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Variability in risk-weighted assets: what does the market think?[1]

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Abstract

The global financial crisis highlighted a number of weaknesses in the regulatory framework, including concerns about excessive variability in banks' risk-weighted assets (RWAs) stemming from their use of internal models. The Basel III reforms that were finalised in 2017 by the Basel Committee on Banking Supervision seek to reduce this excessive RWA variability. This paper develops a novel approach to measuring RWA variability – the variability ratio – by comparing a market-implied measure of RWAs with banks' reported regulatory RWAs. Using a panel data set comprising a large sample of internationally-active banks over the period 2001 to 16, we find that there was a wide degree of RWA variability among banks, and that market-implied RWA estimates were persistently higher than regulatory RWAs. We then assess the determinants of this variability, and find a strong and statistically-significant association between our measure of RWA variability and (i) the share of opaque assets held by banks (eg derivatives); (ii) the degree to which a bank is capital constrained; and (iii) jurisdiction-specific factors. These results suggest that market participants may be applying an 'opaqueness' premium for banks that hold highly-complex instruments, and that the incentive for banks to game their internal models is particularly acute for capital-constrained banks. The results also point to the importance of jurisdiction-specific factors in explaining RWA variability. In addition, we find that RWA variability directly affects banks' own profitability through higher funding costs. Finally, we find that the 2017 Basel III reforms – most notably the output floor – help to reduce excessive RWA variability.

Keywords: bank regulation, capital, Basel III, risk-weighted assets, financial stability

JEL classification: G20, G21, G28

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Contents

I. Introduction

The global financial crisis highlighted a number of fault lines in the regulatory framework, including insufficient levels of high-quality capital, excessive leverage, insufficient consideration of macroprudential risks, and a lack of international standards for liquidity risk. The Basel Committee on Banking Supervision's (BCBS) initial set of "Basel III" reforms in 2010 were motivated primarily to address these shortcoming (BCBS, 2011; 2013a; 2014b; 2015b).

The financial crisis also raised serious questions about the credibility of the risk-weighted asset (RWA) framework. A number of empirical studies by academics, analysts and the BCBS pointed to a large degree of variability in the risk weights estimated by banks' internal models. For example, the BCBS conducted several 'hypothetical portfolio exercises' (BCBS, 2013c; 2013d; 2013e; 2015a), where a number of large internationally-active banks were asked to estimate risk weights using their internal models for the same portfolios. The results of these exercises illustrated a high degree of RWA variability; at the extremes, risk weights varied across banks by more than 600% for the same hypothetical corporate exposures and by over 300% for hypothetical exposures to banks.

This excessive degree of RWA variability has important financial stability implications. Two banks with the same balance sheet and risk tolerance can report significantly different estimates of regulatory capital ratios, consequently undermining the usefulness of the risk-weighted capital framework as a risk-sensitive measure of banks' solvency. These concerns are not just theoretical in nature. At the peak of the global financial crises, a wide range of stakeholders lost faith in banks' reported internally modelled risk-weighted capital ratios. For example, a survey of 130 Asian, European and US equity investors in 2012 – representing 100 institutions with approximately $6 trillion of equities under management – suggested that the vast majority did not trust banks' RWAs, and that they supported the removal of internally-modelled approaches from the regulatory framework (Barclays Capital, 2012).

To that end, the BCBS finalised a set of additional "Basel III" reforms in 2017 with the aim of reducing excessive RWA variability (BCBS, 2017). The reforms include: (i) enhancing the robustness and risk sensitivity of the standardised approaches; (ii) constraining the use of internally-modelled approaches; and (iii) setting an output floor to internally-modelled RWAs. The output floor ensures that the level of a bank's RWAs is not lower than 72.5% of RWAs had the bank calculated capital requirements exclusively using the standardised approaches. Put differently, the output floor sets a limit on the capital benefit a bank can obtain from using internal models relative to the standardised approaches.

There is a growing literature related to the robustness and risk sensitivity of RWAs. Broadly speaking, the issues considered in this literature can be grouped into three strands: (i) the extent to which banks' estimated RWAs exhibit excessive variability; (ii) the degree to which banks' RWAs are consistent with market-based measures of risk; and (iii) the performance of risk-weighted capital ratios in discriminating among banks' solvency and signalling future distress.

Consistent with the analyses conducted by the BCBS, the academic literature generally finds a high degree of excessive RWA variability. For example, Turk-Ariss (2017) finds substantial variations in European banks' RWAs across portfolios for the same country or counterparty. Plosser and Santos (2014) identify significant cross-sectional variation in how US banks rate common borrowers. Mariathasan and Merrouche (2014) examine the relationship between banks' use of internally modelled-approaches and risk weights and find that average risk weights decrease following the use of internal models. Bruno, Nocera, and Resti (2015) find significant differences in European banks' average risk weights, both over time and across countries, which they attribute to differences in banks' size, business model, and asset mix.

The literature also finds a weak association between RWAs and market-based measures of risk. For example, Das and Sy (2012) investigate how market participants factor in banks' estimated RWAs and whether RWAs predict market measures of risk. They find that investors ignored RWAs estimated by banks' internal models during the financial crisis and relied on other balance sheet measures of risk. They also find that RWAs do not generally predict market measures of risk (eg stock return volatility).

In a similar vein, Vallascas and Hagendorff (2013) find that banks' RWAs are not strongly linked with market measures of portfolio risk. While Barakova and Palvia (2014) find that RWAs are associated with banks' portfolio risk, they also find evidence that banks' internally modelled RWAs are not strongly associated with market-based risk indicators. The disconnect between regulatory and market-based risk measures remains well after the start of the global financial crisis; for instance, Sarin and Summers (2016) find that market measures of bank solvency continue to be low despite the improvement in banks' capital ratios.

The third strand of the literature relates to the discriminatory power of regulatory ratios in predicting bank failure. Numerous studies find that risk-weighted capital ratios perform poorly in predicting bank failure and distress relative to other measures such as simple leverage ratios and some market-based measures.[3]

This paper contributes to the literature by developing a new measure of RWA variability – the "Variability Ratio" (VR) – which compares a bank's market-implied measure of RWAs with its regulatory RWAs. This allows us to investigate four questions: (i) what is the extent of RWA variability across banks and over time? (ii) what are the determinants of RWA variability? (iii) does RWA variability affect banks' profitability? and (iv) to what extent do the 2017 Basel III reforms reduce RWA variability?

Based on the proposed VR measure, we find evidence that market-implied RWA estimates are persistently higher than regulatory RWAs for many banks. We explore a number of hypotheses that could drive differences across banks; such as asymmetric information, opaqueness of financial instruments, country specific factors, and gaming of RWAs.

Controlling for risk and bank individual characteristics, we find statistically-significant differences in variability across countries. The degree of variability is higher for banks that are capital constrained. We also find that banks with more exposure to

[3] See, for example, Behn et al (2016), Berger and Bouwman (2013), Brealey et al (2011), Demirgüc-Kunt et al (2013), Estrella et al (2002), Haldane and Madourous (2012), Hogan et al (2013), IMF (2009) and Mayes and Stremmel (2014).

opaque instruments (eg derivatives) have greater risk weight variability. And there is a meaningful economic impact of this variability: banks with higher VRs have higher funding costs. Put differently, excessive RWA variability is not only a financial stability concern but also affects banks' own profitability through higher costs. Finally, we find that the 2017 Basel III reforms, and in particular the output floor, help reduce RWA variability.

The paper is structured as follows. Section II describes the data. Section III introduces the VR and assesses how it performs across time and jurisdictions. In Section IV, we analyse the determinants of RWA variability. Section V examines the impact of RWA variability on banks' funding costs, while Section VI summarises the results of various robustness checks. The impact of the Basel III reforms on RWA variability is assessed in Section VII, while Section VIII concludes.

II. Data and summary statistics

The data used in this paper combines accounting balance sheet and income statement data, regulatory ratios, various market-based prices and risk measures, and macroeconomic data.

Balance sheet indicators and RWAs data are obtained from FitchConnect, while market-based indicators (eg asset volatility, Credit Default Swaps (CDS) spreads and weighted-average cost of capital (WACC)) are obtained from Moody's Analytics Credit Edge, IHS Markit and Bloomberg LP. GDP data is sourced from the BIS statistics.

We also use country-level data on the estimated impact of the Basel III reforms on RWAs from the Basel Committee's data-collection exercises. Access to this data was granted to us by the BCBS.

Banks are matched across the various databases using specific bank identifiers (eg Fitch ID, Markit ID, and CUSIPs) taking into consideration the banking group information where possible. Due to data confidentiality, it is not possible to match the BCBS data to the other data sources at the individual bank level. Hence, when using the BCBS data, the analysis is performed at the aggregated country level.

The initial sample includes 91 large internationally-active banks with total assets in excess of $200bn (as of end-December 2016) that are included in the Basel Committee's assessment exercise for global systemically important banks (BCBS, 2013b). We exclude banks with less than five consecutive annual observations in the RWA time series, resulting in a sample of 76 banks from 21 countries.

The time period of our sample spans from 2001 to 2016, with the majority of the observations available from 2008 to 2016. Combining the various data sources, our database is an unbalanced panel, where the data is available annually. For daily market data (eg CDS spreads), we create annual series by averaging the data over each annual reporting period. This is required in order to combine annual balance sheet data with higher frequency market data, and serves to limit the effect of short-term fluctuations in market data.

Table 1 provides summary statistics for the key variables used in this paper, while Table 2 defines the variables and data sources. Tables 14 to 16 in Annex 1 include additional information on the sample of banks and more detailed summary statistics.

Summary statistics — Table 1

	Number of observations	Banks	Countries	First Year in the sample	Last Year in the sample	Mean	Standard Deviation	Min	25% Percentile	Median	75% Percentile	Max
RWA variability measures												
Variability Ratio (using accounting assets)	948	76	21	2001	2016	2.10	0.93	0.09	1.53	1.93	2.50	6.64
Variability Ratio (leverage ratio exposure)	450	74	21	2010	2016	2.13	0.77	0.79	1.62	1.97	2.43	5.78
Market RWA (LGD = 45%, regression)	1141	76	21	2001	2016	0.98	0.34	0.14	0.76	0.98	1.20	2.68
Market RWA (LGD = 45%, KMV fitted 1)	1141	76	21	2001	2016	0.91	0.27	0.31	0.74	0.91	1.07	1.82
Market RWA (LGD = 45%, KMV fitted 2)	1141	76	21	2001	2016	0.90	0.26	0.31	0.74	0.91	1.08	1.73
Cost of funding												
CDS spread (basis points)	887	67	19	2001	2016	103	96.3	2.13	26.6	85.2	142	872
Weighted average cost of capital (%)	1017	74	21	2001	2016	12.0	3.52	5.72	9.40	11.3	14.0	29.5
Capital ratios and RWA density												
Leverage ratio (%)	1120	76	21	2001	2016	6.10	2.69	-13.7	4.43	5.71	7.61	16.9
Tier 1 capital ratio (%)	1036	76	21	2001	2016	10.7	3.27	3.33	8.26	10.4	12.6	28.7
Regulatory RWA	962	76	21	2001	2016	0.50	0.21	0.14	0.39	0.5	0.61	4.77
Regulatory RWA_LRE	450	74	21	2010	2016	0.51	0.17	0.18	0.39	0.5	0.62	1.1
Balance sheet indicators												
Portfolio mix												
Loans to total assets	1108	76	21	2001	2016	0.50	0.16	0.01	0.41	0.51	0.62	0.83
Securities to total assets	1120	76	21	2001	2016	0.26	0.14	0.04	0.16	0.23	0.32	0.82
Derivatives to total assets	864	75	20	2001	2016	0.06	0.07	0.00	0.01	0.04	0.08	0.56
Asset performance												
Asset volatility (%)	1141	76	21	2001	2016	6.04	3.14	1.83	3.99	5.27	7.23	28.8
Non-performing loans (%)	970	75	21	2002	2016	3.14	3.85	0.02	0.88	1.79	3.80	30.7
Return on assets (%)	1094	76	21	2001	2016	0.77	0.65	-6.53	0.44	0.77	1.07	5.09
Size (natural log of total assets)	1120	76	21	2001	2016	-0.81	1.03	-4.13	-1.50	-0.85	-0.07	1.34
Business model												
Income diversity	1120	76	21	2001	2016	0.50	0.23	0.02	0.33	0.5	0.67	1.00
Funding fragility	1120	76	21	2001	2016	0.20	0.12	0.00	0.11	0.19	0.26	0.89
Efficiency ratio	1120	76	21	2001	2016	0.58	0.21	0.22	0.47	0.57	0.65	4.26
Macroeconomy												
Real GDP growth	1216	76	21	2001	2016	3.22	3.58	-7.8	1.4	2.5	4.1	15.2

Data sources and variable definitions — Table 2

Indicator	Source	Description
Balance sheet, income statement and regulatory ratios	FitchConnect	Monthly balance sheet, income statement and regulatory information used to calculate several indicators and controls in the models: • Size = Natural log of Total Assets • RWA = Total Risk Weighted Assets • Regulatory RWA = RWA / Total Assets • Regulatory RWA_LRE = RWA / Leverage Ratio Exposure • Credit = Total Loans / Total Assets • Securities = Securities / Total Assets • Derivatives = Derivatives / Total Assets • Leverage Ratio = Total Equity / Total Assets • Tier 1 Capital Ratio = Tier 1 Capital / RWA • Return on Assets (ROA) = Net Income / Average Total Assets • Non performing loans (NPL) = Non-Performing Loans / Gross loans • Funding Fragility = Short Term Funding (ex deposits) / (Short + Long Term Funding) • Efficiency Ratio = Non Interest Expenses / (NII + Non Interest Income) • Income diversity = 1 – (NII / Non Interest Income) • Type of Accounting Standard (US-GAAP versus non US GAAP)
G-SIB Indicators	BCBS	Yearly series of G-SIB indicators published by banks and the BCBS for all banks that participate in the BCBS assessment for global systemically important banks (G-SIBs). This data set includes leverage ratio exposure (LRE), which is used to calculate Regulatory RWA_LRE (= RWA / LRE).
KMV model Implied volatility	Moody's Analytics Credit Edge	Daily series of asset volatility implied from the KMV model. The KMV model estimates the probability of default for a 1-year time horizon using an option-pricing based model, treating firm's equity as a call option on the total assets of the firm and estimating the Distance-to-Default.
CDS spread	IHS Markit and Bloomberg LP	Daily quotes of 5 Years Credit Default Swaps on Senior Unsecured and Subordinated (or lower) Tier 2 debt.
Weighted Average Cost of Capital	Bloomberg LP	Daily series of average cost of capital derived by the Capital Asset Pricing Model (CAPM): $CoE = r_f + \beta * country\ risk\ premium$ where the default value for the risk-free rate r_f is the country's 10 Years bond rate.
Country-level estimated impact of the Basel III reforms on RWAs	BCBS quantitative impact studies (QIS)	For various calibrations of the output floor, the aggregate Regulatory RWA_ LRE is calculated for each BCBS member jurisdiction (= RWA / LRE). This data is only used in Table 13 and Figure 11.
Real GDP per country	BIS statistics	

III. Measuring RWA variability using regulatory and market information

A. Internal models and the Basel framework

The Basel framework permits banks to calculate capital requirements using internally-modelled approaches, subject to supervisory approval. The use of internally-modelled approaches in the Basel framework commenced in 1996 with the market risk framework (BCBS, 1996) in response to the growing use by banks of Value-at-Risk models. The BCBS then extended the use of internal models to credit and operational risk as part of the Basel II reforms (BCBS, 2006).

In calculating capital requirements under internally-modelled approaches, banks estimate various risk parameters. For example, for credit risk, the advanced internal ratings-based (A-IRB) approach allows banks to model the probability of default (PD), the loss-given default (LGD), the maturity adjustment factor, and the exposure at default (EAD). A more constrained approach – the foundation internal ratings-based (F-IRB) approach – fixes some of these parameters (in particular the LGD), but still provides discretion for banks to estimate other key risk parameters such as the PD of their exposures (BCBS, 2005). For market risk, banks can calculate capital requirements based on Value-at-Risk internal models, subject to supervisory approval.[4] In a similar vein, banks can receive supervisory approval to estimate their operational risk capital based on internal operational risk measurement systems.[5]

B. Sources and measurement of RWA variability

In principle, variability in banks' RWAs can arise due to a number of factors including: (i) the composition of banks' balance sheets, with high risk assets expected to result in higher RWAs; (ii) different risk assessment perspectives; (iii) some asset classes may be inherently more difficult to model robustly (eg due to limited data) and would therefore be expected to result in greater variability across banks; and (iv) differences in risk management standards and supervisory expectations – put differently, some banks may be more aggressive than others in their modelling practices and could be more incentivised to 'game' their models in order to reduce their RWAs.

From a financial stability perspective, concerns about RWA variability are primarily related to the third and fourth of these factors. RWA variability resulting from differences in banks' risk profile and judgmental risk assessment differences are consistent with the principle of a risk-sensitive regulatory framework. In contrast, variability stemming from inadequate models and gaming behaviour results in capital requirements that are inconsistent with the underlying risk of the assets.

In order to measure excessive RWA variability, it is necessary to control for differences in the underlying riskiness of a bank's assets. Perhaps the most direct way of doing so is to conduct hypothetical portfolio exercises (HPEs), as done by the BCBS in its empirical RWA studies (BCBS, 2013c; 2013d; 2014c; 2015a, 2016a). In principle,

4 As of 1 January 2022, the market risk internal models approach will be based on banks' expected shortfall models (BCBS, 2019).

5 The internally-modelled approaches for operational risk will no longer be permitted as of 1 January 2022 (BCBS, 2017).

any variability in RWA resulting from such HPEs would be attributable to the three remaining factors outlined above. But HPEs also suffer from some limitations, including that such exercises: (i) are highly resource intensive in nature; (ii) are susceptible to gaming, particularly if repeated; and (iii) may not be appropriate for asset classes where heterogeneous and jurisdiction-specific factors play an important role (eg residential mortgages and housing markets can vary significantly across jurisdictions).

