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High-frequency monitoring of growth-at-risk

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Abstract

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Keywords

Growth-at-Risk, mixed-data sampling, Bayesian quantile regressions, financial conditions, euro area.

JEL Classification

C22, E37, E44

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HIGH-FREQUENCY MONITORING OF GROWTH-AT-RISK

LAURENT FERRARA, MATTEO MOGLIANI, AND JEAN-GUILLAUME SAHUC

ABSTRACT. Monitoring changes in financial conditions provides valuable information on the contribution of financial risks to future economic growth. For that purpose, central banks need real-time indicators to adjust promptly the stance of their policy. We extend the quarterly Growth-at-Risk (GaR) approach of [Adrian et al. \(2019\)](#) by accounting for the high-frequency nature of financial conditions indicators. Specifically, we use Bayesian mixed data sampling (MIDAS) quantile regressions to exploit the information content of both a financial stress index and a financial conditions index leading to real-time high-frequency GaR measures for the euro area. We show that our daily GaR indicator (i) provides an early signal of GDP downturns and (ii) allows day-to-day assessment of the effects of monetary policies. During the first six months of the Covid-19 pandemic period, it has provided a timely measure of tail risks on euro area GDP.

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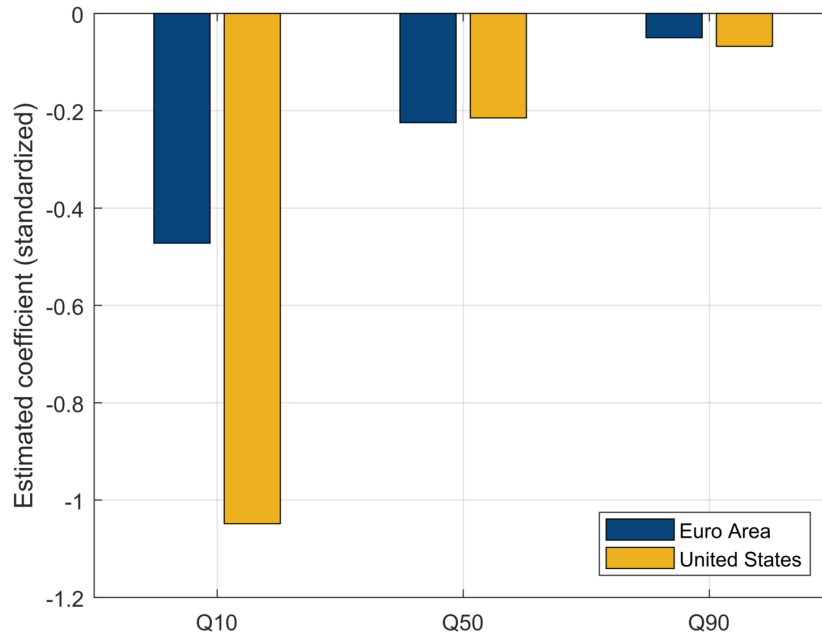
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1. INTRODUCTION

Monitoring changes in financial conditions provides economic decision-makers with valuable information on the contribution of financial risks to future economic growth. To this end, [Adrian et al. \(2019\)](#) developed a tool for evaluating financial risks to economic growth, using a tail-risk approach known as the Growth-at-Risk (GaR), equivalent to the Value-at-Risk concept in finance. This approach is used to keep track of the distortion of the entire expected growth distribution according to financial market developments using quantile regression methods. Quantile regressions provide an estimate of the elasticity of the Gross Domestic Product (GDP) growth rate to financial conditions for any range of values of the economic growth rate, and thus captures the non-linear nature of this relationship. [Figure 1](#) displays the values of these elasticities for various quantiles in the United States and the euro area and shows that the relationship is strongest for changes in GDP located at the bottom of the distribution. This illustrates that a tightening of financial conditions tends to amplify the effects of negative

October 2020. L. Ferrara: SKEMA Business School, University Cote d'Azur, France and Center for Applied Macroeconomic Analysis, Australian National University (e-mail: laurent.ferrara@skema.edu). M. Mogliani: Banque de France, 31 rue Croix des Petits Champs, 75049 Paris, France (e-mail: matteo.mogliani@banque-france.fr). J.-G. Sahuc: Banque de France, 31 rue Croix des Petits Champs, 75049 Paris, France (e-mail: jean-guillaume.sahuc@banque-france.fr). We would like to thank the participants of the 2019 Conference on Real-Time Data Analysis, Methods and Applications, 2020 International Institute of Forecasters Virtual Workshop (Economic Forecasting in Times of Covid-19) and 2020 Virtual International Symposium of Forecasting, for their useful comments and suggestions. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the Banque de France or the Eurosystem.

FIGURE 1. Elasticity of GDP growth to quarterly financial conditions for different quantiles



Notes: Q10, Q50 and Q90 represent the 10% quantile, 50% quantile (or median) and 90% quantile, respectively. Estimates are obtained by replicating the one-step ahead quarterly model in [Adrian et al. \(2019\)](#) over the 2001q1-2019q4 sample. The euro-area financial conditions index is the one proposed by [Petronovich and Sahuc \(2019\)](#) and the U.S. financial conditions index comes from the Chicago Fed (NFCI).

shocks to the real economy, as notably emphasized by [Bernanke and Gertler \(1989\)](#), while an easing of these conditions has a more limited impact on economic activity at the peak of the cycle.

However, the standard GaR approach suffers from several drawbacks arising primarily from a modelling of tail-risks based on quarterly data, while financial indicators are often sampled at higher frequency. To ensure the same frequency, financial conditions indexes are usually aggregated by simple averaging to get the data sampled at the same low-frequency as GDP. Such data aggregation (i) dampens the information content of daily financial indicators and (ii) is likely to lead to biased estimates if the underlying data generating process does not feature a flat-aggregation scheme from high to low frequencies. In addition, this strategy makes the GaR exploiting somewhat outdated financial information, the latter usually entering the model with one quarter lag, while central banks need the most current information to adjust promptly their policy stance.

In this paper, we implement a mixed data sampling (MIDAS) regression approach to obtain a real-time high-frequency GaR measure. More specifically, we extend the MIDAS methodology proposed by ([Ghysels et al., 2005, 2007](#)) by considering quantile regression, and we propose a way to get one-step estimates of the MIDAS-quantile regression model by using an Almon lag polynomial approximation of the high-frequency component. We then consider the 10th percent quantile of the conditional predictive distribution of current euro area GDP growth – which is akin to nowcasting – and compute

a high-frequency measure of current tail-risks on activity that we call the *daily* GaR(10%). Our model combines the information stemming from two daily euro area financial indicators in order to better capture different features of the financial side of the economy: (i) the Composite Indicator of Systemic Stress (CISS) of the European Central Bank (Holló et al., 2012) and (ii) the financial indicator proposed by Petronevich and Sahuc (2019). The first one is a financial stress indicator, which is designed to react more to systemic fragility in financial markets, whereas the second one is a financial conditions index, which is more useful in exploring macro-financial linkages. We also collect seasonally and calendar adjusted vintages of quarterly GDP into a real-time triangle spanning from 1999Q1 to 2020Q2 to perform an historical analysis on a pseudo real-time basis.

We propose several applications to highlight the interests of our daily GaR(10%) measure. We first look at the real-time evolution of the indicator before and during a recession episode, such as the sovereign debt crisis that affected the euro area from 2010 to 2013. Second, we inspect the link between the GaR measure and the main monetary policy decisions announced by the ECB between 2013 and 2018. Third, we evaluate the nowcasting ability of our model, i.e. the ability to assess current GDP growth, based on the entire predictive distribution. Finally, we focus on the Covid-19 pandemic period during the first semester 2020, which offers an interesting case study for assessing extreme macroeconomic risks through our high-frequency measure.

