25
	GJR sk$\mathcal{S}$	0.01	-0.25	-1.45	0.12	-1.54	-1.14	2.86	1.06	-1.21