In the absence of HPEs, previous studies have controlled for differences in risk profiles across banks by: comparing bank estimates of risk to common borrowers and using indirect proxies of balance sheet risk (eg Breuer et al 2008, Grundke, 2005 and Kupiec 2007).

C. The Variability Ratio

We develop an alternative metric to assess RWA variability by comparing a bank's estimated RWAs with the RWAs implied by the market, which we label the VR. Market measures of risk are not perfect and are subject to a number of potential shortcomings (eg procyclicality). However, the way in which the market assesses the relative riskiness of banks should not fundamentally vary across banks. By using a market implied measure of RWAs, we can compare variability in banks' regulatory RWAs with a common and consistent market-derived measure of the riskiness of a banks' assets.

The VR is defined as:

$$VR_{it} = \frac{(Market\ RWA)_{it}}{(Regulatory\ RWA)_{it}}, \tag{1}$$

where *Market RWA* is the market-implied measure of RWAs for bank *i* in period *t*, and the *Regulatory RWAs* are those reported by banks, as described in more detail below.

D. Regulatory risk-weighted assets

The denominator of the VR is the average regulatory risk weight (or risk weight 'density'). This is calculated by dividing total regulatory RWAs by total assets. The latter is based on each bank's accounting standard, which can result in different outcomes. For example, International Financial Reporting Standards (IFRS) have more restrictive derivative offsetting requirements than US GAAP. For a given portfolio, a bank will report a bigger balance sheet size under IFRS relative to US GAAP. To account for these differences in accounting standards we use two different approaches. First, we increase the size of US GAAP-reported total assets based on a scalar of IFRS balance sheet size relative to the US GAAP, as calculated by Hoenig (2016).[6] On average, this results in a 30% increase in the size of the balance sheet of US banks and therefore a corresponding reduction in their average risk weights. Average regulatory risk weights using this approach are denoted *Regulatory RWA*. Secondly, we calculate regulatory risk weights by dividing RWAs with the Basel III leverage ratio exposure measure (denoted *Regulatory RWA_LRE*). We consider this a more robust measure of average regulatory risk-weighted assets, as it uses an

[6] Based on an estimate for the 8 US G-SIBs, the weighted average conversion ratio is 1.3.

accounting-neutral measure of size, and provides greater comparability across countries. But leverage ratio exposure data is only available from 2010 onwards. As such, we make use of both approaches when presenting our results.

E. Market-implied risk-weighted assets

We develop a market-implied measure of RWAs using data on banks' annual expected default frequency (EDF) produced by Moody's KMV model. The latter is calculated based on a Merton distance-to-default model, and is a proxy for the probability of default of a bank. It takes into account both qualitative (eg region, industry type) and quantitative factors of a banks' risk profile.

We average the daily EDF over each calendar year for each bank, resulting in an annualised PD value. This allows us to use this value as an input into the capital requirement formula prescribed by the F-IRB approach to derive a market-implied measure of RWAs. That is, the EDF is the market-implied PD measure. The other risk parameters in the F-IRB formula are prescribed in the Basel framework.[7]

Unlike other market-based measures of risk (eg credit default swap spreads), the EDF is calculated from the perspective of bank equity holders, and is therefore closely aligned with the calibration of regulatory capital requirements. Accordingly, it takes into account both the underlying risk of banks' assets and its level of indebtedness by comparing the total market value of assets with banks' market capitalisation. Our market-implied RWAs are therefore, by construction, sensitive to different levels of bank leverage.

By contrast, regulatory RWAs only reflect the risk of banks' assets, independent of leverage. Therefore, in order to compare market and regulatory RWA densities, we need to control for differences in leverage across banks when calculating the market based measure of RWAs. We use two methods to estimate a market-implied measure of RWAs that is independent of leverage and therefore akin to the regulatory measure: (i) a regression based adjustment; and (ii) a within KMV model adjustment.

(i) Regression based leverage adjustment

In the regression-based approach we first develop a simple model of market-implied RWAs unadjusted for leverage. Market-implied RWAs reflect both the asset and liability characteristics of the bank – which we refer to as *Market RWA_U*. Our regression-based approach delivers a market-implied measure of RWAs that controls for leverage, which we refer to as *Market RWA*.

To arrive to such a measure, we regress *Market RWA_U* for bank *i* in time period *t* as a function of its market leverage ratio and asset volatility as follows:

7 Specifically, under the F-IRB approach, RWAs are calculated according to the following formula: $RWA = 12.5 * \left[LGD * \Phi\left((1-R)^{-0.5} * \Phi^{-1}(PD) + \left(\frac{R}{1-R}\right)^{0.5} * \Phi^{-1}(0.999)\right) - PD * LGD\right] * \frac{(1+(M-2.5)*(0.11852-0.05478*\log(PD))^2)}{1-1.5*(0.11852-0.05478*\log(PD))}$. The parameters LGD and M are set to 45% and 2.5, respectively. The parameter R is the asset value correlation, which varies by asset class. Higher levels of LGD translates into higher market implied risk-weighted assets, as shown in Figure 2.

$$Market\ RWA_{U_{it}} = \alpha + \beta_1 Market\ Leverage\ Ratio_{it} + \beta_2\ Asset\ Volatility_{it} \quad (2)$$

$$+\beta_3\ (Asset\ Volatility)^2_{it} + \tau_t + \mu_i + \varepsilon_{it}$$

Where: the market leverage ratio is defined as the ratio of the bank's market capitalisation to its total assets (market value); asset volatility is based on Moody's KMV model; τ_t are time dummy coefficients; μ_i is the bank specific error, and ε_{it} is the residual. We include the squared value of asset volatility to capture any non-linear relationship between market-implied risk weights and asset volatility.

Table 3 presents the regression estimates of Equation (2). The baseline Model (1) covers the full sample period 2001 to 2016. As expected, there is a strong and significant negative relationship between the *Market Leverage Ratio* and *Market RWA_U*, as banks with greater leverage (ie a lower market leverage ratio) have higher risk weights. The model also suggests that market-implied RWAs are positively related to asset volatility. However, the relationship is non-linear, given that the market risk weights increase at a decreasing rate (as asset volatility rises). This result is expected given the specification of the F-IRB RWA formula.

In Models 2 and 3, we test the sensitivity of the analyses to applying different LGD values in the F-IRB formula. That is, instead of the default 45% LGD value, we also consider LGD values of 40% and 50%. A higher LGD implies that the unadjusted market-implied RWA is more sensitive to the market leverage ratio and asset volatility (ie the magnitude of these coefficients increases accordingly). Model (4) restricts the sample period to 2008-2016 (ie covering the onset of the financial crisis period and subsequent years) and provides similar results to Model (1).

Using the coefficient estimates from Equation (2), the market-implied RWA (adjusted for the average leverage ratio of the banks in the sample) for bank *i* in period *t*, is calculated as follows:

$$Market\ RWA_{\mathrm{it}} = Market\ RWA\_U_{\mathrm{it}} + \beta_1 \left(\overline{\text{Market Leverage Ratio}_{\mathrm{t}}} - \text{Market Leverage Ratio}_{\mathrm{it}}\right) \quad (3)$$

where $\overline{Market\ Leverage\ Ratio_t}$ is the average market leverage ratio (across all banks) in year *t*.

This allows us to hold leverage constant across banks, so that the *Market RWA* only reflects differences in the riskiness of banks' assets.[8]

[8] To test the robustness of the results, we also calculated the leverage adjusted market-implied RWA by replacing each bank's market leverage ratio with the average market leverage ratio for the sample considering only the last two months of the year (ie November and December). The results are very similar and therefore not reported.

Market-implied risk weights unadjusted by leverage				Table 3
	(1)	(2)	(3)	(4)
	Market RWA_U	Market RWA_U	Market RWA_U	Market RWA_U
Constant	0.449***	0.399***	0.499***	0.438***
	(11.78)	(11.78)	(11.78)	(7.94)
Market Leverage Ratio	-0.026***	-0.023***	-0.029***	-0.045***
	(-7.4)	(-7.4)	(-7.4)	(-9.27)
Asset Volatility (%)	0.133***	0.118***	0.148***	0.199***
	(8.77)	(8.77)	(8.77)	(15.55)
[Asset Volatility (%)]^2	-0.003***	-0.002***	-0.003***	-0.005***
	(-3.83)	(-3.83)	(-3.83)	(-8.73)
FIRB-LGD	45%	40%	50%	45%
Asset Volatility Measure	Annual Average	Annual Average	Annual Average	Annual Average
Observations	1141	1141	1141	677
Time dummies	Yes***	Yes***	Yes***	Yes***
Time period	2001-2016	2001-2016	2001-2016	2008-2016
Number of banks	76	76	76	76
Number of countries	21	21	21	21
R-squared	0.74	0.74	0.74	0.75
Estimator	RE (Robust)	RE (Robust)	RE (Robust)	RE (Robust)

Notes: The dependent variable is calculated by substituting the annual average KMV EDF (a measure of a bank's probability of default (PD)) into the Basel Framework F-IRB formula, which assumes a given loss-given-default (LGD), eg 40%, 45% or 50%. T-statistics using robust standard errors in parenthesis.

Legend: * p-value<10%; ** p-value<5%; *** p-value<1%.

(i) Within KMV model adjustment

Given the proprietary nature of KMV, it is not possible to directly control for leverage within the model and re-estimate the EDF. However, within the KMV model, Distance to Default (DD) is approximately equal to the ratio of leverage to asset volatility.

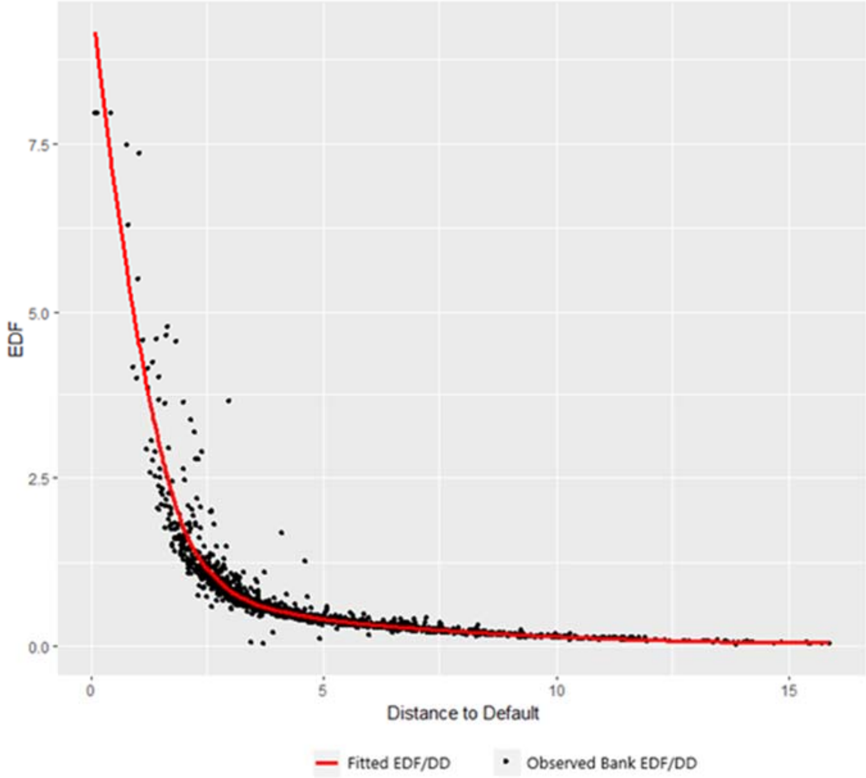
Building on Moody's (2012), the distance of default of bank i can be calculated as:

$$DD_i = \left[\underbrace{\ln\left(\frac{Assets_i}{Debt_i}\right)}_{\text{linear approximation}} + \underbrace{\left(\mu_{it} - \frac{1}{2}\sigma_i^2\right)}_{\text{close to zero}} \right] \times \frac{1}{\sigma_i} \approx \underbrace{\left(\frac{Assets_i - Debt_i}{Assets_i}\right)}_{\text{leverage}} \times \frac{1}{\sigma_i} = \frac{Leverage_i}{\sigma_i} \quad (4)$$

It is therefore possible to measure DD for a bank given its asset volatility and the market average leverage. With this leverage adjusted measure of DD, it is then possible to map this measure of DD to the EDF, which can be interpreted as a leverage adjusted measure of EDF.

Figure 1 illustrates the process. It shows the fitted non-linear relationship between EDF and DD. To map the leverage adjusted DD to a leverage adjusted EDF we use two approaches. First, we map DD to EDF using the fitted curve (fitted 1). This ignores deviations from the fitted curve, and can be thought of as an expected value approach. The second approach retains the deviation from the curve when mapping the leverage adjusted DD to EDF using the fitted curve (fitted 2). Retaining the deviation from the fitted curve allows for unobserved factors, in addition to DD, to affect the estimated EDF.

Empirical relationship between EDF and distance to default — Figure 1



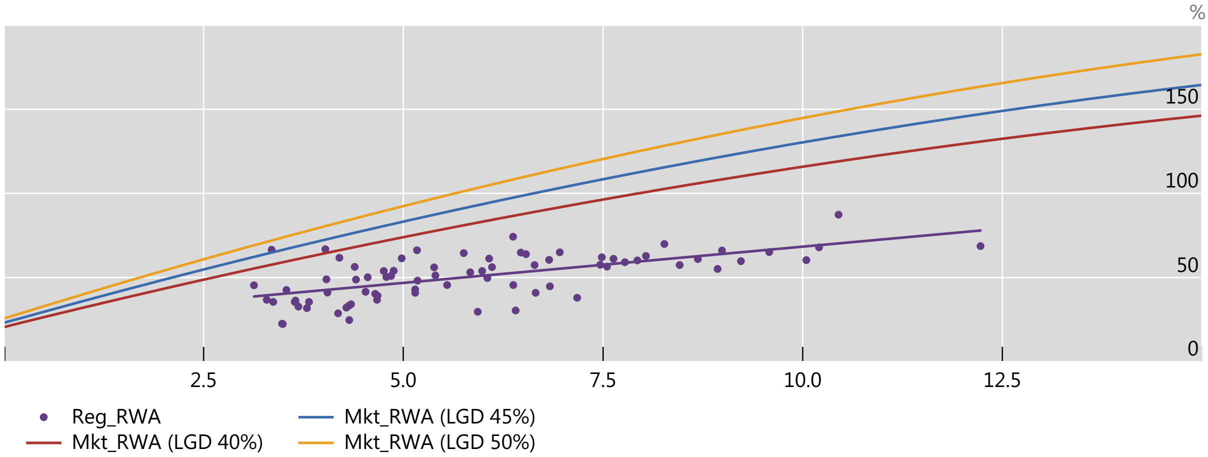
For the remainder of the paper we use present our baseline results using the regression-based approach for calculating the leverage adjusted measure of market RWAs. As a robustness check we present a summary of the results using the within KMV model adjustment approaches. These results are summarised in Table 12.

F. Asset volatility and leverage

Figure 2 plots the relationship between asset volatility and the estimated *Market RWA* under different LGD assumptions and *Regulatory RWA*. The *Market RWA* (the red, blue and yellow lines) are based on the estimates from Table 3 (Models 1 to 3). As implied by the regression estimates, RWAs increase with asset volatility at a decreasing rate (ie the line is concave). Each purple dot shows the average *Regulatory RWA* for each bank in the sample and its corresponding asset volatility.

For the purposes of presentation, we have constructed the curves given the average level of the market leverage ratio, which across the entire sample is 10.3%.

Regulatory and market-implied risk weights for different levels of asset volatility | Figure 2



Asset volatility is on the X-axis and risk weights are on the Y-axis. Estimation based on Equations (1)-(3) in Table 3.

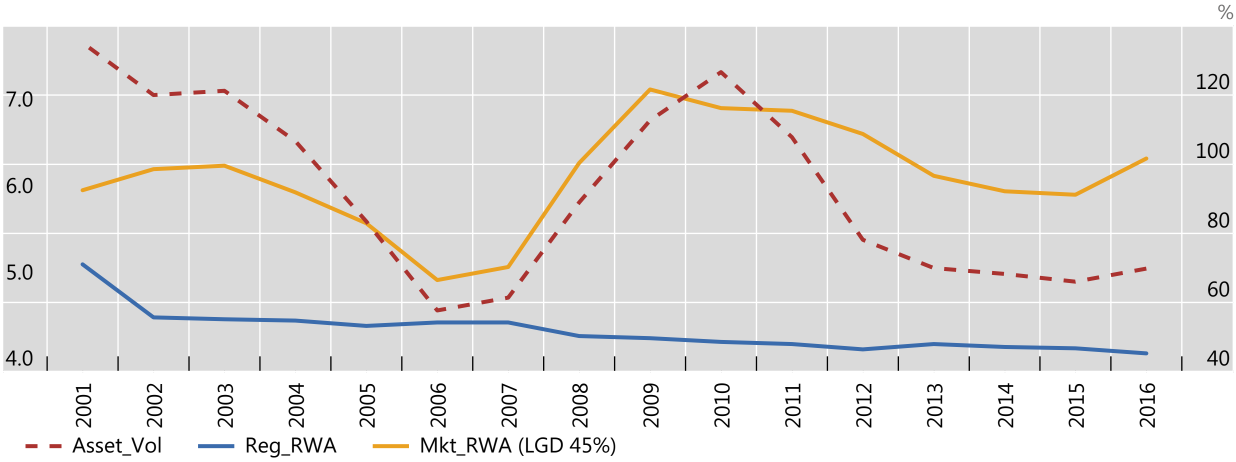
There are three main takeaways from Figure 2. First, for any given level of asset volatility, banks' regulatory risk weights vary considerably. For an equivalent level of riskiness of banks' assets (as measured by asset volatility), there is a high degree of variability in banks' estimated regulatory RWAs. This variability is evident even though the regulatory RWA for each bank has been averaged over the entire sample period.