We show that our high-frequency approach provides an efficient monitoring of financial risks weighing on the euro area. For instance, our daily GaR(10%) measure would have led to an advanced detection of the GDP downturn observed during the European sovereign debt crisis, by steadily declining by approximately 1%, more than a quarter ahead of the start of the recession in 2011Q4. In addition, it provides a day-to-day benchmark for monetary policy by revealing information about how economic activity is likely to react to new announcements. We observe in particular that each new announcement of unconventional monetary policies between 2013 and 2018 coincided with an increase in the value of the GaR(10%). Further, although not designed to be a pure nowcasting model, our model displays superior overall and tail predictive ability compared with several competitors. Finally, during the first semester of 2020, it has provided a timely indication of tail risks on euro-area GDP, especially since the World Health Organization (WHO) announcement recognizing the Covid-19 epidemic as a global pandemic on 11 March.

Our paper contributes to the very recent literature on the use of quantile regressions to evaluate macroeconomic risks (see Adrian et al., 2019, Gonzalez-Rivera et al., 2019, or Figueres and Jarocinski, 2020), as well as on mixed frequency data models to assess current economic conditions. Against this background, Mazzi and Mitchell (2020), Lima et al. (2020) or Carriero et al. (2020) find that using high-frequency information provides substantial gains in terms of forecasting accuracy. Carriero et al.

(2020) notably show that Bayesian mixed frequency quantile regressions are superior to the usual frequentist approach. Our paper does not solely focus on nowcasting but also proposes a new piece to the policymakers' toolkit for real-time macro-financial surveillance.

In the remainder of the paper, Section 2 introduces the Growth-at-Risk approach with mixed data sampling, Section 3 presents the data and the Bayesian regression, Section 4 proposes some applications, including a focus on the Covid-19 crisis, and Section 5 concludes.

2. GROWTH-AT-RISK WITH MIXED FREQUENCY DATA SAMPLING

After presenting the standard quarterly Growth-at-Risk approach, we show how to adapt it to the case of higher-frequency independent variables.

2.1. The Growth-at-Risk approach. Since the Global Financial Crisis and the ensuing Great Recession in 2008-09, financial institutions have step up their monitoring of financial conditions in order to be able to rapidly react to any possible financial shocks before its transmission to the real economy. [Adrian et al. \(2019\)](#) have recently developed a methodology, known as the Growth-at-Risk (GaR), for measuring financial risks or vulnerabilities to U.S. economic growth. This approach is now widely used by the International Monetary Fund to assess risks to the global financial system in its flagship biannual *Global Financial Stability Report* (see, for instance, [IMF, 2019](#)).

The GaR approach relies on a quantile regression of GDP growth on past financial conditions and past GDP, accounting thus for non-linearities in a very simple econometric model of macro-financial linkages. Indeed, both theoretical and empirical literature have shown that financial markets play a key role in the transmission and propagation of shocks to the economy, but the channels of transmission are highly complex and present a strong degree of non-linearity. For instance, building on earlier theoretical contributions such as [Bernanke and Gertler \(1989\)](#), [Carlstrom and Fuerst \(1997\)](#), [Kiyotaki and Moore \(1997\)](#), or [Bernanke et al. \(1999\)](#), the recent literature shows that financial constraints can lead to highly nonlinear dynamics in the economy's response to shocks (asymmetric impulse responses following a negative or a positive shock). Recently, [Hubrich and Tetlow \(2015\)](#) evaluate empirically the diagnostic for models of financial frictions and show that (i) a single-regime model of the macroeconomy and financial stress is inadequate to capture the dynamics of the economy and (ii) output reacts differently to financial shocks in times of financial stress than in normal times.

As in [Adrian et al. \(2019\)](#), let us assume that we want to assess the joint effect of past GDP growth (y_{t-h}) and a given financial conditions indicator (x_{t-h}), where h is the forecast horizon, on the current GDP growth (y_t). We assume at this stage that both variables have been sampled at the same quarterly frequency. The methodology dealing with frequency mismatches is the core of this paper and will be presented in the following section. Beyond the standard linear ordinary least squares

(OLS) approach, the quantile regression framework put forward by [Koenker and Bassett \(1978\)](#) is an efficient way to introduce non-linearities in the relationship between y_t and the predictors. Instead of minimizing the sum of squared errors as in the OLS approach, the quantile estimation is based on the asymmetric minimization of the weighted absolute errors. The quantile regression also presents the great advantage of estimating the entire conditional quantile function, providing thus estimates of the whole conditional distribution.

Let's consider the following quantile regression:

$$y_t = \beta_1(\tau)y_{t-h} + \beta_2(\tau)x_{t-h} + \epsilon_t, \quad (1)$$

where the vector of coefficients $\beta(\tau) := (\beta_1(\tau), \beta_2(\tau))'$ depends on the τ -th quantile of the random error term ϵ_t . The coefficients $\hat{\beta}(\tau)$ are obtained by minimizing the following loss function:

$$\sum_{t=1}^T \rho_\tau(y_t - \beta(\tau)'z_{t-h}), \quad (2)$$

where $\mathbf{z}_{t-h} = (y_{t-h}, x_{t-h})'$, $\rho_\tau(u) = u(\tau - I(u < 0))$ is the check loss function, and $I(\cdot)$ denotes the indicator function. [Koenker and Bassett \(1978\)](#) proved that the predicted value $\hat{Q}_{y_t}(\tau|\mathbf{z}) = \hat{\beta}(\tau)'z_{t-h}$ is a consistent linear estimator of the conditional quantile function of y_t . In order to provide an evaluation of financial risks to future economic activity, an estimate of the future quantile function of $y_{T|T-h}$, conditional on sample information available up to $T - h$, is given by:

$$\hat{Q}_{y_{T|T-h}}(\tau|\mathbf{z}) = \hat{\beta}(\tau)'z_{T-h}. \quad (3)$$

Based on estimates of the conditional quantile function over a discrete number of quantile levels, it is possible to estimate the full continuous conditional distribution of $y_{T|T-h}$. As in [Adrian et al. \(2019\)](#), we fit a flexible distribution, known as the generalized Skewed-Student distribution, in order to smooth the estimated conditional quantile function of $y_{T|T-h}$ and recover a probability density function.¹ This specific distribution allows for fat tails and asymmetry and boils down to the Normal distribution as a specific case. The generalized Skewed-Student distribution has the following density function:

$$f(y; \mu, \sigma, \alpha, \nu) = \frac{2}{\sigma} t\left(\frac{y - \mu}{\sigma}; \nu\right) T\left(\alpha \frac{y - \mu}{\sigma} \sqrt{\frac{\nu + 1}{\nu + \left(\frac{y - \mu}{\sigma}\right)^2}}; \nu + 1\right), \quad (4)$$

where μ is a location parameter, σ a scale parameter, ν a fatness parameter and α a shape parameter. $t(\cdot)$ and $T(\cdot)$ are respectively the probability density function (*pdf*) and the cumulative density function (*cdf*) of the standard Student distribution ([Azzalini and Capitanio, 2003](#)).

¹As noted by [Adrian et al. \(2019\)](#), Equation (3) represents an approximate estimate of the quantile function, which is difficult to map into a probability distribution function due to approximation error and estimation noise.

In practice, the four parameters of the generalized Skewed-Student distribution are estimated through a quantile matching approach aiming at minimizing the squared distance between the estimated conditional quantile functions and the inverse *cdf* of the generalized Skewed-Student distribution given by:

$$\min_{\mu, \sigma, \alpha, \nu} \sum_{\tau} \left[\widehat{Q}_{y_{T|T-h}}(\tau|\mathbf{z}) - F^{-1}(\tau; \mu, \sigma, \alpha, \nu) \right]^2, \quad (5)$$

where $F^{-1}(\cdot)$ is the inverse cumulative Skewed-Student distribution. Finally, from the fitted quantile function, $F^{-1}(\tau; \widehat{\mu}, \widehat{\sigma}, \widehat{\alpha}, \widehat{\nu})$, it is possible to compute some downside risk measures, such expected shortfall at a given probability level. Due to the short data sample used in our empirical part, we shall focus on the lower 10th percent quantile of the predicted distribution (see also [Figueres and Jarocinski, 2020](#)), called the GaR(10%), which is given by:

$$Q_{y_{T|T-h}}^*(\tau = 0.10|\mathbf{z}) := F^{-1}(\tau = 0.10; \widehat{\mu}, \widehat{\sigma}, \widehat{\alpha}, \widehat{\nu}). \quad (6)$$

This can be interpreted as the expected value of future GDP at 10% probability, stemming from the conditional quantile function of $y_{T|T-h}$.

2.2. Introducing the MIDAS-quantile regression. The problem with the setup described above is that both the aggregation of high-frequency financial indicators into the lower frequency of GDP as well as the lag structure of the specification in Equation (1) prevent the model from reacting readily to sudden shocks. Hence, from the policymaker point of view, the GaR model appears an impractical tool for monitoring financial risks to activity in real-time.

We then propose to adapt Equation (1) to take into account the possible high-frequency nature of the regressor. Let us assume that the financial indicator x_t is available on a daily basis, i.e. virtually without delay, and denote it $x_t^{(d)}$ (i.e. it is observed about $d = 60$ times on average between quarters $t - 1$ and t). According to these features, we can build a high-frequency real-time GaR measure which relates current GDP growth to past *and* current (up to the latest available daily observation) financial conditions. For this purpose, the model used throughout this paper follows a mixed data sampling (MIDAS)-quantile regression (MIDAS-QR):

$$y_t = \beta_1(\tau)y_{t-1} + \beta_2(\tau) \sum_{c=0}^{C-1} \widetilde{B}(c; \boldsymbol{\theta}(\tau)) L^{c/d} x_{t-h_d}^{(d)} + \epsilon_t \quad (7)$$

where $\widetilde{B}(c; \boldsymbol{\theta}(\tau))$ is a weighting function (normalized to sum up to 1), which depends on a vector of parameters $\boldsymbol{\theta}(\tau)$ and a lag order $c = 0, \dots, C - 1$. Note that the forecast horizon is expressed in high-frequency terms ($h_d = 0, 1/d, 2/d, \dots$). While [Ghysels et al. \(2016\)](#) propose the Beta lag polynomial function for the quantile weighting function, we choose a simple polynomial approximation of the underlying true weighting structure provided by the (un-normalized) Almon lag polynomial

$B(c; \boldsymbol{\theta}(\tau)) = \sum_{i=0}^p \theta_i(\tau) c^i$, where $\boldsymbol{\theta}(\tau) := (\theta_0(\tau), \theta_1(\tau), \dots, \theta_p(\tau))'$, similarly to [Lima et al. \(2020\)](#) and [Mogliani and Simoni \(in press\)](#). Under the so-called “direct method”, Equation (7) with (unnormalized) Almon lag polynomials can be reparameterized as:

$$y_t = \beta_1(\tau) y_{t-1} + \boldsymbol{\theta}(\tau)' \tilde{\mathbf{x}}_{t-h_d}^{(d)} + \epsilon_t, \quad (8)$$

where $\boldsymbol{\theta}(\tau)$ is a vector featuring $(p+1)$ parameters, $\tilde{\mathbf{x}}_t^{(d)} := \mathbf{Q} \mathbf{x}_t^{(d)}$ is a $(p+1) \times 1$ vector of linear combinations of the observed high-frequency financial indicator, $\mathbf{x}_t^{(d)} := (x_t^{(d)}, x_{t-1/d}^{(d)}, \dots, x_{t-(C-1)/d}^{(d)})'$ is a $(C \times 1)$ vector of high-frequency lags, and \mathbf{Q} is a $(p+1 \times C)$ polynomial weighting matrix, with $(i+1)$ -th row $[0^i, 1^i, 2^i, \dots, (C-1)^i]$ for $i = 0, \dots, p$. Note that an estimate of the slope coefficient $\beta_2(\tau)$ in Equation (7) can be computed as $\hat{\beta}_2(\tau) = \hat{\boldsymbol{\theta}}(\tau)' \mathbf{Q} \boldsymbol{\iota}_C$, where $\boldsymbol{\iota}_C$ is a $(C \times 1)$ vector of ones.

The main advantage of the Almon lag polynomial is that Equation (8) is linear and parsimonious, as it depends only on $(p+1)$ parameters for the high-frequency variable. Further, linear restrictions on the value and slope of the lag polynomial $B(c; \boldsymbol{\theta}(\tau))$ may be placed for any $c \in (0, C-1)$. Endpoint restrictions, such as $B(C-1; \boldsymbol{\theta}(\tau)) = 0$ and $\nabla_c B(c; \boldsymbol{\theta}(\tau))|_{c=C-1} = 0$, may be desirable and economically meaningful, as they jointly constrain the weighting structure to tail off slowly to zero ([Mogliani and Simoni, in press](#)). As a result, the number of parameters in Equation (8) reduces from $(p+1)$ to $(p-r+1)$, where $r \leq p$ is the number of restrictions.

The generalized Skewed-Student distribution is then fitted on the estimated high-frequency conditional quantile function $\hat{Q}_{y_{T|T-h_d}}(\tau | y_{T-1}, \tilde{\mathbf{x}}_{T-h_d}^{(d)})$, and we recover our **high-frequency GaR(10%)** indicator:

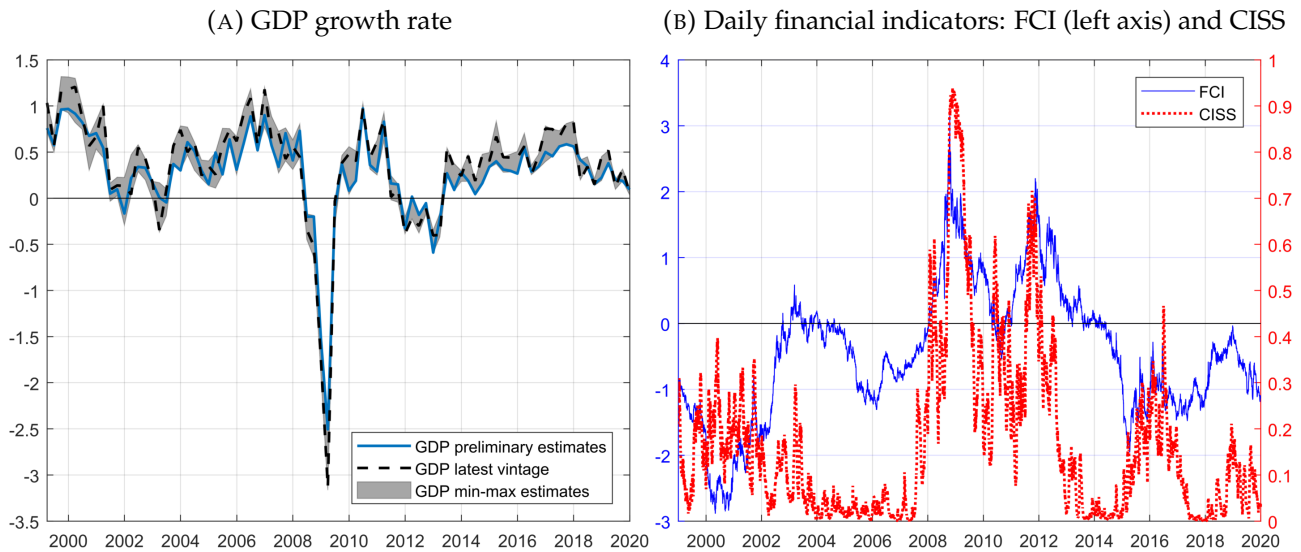
$$Q_{y_{T|T-h_d}}^*(\tau = 0.10 | y_{T-1}, \tilde{\mathbf{x}}_{T-h_d}^{(d)}). \quad (9)$$

3. DATA AND INFERENCE

This section describes the data used in our empirical applications as well as the algorithms involved in the Bayesian quantile estimation.