Second, for a given asset volatility level, banks' estimated regulatory risk weights are lower than those implied by the market. Put differently, the market assigns a greater degree of risk to banks' assets than those assigned directly by banks under the regulatory framework. This applies irrespective of the assumed LGD used in the F-IRB formula.

Third, regulatory RWAs appear to be less risk-sensitive than market-implied RWAs. The slope of the fitted line of the regulatory RWAs is flatter than the curves for the different market-implied risk-weights. There is however a positive relationship between regulatory and market RWAs and asset volatility.

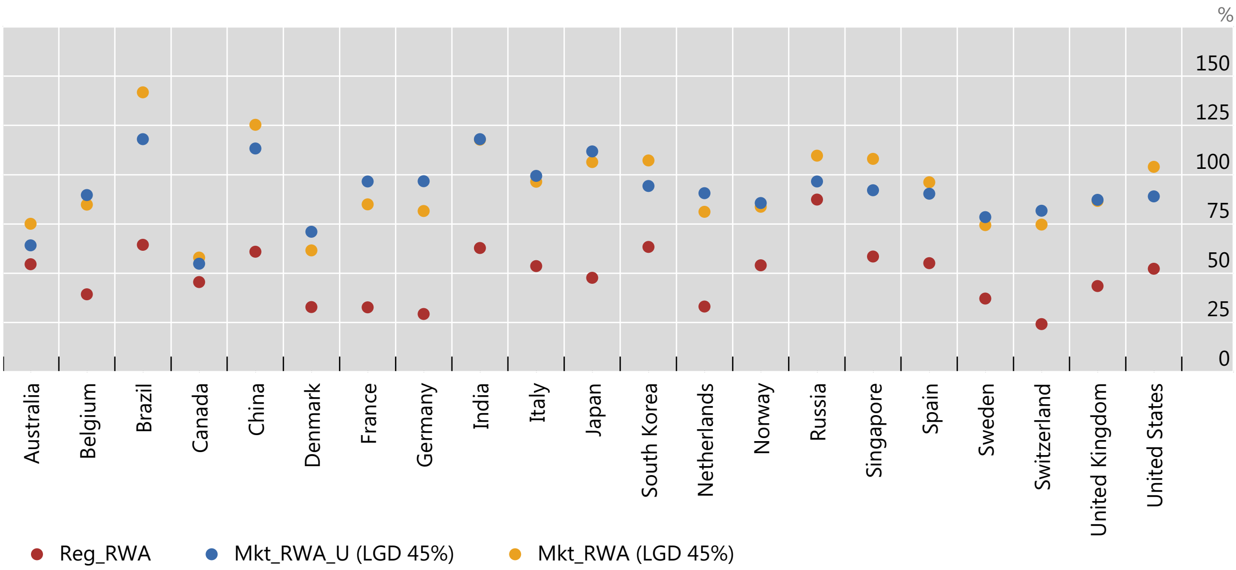
Figure 3 shows the evolution of risk weights (both regulatory- and market-implied as given by baseline Model 1) and asset volatility over the period 2001-2016. Both the market-implied risk weights and asset volatility are significantly more cyclical than regulatory risk weights. The former declines during the pre-crisis boom period, and then increases sharply with the onset of the financial crises in 2008. By 2016, the market-implied measure of RWA declines, but remains well above its pre-crisis lows. By contrast, regulatory risk weights decline gradually throughout the sample period and are consistently below the market implied risk weights.

Regulatory risk weights, market implied risk weights and asset volatility | Figure 3



Left hand side Y-axis: asset volatility, right hand side Y-axis: average risk weights.

Regulatory and market-implied RWAs (2001 – 2016) | Figure 4



The ratios are averages within each country. A bank level average is first calculated over the sample period, before calculating the weighted average by country.

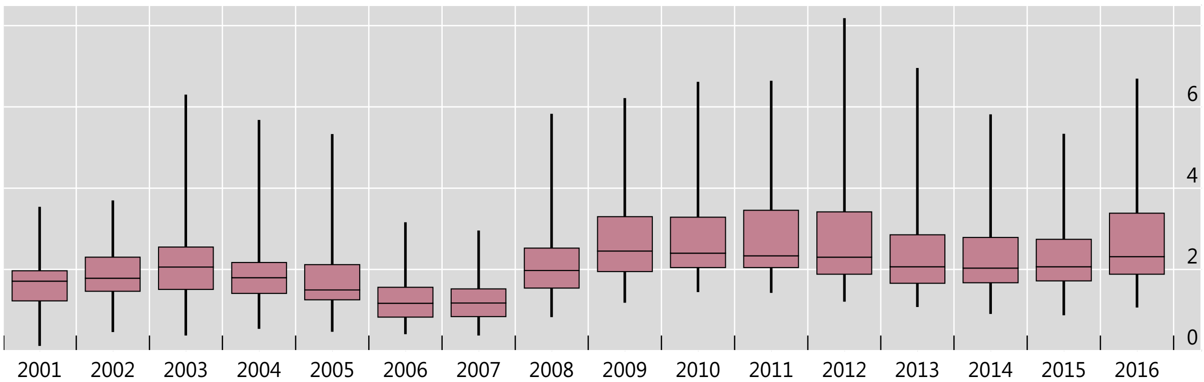
Figure 4 compares regulatory risk weights (red dots), market-implied risk weights unadjusted for leverage (blue dots) and market-implied risk weights adjusted for leverage (yellow dots) – given by the baseline Model 1 - across jurisdictions. In all jurisdictions, average regulatory risk weights are below the market-implied risk weights. There are three broad clusters of regulatory risk weights across jurisdictions: (i) low risk weights (close to 25%); (ii) medium risk weights (around 50%); and (iii) relatively high risk weights (RWAs above 60%). Figure 4 also shows the effect of the leverage adjustment on the market-implied RWA across jurisdictions. For example, the market-implied risk weights in countries with relatively low levels of leverage (eg Brazil, China, Russia, South Korea and the US) increases as a result of our adjustment. Conversely, the leverage adjustment lowers the market-implied risk weights in countries with relatively high levels of leverage (eg France, Germany, Japan, Italy and the Netherlands), thereby narrowing the gap between market and regulatory RWAs.

G. Cross-country and time dimensions of the Variability Ratio

The preceding analysis focused on the development and analysis of the numerator and denominator of the VR. Bringing these two components together, this section investigates the performance of the VR across banks and jurisdictions. Figure 5 shows the VR distribution across banks over the period 2001 to 2016. For most of this period, the median value of the VR is around 2 (ranging from 1.6 to 2.4). A VR of 2 implies that the market-implied risk weight of a bank is twice that of the regulatory risk weight. Throughout this period, the median regulatory risk weight was always below the level implied by our market measure of bank risk. The median value and interquartile range for the VR are lowest in the period immediately preceding the crisis period (2006 to 2007), which largely reflects cyclicality in the market-implied measure of RWAs, relative to the stability of average regulatory risk weights.

Variability Ratio over time

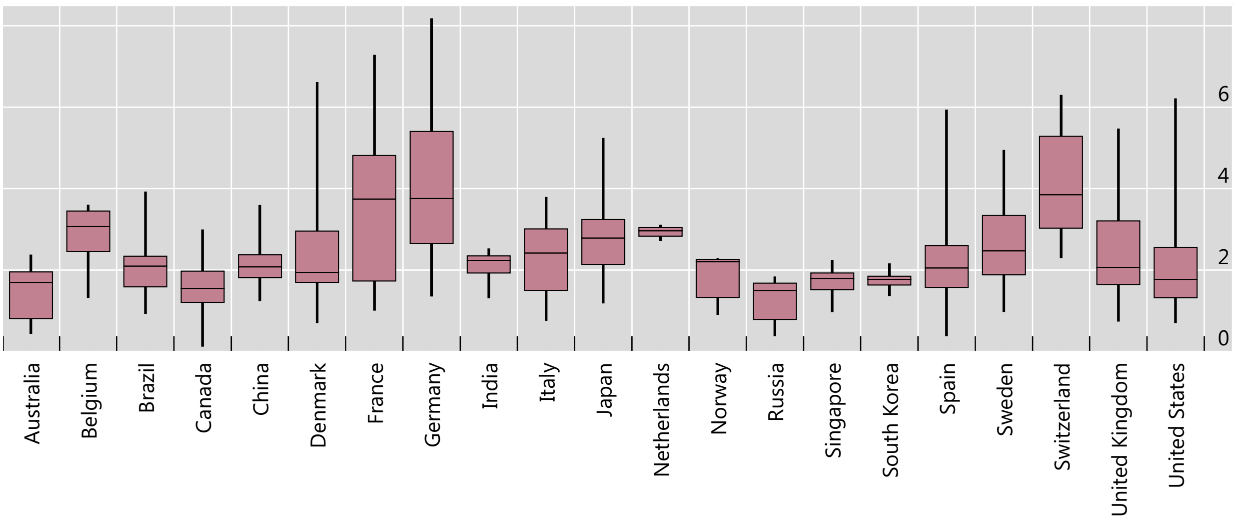
Figure 5



Cross-country differences in the VR are shown in Figure 6 for the period 2001 to 2016. There is considerable variation both across and within countries. Although not shown, this is also the case for the period 2008 to 2016 only (ie ignoring the pre-crisis years).

Variability Ratio by country: 2001–2016

Figure 6



IV. The determinants of RWA variability

Having developed our measure of RWA variability, we now turn to the question of what are its drivers. In principle, there are a number of reasons why market-implied and regulatory measures of RWAs could differ, resulting in a VR greater than or less than one. We consider four hypotheses that could potentially explain such variability, as measured by the VR:

(H1) *Asymmetric information / opaqueness*: Banks could have an information advantage regarding the riskiness of some or all of their assets compared to market participants. For example, there may be insufficient public information on certain complex instruments or opaque assets held by banks. This could lead to differences in risk assessments, but the direction of the difference is unclear as market assessments of risk could be higher or lower than bank assessments of the same risk.

(H2) *Differences in risk assessments*: For a given information set, market participants may be more or less risk averse than banks. Moreover, market assessments may incorporate other factors such as perception that some banks are considered Too-Big-Too-Fail (TBTF), which would imply a lower VR for such banks.

(H3) *Jurisdiction-specific effect:* There could be structural differences across markets, such as legal and institutional factors, that may lead to variation between market and regulatory measures of risk. For example, legal differences across jurisdictions may affect losses on defaulted loans, which are assumed fixed across jurisdictions in the F-IRB. To the extent that such differences are reflected in market measures of risk, this could result in a VR greater or less than one.

(H4) *Gaming*: Another source of RWA variability could be due to banks gaming their internal models. This understating of risk results in a gap between the market-implied and regulatory risk weights, resulting in a VR greater than one.

A. Model specification and estimation

To test the four hypotheses outlined above, we specify and estimate various models of: (i) the determinants of the *VR*; and (ii) the determinants of average regulatory risk weights, *Regulatory RWA*. While the focus of the analysis is on the determinants of the VR, the models of the determinants of *Regulatory RWA* serve as a robustness check, and allow us to check whether the VR results are driven by either the numerator (*Market RWA*) or denominator (*Regulatory RWA*) of the ratio.

In general form, the model specification is given as[9]:

$$\begin{aligned} VR_{it} = \alpha + \beta(Portfolio\ Mix_{it}) + \gamma(Asset\ Quality_{it}) + \kappa\,(Size_{it}) \\ + \eta(Business\ Model_{it}) + \zeta\,(Macro_{ct}) + \kappa(Country_c) \\ + \tau\,(Year_t) + \mu_i + \varepsilon_{it} \end{aligned} \qquad (5)$$

Where for bank i, in period t and country c, *Portfolio Mix* includes the ratio of loans to assets, securities to assets and derivatives to assets; *Asset Quality* includes non-performing loans and return on assets; *Size* is the natural log of total assets; *Business Model* includes measures of funding fragility, income diversity and efficiency; *Macro* is real GDP growth; *Country* and *Year* are country and time dummies respectively; u_i are the bank specific effects, and ε_{it} is the residual. The definition of each variable used in Equation 5 and the data sources are summarised in Table 2.

Equation 5 includes a range of variables that capture elements or more than one of the four hypotheses. That is, there is not necessarily a direct mapping between a particular hypothesis and the explanatory variables. For example, the *Size* variable potentially captures elements of hypotheses 2 and 4. On the one hand, to the extent that market participants assume that larger banks benefit from (implicit) government support, these banks would be expected to have a lower VR than smaller banks, all else equal (hypothesis 2). On the other hand, larger banks are more likely to undertake complex business operations and have a greater reliance on internal models, which could increase the VR (hypothesis 4).

The country dummy variables also allow us to test whether VRs are significantly different across countries, relative to the omitted base country which is the US. The annual time dummies account for potential cyclicality of the VR, while real DGP growth controls for the impact of the macroeconomy on market and regulatory measures of bank risk. We also include a number of control variables to capture differences in bank business models and asset risk.

We estimate several panel models using Random Effects (RE) and use robust estimators. The choice of the RE estimation is mainly driven by our interest in

[9] The specification of the model where the dependent variable is Regulatory RWA is largely the same as for Equation 4 and is detailed under hypothesis 3.

modelling RWA variability across three dimensions, banks (the individual effects), countries, and time. We conducted a number of statistical tests which supported the random effects specification. However, similar results are obtained when estimating the models using fixed effects with either firm or country dummies.[10]

To maximise the number of observations, we estimate the models using unbalanced panels, which include observations over a 16 year period (2001 to 2016). However, the sample size is smaller for the first 5 years (less than 50 banks) compared to the post-crisis period (greater than 70 banks).

Hypothesis 1: Information asymmetry and opaqueness of financial instruments

Table 4 presents the estimated regressions for the VR following the specification presented in Equation 5. Model 1 includes the full period sample (2001-2016), while the following three columns cover the pre-crisis period (Model 2), crisis period (Model 3) and post-crisis period (Model 4). The models are estimated over distinct periods to check the stability of the relationships across time. The column on the right (Model 5) measures the VR using *Regulatory RWA_LRE* (ie using the leverage ratio exposure measure). In this specification, the time series covers only the period post-crisis (2010-2016), given data on banks' leverage ratio exposure measure is limited to the post-crisis period. The advantage of Model 5 is that the leverage ratio exposure measure provides a more consistent basis for measuring exposure, relative to total assets which is affected by differences in accounting standards across jurisdictions.

The first hypothesis suggests that the opacity of banks' assets (or assets where banks have an information advantage over market participants) is a driver of variability. This is supported by the regression results. For example, Model 1 in Table 4 shows that there is a strong statistically significant association between the amount of banks' derivatives holdings – a relatively complex and opaque set of securities – and the VR. The sign of the coefficient suggests that banks with a greater share of such securities have a higher VR. Similarly, banks with a greater share of credit to total assets have a lower VR. This is consistent with the view that the market may be placing an 'opaqueness' premium when assessing the risk of such banks (resulting in market RWAs being greater than regulatory RWAs).

A similar result is shown in Model 4, which focuses on the post-crisis period. Again, there is a strong and statistically-significant positive relationship between the share of derivatives and the VR. This could suggest that, despite post-crisis regulatory reforms (which include additional disclosure requirements), the market continues to view banks with a larger share of opaque assets as riskier than other banks, all else equal.

[10] We performed the following tests: (i) the panel specification is supported by testing the residuals from OLS estimation are different from the RE estimation; (ii) the Hausman test showed the regressors were not linearly correlated to the residuals, supporting the RE estimation; (iii) the white test for heteroscedasticity supports the use of the Robust estimator; and (iv) we checked for multicollinearity by investigating the Variance Inflation Factors (VIF).

Determinants of the variability ratio (VR) Table 4

		VR (Regulatory RWA density using assets)				VR (Regulatory RWA using LRE) (5)
	Dependent variable	(1)	(2)	(3)	(4)	
Portfolio Mix	Credit to Assets	-1.504***	-2.262***	-2.473***	-1.418***	-1.58**
		(-3.21)	(-3)	(-2.84)	(-2.44)	(-2.08)
	Securities to Assets	-0.126	1.549*	0.377	-0.694	0.028
		(-0.17)	(1.77)	(0.38)	(-1.06)	(0.04)
	Derivatives to Assets	4.793***	0.319	1.523	4.551***	1.254
		(4.61)	(0.33)	(1.05)	(3.68)	(1.12)
Asset Quality	Non-performing Loans	0.064***	0.104	0.075**	0.004	-0.004
		(3.45)	(1.33)	(2.1)	(0.2)	(-0.23)
	ROA	-0.212***	-0.057	-0.369***	-0.161***	-0.136
		(-3.8)	(-0.59)	(-3.06)	(-3.6)	(-1.17)
Macroeconomy	Real GDP Growth	0.009	-0.033	0.017	-0.018	-0.024
		(0.45)	(-1.41)	(1.4)	(-0.57)	(-0.95)
Size	Log of Assets	-0.215**	-0.042	-0.042	-0.156**	-0.219***
		(-2.41)	(-0.58)	(-0.58)	(-1.96)	(-2.97)
Business model	Funding Fragility	0.172	0.313	-1.633*	1.676**	0.351
		(0.27)	(0.67)	(-1.82)	(2.09)	(0.42)
	Income Diversity	-0.12	0.022	0.102	-0.016	0.513*
		(-0.37)	(0.06)	(0.39)	(-0.05)	(1.74)
	Efficiency	-0.213	-0.026	-0.333***	0.462	0.864
		(-1.27)	(-0.05)	(-2.56)	(0.99)	(1.61)
Country Dummies	Australia	-0.056	0.196	0.367	0.184	0.905***
(base = United States)		(-0.21)	(0.66)	(1.07)	(0.55)	(2.86)
	Brazil	-0.223	-0.975	-0.277	-0.085	0.369
		(-0.73)	(-1.55)	(-0.79)	(-0.23)	(1.15)
	Canada	-0.587***	-0.889***	-0.31	-0.384***	0.019
		(-3.41)	(-4.38)	(-1.32)	(-2.65)	(0.11)
	China	0.000	0.914**	0.211	0.065	0.974***
		(0.000)	(2.2)	(0.92)	(0.17)	(3.08)
	France	0.386	-1.223***	0.636*	1.008***	1.276***
		(1.45)	(-2.77)	(1.7)	(2.44)	(4.44)
	Germany	0.001	-1.118***	0.307	1.029**	1.212***
		(0)	(-2.89)	(0.6)	(2.17)	(3.54)
	Italy	-0.521**	-0.446	-0.646***	0.295	0.705**
		(-2.23)	(-1.48)	(-2.57)	(0.75)	(2.04)
	Japan	0.696***		0.657*	0.601***	1.123***
		(2.93)		(1.88)	(2.92)	(5.12)
	South Korea	-0.468***		-0.573***	-0.064	0.442*
		(-2.5)		(-2.58)	(-0.37)	(1.7)
	Singapore	-0.363*	-0.348	-0.338	0.111	0.482**
		(-1.78)	(-1.02)	(-1.4)	(0.61)	(2.1)
	Spain	-0.299	-0.067	-0.434	0.333	0.802***
		(-1.43)	(-0.35)	(-1.56)	(1.03)	(2.97)
	Sweden	0.272	0.069	0.345	0.928***	1.04***
		(1.15)	(0.28)	(1.14)	(2.97)	(3.68)
	Switzerland	0.849***	0.293	1.681***	0.16	0.949***
		(2.75)	(0.63)	(6.43)	(0.76)	(3.58)
	United Kingdom	-0.332	-0.354	-0.144	-0.252	0.323
		(-1.3)	(-1.31)	(-0.3)	(-0.95)	(1.41)
	Belgium and Netherlands	-0.328	-0.366	0.752	-0.404	0.424
		(-1.5)	(-1.41)	(1.04)	(-1.29)	(1.54)
	Denmark and Norway	0.088	-0.586***	-0.244	0.698***	1.009**
		(0.31)	(-3.07)	(-1.27)	(2.9)	(2.08)
	India and Russia	-0.335**	-1.073***	-0.098	0.22	0.821***
		(-2.06)	(-4.11)	(-0.36)	(0.91)	(3.86)
Time Control	Year Dummies	Yes***	Yes***	Yes***	Yes***	Yes***
	Time period	2001-2016	2001-2007	2008-2011	2012-2016	2010-2016
Model statistics	Observations	752	164	238	350	416
	Number of Banks	74	49	68	74	72
	Number of Countries	20	18	20	20	20
	R-squared (overall)	0.63	0.85	0.68	0.74	0.61

Significance of the coefficients: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated as panel with Random Effects (robust estimator).

To further investigate the impact of complex and opaque assets on the VR, we estimate the impact of the indicators used to determine whether a bank is a global systemically-important banks (G-SIB) (see BCBS (2013b)). The G-SIB framework includes a set of indicators that capture different dimensions of systemic risk, such as size, interconnectedness, substitutability, complexity and cross jurisdictional activity. The G-SIB indicators use consistent definitions across banks and countries, which allows for a more comparable assessment compared to accounting values. However, the consistency of the G-SIB indicators comes at the cost of a reduced sample size that covers only four year (2013-2016).

The model is specified as follows:

$$VR_{it} = \alpha + \beta\,(GSIB\ Indicator_{it}) + \kappa(Country_c) + \tau\,(Year_t) + \mu_i + \varepsilon_{it} \quad (6)$$

Where *GSIB Indicator* represents the set of five systemic risk dimensions in the G-SIB framework: (i) the Leverage Ratio Exposure (LRE) measure (size); (ii) inter-financial assets and liabilities and securities outstanding (interconnectedness); (iii) payments, custody and underwriting (substitutability); (iv) OTC derivatives, trading and available for sale (AFS) securities and Level III assets (complexity); and, (v) cross-jurisdictional claims and liabilities (cross jurisdictional activity). The model also includes time and country dummies.

The estimates of Equation 6 are presented in Table 5. Following the previous analysis, Models 1 to 6 differ from Models 7 to 12 in their VR definition. The first six models normalise regulatory RWA by total assets and the latter six models normalise regulatory RWA by LRE. Models 1 and 7 include the full set of G-SIB indicators while the other models test each set of G-SIB indicators separately. Consistent with the results in Table 4, the results in Models 1 and 7 (and in Models 5 and 11) show a positive relationship between OTC derivatives and the VR, which is significant at the 1% level. This provides additional support for the opaqueness hypothesis. Moreover, Model 1 provides some evidence of a positive relationship between the VR and trading and AFS securities (which are more closely associated with market risk exposures) and level 3 assets, which are valued based on a banks' models and also often viewed as opaque assets).

Determinants of the variability ratio (VR) using G-SIB indicators — Table 5

		VR (Regulatory RWA using Assets)						VR (Regulatory RWA using LRE)					
G-SIB Category	GSIB Indicator	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
Size	LRE Measure	-0.136	-0.036					-0.075	-0.015				
		(-1.07)	(-0.45)					(-0.73)	(-0.21)				
Interconnectedness	Interfinancial System liabilities	-0.032		0.021				-0.019		0.015			
		(-0.31)		(0.2)				(-0.21)		(0.17)			
	Interfinancial System assets	0.057		0.145***				0.089		0.168***			
		(0.85)		(2.51)				(1.59)		(3.06)			
	Securities outstanding	-0.13		-0.222**				-0.31***		-0.371***			
		(-1.22)		(-2.12)				(-2.44)		(-2.9)			
Substitutability	Payments	0.053			0.085			0.008			0.051		
		(0.66)			(1.21)			(0.12)			(0.8)		
	Custody	-0.041			-0.023			-0.031			-0.011		
		(-1.5)			(-0.73)			(-1.36)			(-0.35)		
	Underwriting	-0.05			-0.043*			-0.045			-0.04		
		(-1.6)			(-1.7)			(-1.47)			(-1.5)		
Complexity	OTC Derivatives	0.212***				0.115**		0.191***				0.126***	
		(2.93)				(2.08)		(2.98)				(2.68)	
	Trading and available for sale securities	0.073*				0.063		0.049				0.042	
		(1.63)				(1.47)		(1.01)				(0.89)	
	Level 3 Assets	0.053**				0.025		0.031				0.003	
		(2.28)				(1.14)		(1.53)				(0.16)	
Cross Jurisdictional	Claims	-0.041					0.017	-0.075					0.002
		(-0.63)					(0.29)	(-1.17)					(0.03)
	Liability	-0.039					-0.001	-0.013					0.027
		(-1.35)					(-0.02)	(-0.38)					(0.57)
Country Control	Country Dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
	Number of Countries	20	20	20	20	20	20	20	20	20	20	20	20
Time Control	Year Dummies	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***	Yes***
	Time period	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016	2013-2016
Model statistics	Observations	261	278	278	270	269	278	261	278	278	270	269	278
	Number of Banks	71	74	74	73	72	74	71	74	74	73	72	74
	R-squared (overall)	0.73	0.66	0.67	0.68	0.69	0.66	0.72	0.63	0.67	0.66	0.67	0.64

Significance of the coefficients: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated as panel with Random Effects (robust estimator).

Hypothesis 2: Differences in risk assessments and perspectives

The second hypothesis relates to differences in risk assessments and perspectives between market participants and banks. Quantifying such differences is inherently difficult, given the judgemental element related to risk analysis. So we focus on one possible area of difference: the likelihood of government support.

While post-crisis reforms, including both going- and gone-concern regulatory requirements and measures related to bank resolution regimes, have sought to end the perceived 'too-big-to-fail' (TBTF) status of some banks, market participants could still be of the view that some banks would receive implicit or explicit support in times of stress. All else equal, our market measure of risk would therefore view such banks as less risky than other banks.

To examine this hypothesis, we test whether bank size affects the VR. In this context, the implied market RWA (and therefore the VR) for a bank viewed as TFBF would be lower than for a bank that is not viewed as TBTF.

The results in Table 4 provide some evidence to support the TBTF hypothesis. Models 1, 4 and 5 show a significant negative relationship between bank size and the VR. Interestingly, a common feature of these models is that the sample estimation period includes the post-crisis period. Although, the TBTF hypothesis is usually associated with the size of the bank, the G-SIB framework includes other systemic risk dimensions in the identification process. The results in Table 5, which focus on the decomposition of G-SIB indicators, suggest a negative but statistically insignificant association between the VR and bank size. By contrast, other systemic risk dimensions are significant, most notably complexity, and to a lesser extent interconnectedness.

Hypothesis 3: Jurisdiction-specific effects

The third hypothesis relates to jurisdiction specific effects. Put simply, there may be structural and institutional differences across countries that result in different market and regulatory assessments of the riskiness of bank assets. The coefficients on the country dummy variables measure whether the VR in a particular country differs from the US (which is omitted from the regression).

The results in Table 4 show strong statistically significant differences in the VR across countries, even after controlling for various measures of bank risk, business model features, the influence of the macroeconomy, and bank-specific effects. The results do however vary depending on whether the sample period is pre- or post-crisis.

For the post-crisis period (2010 to 2016), most countries have a significantly higher VR than the US, with the largest differences observed for Germany, Japan, and France. There is however no significant difference in the VR between the US and five other countries (Brazil, Canada, the UK, and Belgium and the Netherlands).[11] Canada is the only country where there is some evidence of a significantly lower VR relative to the US in the post-crisis period sample, however this result is only observed in Model 4 (which uses assets to measure size) and not in Model 5 (which uses the

[11] To ensure that there is a sufficient number of banks represented by each country dummy variable, banks from some jurisdictions are combined into groups, namely Belgium and The Netherlands, Denmark and Norway, and India and Russia.

leverage ratio exposure measure). As noted above, the post-crisis results differ from the pre-crisis period (2001–2007). During the pre-crisis period, relative to the US, the VR is significantly lower in Canada, France, Germany, Denmark and Norway, and India and Russia. Finally, China is the only country where the VR is significantly positive in both the pre-crisis and post-crisis periods (Models 2 and 5). A possible explanation is that the market might find it harder to assess asset risk in jurisdictions with relatively limited data on banks' risk and exposures, resulting in a higher VR for banks in that jurisdiction compared to banks in the US – a kind of country specific opaqueness.

At the country level, it is not possible to determine whether differences in the VR are driven by banking or supervisory practices that influence regulatory RWAs, market perceptions of the riskiness of banking systems in particular countries, or other legal and institutional characteristics. We do however know that the country specific differences are not driven by bank size, portfolio mix, asset performance, business model characteristics, bank size, or other bank-specific affects.

To further explore how country dummies affect the VR, we estimate a model where the dependent variable is *Regulatory RWA* (ie the denominator of the VR). This serves as a robustness test with the VR regression results, and also allows us to identify whether the country effects drive differences in regulatory or market-implied RWAs. The *Regulatory RWA* model follows the specification given by Equation 5, but includes KMV asset volatility as an additional measure of asset quality. This variable is included as an independent measure of bank risk. It is not included in VR model since the *Market RWA* (and therefore *VR*) already incorporates this information.

The regression estimates are presented in Table 6. A negative (positive) coefficient on a country dummy variable implies that *Regulatory RWA* are lower (higher) in a given country relative to the US, all else equal. Unlike the results for the VR regressions, the results in Table 6 are stable across the various sample periods (pre- and post-crisis), implying that regulatory measures of RWA are far more stable than the market implied measures of asset risk. As shown in Section II of the paper, the time series variation in the *VR* is driven by changes in the *Market RWA*, rather than changes in *Regulatory RWA*.

A striking feature of the results in Table 6 is that banks from emerging market economies (Brazil, China, India and Russia) have significant and persistently higher regulatory RWAs than the US, whereas banks domiciled in advanced economies (Australia, Germany, Italy, Japan, Spain, Sweden, Switzerland, the UK, Belgium and The Netherlands, and Denmark and Norway) have persistently lower regulatory RWAs. The results for South Korea and Singapore are mixed.

More generally, the results in Tables 4 and 6 point to five broad findings. First, we find a group of countries (including France, Germany, Japan, Sweden and Switzerland) that have a statistically-significant and positive association with the VR, and a negative association with *Regulatory RWA*. Put differently, even after controlling for a range of factors, banks in these jurisdictions exhibit a higher degree of RWA variability and have lower regulatory RWAs compared to the baseline US banks. This could be due to a number of factors, including jurisdiction-specific institutional features, and differences in supervisory approaches and oversight of banks' internal models.

Second, we find a positive and significant association between the China dummy and both the VR and regulatory RWAs. Even though Chinese banks have higher regulatory risk weights compared to the baseline US banks, they exhibit a higher degree of variability based on the market measure. This could be due to an incremental ‘information asymmetry’ effect being applied to Chinese banks, where the market is placing an additional jurisdiction-specific ‘opaqueness’ premium on such banks. A similar patterns is observed for India and Russia.

Third, we find the reverse for Canadian banks, which report lower regulatory RWAs compared to US banks, but also exhibit a lower degree of RWA variability. It is unclear what could be driving this outcome, which suggests that lower average risk weights do not necessarily imply greater RWA variability.

Fourth, the results show that banks with a greater share of credit to assets have significantly higher regulatory RWAs and lower RWA variability.

Finally, the results in Table 6 point to a negative and statistically significant association between asset volatility and regulatory RWAs. This suggests that a higher degree of bank risk as measured by asset volatility is associated with lower regulatory-determined RWAs. This result is counter-intuitive and raises questions about the relationship between market and regulatory measures of asset risk. We explore this issue further in the following section where we examine the gaming hypothesis.

Determinants of RWA						Table 6
		Regulatory RWA using Assets				Regulatory RWA
	Dependent variable	(1)	(2)	(3)	(4)	using LRE (5)
Portfolio Mix	Credit to Assets	0.511***	0.772***	0.357***	0.513***	0.589***
		6.59	7.51	4.05	8.53	6.13
	Securities to Assets	-0.006	0.049	-0.134*	0.094	0.022
		-0.07	0.58	-1.91	1.53	0.23
	Derivatives to Assets	0.023	-0.02	-0.017	-0.029	0.205
		0.25	-0.14	-0.14	-0.18	0.98
Asset Performance	KMV Asset Volatility	-0.009**	-0.006	-0.006**	-0.005	-0.009*
		-1.98	-1.34	-2.07	-1.12	-1.92
	Lagged NPL	0.00	-0.011*	0.00	-0.001	0.002
		-0.11	-1.69	-0.04	-0.58	0.66
	ROA	0.013*	0.028	0.014*	-0.002	-0.007
		1.67	1.43	1.73	-0.32	-0.38
Macroeconomy	Real GDP Growth	-0.006***	-0.001	-0.004***	0	0.003
		-3.06	-0.33	-3.23	0.02	1.01
Size	Log of Assets	-0.003	0.003	-0.013	0.014	0.003
		-0.19	0.16	-1.28	1.34	0.18
Business model	Funding Fragility	0.073	0.015	0.103	-0.066	0.049
		1.09	0.26	1.62	-1.2	0.52
	Income Diversity	0.026	0.041	0.038	0.034	-0.015
		0.8	1.01	1.31	0.96	-0.32
	Efficiency Ratio	0.017	0.151***	0.013	-0.057	-0.018
		1.16	3.15	1.13	-1.1	-0.22
Country Dummies	Australia	-0.183***	-0.109**	-0.166***	-0.185***	-0.304***
(base = United States)		-5.46	-2.37	-3.3	-5.14	-5.88
	Brazil	0.158***	0.323**	0.134***	0.187***	0.135***
		2.77	1.96	2.7	4.05	2.85
	Canada	-0.199***	-0.133***	-0.168***	-0.206***	-0.302***
		-6.65	-3.43	-4.71	-7.9	-8.11
	China	0.131***	0.111	0.087**	0.114***	-0.019
		3.78	1.26	2.35	2.74	-0.45
	France	-0.198***	-0.082**	-0.178***	-0.185***	-0.265***
		-6.02	-2.33	-4.89	-5.36	-5.26
	Germany	-0.204***	-0.09**	-0.202***	-0.157***	-0.296***
		-6.44	-2.2	-4.48	-2.97	-4.73
	Italy	-0.202***	-0.114	-0.172*	-0.202***	-0.291***
		-2.55	-1.15	-1.66	-3.21	-2.91
	Japan	-0.164***		-0.105**	-0.171***	-0.262***
		-5.12		-1.95	-6.37	-7.4
	South Korea	0.006		0.097***	-0.018	-0.170***
		0.24		2.69	-0.8	-3.73
	Singapore	0.027	0.195**	0.021	-0.019	-0.089**
		0.69	2.27	0.39	-0.63	-2.38
	Spain	-0.115***	-0.035	-0.074**	-0.111***	-0.223***
		-4.02	-0.94	-1.95	-3.25	-4.22
	Sweden	-0.281***	-0.154***	-0.205***	-0.349***	-0.421***
		-9.87	-4.12	-5.64	-8.78	-7.57
	Switzerland	-0.225***	-0.153***	-0.222***	-0.18***	-0.308***
		-8.43	-3.81	-8.61	-4	-9.18
	United Kingdom	-0.15***	-0.08*	-0.132***	-0.135**	-0.233***
		-3.24	-1.83	-2.46	-2.16	-3.57
	Belgium and Netherlands	-0.202***	-0.114	-0.172*	-0.202***	-0.291***
		-2.55	-1.15	-1.66	-3.21	-2.91
	Denmark and Norway	-0.204***	-0.122***	-0.086***	-0.221***	-0.296***
		-5.29	-3.86	-2.92	-5.49	-3.13
	India and Russia	0.274***	0.061	0.3***	0.331***	0.285***
		7.64	0.98	6.62	7.55	4.74
Time Control	Year Dummies	Yes***	Yes***	Yes***	Yes***	Yes***
	Time period	2001-2016	2001-2007	2008-2011	2012-2016	2010-2016
Model statistics	Observations	752	164	238	350	416
	Number of Banks	74	49	68	74	72
	Number of Countries	20	18	20	20	20
	R-squared (overall)	0.80	0.83	0.83	0.87	0.80

Significance: * p-value<10%; ** p-value<5%; *** p-value<1%. All models estimated using Random Effects (robust estimator).