3.1. Data. In our applications, we focus on recent events that have impacted the euro area economy. As an aggregate measure of economic activity, we use the quarter-on-quarter growth rate of GDP for the euro area as whole (Figure 2a). To perform the analysis on a pseudo real-time basis, we collect seasonally and calendar adjusted vintages of quarterly GDP from Eurostat and ECB. The data are composed of multiple releases for the same vintage (preliminary flash estimate, flash estimate, and

FIGURE 2. Euro area GDP and daily financial conditions indices (1999-2019)



Notes: Panel A displays the GDP growth rate with the uncertainty associated with the estimates represented by the gray area. Panel B plots the two euro-area daily financial indicators: the financial conditions index (FCI) proposed by [Petronovich and Sahuc \(2019\)](#) and the composite indicator of systemic stress (CISS) proposed by [Holló et al. \(2012\)](#).

regular estimates), whose number and publication delays vary overtime, and are collected into a real-time triangle spanning from 1999Q1 to 2019Q4. Actual historical release dates are also identified and matched with each vintage.²

As regards the high-frequency financial indicators, we consider two alternative daily euro area time series: (i) a financial stress indicator, which is designed to react to systemic fragilities within financial markets, and (ii) a financial conditions index, which is more useful in exploring macro-financial linkages. The two indicators complement each other in capturing different features of the financial side of the economy, as can be seen on Figure 2b.³

The financial stress indicator is the Composite Indicator of Systemic Stress (CISS) developed by the European Central Bank ([Holló et al., 2012](#)). The main methodological innovation of the CISS is the application of basic portfolio theory to the aggregation of five market-specific sub-indexes, namely the foreign exchange market, the equity market, the money market, the bond market and the financial intermediaries. The aggregation takes into account time-varying cross-correlations between the five sub-indexes. As a result, the CISS puts relatively more weight on situations in which stress prevails in several market segments at the same time, capturing the idea that financial stress is more systemic and

²In expression (9), y_{T-1} is not available until its actual publication, usually around 30-45 days after the end of quarter $T - 1$. To overcome this issue without affecting the real-time nature of the analysis, we use the EuroCoin indicator as a proxy of past GDP growth. This indicator is released by the end of quarter $T - 1$, and real-time vintages are available on the [CEPR](#) website.

³Both financial indicators are freely available on the European Central Bank Statistical Data Warehouse (CISS) and on the Banque de France Webstat (FCI), respectively.

thus more dangerous for the economy as a whole if financial instability spreads more widely across the whole financial system. [Holló et al. \(2012\)](#) proposed the determination of critical levels for the CISS using the endogenous outcomes of two econometric regime-switching models.

The financial conditions index (FCI) is the one proposed by [Petronevich and Sahuc \(2019\)](#). This new FCI is based on six main components (rates, credit, equity, uncertainty, inflation, and exchange rates) extracted from eighteen daily series through a principal component analysis. The FCI is then computed by aggregating these components using time-varying weights, which are based on univariate conditional volatilities estimated through a GARCH(1,1) model. As greater volatility increases the weight of the corresponding component, the FCI may put relatively more weight on single stressed components, whose signal is hence not muted by the state of the other components. As a result, the FCI resorts on information stemming from the actual level of the components and their volatility.

3.2. Bayesian estimation. In the standard quantile regression ([Koenker and Bassett, 1978](#)), the distribution of the residuals ϵ_t in Equation (8) is unspecified (a non-parametric distribution) and the estimation of the τ -th quantile regression coefficients is the solution to the minimization of the loss function given by (2). Let's denote $\mathbf{X}_t = (y_{t-1}, \tilde{\mathbf{x}}_{t-h_d}^{(d)})'$ and $\Theta(\tau) = (\beta_1(\tau), \theta(\tau))'$. [Yu and Moyeed \(2001\)](#) showed that the minimization of $\sum_{t=1}^T \rho_\tau(y_t - \Theta(\tau)' \mathbf{X}_t)$ is equivalent to maximizing a likelihood function under the asymmetric Laplace error distribution (ALD) for ϵ_t .⁴ According to [Kozumi and Kobayashi \(2011\)](#), the ALD $f(\epsilon|\sigma)$ can be viewed as a mixture of an exponential and a scaled Normal distribution. Considering the random variables $\nu \sim \text{Exp}(1)$ and $\omega \sim \mathcal{N}(0, 1)$, then $\epsilon = \zeta_1 \sigma \nu + \zeta_2 \sigma \sqrt{\nu} \omega$ follows the skewed distribution $f(\epsilon|\sigma)$ above, with:

$$\zeta_1 = \frac{1 - 2\tau}{\tau(1 - \tau)} \quad \text{and} \quad \zeta_2 = \frac{2}{\tau(1 - \tau)}.$$

Hence, using this expression for ϵ , we can rewrite Equation (8) as:

$$y_t = \Theta(\tau)' \mathbf{X}_t + \zeta_1 \tilde{\nu}_t + \zeta_2 \sqrt{\sigma \tilde{\nu}_t} \omega_t, \quad (10)$$

where $\tilde{\nu}_t = \sigma \nu_t$ follows the exponential distribution $\text{Exp}(\sigma)$, with density function $f(\tilde{\nu}_t|\sigma) = \sigma^{-1} \exp(-\tilde{\nu}_t/\sigma)$.

Then, the conditional likelihood function stems from a Normal distribution and takes the following

⁴The ALD has density

$$f(\epsilon|\sigma) = \frac{\tau(1 - \tau)}{\sigma} \exp\left[-\frac{\rho_\tau(\epsilon)}{\sigma}\right],$$

and moments:

$$E(\epsilon) = \sigma \frac{1 - 2\tau}{\tau(1 - \tau)} \quad V(\epsilon) = \sigma^2 \frac{1 - 2\tau(1 - \tau)}{\tau^2(1 - \tau)^2}.$$

Both theoretical and empirical results support the use of the ALD in the context of quantile regressions, even when the true distribution of the data is not ALD ([Sriram et al., 2013](#)).

form:

$$f(y|\mathbf{X}, \Theta, \tilde{v}, \sigma, \tau) \propto \prod_{t=1}^T \frac{1}{\xi_2 \sqrt{\sigma \tilde{v}_t}} \exp \left[-\frac{1}{2} \sum_{t=1}^T \frac{(y_t - \Theta(\tau)' \mathbf{X}_t - \xi_1 \tilde{v}_t)^2}{\xi_2^2 \sigma \tilde{v}_t} \right].$$

We consider standard conditionally Normal prior that leads to the following hierarchical representation of the Bayesian MIDAS quantile regression (BMIDAS-QR):

$$y|\mathbf{X}, \Theta, \sigma, \tilde{v}, \tau \sim \mathcal{N}(\Theta(\tau)' \mathbf{X}_t + \xi_1 \tilde{v}_t, \xi_2^2 \sigma \tilde{v}),$$

$$\Theta|\tau \sim \mathcal{N}(\Theta_0, \Sigma_0),$$

$$\tilde{v}|\sigma \sim \text{Exp}(\sigma),$$

$$\sigma \sim \text{Inv-Gamma}(a_1, b_1).$$

As shown notably by [Khare and Hobert \(2012\)](#), the full conditional posteriors are given by:

$$\Theta|\mathbf{X}, \sigma, \tilde{v}, \tau \sim \mathcal{N}(\mathbf{A}^{-1} \mathbf{B}, \mathbf{A}^{-1}),$$

$$\tilde{v}_t|\mathbf{X}, \Theta, \sigma, \tau \sim \text{GiG} \left(\frac{1}{2}, \frac{(y_t - \Theta(\tau)' \mathbf{Z}_t)}{\xi_2^2 \sigma \tilde{v}_t}, \frac{\xi_1^2 + 2\xi_2^2}{\sigma \xi_2^2} \tilde{v}_t \right),$$

$$\sigma|\mathbf{X}, \Theta, \tilde{v}, \tau \sim \text{inv-Gamma} \left(\frac{3T}{2} + a_1, \sum_{t=1}^T \frac{(y_t - \Theta(\tau)' \mathbf{Z}_t - \xi_1 \tilde{v}_t)^2}{2\xi_2^2 \tilde{v}_t} + \sum_{t=1}^T \tilde{v}_t + b_1 \right),$$

where $\mathbf{A} = (\mathbf{X}' \mathbf{D}^{-1} \mathbf{X} + \Sigma_0^{-1})^{-1}$, $\mathbf{B} = \mathbf{X}' \mathbf{D}^{-1} (y - \xi_1 \tilde{v}) + \Sigma_0^{-1} \Theta_0$, and $\mathbf{D} = \text{diag}(\xi_2^2 \sigma \tilde{v}_t)$.