Hypothesis 4: Gaming behaviour

The fourth hypothesis reflects the possibility of banks abusing the discretion that is provided by internally-modelled approaches in the regulatory framework. Put simply, some banks may seek to game these models and low-ball their risk weights. This results in a disconnect between the risk of their assets – including the market assessment of such risk – and their reported regulatory RWAs. Previous empirical studies have found evidence that points to such gaming behaviour (eg (Behn, Haselmann, & Vig, 2016), (Behn, Haselmann, & Vig, 2016) and (Plosser & Santos, 2014)).

Discretion when used as initially intended by the regulatory framework, will naturally lead to a certain degree of model output heterogeneity. Moreover, modelled output will also reflect: (i) differences in modelling techniques; although, the regulatory framework restricts the modelling choices, variation remains because no precise modelling approach is prescribed by the framework; (ii) data reflecting different default profiles; eg if a bank has experienced few defaults in the past, its IRB model will likely forecast a lower PD than a bank with more defaults; and, (iii) differences in governance and banking supervision; eg the process to approve the use of an IRB model differs across jurisdictions, which could result in different levels of model reliance and conservatism.

Even though some heterogeneity in banks' internal risk assessment is expected (and desirable), driving short-term differences between market-implied and regulatory RWAs, persistently high VRs across time could point to non-risk based factors as unduly affecting how regulatory RWAs are calculated, raising concerns that banks are potentially gaming the framework.

To test the gaming hypothesis, we explore which banks may be more incentivised to game their modelled risk weights and the extent to which their risk weights deviated from market-implied measures of risk. In particular we investigate whether banks that are more capital constrained are more likely to game the regulatory framework; and, whether regulatory RWAs reflect the underlying risk of banks' assets.

In the first instance, we rank the banks in the sample based on their reported Tier 1 risk-based capital ratio in 2006. We use this as a reference point as these were based on Basel I risk-weighted ratios (where modelling discretion was limited to market risk). Figures 7-10 show the evolution of these banks' risk-weighted ratios and VR for the banks in the 1st (blue line in the figures and labelled as Q1) and 4th (yellow line in the figures and labelled as Q4) quartiles from 2001 to 2016. The following can be observed from the charts: (i) the banks with the lowest risk-weighted ratios in 2006 (as shown in the blue first quartile line) saw a marked increase in their capital ratios over the subsequent decade, with the ratios converging around 2012 (Figure 7); (ii) much of this increase in capital ratios resulted from a decline in these banks regulatory RWAs (Figure 8), with a particularly pronounced fall following the introduction of internally-modelled approaches for credit and operational risk; (iii) yet this reported decline in the risk profile of these banks is not reflected in the market measure of risk (Figure 9), which results in these banks having some of the highest VR (Figure 10).

This suggests that banks that were more capital constrained (banks in the 1st quartile) at the start of the global financial crisis may have had greater incentive to abuse the discretion provided by internally-modelled approaches. As a result, the gap between the market- and regulatory-implied measures of risk of these banks increased over time.

Figure 7 – Tier 1 ratio for low (Q1) and high-quartile (Q4) banks in 2006

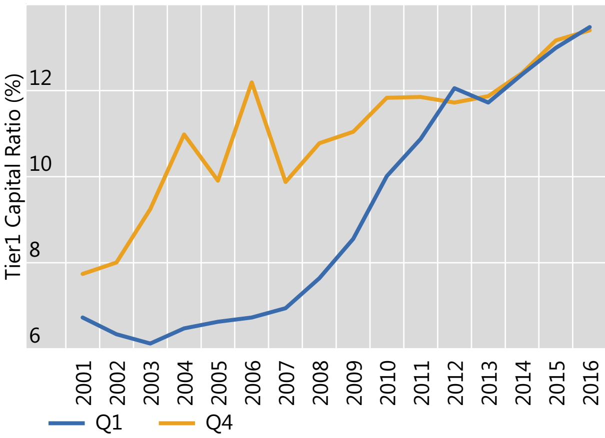


Figure 8 – Regulatory RWA for banks with low (Q1) and high (Q4) Tier 1 ratios in 2006

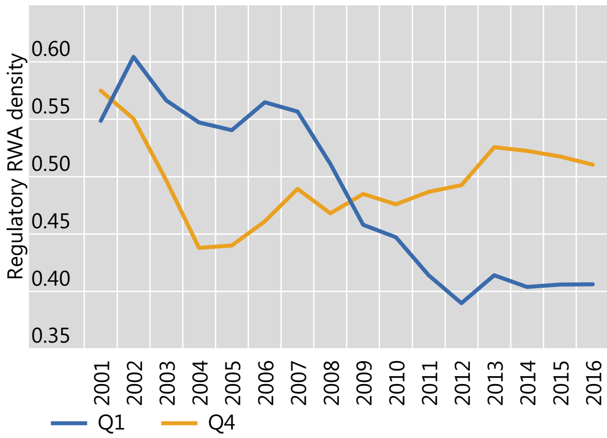


Figure 9 – Market RWA for banks with low (Q1) and high (Q4) Tier 1 ratios in 2006

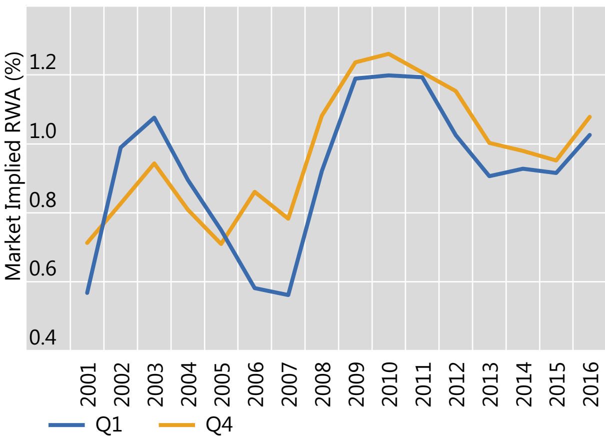
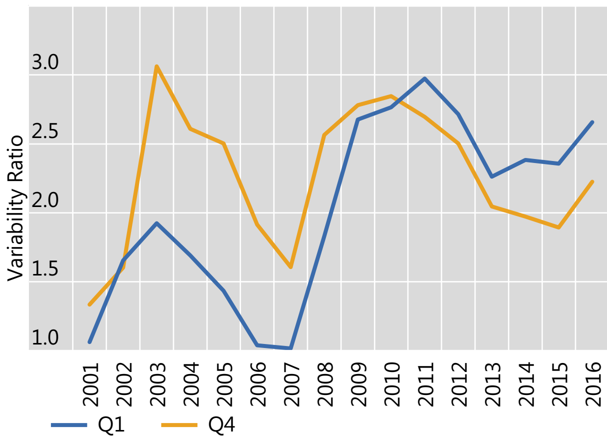


Figure 10 – VR for banks with low (Q1) and high (Q4) Tier 1 ratios in 2006



To check the robustness of this narrative, we re-estimate the VR and Regulatory RWA models (as given by Equation 5), but adding interaction terms between time period and the bank being designated to a particular quartile given its Tier 1 capital ratio in 2006. [12] This allows us to verify whether changes that were visually apparent in the regulatory RWA (Figure 8) and in VR (Figure 10), are statistically significant.

The regression results shown in Tables (7) and (8) corroborate the findings in Figures 7-10, providing evidence in support of the gaming hypothesis. In particular, we find a positive and statistically-significant association between the VR and capital constrained banks (ie the first quartile of banks as measured by their risk-weighted capital ratio in 2006). This is particularly the case in the post-crisis period from 2013 onwards, and suggests that these banks may have been incentivised to game their internally-modelled RWAs to meet the higher regulatory requirements following the global financial crisis. In contrast, there is no significant association between the VR and other banks. Similarly, Regulatory RWAs are significantly lower for capital

[12] Note that the *Regulatory RWA* regression include asset volatility as an explanatory variable.

constrained banks relative to other banks. Finally, the results in Tables 7 and 8 are sensitive to whether country dummies are included in the regressions, which may reflect a concentration of capital constrained banks in certain countries.

Regulatory RWA and asset volatility

In Table 6, we reported a significant negative relationship between regulatory RWAs and asset volatility, which is particularly strong during the crisis period (2008-2011). The finding is counter-intuitive as it would be expected that regulatory and market implied measures of risk should be positively correlated. A possible explanation for this finding is bank gaming of internal models which results in regulatory RWAs not appropriately reflecting underlying asset risk, and thereby being uncorrelated or negatively correlated to market measures of risk. Alternatively, it is also possible that the market implied measures of risk could be inaccurate, due for example to asymmetric information or greater cyclicality in market risk assessments, which drive a divergence between the regulatory and market-implied risk measures.

To explore the issue further we estimate a slightly different version of Equation 5, where we include the second order effect of asset volatility as a regressor to check for potential non-linearity. Secondly, we estimate the models on two sub-samples of banks: high asset volatility banks and low asset volatility banks. Our conjecture is that banks with higher asset volatility have a greater incentive to game their regulatory RWAs than banks with low asset volatility, which results in a divergence between regulatory and market implied risk measures.

The results from these additional regressions are presented in Table 9 and are restricted to observations during the crisis period (ie 2008-2011). Model 1 reflects the estimation for the full sample of banks; Model 2 restricts the estimation to the banks with asset volatility above the median of the asset distribution for the crisis period (this threshold was 5.2%); and Model 3 restricts the estimation to banks with asset volatility below the median.

The results in Table 9 show that the negative relationship between regulatory RWAs and asset volatility is confined to banks with high asset volatility. There is a positive, though insignificant relationship for low volatility banks. These results are consistent with our conjecture that banks with higher asset risk have a greater incentive to game their regulatory RWAs, leading to a negative relationship between regulatory and market-implied risk measures. This provides further evidence to support the gaming hypothesis.

Variability Ratio and capital constrained banks — Table 7

		Model (1)			Model (2)		
		Quartile of banks sorted by Tier 1 capital ratio in 2006			Quartile of banks sorted by Tier 1 capital ratio in 2006		
	Year	1st	2nd	3rd	1st	2nd	3rd
Interaction between year and quartile of banks based on 2006 Tier 1 capital ratio (Base = 4th Quartile)	2001	-0.514*		-0.319	-1.237***		-0.394
		(-1.74)		(-0.69)	(-4.39)		(-0.9)
	2002	-0.842***		-0.041	-1.507***		-0.056
		(-2.65)		(-0.11)	(-5.17)		(-0.16)
	2003	-0.952**		-0.485	-1.628***		-0.405
		(-2.4)		(-0.97)	(-5.54)		(-1.09)
	2004	-0.521	0.865**	-0.101	-1.119***	0.605*	-0.112
		(-1.48)	(2.14)	(-0.26)	(-3.65)	(1.91)	(-0.39)
	2005	-0.23	0.273	0.023	-0.737***	-0.004	-0.017
		(-0.72)	(0.67)	(0.06)	(-2.76)	(-0.01)	(-0.06)
	2006	-0.1	-0.036	-0.123	-0.6***	-0.309	-0.147
		(-0.4)	(-0.12)	(-0.43)	(-2.48)	(-1.06)	(-0.6)
	2007	0.063	-0.081	-0.011	-0.451	-0.38	-0.049
		(0.24)	(-0.3)	(-0.04)	(-1.53)	(-1.32)	(-0.19)
	2008	-0.192	-0.083	-0.103	-0.664**	-0.332	-0.113
		(-0.64)	(-0.25)	(-0.32)	(-2.24)	(-1.09)	(-0.42)
	2009	0.049	0.297	0.336	-0.462**	0.028	0.345
		(0.19)	(1.02)	(0.92)	(-2.2)	(0.12)	(1.1)
	2010	0.015	0.186	0.056	-0.503***	-0.077	0.068
		(0.06)	(0.67)	(0.18)	(-2.77)	(-0.38)	(0.24)
	2011	0.006	0.427	0.015	-0.485**	0.168	0.034
		(0.03)	(1.33)	(0.07)	(-2.42)	(0.68)	(0.17)
	2012	0.096	0.615	0.016	-0.4**	0.371	0.035
		(0.51)	(1.58)	(0.07)	(-2.31)	(1.13)	(0.16)
	2013	0.288*	0.372	0.066	-0.192	0.143	0.111
		(1.77)	(1.32)	(0.36)	(-1.2)	(0.63)	(0.59)
	2014	0.473***	0.235	-0.12	0.012	0.028	-0.056
		(2.74)	(1.04)	(-0.68)	(0.09)	(0.15)	(-0.31)
	2015	0.552**	0.114	-0.25	0.111	-0.088	-0.181
		(2.37)	(0.5)	(-1.62)	(0.52)	(-0.45)	(-1.11)
	2016	0.594**	0.413	-0.222	0.144	0.212	-0.169
		(2.23)	(1.61)	(-1.17)	(0.6)	(0.89)	(-0.89)
Bank specific controls	Portfolio mix		Yes***			Yes***	
	Asset Performance		Yes***			Yes***	
	Size		Yes**			Yes**	
	Business Model		Yes			Yes	
	Macroeconomy		Yes**			Yes**	
	Number of Banks		74			74	
Country Control	Country Dummies		No			Yes***	
	Number of Countries		20			20	
Time Control	Year Dummies		Yes***			Yes***	
	Time period		2001-2016			2001-2016	
Model statistics	Observations		781			781	
	R-squared (overall)		0.53			0.66	

Bank specific controls include portfolio mix (Credit to Assets, Securities to Assets, Derivatives to Assets), Asset performance (Lagged non-performing loans and Real GDP Growth), Size (log of assets), Business model (Funding Fragility, income diversity, efficiency ratio).
Significance of the coefficients: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated as panel with Random Effects (robust estimator).

Regulatory RWA and capital constrained banks — Table 8

		Model (3)			Model (4)		
		Quartile of banks sorted by Tier 1 capital ratio in 2006			Quartile of banks sorted by Tier 1 capital ratio in 2006		
Dependent variable	Year	1st	2nd	3rd	1st	2nd	3rd
Interaction between year and quartile of banks based on 2006 Tier 1 capital ratio (Base = 4th Quartile)	2001	-0.122***		1.059	0.086		1.117
		(-4.17)		(1.08)	(1.06)		(1.1)
	2002	-0.055*		0.004	0.092		0.017
		(-1.71)		(0.09)	(1.38)		(0.32)
	2003	-0.036		0.032	0.124**		0.018
		(-1.37)		(0.74)	(2.09)		(0.35)
	2004	-0.108***	-0.076	0.023	0.035	-0.01	0.022
		(-3.2)	(-1.55)	(0.54)	(0.59)	(-0.18)	(0.49)
	2005	-0.015	-0.069	-0.008	0.117**	-0.003	0.01
		(-0.32)	(-1.6)	(-0.14)	(2.29)	(-0.06)	(0.22)
	2006	-0.026	-0.066	-0.009	0.101**	-0.008	0.006
		(-0.64)	(-1.53)	(-0.16)	(2.12)	(-0.17)	(0.12)
	2007	-0.053	-0.079**	0.01	0.08	-0.015	0.008
		(-1.3)	(-2)	(0.21)	(1.6)	(-0.38)	(0.19)
	2008	-0.063*	-0.057	0.045	0.07	-0.011	0.029
		(-1.71)	(-1.43)	(1.06)	(1.48)	(-0.31)	(0.85)
	2009	-0.072**	-0.058	0.049	0.056	-0.001	0.026
		(-2.22)	(-1.58)	(1.05)	(1.58)	(-0.02)	(0.77)
	2010	-0.063**	-0.051	0.04	0.058*	0.002	0.026
		(-2.15)	(-1.48)	(0.87)	(1.73)	(0.07)	(0.87)
	2011	-0.076***	-0.055	0.047	0.046	0	0.029
		(-2.58)	(-1.51)	(0.99)	(1.56)	(0.01)	(1.01)
	2012	-0.115***	-0.064	0.04	0.02	-0.003	0.028
		(-2.88)	(-1.54)	(0.8)	(0.7)	(-0.12)	(1.05)
	2013	-0.118***	-0.066	0.029	0.01	-0.002	0.014
		(-2.72)	(-1.47)	(0.61)	(0.35)	(-0.08)	(0.54)
	2014	-0.119***	-0.063	0.052	0.003	0.002	0.032
		(-2.58)	(-1.41)	(1.1)	(0.1)	(0.07)	(1.13)
	2015	-0.12***	-0.067	0.065	0.011	0.008	0.049*
		(-2.59)	(-1.54)	(1.34)	(0.36)	(0.26)	(1.68)
	2016	-0.109**	-0.075*	0.051	0.023	0.003	0.041
		(-2.33)	(-1.76)	(1.12)	(0.75)	(0.1)	(1.46)
Bank specific controls	Portfolio mix		Yes**			Yes***	
	Asset Performance		Yes			Yes***	
	Size		Yes			Yes	
	Business Model		Yes**			Yes	
	Macroeconomy		Yes			Yes*	
	Number of Banks		74			74	
Country Control	Country Dummies		No			Yes***	
	Number of Countries		20			20	
Time Control	Year Dummies		Yes***			Yes***	
	Time period		2001-2016			2001-2016	
Model statistics	Observations		790			790	
	R-squared (overall)		0.39			0.53	

Bank specific controls include portfolio mix (Credit to Assets, Securities to Assets, Derivatives to Assets), Asset performance (Lagged non-performing loans and Real GDP Growth), Size (log of assets), Business model (Funding Fragility, income diversity, efficiency ratio). Significance of the coefficients: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated as panel with Random Effects (robust estimator).