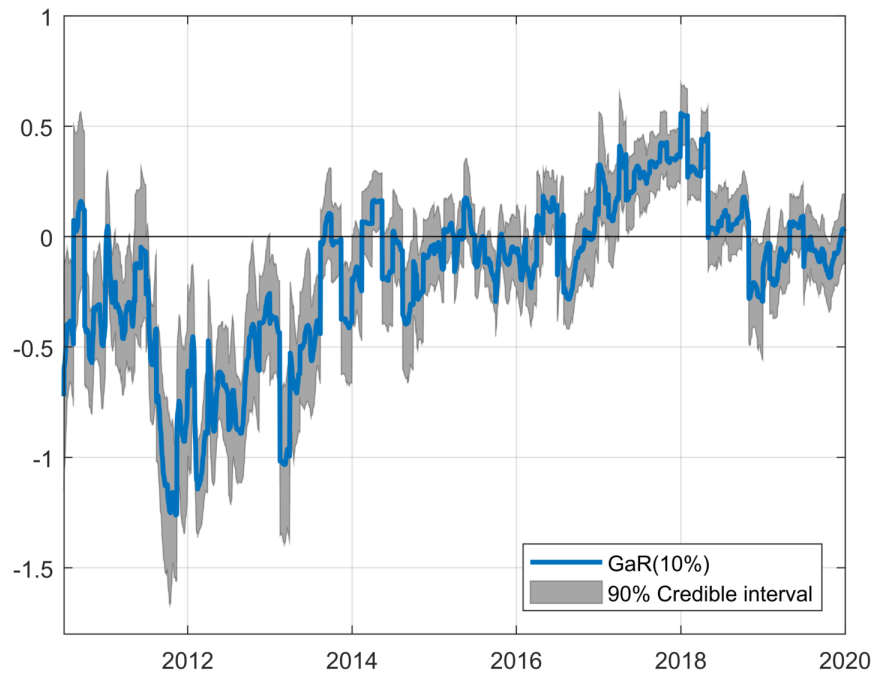
Let's denote $\hat{Q}_{y_{T|T-h_d}}^{(n)}(\tau|\mathbf{X})$ the n -th posterior conditional quantile estimate of $y_{T|T-h_d}$ given by the Markov chain Monte Carlo (MCMC) algorithm, for $n = 1, \dots, N$. The τ -th conditional quantile point estimate is then given by:

$$\hat{Q}_{y_{T|T-h_d}}(\tau|\mathbf{X}) = \frac{1}{N} \sum_{n=1}^N \hat{Q}_{y_{T|T-h_d}}^{(n)}(\tau|\mathbf{X}),$$

that is the BMA predicted value from regression (10) for each quantile τ . Then, as described in Section 2.2, we fit the Skewed-Student distribution to $\hat{Q}_{y_{T|T-h_d}}(\tau|\mathbf{X})$ and we recover the high-frequency (daily) GaR(10%) indicator from $Q_{y_{T|T-h_d}}^*(\tau = 0.10|\mathbf{X})$. Finally, note that the Bayesian estimation provides a natural estimate of the standard error of the quantile function, as the conditional likelihood implies that the conditional quantile function is normally distributed. We can hence provide a measure of uncertainty surrounding the estimated daily GaR(10%) by computing its credible interval at some $(1 - \alpha)$ level. In order to obtain asymptotically valid credible intervals, we implement the correction to the covariance matrix of the posterior chain proposed by [Yang et al. \(2016\)](#).

3.3. Combining Growth-at-Risk measures. As shown in Figure 2b, the FCI and the CISS present very similar high-frequency patterns, pointing to a strong correlation between these two series. Hence,

FIGURE 3. The daily combined GaR(10%) over the 2010Q3–2019Q4 period



Note: The daily combined GaR(10%) corresponds to the lower 10th percentile of the distribution of the expected real GDP growth, based on the combination of two financial conditions indicators.

using the two indicators together in quantile regression (9) would likely introduce multicollinearity in the model, leading to poor inference and predictive results. To address this issue, we adopt a strategy which consist in combining density forecasts. More specifically, we implement the following steps:

- (1) From Section 3.2, the full *continuous* conditional predictive quantile function $Q_{i,y_{T|T-h_d}}^*(\tau|\mathbf{X}_i)$ is computed for \mathbf{X}_i including either the CISS ($i = 1$) or the FCI ($i = 2$).
- (2) For each model $i = \{1, 2\}$, the predictive quantile function is converted into density forecasts, and a measure of their predictive performance is computed. We choose the Quantile Weighted Probability Score (QWPS; Gneiting and Ranjan, 2011), which provides a metrics for the evaluation of the predictive ability of a model by emphasising the (left) tail of the estimated density forecasts.
- (3) Combination weights $\omega_{i,T-h_d}$ are computed recursively using a discounted QWPS combinations method, similar to the point forecast approach of Stock and Watson (2004) and Andreou et al. (2013):

$$\omega_{i,T-h_d} = \frac{w_{i,T-h_d}^{-\kappa}}{\sum_i w_{i,T-h_d}^{-\kappa}},$$

where

$$\omega_{i,T-h_d} = \sum_{j=T_0}^{T_\ell} \delta^{T_\ell-j} \text{QWPS}_{i,j},$$

and $\kappa = 2$, $\delta = 0.9$ (the discount factor), T_0 is the point at which the first prediction is computed, and T_ℓ is the point at which the most recent prediction can be evaluated.⁵

(4) Finally, the combined conditional predictive quantile function is computed as:

$$Q_{c,y_{T|T-h_d}}^*(\tau|\mathbf{X}) = \sum_i \omega_{i,T-h_d} \times Q_{i,y_{T|T-h_d}}^*(\tau|\mathbf{X}_i).$$

From the obtained combined quantile function, we recover the high-frequency (daily) *combined* GaR(10%) indicator $Q_{c,y_{T|T-h_d}}^*(\tau = 0.10|\mathbf{X})$. This daily indicator, as well as its estimated 90% credible interval, is presented in Figure 3 over the period 2010Q3-2019Q4.

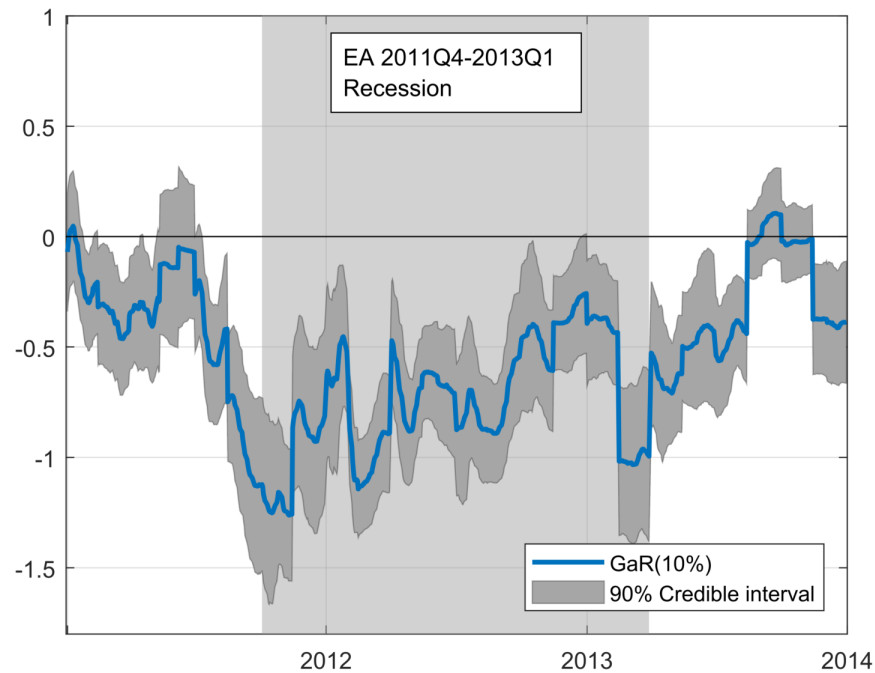
4. EMPIRICAL RESULTS

This section presents four applications on the euro area economy which illustrate the practical interest of using a daily GaR measure. The first application focuses on the real-time evolution of the indicator during the European sovereign debt crisis. The second one highlights its strong link with the main monetary policy decisions taken between 2013 and 2018. In a third application, we evaluate its nowcasting properties when trying to track in real-time GDP growth. Finally, we evaluate the behaviour of our high-frequency measure during the first six months of the Covid-19 pandemic.

4.1. The European sovereign debt crisis. As a first illustration, we take the example of the European sovereign debt crisis that affected the euro area from 2010 to 2013. The 2008 financial crisis had indeed left its mark on public finances, leading to a significant increase in government bond yield spreads. Despite a rescue package for Greece, financial tensions intensified again due to the worsening of public finances in several other euro area countries and to the contagion arising from the undertaken agreement to restructuring the Greek sovereign debt by mid-July 2011. The sovereign debt crisis increasingly turned into a twin sovereign debt and banking crisis. Further negative feedback loops between vulnerable banks, indebted sovereigns and weak economies took hold in several countries and led to acute financial fragmentation along country borders (Hartmann and Smets, 2018). Economic confidence fell, the economy slowed down rapidly and the euro area entered a double-dip recession in the fourth quarter of 2011 until the first quarter of 2013, according to the CEPR business cycle chronology.

⁵Because the analysis is performed in pseudo real-time, $T_\ell \neq T - h_m$. It follows that $\omega_{i,T-h_d} = \omega_{i,T-(h_d+1)}$ as long as a new point is available for evaluation.

FIGURE 4. The GaR(10%) during the euro- area sovereign debt crisis



Note: The GaR(10%) corresponds to the lower 10th percentile of the distribution of the expected real GDP growth.

Figure 4 shows that the GaR(10%) hovered between 0% and -0.5% during the first semester of 2011. This is consistent with very mild risks to activity as, up to end-June 2011, the growth rate of GDP for the euro area could have only be expected to run into a slightly negative territory at 10% probability. As of mid-April 2011, the contagion effects of the deterioration in the sovereign CDS spreads started to signal that they may be long-lasting. The situation deteriorated on July 2011. In July 1st, the GaR measure started dropping rapidly, reaching -1.2% in the fourth quarter of 2011 when the euro zone enters recession. This date precedes the announcement of the Moody's downgrade of Portugal in July 5th. This announcement, along with the continuing fears of a Greek default, could have triggered a sell-off in Spanish and Italian government bonds. By July 18th, the Italian government bond yields had increased by almost 100 basis points, while Spanish bond yields had increased by more than 80 basis points. The downgrading of sovereign ratings escalated and pushed bond rates up to critical levels for peripheral European countries. From April 1st, the GaR measure returned to its pre-crisis level, consistently with the first signals of an easing of financial conditions and the end of the recession.

All in all, the results show that our daily GaR(10%) would have been able to correctly track in real-time this recession episode. However, and more interestingly, the GaR(10%) measure tends to rapidly fall a quarter ahead of the beginning of the recession, dropping from a value close to zero to about -1% in only a few months. This swift change in the GaR can be seen as a possible early signal of recession led by a deterioration in financial conditions.

4.2. Unconventional monetary policy measures announcements. We now turn to the link between the daily GaR measure and unconventional monetary policies. Since 2013, the macroeconomic situation in the euro area has been characterised by increased risks threatening price stability and the anchoring of inflation expectations. Price developments have gradually moved away from values consistent with the ECB definition of price stability, i.e. a rate of inflation, as measured by the harmonised index of consumer prices (HICP), close but below 2%. The decline in inflation expectations (measured by the ECB's survey of professional forecasters and financial market indicators) suggested a risk of disanchoring expectations and the possibility of low inflation dynamics, and even deflation. Faced with these growing risks of disanchoring expectations, in other words a loss of bearings among economic agents with regards to the value of prices denominated in euros, the Eurosystem responded by taking a number of unconventional measures.

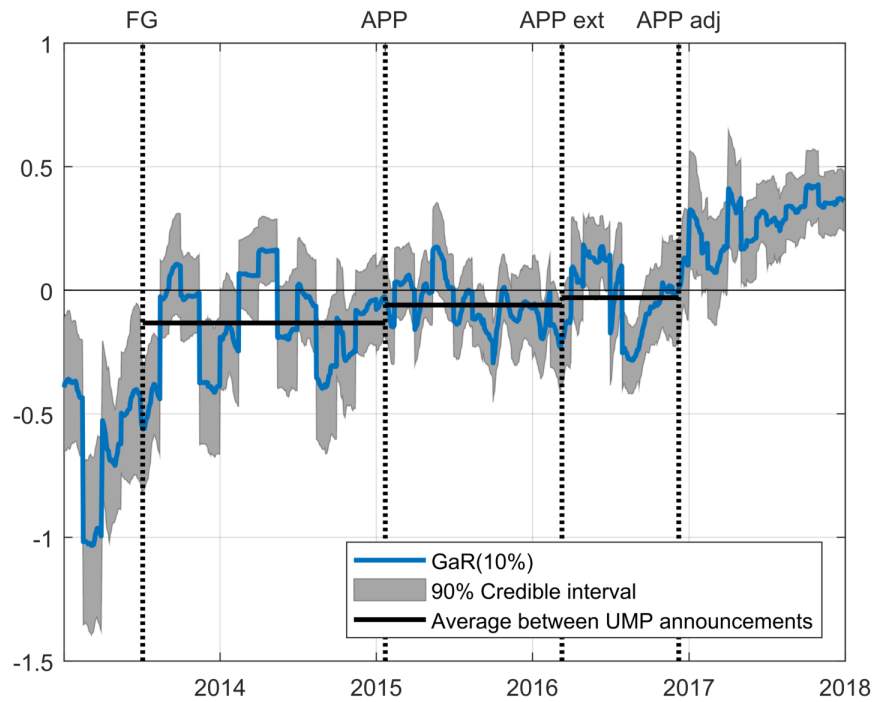
In particular, four major announcements are recorded between 2013 and 2018. First, the ECB has implemented forward guidance (FG) about the future course of monetary policy since July 2013. Forward guidance corresponds to a commitment on the future path of interest rates, so as to influence not only the short-term rates, which reached their lower bound close to zero, but mainly longer-term rates which are to a large extent determined by expectations of future short-term rates.

Second, the ECB decided to launch a large asset purchase programme (APP) on January 22nd 2015. It consists of purchases on the secondary market of private securities and euro-denominated investment-grade securities issued by euro area governments and institutions. Under this programme, the combined purchases of public and private sector securities between March 2015 and September 2016 would amount to 1.14 trillion euros. The APP programme was subsequently extended and adjusted in several occasions, notably by increasing the duration and total amount of purchases.

On March 16th 2016, the ECB decided to extend the monthly purchases under the APP (extended APP) from 60 billion euros to 80 billion euros, including a new corporate securities purchase programme (CSPP), starting from April 2016, intended to run until the end of March 2017, or beyond, if necessary. This measure was accompanied by a series of four targeted longer-term refinancing operations (TLTRO II) in order to ease private sector credit conditions and to stimulate credit creation. The interest rate on these operations, each with a maturity of four years, was fixed at the main refinancing operations rate prevailing at the time of take-up. In addition, the rate on the deposit facility was lowered by 10 basis points to -0.40%.