Regulatory RWA and asset volatility				Table 9
		VR (RWA by assets)		
		(1)	(2)	(3)
Asset Volatility	Vol (%)	-0.016**	-0.019**	0.061
		(-2.16)	(-2.18)	(0.83)
	Vol^2	0.0001	00.001*	-0.01
		(1.6)	(1.8)	(-1.02)
Bank specific controls	Portfolio mix	Yes***	Yes***	Yes***
	Asset Performance	Yes	Yes	Yes
	Size	Yes	Yes	Yes
	Business Model	Yes	Yes**	Yes***
	Number of Banks	71	74	74
Macroeconomy	Real GDP growth	Yes***	Yes***	Yes**
Country Control	Country Dummies	Yes***	Yes***	Yes***
	Number of Countries	20	20	20
Time Control	Year Dummies	Yes**	Yes*	Yes**
	Time period	2008-2011	2008-2011	2008-2011
Model statistics	Observations	261	278	78
	R-squared (overall)	0.76	0.66	0.67

The bank interaction with asset volatility is measured as the interaction of a country dummy (equal to 1 if the banks is headquartered in a particular country and zero otherwise) and asset volatility. Bank specific controls include portfolio mix (Credit to Assets, Securities to Assets, Derivatives to Assets), Asset performance (Lagged non- performing loans), Size (log of assets), Business model (Funding Fragility, income diversity, efficiency ratio). Significance of the coefficients: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated as panel with Random Effects (robust estimator).

V. The impact of risk weighted asset variability on banks' cost of funding

The previous sections have highlighted a significant degree of excessive variability in bank RWAs, which raises important financial stability questions for policymakers. It also raises the question of whether this variability impacts banks directly. This section considers the impact of RWA variability on bank funding costs. Specifically, we test whether the VR is a significant driver of a bank's weighted average cost of capital (WACC) and Credit Default Swap (CDS) spreads.

A. Cost of total funding

Following the same general approach as in the previous section, we model the determinants of the WACC as a function of variables that measure: asset performance, portfolio mix, bank size, bank business model characteristics, macroeconomic conditions, and country and time period dummies. In addition, we include a set of bank capital related variables: the Tier 1 risk-based capital ratio, the leverage ratio, and the VR. Controlling for the other factors that could influence a bank's WACC, our main interest in is in testing whether the VR is significant. That is, does RWA variability affect a bank's funding costs and thereby its profitability. The model specification is given by Equation 7:

$$\begin{aligned} WACC_{it} &= \alpha + \theta(Capital\ Measures_{it}) + \beta(Portfolio\ Mix_{it}) \\ &\quad + \gamma(Asset\ Quality_{it}) + \delta\ (Size_{it}) + \eta(Business\ Model_{it}) \\ &\quad + \zeta\ (Macro_{ct}) + \kappa(Country_c) + \tau\ (Year_t) + \mu_i + \varepsilon_{it} \end{aligned} \qquad (7)$$

The results from various estimations of the model are presented in Table 10. Regressions 1 to 4 normalise RWA by total assets and cover the full sample period (2001 – 2016), while Regression 5 uses leverage ratio exposure to calculate the VR and leverage ratio, and is restricted to the 2010 – 2016 period. The results are very consistent across all five regressions. The VR is always positive and statistically significant, suggesting that banks which the market views as having higher RWA variability also face higher funding costs. We also find that WACC is significantly positively related to Non-performing loans and Funding Fragility, and negatively related to the Tier 1 Capital Ratio. That is, consistent with what would be expected, poor asset quality, greater reliance on short-term wholesale funding, and lower risk-based capital ratios all raise banks' funding costs. There is also a strong macro effect, with funding costs negatively related to real GDP growth. Finally, it is worth noting that the leverage ratio is insignificant, which is consistent with the Modigliani-Miller theorem that capital structure does not affect overall funding costs.

B. Credit default swap (CDS) spreads

We replicate the previous analysis, but this time using CDS spreads as the dependent variable. The model specification is adjusted to also include CDS contract specific variables and a range of market pricing variables that are commonly used in the literature. Our specification is similar to Drago, Di Tommaso and Thornton (2017) who model CDS spreads as a function of both balance sheet and market variables. Other studies, such as Chiaramonte and Casu (2012) use only balance sheet determinants, or focus only on market variables (see Annaert, De Ceuster, Roy and Vespro (2013)). The balance sheet measures that are used in these studies are similar to those we have used in earlier sections of this paper. Hence we modify our earlier models (which focused on balance sheet measures) by also including a range of market variables[13]. The model specification is given by Equation 8:

$$\begin{aligned} CDS\ Spread_{it} = {} & \alpha + \theta(Capital\ Measures_{it}) + \lambda(Market\ Variables_{it}) \\ & + \beta(Portfolio\ Mix_{it}) + \gamma(Asset\ Quality_{it}) + \delta\ (Size_{it}) \\ & + \eta(Business\ Model_{it}) + \zeta\ (Macro_{ct}) + \kappa(Country_c) \\ & + \tau\ (Year_t) + \mu_i + \varepsilon_{it} \end{aligned} \quad (8)$$

In the context of modelling CDS spreads, the capital measures capture a bank's ability to absorb losses and shareholders incentives for risk-taking, the portfolio mix and asset quality variables measure asset risk, size proxies potential TBTF benefits and economies of scale, while the business model variables capture funding risk and operational performance. We expect higher capital ratios (risk-based and leverage), higher profitability, and greater income diversity and efficiency to result in lower CDS spreads. Conversely, RWA variability, asset volatility, non-performing loans and funding fragility are expected to increase spreads.

Macroeconomic conditions are captured by real GDP growth, the risk free interest rate (measured by the 2-year government bond yield) and the risk-free term

13 CDS contracts can differ by the seniority of debt on which the CDS contract is issued and the type of restructuring clauses in the contract (see for example Packer and Zhu, BIS Quarterly Review (2005)). In our dataset these factors are fixed for a given firm and therefore captured in the firm fixed effects.

structure (the yield difference between 10- and 2-year government bonds). We expect higher GDP growth and to be associated with lower CDS spreads. The signs on the risk free rate and risk-free term structure are uncertain. Through the mechanics of the Merton (1974) model, a higher risk free rate and term spread implies a high drift rate and therefore higher returns, reducing the risk-neutral probability of default (see for example Yang and Tan (2006)). Moreover, a higher risk free rate could proxy sovereign risk which transmits to bank risk through the bank-sovereign nexus. Conversely, a higher risk free and term spread could also indicate expectations of higher growth and therefore lower credit risk.

The set of market variables capture country and global risk factors. Country level credit risk is measured using the sovereign CDS spread, while country stock market returns measure general market conditions, and the VIX is used to proxy global market volatility. We expect, sovereign CDS spreads and market volatility to be positively related to bank CDS spreads, and negatively related to country specific equity market returns.

As the CDS spread data may change significantly over a very short period and is likely to incorporate information in balance sheet measures around the time of their release, we calculate the market variables using one-month windows around the end of year balance-sheet date. Specifically, we calculate monthly averages of the market risk variables, up to two months prior to the balance sheet date, during the month of the balance sheet date, and up to two months after the balance sheet date. In this way we account for information leakage before the publication of balance sheet data, and also for the information to be incorporated with a lag of up to two months.

Table 11 presents the regression results for five models, where the only difference between the various models is the month over which the market data is calculated. In all the regressions, we find that the VR has a strong positive and statistically-significant relationship with banks' CDS spreads. Put differently, banks with a higher degree of RWA variability face higher funding costs as proxied through CDS spreads. Although not reported, we re-estimated the model omitting the market variables and using annual data as in the previous analysis and again found a very strong and significant relationship between the VR and bank CDS spreads.

In terms of the other drivers of CDS spreads, our results are consistent with our a priori expectations. Looking at the market risk variables, sovereign CDS spreads have a strong positive influence on bank CDS spreads, which is consistent with the close link between market assessments of bank and sovereign risk. There is also some evidence of a positive relationship between CDS spreads and the risk-free rate and term structure, however the variables are mostly insignificant.

We find both the Tier 1 capital ratio and the leverage ratio are negative and statically significant, which is consistent with capital providing protection against default. There is also a very strong and statistically significant negative relationship between bank size and CDS spreads, which could suggest that CDS buyers perceive bigger banks benefit from implicit government support. In terms of the bank portfolio mix, banks with a greater proportion of credit to assets have lower CDS spreads, perhaps indicating that the market applies a risk premium to banks with greater investment banking and trading business. Finally, real GDP growth is also highly significant and negatively related to CDS spreads.

Overall, the analysis of the determinants of the WACC and CDS spreads produce very similar results, and strongly point to the importance of RWA variability as a driver of bank funding costs.

Determinants of Weighted Average Cost of Capital (WACC)						Table 10
		Regulatory RWA				Regulatory RWA_LRE
		(1)	(2)	(3)	(4)	(5)
Bank capital measures	Variability Ratio	0.91***	0.51***			1.011**
		(2.97)	(2.46)			(2.14)
	T1 Capital	-0.19***		-0.067*		-0.204***
		(-3.77)		(-1.75)		(-2.45)
	Leverage Ratio	0.125		-0.007		-0.058
		(1.17)		(-0.07)		(-0.34)
Asset Performance	KMV Asset Volatility	-0.069			0.055	-0.096
		(-0.52)			(0.53)	(-0.37)
	Lagged non-performing loans	0.367***	0.37***	0.41***	0.391***	0.466***
		(3.94)	(3.75)	(4.21)	(4.01)	(4.31)
	ROA	0.015	-0.081	-0.135	-0.187	-1.877***
		(0.02)	(-0.13)	(-0.21)	(-0.3)	(-2.84)
	Real GDP Growth	-0.147**	-0.177***	-0.155**	-0.174***	-0.299**
		(-2.22)	(-2.62)	(-2.22)	(-2.59)	(-2.38)
Size	Log of Assets	0.17	0.284	0.15	0.26	-0.259
		(0.85)	(1.34)	(0.75)	(1.28)	(-0.95)
Business model	Funding Fragility	4.927***	5.245***	4.919***	5.07***	1.011**
		(2.65)	(2.78)	(2.68)	(2.61)	(2.14)
	Income Diversity	-0.865	-0.738	-0.773	-0.794	-0.204***
		(-0.98)	(-0.84)	(-0.87)	(-0.89)	(-2.45)
	Efficiency Ratio	-1.284	-1.32	-1.246	-1.556	-0.058
		(-1.22)	(-1.21)	(-1.18)	(-1.41)	(-0.34)
Country Dummies	Australia	-1.414*	-1.702***	-1.657**	-1.682***	-3.833***
(base = United States)		(-1.78)	(-2.67)	(-2.07)	(-2.6)	(-2.73)
	Brazil	-2.438	-2.63*	-2.878*	-2.862*	-2.095
		(-1.47)	(-1.73)	(-1.8)	(-1.79)	(-1.27)
	Canada	-0.837	-1.428***	-1.788***	-1.568***	-2.443***
		(-1.29)	(-3.71)	(-3.13)	(-3.16)	(-2.71)
	China	-0.973	-0.698	-0.989	-0.914	-2.53
		(-0.9)	(-0.73)	(-0.95)	(-0.9)	(-1.42)
	France	-1.931**	-1.953**	-1.914*	-1.678*	-4.282***
		(-2.28)	(-2.39)	(-1.91)	(-1.79)	(-3.57)
	Germany	-1.306	-1.588**	-1.704*	-1.475	-5.272***
		(-1.54)	(-2.15)	(-1.74)	(-1.61)	(-4.59)
	Italy	-1.662**	-1.869**	-2.203***	-2.079***	-4.852***
		(-2.07)	(-2.38)	(-2.59)	(-2.55)	(-3.85)
	Japan	0.497	0.357	0.583	0.741	-1.308
		(0.77)	(0.71)	(0.9)	(1.47)	(-1.34)
	South Korea	2.44***	2.133***	2.046***	1.932***	-0.47
		(3.15)	(2.86)	(2.65)	(2.56)	(-0.49)
	Singapore	-2.071***	-2.285***	-2.461***	-2.472***	-3.615***
		(-3.42)	(-3.94)	(-4.18)	(-4.32)	(-4.1)
	Spain	-0.267	-0.601	-0.755	-0.68	-3.368***
		(-0.32)	(-0.8)	(-0.9)	(-0.91)	(-3.22)
	Sweden	-1.572*	-2.392***	-2.042**	-2.15***	-4.032***
		(-1.89)	(-3.57)	(-2.41)	(-3.18)	(-2.7)
	Switzerland	-2.232**	-3.072***	-2.554***	-2.642***	-2.743***
		(-2.02)	(-3.01)	(-2.51)	(-2.74)	(-2.69)
	United Kingdom	-0.581	-1.118**	-1.36**	-1.28**	-2.764***
		(-0.89)	(-1.96)	(-1.92)	(-2.03)	(-3.44)
	Belgium and Netherlands	-1.385*	-2.139***	-2.178***	-2.223***	-4.637***
		(-1.82)	(-3.4)	(-2.79)	(-3.49)	(-4.03)
	Denmark and Norway	0.658	0.101	0.177	0.21	-2.501**
		(0.64)	(0.12)	(0.15)	(0.23)	(-1.94)
	India and Russia	2.232*	1.948*	1.85*	1.464	3.281
		(1.63)	(1.91)	(1.78)	(1.13)	(1.61)
Time control	Year Dummies	Yes***	Yes***	Yes***	Yes***	Yes***
	Time period	2001-2016	2001-2016	2001-2016	2001-2016	2010-2016
Bank specific control	Portfolio mix	Yes	Yes	Yes	Yes	Yes***
Model statistics	Observations	702	709	710	727	396
	Number of Banks	72	72	72	72	70
	Number of Countries	20	20	20	20	20
	R-squared (overall)	0.65	0.64	0.64	0.64	0.68

RWA normalised by assets in models (1) to (4), and by LRE in model (5). Portfolio mix include Credit to Assets, Securities to Assets and Derivatives to Assets. Significance: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated using Random Effects (robust estimator).

Determinants of Credit Default Swap (CDS) spreads						Table 11
		Month average of the market indicators and dependent variable				
Model		Nov (Year t) (1)	Dec (Year t) (2)	Jan (Year t+1) (3)	Feb (Year t+1) (4)	Mar (Year t+1) (5)
Market Indicators	CDS Sovereign spread	1.088***	1.036***	0.966***	0.786***	0.759***
		(6.71)	(9.12)	(8.97)	(9.14)	(8.84)
	Risk free interest rate	-1.871	0.99	0.889	7.11***	11.464***
		(-0.32)	(0.25)	(0.25)	(2.64)	(3.43)
	Risk-free term structure	-8.072	-2.563	4.421**	3.696	0.932
		(-1.39)	(-0.81)	(2.35)	(1.43)	(0.51)
	Return on equity Index	2.688	0.64	0.006	-0.115	0.461
		(1.31)	(1.33)	(0.01)	(-0.12)	(0.52)
	Global market volatility	14.847	-0.43	6.664	-0.072	0.533
		(0.67)	(-0.1)	(0.24)	(-0.03)	(0.22)
Variability measure	Variability Ratio	15.342***	9.452**	8.199**	12.331***	14.137***
		(3.01)	(2.35)	(2.33)	(4.00)	(4.55)
Capital measures	Tier 1 Capital	-3.39**	-2.805**	-3.473***	-4.286***	-4.994***
		(-2.24)	(-2.18)	(-2.68)	(-3.21)	(-2.57)
	Leverage ratio	-15.123	-22.096*	-17.035*	-11.86	-10.045
		(-0.86)	(-1.77)	(-1.73)	(-1.22)	(-0.94)
Asset Performance	Lagged non-performing loans	-3.832	-3.699*	-2.772	-2.462	-2.342
		(-1.57)	(-1.67)	(-1.57)	(-1.46)	(-1.42)
Portfolio Mix	Credit to Assets	-264.451**	-265.583***	-214.701***	-184.619**	-124.691
		(-2.07)	(-2.51)	(-2.51)	(-2.05)	(-1.18)
	Securities to Assets	-18.182	-19.164	-13.098	-25.477	34.59
		(-0.14)	(-0.18)	(-0.14)	(-0.31)	(0.37)
	Derivatives to Assets	-106.737	-112.164	-61.385	-56.301	17.666
		(-0.83)	(-0.97)	(-0.65)	(-0.62)	(0.15)
Macroeconomy	Real GDP Growth	-2.131	-1.459	-2.437**	-2.744**	-2.434**
		(-1.53)	(-1.03)	(-1.95)	(-2.39)	(-2.14)
Size	Log of Assets	-46.613**	-60.696***	-55.685***	-49.989***	-40.205***
		(-2.31)	(-3.23)	(-3.71)	(-3.24)	(-2.49)
Business model	Funding Fragility	-150.873	-135.372	-106.814	-85.059	-88.272
		(-1.25)	(-1.25)	(-1.2)	(-1.09)	(-1.04)
	Income Diversity	8.806	11.434	10.917	41.983	26.079
		(0.24)	(0.31)	(0.34)	(1.52)	(0.81)
	Efficiency Ratio	46.933	64.631**	12.596	11.94	0.552
		(1.52)	(2.19)	(0.68)	(1.12)	(0.05)
Time control	Year Dummies	Yes***	Yes***	Yes***	Yes***	Yes***
	Time period	2001-2016	2001-2016	2001-2016	2001-2016	2001-2016
Model statistics	Observations	405	404	407	413	399
	Number of Banks	47	47	47	47	46
	Number of Countries	15	15	15	15	15
	R-squared (overall)	0.68	0.70	0.72	0.68	0.68

Market indicators and the dependent variable (CDS spreads) are calculated as averages over the particular month (ie November and December of year t or January, February and March of the following year (t+1)). The VR is calculated as the average over the calendar year (t) and the balance sheet measures are as at the end of the calendar year (t). Significance of the coefficients: * p-value<10%; ** p-value<5%; *** p-value<1%. All models were estimated as using Fixed Effects (robust estimator).

VI. Robustness checks

Table 12 provides a summary of the overall results of the paper, along with various robustness checks. Model 1 shows the key findings from the models of the determinants of variability (VR regressions), WACC, and CDS spreads. Models 2 and 3 show the results from using the within KMV model adjustment for leverage instead of the regression based approach. There are two variants of the within KMW model: (i) fitting to the curve with deviations; and (ii) fitting to the curve assuming zero deviations. Models 1 to 3 all present results that use the Basel II Foundation IRB approach to transform PDs into RWAs. Models 4 and 5 define the dependent variable as PD/RWA, thereby avoiding the need to apply the Foundation IRB transformation of PD into RWA. Model 4 includes deviation from the fitted curve when calculating the leverage adjusted PD whereas Model 5 does not. Finally, Model 6 uses the ratio of asset volatility to Regulatory RWAs as the measure variability. This avoids the need for any leverage adjustment or the need to transform PD into RWA using a regulatory formula. The limitation of this approach is the regulatory RWAs are calculated by transforming PD into a downturn measure. The same non-linear transformation is not applied to the measure of asset volatility.