On December 8th 2016, the ECB decided to adjust the parameters of the APP (adjusted APP) : (i) the maturity range of the public sector purchase programme broadened by decreasing the minimum remaining maturity for eligible securities from two years to one year and (ii) purchases of securities under the APP with a yield to maturity below the interest rate on the ECB's deposit facility permitted

FIGURE 5. The GaR 10% and unconventional monetary policy announcements



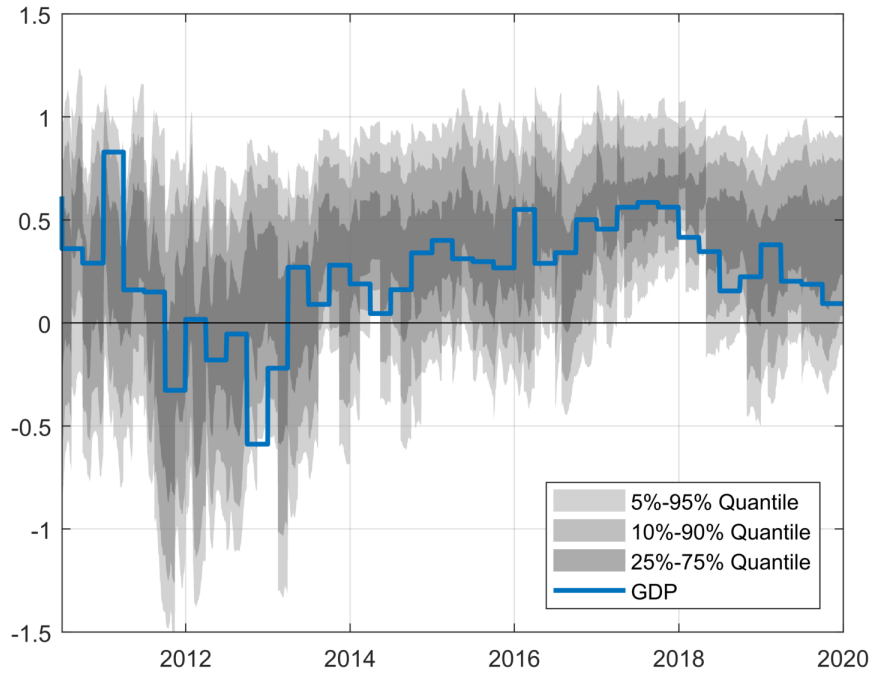
Notes: The GaR(10%) corresponds to the lower 10th percentile of the distribution of the expected real GDP growth. FG: forward guidance, APP: asset purchase programme, APP ext: extension of the APP, and APP adj: adjusted parameters of the APP.

to the extent necessary. In addition, the APP was announced to be continued at the monthly pace of 80 billion euros until the end of March 2017. From April 2017, the net asset purchases were intended to continue at a monthly pace of 60 billion euros until the end of December 2017, or beyond, if necessary.

Figure 5 plots the daily GaR(10%) together with the four monetary policy announcement dates (represented by the vertical dotted lines). It shows that the GaR(10%) was very reactive to new monetary policy measures by increasing immediately after each announcement. We also observe that the average GaR value increased systematically between two announcements (represented by a horizontal black line). This illustrates the fact that the daily GaR(10%) is an interesting indicator to carry out event studies, as it reveals important information about how economic activity is likely to react to monetary policy measures, through the channel of financial conditions. Consequently, we argue that this new high-frequency GaR measure can be useful for central banks in order to check the immediate effects of their policies on macroeconomic risk and to subsequently adjust adequately their monetary policy stance.

4.3. Nowcasting GDP. In this subsection, we evaluate the overall nowcasting performance of our BMIDAS-QR model, beyond the GaR measure. For this purpose, we consider the predictive densities

FIGURE 6. Nowcasting GDP with the BMIDAS-QR model



Note: The BMIDAS-QR model is the Bayesian mixed data sampling (MIDAS) model linking quarterly GDP and daily financial conditions indices estimated with quantile regression (QR) methodology.

obtained from the conditional predictive quantile function $Q_{c,y_{T|T-h_d}}^*(\tau|\mathbf{X})$. These densities are reported in Figure 6, along with the preliminary estimates of quarterly GDP. A visual inspection of the figure suggests that the conditional distributions can track the actual GDP growth fairly well, notably during the 2011-2013 recession episode (see Section 4.1), as well as during the acceleration of activity in 2016-2017 and the following deceleration in 2018-2019.

Forecasts from our model are first compared to those from a benchmark specification, given by a simple Bayesian AR(1) regression (BAR). Consistently with the conditional distribution approach investigated in the present paper, we concentrate mainly on density forecasts, which are evaluated by the means of four various criteria: average log-Score differentials (LS), average Continuous Ranking Probability Score ratios (CRPS; Gneiting and Raftery, 2007), average Quantile-Weighted Probability Score ratios (QWPS; Gneiting and Ranjan, 2011) and average Quantile Score ratios (QS). For CRPS, QWPS and QS criteria, values less than one indicate that our combined model outperforms the benchmark. For the LS criterion, positive values indicate that our model produces more accurate density forecasts than the BAR. As a robustness check, we further consider density forecasts from two competing models, namely a combined Bayesian MIDAS model (BMIDAS) and a Bayesian Quantile AR(1) regression (BQAR). Combined BMIDAS density forecasts are computed using the same combination strategy as outlined in Section 3.3, where the underlying univariate models and densities are estimated

TABLE 1. Out-of-sample results: relative accuracy of density forecasts

h_d	BMIDAS-QR				BMIDAS				BQAR(1)			
	LS	CRPS	QWPS	QS(0.10)	LS	CRPS	QWPS	QS(0.10)	LS	CRPS	QWPS	QS(0.10)
0	0.22	0.91	0.86	0.79	-0.03	1.06	0.97	0.95	0.13	0.94	0.97	0.95
10	0.22	0.90	0.84	0.77	-0.03	1.04	0.96	0.96	0.13	0.94	0.97	0.95
20	0.24	0.88	0.83	0.77	-0.02	1.03	0.96	0.95	0.13	0.94	0.97	0.94
40	0.10	1.01	1.01	0.88	-0.05	1.14	1.09	0.94	0.13	0.95	0.96	0.87
60	0.10	0.99	1.00	0.85	-0.05	1.11	1.07	0.94	0.14	0.94	0.95	0.87

Notes: LS, CRPS, QWPS, and QS denote respectively the log-score, the continuously ranked probability score, the quantile weighted probability score, and the quantile score (evaluated at $\tau = 0.10$), in relative terms with respect to the BAR(1) benchmark. Bold values denote the best outcomes for each forecast horizon h_d .

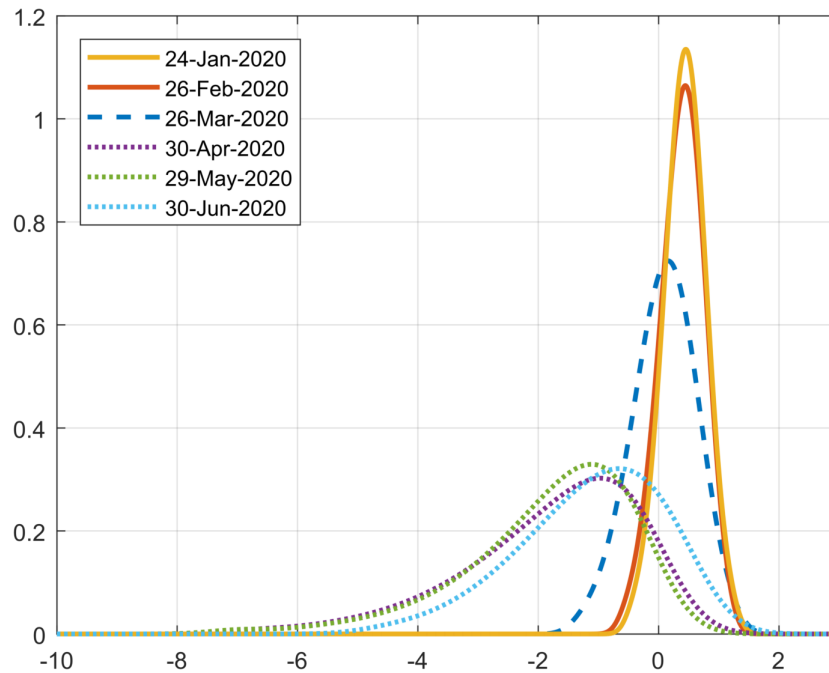
using the approach described in [Pettenuzzo et al. \(2016\)](#). The BQAR model is similar to specification (8) but with only the lagged GDP in the quantile regression.