As can been seen from the summary table, there is a high degree of consistency in the findings across the various robustness checks. In particular, portfolio mix, size and country specific factors are always significant determinants of RWA variability. Moreover, the models of the determinants of WACC and CDS spreads remain largely unchanged, with the measure of RWA variability always having the correct sign and in most cases is statistically significant.

Summary of key results and robustness checks — Table 12

	(1)	(2)	(3)	(4)	(5)	(6)
Measure of RWA Variability	(Market RWA / Regulatory RWA)	(Market RWA / Regulatory RWA)	(Market RWA / Regulatory RWA)	(Market PD / Regulatory RWA)	(Market PD / Regulatory RWA)	(Asset Volatility / Regulatory RWA)
Market PD leverage adjustment	Regression approach	Within KMV (fitted + deviations)	Within KMV (fitted)	Within KMV (fitted + deviations)	Within KMV (fitted)	NA
Regulatory model to transform PD into RWA	Foundation IRB (LGD= 45%)	Foundation IRB (LGD= 45%)	Foundation IRB (LGD= 45%)	NA	NA	NA
Variability Regression	**Table 4**					
- Portfolio mix	Credit: (-)*** n.s. Derivatives: (+)***	Credit: (-)*** Securities: (+)* Derivatives: (+)***	Credit: (-)*** Securities: (+)* Derivatives: (+)***	Credit: (-)** n.s. Derivatives: (+)***	Credit: (-)** Securities: (+)** n.s.	Credit: (-)*** Securities: (+)*** Derivatives: (+)**
- Size	(-)***	(-)***	n.s.	n.s.	(-)***	(-)***
- Country dummies	(+/-)***	(+/-)***	(+/-)***	(+/-)***	(+/-)***	(+/-)***
WACC regression	**Table 10**					
- VR	(+)***	(+)**	(+)***	n.s.	n.s.	(+)**
- T1 Capital	(-)***	(-)***	(-)***	(-)***	(-)*	(-)***
- Leverage	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
- Asset volatility	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
- Size	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
CDS regression	**Table 11**					
- VR	(+)***	(+)**	n.s.	(+)**	(+)*	(+)*
- T1 Capital	(-)***	(-)***	(-)***	(-)***	(-)***	(-)***
- Leverage	(-)*	(-)***	(-)***	(-)***	(-)***	(-)***
- Size	(-)***	(-)***	(-)***	(-)***	(-)***	(-)***

Notes: n.s. indicates not significant (p-value>10%); * p-value<10%; ** p-value<5%; *** p-value<1%. The signs in the brackets show the sign of the coefficient in the respective regression. All models are estimated using random effects (robust estimator), except for the CDS regressions which are estimated using fixed effects. NA indicates not applicable.

VII. The impact of Basel III on RWA variability

As noted earlier, one of the main objectives of the recently-finalised Basel III reforms is to reduce excessive RWA variability. So a natural question is what impact these reforms have on the VR. While the reforms have yet to be fully implemented, we make use of regulatory data submitted to the BCBS as part of the Basel III quantitative impact study and assess the impact of the output floor on the VR. This exercise was conducted based on banks' end-2015 balance sheet. In line with the BCBS data confidentiality guidelines, the data is aggregated at a country level.

The country level analysis is performed as follows. The asset-weighted market-implied risk weight is calculated for each BCBS member country for the calendar year 2015. As previously, the VR is simply computed as the ratio between the market-implied average risk weight and the regulatory average risk weight for each country.[14] The BCBS data allows us to calculate the latter under different scenarios, including: (i) with no output floor in place; and (ii) with output floors of different calibrations.

Table 13 shows that the VR and variability across countries decreases substantially as the calibration of the floor increases.[15] For example, the range in VRs (maximum – minimum) across countries declines from 2.0 (without an output floor) to 0.8 (for an output floor of 75% or higher). As financial stability concerns with excessive RWA variability are primarily related to outlier banks with relatively low-estimated RWAs, we also compute the range between the maximum and mean VRs. In this case, the range declines from 1.5 (without an output floor) to 0.3 (for an output floor of 80%). The marginal benefit of a floor in reducing VRs declines at higher calibrations, with most of the benefit of a floor (in terms of reducing high VRs) obtained at around a 75% floor calibration.

Variability Ratio at various output floor calibrations — Table 13

	0% Floor	60% Floor	70% Floor	75% Floor	80% Floor
Min	1.3	1.3	1.2	1.2	1.2
Mean	2.2	2.1	2.0	2.0	1.9
Max	3.7	3.5	3.2	3.0	2.8
Range (Max – Min)	2.4	2.2	2.0	1.8	1.6
Range (Max – Mean)	1.5	1.4	1.2	1.0	0.9

Sample of 17 countries. Data as at end 2015

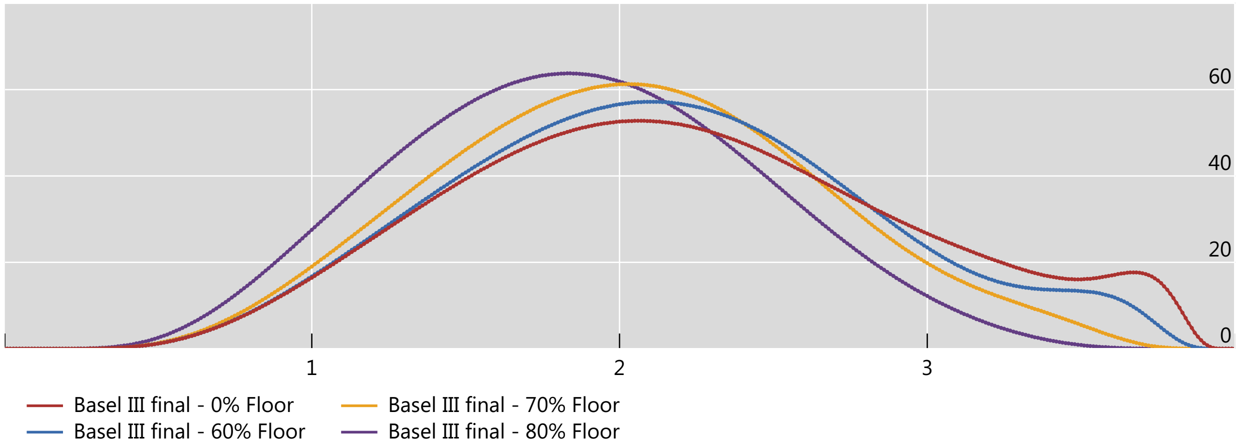
Figure 11 below clearly shows the reduction in RWA variability as measured by the VR due to the application of the output floor. The impact of higher floor calibrations is reflected in a left-shift of the distribution of the VR which suggests that regulatory risk weights that include the application of an output floor are more closely aligned with those assigned by the market. Moreover, the tails of the VR distribution are not as heavy at higher floor calibrations, confirming the reduction in RWA variability across countries.

14 Note that in this case, the average regulatory risk weight is calculated using the leverage ratio exposure measures as the denominator. Hence, it is not necessary to adjust the data to account for differences in accounting standards.

15 The VR is based on the baseline model 1 reported in Table 4.

Variability Ratio density function at various output floor calibrations

Sample of 17 countries. Data as at end 2015 Figure 11



Source: BCBS and authors' calculations.

VIII. Conclusion

The global financial crisis highlighted a number of shortcomings with the regulatory framework. The initial set of post-crisis reforms developed by the BCBS sought to address many of them. But a key outstanding issue related to excessive variability stemming from banks' internally-modelled RWAs.

In this paper we develop a new measure of RWA variability – the VR - that utilises market data to determine a market-implied estimate of a bank's RWAs. Using this measure, we find considerable variability in regulatory RWAs, both across banks and jurisdictions. Regulatory RWAs are roughly half the level of market-implied RWAs.

Regarding the determinants of this variability, we find a strong and statistically-significant association between our measure of RWA variability and: (i) the share of opaque assets held by banks (eg derivatives); (ii) the degree to which a bank is capital constrained, which is consistent with the gaming hypothesis; and (iii) jurisdiction-specific factors. These results suggest that market participants may be applying an 'opaqueness' premium for banks that hold highly-complex instruments, and that the incentive for banks to game their internal models is particularly acute for capital-constrained banks. The results also point to jurisdiction-specific factors which could also explain RWA variability. We also find that RWA variability directly affects banks' own profitability through higher funding costs.

Finally, the introduction of the finalised Basel III reforms, and in particular the output floor, reduces RWA variability, with greater reductions in variability observed for higher calibrations of the floor.

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Annex I: Additional summary statistics

List of banks in the sample — Table 14

Country	Bank
Australia	Commonwealth Bank of Australia
	National Australia Bank Limited
	Westpac Banking Corporation
	Australia and New Zealand Banking Group
Belgium	KBC Group
Brazil	Banco Bradesco
	Banco do Brasil
	Itau Unibanco
Canada	The Bank of Nova Scotia
	Royal Bank of Canada
	Canadian Imperial Bank of Commerce
	Bank of Montreal
	Toronto-Dominion Bank
China	Agricultural Bank of China Limited
	Bank of Communications Co.
	China Everbright Bank
	China CITIC Bank Corporation Limited
	Ping An Bank Co.
	China Merchants Bank
	Hua Xia Bank Co.
	China MinSheng Banking Corporation
	Bank of Beijing
	Bank of China
	Shanghai Pudong Development Bank
	Industrial and Commercial Bank of China
Denmark	Danske Bank
France	Societe Generale
	BNP Paribas
	Credit Agricole
Germany	Deutsche Bank
	Commerzbank
India	State Bank of India
Italy	UniCredit
	Intesa Sanpaolo
Japan	Nomura Holdings
	Mizuho Financial Group
	Sumitomo Mitsui Trust Holdings
	Mitsubishi UFJ Financial Group

List of banks in the sample	Table 14
Country	Bank
	Sumitomo Mitsui Financial Group
South Korea	Shinhan Financial Group Co. Hana Financial Group KB Financial Group
Netherlands	ING Group
Norway	DNB ASA
Russia	Sberbank of Russia
Singapore	DBS Group Holdings Oversea-Chinese Banking Corp United Overseas Bank
Spain	Banco de Sabadell Banco Santander Banco Bilbao Vizcaya Argentaria Bankia. CaixaBank
Sweden	Skandinaviska Enskilda Banken Svenska Handelsbanken Swedbank Nordea Bank
Switzerland	Credit Suisse Group UBS Group
United Kingdom	Barclays HSBC Holdings Lloyds Banking Group The Royal Bank of Scotland Group Standard Chartered
United States	JPMorgan Chase Morgan Stanley Goldman Sachs Capital One Citigroup Wells Fargo State Street SunTrust Banks Bank of America U.S. Bancorp BB&T PNC Financial Services Group

Summary of statistics of key variables per country (2001-2016)

Table 15a

Variable	Australia obs	Australia mean	Australia sd	Belgium obs	Belgium mean	Belgium sd	Brazil obs	Brazil mean	Brazil sd	Canada obs	Canada mean	Canada sd	China obs	China mean	China sd	Denmark obs	Denmark mean	Denmark sd	France obs	France mean	France sd
Variability Ratio	59	1.53	0.63	10	2.51	0.66	45	2.22	0.43	74	1.53	0.59	117	2.11	0.5	16	2.08	1.54	42	2.86	1.53
Variability Ratio_LRE	28	1.83	0.28	7	2.09	0.46	20	1.96	0.44	35	1.63	0.39	65	1.83	0.37	7	2.17	1.19	21	3.08	0.75
Market RWA_U (LGD = 45%)	64	0.64	0.2	16	0.9	0.29	48	1.18	0.28	80	0.55	0.16	145	1.13	0.18	16	0.71	0.38	47	0.97	0.39
Market RWA (LGD = 45%)	64	0.75	0.2	16	0.85	0.28	48	1.43	0.2	80	0.58	0.17	145	1.3	0.23	16	0.62	0.38	47	0.85	0.39
CDS Spread	62	56.32	45.52	0	na	na	21	239.2	110.5	73	56.52	37.32	67	155.7	79.55	16	116	110.1	47	77.28	72.12
Weighted Average Cost of Capital	48	10.06	3.19	14	13.29	4.63	48	12.45	3.38	80	9.87	2.22	133	11.65	3.1	16	10.81	3.81	26	13.77	3.6
Leverage Ratio	64	5.98	0.95	16	4.53	0.91	47	7.86	1.85	80	4.68	0.81	150	5.08	2.9	16	3.61	0.55	48	3.98	0.8
T1 regulatory Capital Ratio	64	8.82	1.82	10	13.04	3.13	43	12.22	1.75	80	11.04	1.57	139	8.87	2.12	16	12.43	5.09	48	10.21	2.51
Regulatory RWA	59	0.55	0.13	10	0.39	0.04	45	0.64	0.09	74	0.46	0.51	129	0.61	0.07	16	0.33	0.09	43	0.33	0.06
Regulatory RWA_LRE	28	0.51	0.05	7	0.52	0.11	20	0.73	0.09	35	0.41	0.05	65	0.66	0.07	7	0.31	0.04	21	0.38	0.05
Loans to total assets	64	0.71	0.07	16	0.45	0.05	47	0.36	0.05	80	0.49	0.06	150	0.52	0.06	16	0.54	0.05	48	0.35	0.06
Securities to total assets	64	0.1	0.03	16	0.35	0.03	47	0.37	0.06	80	0.29	0.06	150	0.21	0.07	16	0.2	0.06	48	0.3	0.1
Derivatives to total assets	45	0.06	0.02	12	0.05	0.03	47	0.01	0.01	80	0.08	0.03	119	0	0	13	0.1	0.03	37	0.17	0.05
Asset Volatility (KMVI)	64	4.46	1.21	16	4.36	0.89	48	10.79	3.35	80	3.3	0.75	145	8.67	3.08	16	3.68	1.4	47	3.91	1.29
Non-Performing Loans (NPL)	60	0.64	0.37	15	5.37	3.3	44	8.3	2.15	75	0.99	0.55	136	4.18	6.93	15	2.44	2.13	35	4.94	1.48
Return on Assets (ROA)	63	0.95	0.24	16	0.49	0.55	46	1.87	0.74	80	0.75	0.26	145	0.91	0.35	16	0.34	0.22	47	0.34	0.18
Real GDP Growth per country	64	2.92	0.76	16	1.39	1.45	48	2.45	3.12	80	1.94	1.46	192	9.45	2	16	0.92	1.88	48	1.15	1.32
Size	64	-0.99	0.66	16	-1.07	0.27	47	-1.63	0.88	80	-0.92	0.5	150	-0.94	1.2	16	-0.77	0.38	48	0.43	0.5
Income Diversity	64	0.23	0.05	16	0.22	0.06	47	0.38	0.07	80	0.17	0.06	150	0.17	0.09	16	0.19	0.03	48	0.28	0.11
Funding Fragility	64	0.34	0.1	16	0.47	0.22	47	0.36	0.11	80	0.64	0.14	150	0.21	0.11	16	0.24	0.1	48	0.54	0.14
Efficiency Ratio	64	0.48	0.05	16	0.64	0.16	47	0.58	0.07	80	0.65	0.16	150	0.38	0.1	16	0.56	0.04	48	0.66	0.04

Summary of statistics of key variables per country (2001-2016) - continued

Table 15b

	Germany			India			Italy			Japan			Netherlands			Norway			Russia		
Variable	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd
Variability Ratio	32	3.04	1.51	8	2.02	0.34	27	1.97	0.76	66	2.34	0.84	3	2.5	0.3	12	1.64	0.53	14	1.34	0.54
Variability Ratio_LRE	14	3.42	0.75	6	2.19	0.15	14	2.3	0.43	33	2.84	0.84	3	2.63	0.73	7	1.63	0.17	6	1.61	0.12
Market RWA_U (LGD = 45%)	32	0.97	0.31	16	1.18	0.51	32	0.99	0.3	75	1.12	0.23	16	0.91	0.23	16	0.86	0.17	16	0.97	0.45
Market RWA (LGD = 45%)	32	0.82	0.33	16	1.2	0.52	32	0.96	0.27	75	1.07	0.23	16	0.81	0.23	16	0.91	0.21	16	1.1	0.55
CDS Spread	32	83.1	61.25	13	176.3	81.68	32	114.3	118.8	44	105.6	71.23	16	70.06	55.48	2	81.41	2.01	12	253.5	123.5
WACC	32	12.67	2.88	9	12.93	0.83	32	13.05	4.26	68	13.83	4.18	16	13.89	3.73	16	10.68	2.96	10	15.91	4.90
Leverage Ratio	32	3.17	1.16	15	5.63	0.57	32	6.61	1.41	74	4.27	2	16	3.72	1.2	12	5.72	0.77	16	10.26	1.47
T1 regulatory Capital Ratio	32	10.88	3.07	12	9.12	0.63	30	9.14	2.49	66	9.78	3.22	3	14.76	1.45	12	10.52	3.49	16	11.41	1.71
Regulatory RWA	32	0.29	0.08	8	0.63	0.05	27	0.54	0.11	66	0.48	0.11	3	0.33	0.04	12	0.54	0.11	14	0.87	0.07
Regulatory RWA_LRE	14	0.34	0.09	6	0.6	0.09	14	0.52	0.06	33	0.41	0.09	3	0.32	0.02	7	0.57	0.08	6	1.0	0.11
Loans to total assets	32	0.3	0.11	15	0.55	0.1	32	0.56	0.03	74	0.44	0.17	16	0.47	0.1	12	0.6	0.04	16	0.67	0.09
Securities to total assets	32	0.32	0.08	15	0.31	0.08	32	0.21	0.06	74	0.42	0.18	16	0.27	0.05	12	0.2	0.03	16	0.17	0.07
Derivatives to total assets	32	0.21	0.12	0	na	na	24	0.07	0.03	28	0.05	0.02	12	0.04	0.01	12	0.06	0.02	11	0.01	0.01
Asset Volatility (KMV Model)	32	3.57	0.68	16	6.72	2.2	32	5.18	0.99	75	5.22	1.78	16	4.15	0.83	16	5.01	0.94	16	9.48	4.87
Non-Performing Loans (NPL)	30	4	1.84	8	3.61	0.98	27	8.12	5.1	54	3.03	2.33	15	2.19	0.7	11	1.64	0.64	15	3.09	2.24
Return on Assets (ROA)	32	0.08	0.24	14	0.85	0.17	31	0.22	0.69	70	0.29	0.52	15	0.43	0.28	12	0.76	0.2	16	2.17	1.14
Real GDP Growth per country	32	1.19	2.27	16	7.26	1.99	32	0.08	1.96	80	0.79	1.98	16	1.19	1.83	16	1.56	1.29	16	3.49	4.36
Size	32	0.09	0.61	15	-1.43	0.55	32	-0.35	0.61	74	-0.35	1	16	0.25	0.33	12	-1.22	0.27	16	-1.74	0.98
Income Diversity	32	0.19	0.08	15	0.07	0.03	32	0.19	0.06	74	0.23	0.12	16	0.17	0.05	12	0.22	0.08	16	0.07	0.06
Funding Fragility	32	0.51	0.2	15	0.32	0.09	32	0.49	0.12	74	0.75	0.17	16	0.39	0.24	12	0.42	0.08	16	0.38	0.11
Efficiency Ratio	32	0.82	0.16	15	0.52	0.05	32	0.65	0.08	74	0.66	0.45	16	0.65	0.06	12	0.47	0.05	16	0.51	0.10

Summary of statistics of key variables per country (2001-2016) - continued

Table 15c

	Singapore			South Korea			Spain			Sweden			Switzerland			United Kingdom			United States		
Variable	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd
Variability Ratio	39	1.81	0.34	22	1.56	0.17	61	1.89	0.9	56	2.32	0.96	18	3.35	1.1	80	2.18	0.94	147	2.1	0.85
Variability Ratio_LRE	11	1.72	0.16	8	1.66	0.3	23	2.09	0.45	28	2.52	0.74	11	3.2	1.21	35	2.18	0.62	68	1.77	0.69
Market RWA_U (LGD = 45%)	48	0.92	0.14	42	0.94	0.28	64	0.9	0.35	64	0.78	0.2	32	0.82	0.19	80	0.87	0.26	192	0.89	0.26
Market RWA (LGD = 45%) adjusted by Leverage	48	1.08	0.15	42	1.12	0.41	64	0.97	0.33	64	0.74	0.19	32	0.84	0.19	80	0.87	0.23	192	1.04	0.25
CDS Spread	44	85.29	44.98	0	na	na	67	175.1	183.2	55	81.13	75.92	32	69.73	51.72	68	88.35	70.62	184	92.61	76.32
WACC	45	9.49	1.4	20	14.86	2.63	61	13.43	3.8	64	10.35	2.45	25	11.07	2.12	62	13.23	4.4	192	11.92	2.97
Leverage Ratio	48	9.24	1.08	37	7.44	1.34	62	6.02	1.48	64	4.46	0.69	19	4.53	0.8	80	5.13	1.41	192	9.1	2.62
T1 regulatory Capital Ratio	48	12.86	1.87	20	10.31	2.38	62	9.81	2.25	64	12.05	6.38	18	16.06	3.11	80	10.94	3.06	173	11.54	3.01
Regulatory RWA	39	0.58	0.09	22	0.63	0.08	62	0.55	0.13	56	0.37	0.13	18	0.24	0.06	80	0.43	0.12	147	0.52	0.13
Regulatory RWA_LRE	11	0.61	0.05	8	0.59	0.15	23	0.53	0.07	28	0.33	0.12	11	0.26	0.05	35	0.44	0.09	68	0.58	0.17
Loans to total assets	48	0.52	0.08	37	0.68	0.03	62	0.61	0.09	64	0.61	0.09	19	0.24	0.07	80	0.45	0.11	180	0.45	0.24
Securities to total assets	48	0.17	0.04	37	0.19	0.03	62	0.2	0.07	64	0.14	0.06	19	0.48	0.11	80	0.23	0.07	192	0.33	0.18
Derivatives to total assets	39	0.03	0.02	32	0.01	0.01	52	0.05	0.03	48	0.07	0.05	19	0.08	0.07	62	0.16	0.12	140	0.04	0.03
Asset Volatility (KMV Model)	48	7.36	1.89	42	8.13	6.26	64	5.41	1.86	64	4.32	0.84	32	4.2	0.93	80	4.79	1.58	192	7	2.78
Non-Performing Loans (NPL)	45	3.2	2.81	32	1.53	0.6	57	5.04	4.51	60	1.06	0.72	17	1.44	1.74	75	3.75	2.55	144	1.62	1.27
Return on Assets (ROA)	45	1.06	0.22	32	0.68	0.29	61	0.51	1	64	0.59	0.23	17	0.27	0.39	80	0.48	0.53	192	1.03	0.63
Real GDP Growth per country	48	5.1	4.11	48	3.88	1.67	80	1.54	2.53	64	2.19	2.55	32	1.71	1.55	80	1.75	1.82	192	1.79	1.5
Size	48	-1.93	0.57	37	-1.62	0.48	62	-0.95	1.03	64	-1.23	0.54	19	-0.02	0.13	80	0.04	0.85	192	-0.83	1.1
Income Diversity	48	0.13	0.06	37	0.2	0.28	62	0.22	0.07	64	0.26	0.09	19	0.25	0.09	80	0.18	0.08	192	0.18	0.16
Funding Fragility	48	0.51	0.09	37	0.41	0.15	62	0.43	0.09	64	0.44	0.16	19	0.75	0.19	80	0.62	0.16	192	0.71	0.18
Efficiency Ratio	48	0.42	0.03	37	0.57	0.13	62	0.55	0.07	64	0.53	0.08	19	0.97	0.58	80	0.64	0.15	192	0.64	0.12

Summary of statistics of key variables per year (2001-2008)

Table 16a

	2001			2002			2003			2004			2005			2006			2007			2008		
Variable	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd
Variability Ratio	27	1.45	0.64	34	1.69	0.7	39	1.91	0.86	41	1.69	0.71	47	1.54	0.66	52	1.18	0.51	59	1.24	0.55	65	2.12	0.84
Variability Ratio_LRE	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na
Market RWA_U (LGD = 45%)	59	0.89	0.24	63	0.93	0.36	66	0.93	0.29	66	0.84	0.29	67	0.76	0.27	70	0.61	0.25	73	0.58	0.21	73	0.92	0.24
Market RWA (LGD = 45%)	59	0.98	0.41	63	1.01	0.43	66	1.02	0.34	66	0.94	0.4	67	0.85	0.38	70	0.68	0.33	73	0.73	0.38	73	1.01	0.32
CDS Spread	29	41.92	41.41	40	58.68	70.86	46	36.2	40.57	52	33.21	73.88	54	25.18	35.44	57	17.69	19.85	57	28.25	17.25	58	136.3	69.89
WACC	42	7.99	1.23	47	8.58	1.29	49	9.51	2.03	53	8.64	1.63	55	9.48	1.91	56	9.37	1.52	65	9.92	1.48	67	11.74	1.89
Leverage Ratio	57	5.98	2.49	63	5.76	2.67	65	5.42	3.52	65	5.43	3.45	67	5.69	2.74	67	5.91	2.75	67	5.61	3.67	72	5.21	2.31
T1 regulatory Capital Ratio	46	8.25	1.84	52	8.46	2.29	56	8.6	2.24	56	8.75	2.54	58	8.48	1.97	58	8.91	2.17	62	8.47	2.03	67	9.57	2.68
Regulatory RWA	28	0.71	0.81	34	0.56	0.14	41	0.55	0.15	43	0.55	0.14	50	0.53	0.15	53	0.54	0.15	59	0.54	0.15	67	0.5	0.15
Regulatory RWA _LRE	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na	0	na	na
Loans to total assets	56	0.51	0.15	62	0.51	0.16	64	0.51	0.16	64	0.51	0.17	66	0.5	0.17	66	0.51	0.17	66	0.5	0.17	71	0.5	0.17
Securities to total assets	57	0.23	0.12	63	0.24	0.13	65	0.26	0.13	65	0.26	0.14	67	0.28	0.15	67	0.27	0.15	67	0.28	0.15	72	0.24	0.13
Derivatives to total assets	13	0.06	0.04	16	0.07	0.05	17	0.07	0.05	28	0.05	0.04	49	0.05	0.05	53	0.04	0.04	56	0.06	0.05	63	0.1	0.11
Asset Volatility (KMV Model)	59	7.81	4.43	63	7.2	4.01	66	7.25	4.28	66	6.67	4.34	67	5.74	3.64	70	4.71	2.9	73	4.85	3.19	73	5.96	3.09
Non-Performing Loans (NPL)	0	na	na	48	4.08	5.93	54	4.73	5.45	57	4.44	5.53	57	3.26	4.65	58	2.47	3.79	59	2.27	3.61	62	2.08	3.37
Return on Assets (ROA)	55	0.88	0.75	58	0.78	0.6	63	0.83	0.6	61	0.93	0.67	63	0.97	0.72	67	1.08	0.56	67	0.99	0.54	68	0.57	0.66
Real GDP Growth per country	76	2.88	2.67	76	3.39	2.94	76	3.55	3.15	76	4.76	2.86	76	4.48	3.29	76	4.99	3.76	76	5.15	4.39	76	2.19	3.58
Size	57	-1.8	1.03	63	-1.7	1.05	65	-1.45	1.04	65	-1.25	1.05	67	-1.13	1.04	67	-0.95	1.01	67	-0.73	1.01	72	-0.74	1.02
Income Diversity	57	0.26	0.16	63	0.24	0.15	65	0.24	0.15	65	0.23	0.15	67	0.21	0.14	67	0.21	0.14	67	0.2	0.11	72	0.19	0.09
Funding Fragility	57	0.48	0.22	63	0.5	0.24	65	0.54	0.24	65	0.56	0.23	67	0.55	0.22	67	0.53	0.22	67	0.47	0.2	72	0.36	0.22
Efficiency Ratio	57	0.61	0.11	63	0.61	0.12	65	0.59	0.14	65	0.58	0.1	67	0.57	0.11	67	0.54	0.09	67	0.55	0.12	72	0.66	0.42

Summary of statistics of key variables per year (2009-2016)

Table 16b

Variable	2009			2010			2011			2012			2013			2014			2015			2016		
	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd	obs	mean	sd
Variability Ratio	66	2.63	0.89	72	2.6	0.83	74	2.64	0.94	74	2.6	1.07	73	2.18	0.81	75	2.1	0.7	75	2.08	0.71	75	2.45	0.9
Variability Ratio _LRE	0	na	na	52	2.3	0.76	59	2.32	0.78	61	2.32	0.89	64	1.82	0.66	69	1.8	0.54	71	2.02	0.66	74	2.39	0.83
Market RWA_U (LGD = 45%)	73	1.15	0.27	75	1.11	0.22	76	1.11	0.23	76	1.05	0.27	76	0.94	0.26	76	0.89	0.26	76	0.89	0.28	76	1.00	0.27
Market RWA (LGD = 45%)	73	1.22	0.28	75	1.17	0.23	76	1.16	0.21	76	1.09	0.24	76	0.97	0.24	76	0.92	0.24	76	0.91	0.27	76	1.02	0.25
CDS Spread	60	165	72.93	60	124.7	47.28	60	187.7	111.9	61	217.6	139.5	63	149.4	93.5	64	104.4	58.57	64	109.7	79.95	62	120.7	69.69
WACC	67	14.12	3.39	72	15.86	3.33	74	15.73	3	74	14.15	2.61	74	13.6	2.91	74	13.18	3.36	74	11.94	2.69	74	11.56	2.66
Leverage Ratio	72	5.92	2.57	75	6.28	2.43	75	6.29	2.42	75	6.38	2.5	75	6.63	2.21	75	6.75	2.15	75	7.01	2.06	75	6.97	2.06
T1 regulatory Capital Ratio	68	10.67	2.45	73	11.35	2.62	73	11.57	2.27	72	12.22	2.8	72	12.28	2.83	73	12.72	2.82	75	13.43	3.32	75	14.07	3.65
Regulatory RWA	68	0.5	0.14	73	0.49	0.14	74	0.48	0.15	74	0.46	0.16	73	0.48	0.16	75	0.47	0.16	75	0.47	0.15	75	0.45	0.15
Regulatory RWA_LRE	0	na	na	52	0.52	0.13	59	0.54	0.15	61	0.51	0.18	64	0.56	0.19	69	0.54	0.17	71	0.47	0.15	74	0.46	0.15
Loans to total assets	71	0.51	0.16	74	0.51	0.16	74	0.5	0.16	74	0.49	0.16	75	0.49	0.16	75	0.48	0.16	75	0.49	0.16	75	0.49	0.16
Securities to total assets	72	0.26	0.15	75	0.26	0.15	75	0.25	0.14	75	0.26	0.14	75	0.27	0.14	75	0.27	0.13	75	0.27	0.13	75	0.27	0.13
Derivatives to total assets	65	0.07	0.08	71	0.06	0.07	70	0.07	0.09	70	0.06	0.08	72	0.05	0.07	73	0.06	0.08	74	0.06	0.07	74	0.05	0.07
Asset Volatility (KMV Model)	73	6.91	2.68	75	7.47	2.98	76	6.71	2.13	76	5.52	1.8	76	5.2	1.76	76	5.13	1.71	76	5.04	1.79	76	5.19	1.75
Non-Performing Loans (NPL)	68	2.15	1.79	69	3.06	2.56	73	3.16	2.54	73	3.13	2.8	73	3.34	3.43	73	3.48	4.02	73	3.11	3.65	73	2.88	3.27
Return on Assets (ROA)	72	0.45	0.76	71	0.76	0.47	75	0.7	0.66	75	0.63	1	74	0.71	0.58	75	0.74	0.46	75	0.73	0.45	75	0.67	0.49
Real GDP Growth per country	76	-0.86	4.98	76	4.85	3.92	76	3.28	3.14	76	2.32	2.99	76	2.58	2.72	76	2.91	2.21	76	2.66	2.49	76	2.46	2.32
Size	72	-0.65	0.97	75	-0.59	0.92	75	-0.49	0.88	75	-0.4	0.82	75	-0.37	0.78	75	-0.37	0.78	75	-0.43	0.77	75	-0.4	0.76
Income Diversity	72	0.19	0.11	75	0.19	0.1	75	0.18	0.1	75	0.19	0.1	75	0.19	0.1	75	0.19	0.1	75	0.18	0.11	75	0.19	0.12
Funding Fragility	72	0.49	0.24	75	0.5	0.22	75	0.47	0.22	75	0.48	0.23	75	0.5	0.23	75	0.52	0.23	75	0.53	0.22	75	0.56	0.21
Efficiency Ratio	72	0.61	0.46	75	0.54	0.12	75	0.56	0.15	75	0.55	0.14	75	0.57	0.16	75	0.57	0.16	75	0.57	0.17	75	0.57	0.19

Annex II: Example of leverage ratio adjustment

To illustrate the leverage ratio adjustment, consider the example in Table 17 where two banks (US Bancorp and DNB ASA) have very similar asset volatilities (just over 5.1%), but U.S. Bancorp has a market leverage ratio of 16.9% compared to DNB ASA of 7%. Even though both banks have a similar asset risk profile (as measured by asset volatility), DNB ASA has much higher leverage and is therefore riskier than U.S. Bancorp. This difference in leverage is reflected in its higher EDF (0.38 for DNB ASA versus 0.24 for US Bancorp). The difference in leverage between two banks is also captured by the market-implied risk weight measure, which does not adjust for leverage. That is, the unadjusted market RWA for US Bancorp is 0.65 compared to 0.80 for DNB ASA.

The Market RWA controls for differences in leverage between banks, so that differences in the measure of Market RWA only reflect differences in asset volatility and model estimation error. To illustrate, using the coefficient estimates for Equation 3 which are presented in Model 1 of Table 3, the Market RWA for US Bancorp in 2016 is calculated as follows:

$$(\text{Market RWA})_{US\ Bancorp} = 0.65 - .026 * (6.85 - 16.91) = 0.92$$

Where the Unadjusted Market RWA = 0.65, the estimate $\beta_1 = -0.026\ (see\ Table\ 3)$, the sample average market leverage ratio = 6.85, and the market leverage ratio for US Bancorp = 16.91. A similar process is followed for DNB ASA.

As shown in Table 17, after adjusting for differences in leverage, the difference between the market-implied measure of risk weighted assets for the two banks is significantly diminished, reflecting that both banks have similar levels of asset volatility.

Example of leverage adjustment and impact on market-implied risk weights — Table 17

	US Bancorp	DNB ASA
Asset Volatility (%)	5.16	5.17
Market leverage ratio (%)	16.91	7.05
Expected Default Frequency (EDF)	0.24	0.38
Market RWA_U	0.65	0.80
Market RWA	0.92	0.81

Example based on 2016 data, where the sample average leverage ratio is equal to 6.85%.

As a sensitivity test, we also calculated the market implied RWA directly using the model coefficient estimates from Equation 2 (which are reported in Table 3). For example, using asset volatility for US Bancorp and assuming it had the average market leverage ratio in 2016 (rather than its actual market leverage ratio), the Market RWA is given by:

$$(\text{Market RWA})_{US\ Bancorp} = 0.449 - .026 * (6.85) + 0.1333 * (5.16) - .003 * (5.16^2) = 0.88$$

The conclusions in the paper are not affected by which approach is used to calculate the leverage adjusted Market RWA.

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