The results, reported in Table 1, point to a systematic outperformance of our BMIDAS-QR model with respect to the BAR(1) benchmark and all the competitors for relatively short forecast horizons (up to 20 business days). In particular, the QWPS and QS measures suggest that the model can provide accurate and timely indications of downward risks to GDP growth about one month before the end of the quarter. However, for longer horizons, the model appears slightly outperformed by the BQAR(1) regression, suggesting that early financial data do not clearly convey useful information for assessing current GDP growth. It is nevertheless worth noting that our model always outperforms the combined BMIDAS regressions, which embed exactly the same information as our quantile regressions. This empirical evidence confirms the importance of accounting for non-linearities when modelling and predicting real activity with financial indicators.

4.4. The Covid-19 pandemic. In this subsection, we focus on the Covid-19 crisis period that affected the euro area, as well as the global economy, during the first semester of 2020. This shock is the most damaging event since the Great Depression and rather closer to a disaster, in the Robert Barro's sense, than to a classical recession.

During the first two months of 2020, the impact of Covid-19 on the euro area economy has been basically non-significant, as it was not clear that the propagation of the coronavirus coming from China was about to turn into a global pandemic. The first anecdotal evidence came through the disruption of global value chains and diminishing external demand stemming from China. This lack of reaction from financial markets can be seen in Figure 7: there is basically no shift in the conditional distribution of GDP growth for the first quarter of 2020 predicted by our model between January 24th (yellow curve) and February 26th (orange curve). Markets' sentiment started to turn negative in the last days of February, with the Euro Stoxx 50 dropping by about 27% by March 19th. Markets eased only after the ECB announced on March 18th the deployment of a new Pandemic Emergency Purchase Program,

FIGURE 7. Probability density functions of conditional GDP growth

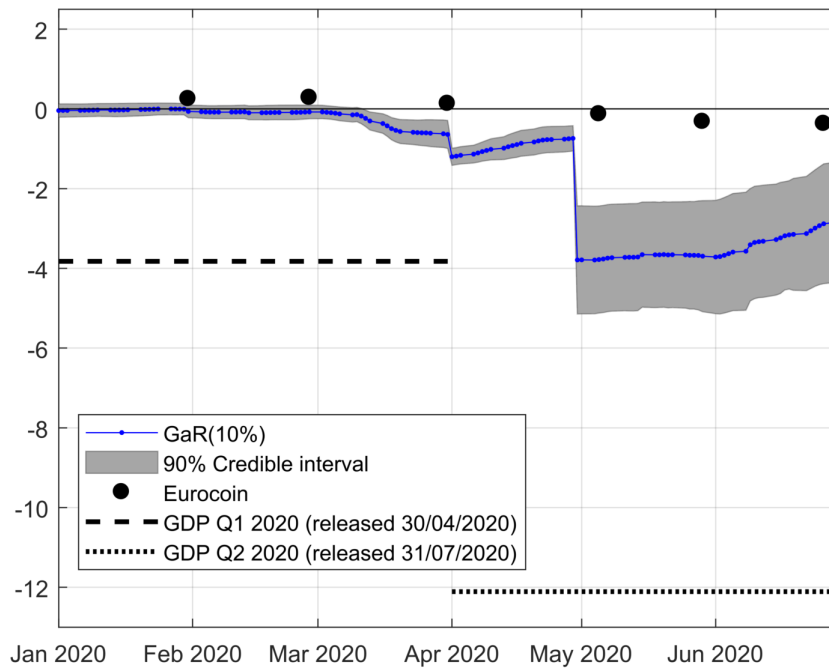


with an envelope of 750 billion euros until the end of the year, in complement of an initial smaller plan of 120 billion euros decided on March 12th.

In fact, as shown in Figure 8, the first significant decline in the GaR(10%) coincides with the WHO announcement recognizing the Covid-19 epidemic as a global pandemic, that came on March 11th. Mid-March also corresponds to the start of stringent lockdown measures within euro area countries. The daily GaR(10%) measure undergoes two main large drops, one at the end of March and the other at the end of April. The first one is due to the large drop in stock prices previously mentioned. This can also be seen in Figure 7, where the predictive distribution of GDP growth for 2020q1 estimated on March 26th began to shift to the left (dashed blue curve). The second drop is due to the integration of GDP growth for the first quarter of 2020 into the model. This shift is also clearly visible in Figure 7 (dotted purple curve).

Two interesting features arise from this empirical analysis. First, we compare our measure with the EuroCoin indicator provided by the CEPR, that can be interpreted as a real-time nowcast of euro area GDP growth. As can be seen on Figure 8, EuroCoin stayed quite high throughout the first semester, showing only slightly negative values starting end of April onwards (-0.13), reaching -0.32 in May while the strongly negative GDP growth in the first quarter of 2020 was already known (-3.8% in quarter-over-quarter growth, published on April 30th). As regards the second quarter, EuroCoin was also unable to reproduce the wide fall in quarterly GDP growth (-12.1%, as published on July 31st), only reaching a minimum of -0.64% in August 2020. Although it is fair to say that EuroCoin only aims

FIGURE 8. The GaR 10% and the Covid-19 pandemic



Note: The GaR(10%) corresponds to the lower 10th percentile of the distribution of the expected real GDP growth.

at tracking a monthly *smoothed* estimate of quarterly GDP growth in the euro area, the deviation from actual GDP growth is however huge. A potential reason underlying this discrepancy is that this index is mainly based on macroeconomic information that comes with a delay and that industrial production information is likely to be over-weighted in the index. In quite contrast, our daily GaR measure has started to provide a clear signal of imminent deterioration of economic activity since mid-March.

Second, despite the timeliness of the signal provided by our daily GaR, its amplitude was fairly lower than the drop observed on GDP growth. This gap can be explained by the nature of the shock underlying the Covid-19 recession. Indeed, it turns out that this recession can be understood as a mix of supply and demand shocks, amplified by an uncertainty shock. On the other hand, the financial shock has been quite limited so far, mainly due to the swift and strong monetary policy response of the ECB. The synchronised reaction of the largest central banks over the world also likely contributed to globally sustain the financial sector. In our view, this explains the limited shift and skewness of the estimated distributions presented in Figure 7. However, the financial risk on GDP growth is still present, as we don't know how the current crisis will evolve in upcoming months. In this respect, we think that our daily GaR measure will continue to be useful to track future risks on economic growth stemming from the financial sector during this major adverse economic event.

5. CONCLUSIONS

This paper extends the quarterly Growth-at-Risk (GaR) approach of [Adrian et al. \(2019\)](#) by accounting for the high-frequency nature of financial conditions. Specifically, we use Bayesian mixed data sampling (MIDAS) quantile regressions to exploit the information content of a financial stress indicator and a financial conditions index to construct real-time high-frequency GaR measures for the euro area. We show that our daily GaR: (i) provides an early signal of GDP downturns and (ii) allows day-to-day assessment of the effects of monetary policies. During the first six months of the Covid-19 pandemic period, it has provided a timely indication of tail risks on euro-area GDP. This new high-frequency GaR measure could be efficiently used by monetary policy-makers in order to assess the impact of monetary policy changes on economic risk, through the lens of financial market perception.

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