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Abstract

We study the co-movement in international zero-coupon government bond yields using a recently proposed methodology by Choi *et al.* (2018) and Choi *et al.* (2021) for the estimation of multilevel factor models. We employ a readily available non-proprietary dataset coupled with open-source code which facilitates reproduction of the results but also comparability with the existing bibliography. The ten countries dataset is cross-sectionally expanded to eleven countries with newly constructed data series on the term structure of Greek constant-maturity, government zero-coupon bond rates. We find that the country pair US-Germany is most suitable as an initial candidate for global factor estimation. We confirm that three global factors account for most of the variation in zero-coupon bond yields leaving a small proportion to be (contemporaneously) explained by local factors. Global inflation and global real activity are related to the global level and slope factors. The third global factor, "curvature", is strongly related to economic/financial uncertainty linked to systemic risk stemming from the US financial markets.

Keywords: Sovereign bonds; Yield curve; Term structure; Multilevel factor model; Global factors; Local factors

JEL classification: C10, E43, G12, G15

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1 Introduction

The importance of bond markets and consequently of sovereign bond markets in modern economies is unquestionable. Sovereign bond markets are intimately connected with budget deficit funding and the conduct of monetary policy. This paper addresses the question of whether information consolidation from international yield curves can help to uncover contemporaneous dependency patterns among yield curves of different countries, updating our knowledge on the leading role of specific countries and the importance of increased globalization and financial integration.

The point of origin for our empirical work is the paper of Diebold *et al.* (2008) who extend the modeling approaches and findings of Litterman & Scheinkman (1991), Diebold & Li (2006) and Diebold *et al.* (2006), to a multi-country framework with unobservable global and local (that is country) factors. Diebold *et al.* (2008) examine the yields from a set of four countries (Germany, Japan, UK, US) and they extract two global factors, a global level and a global slope factor, and the corresponding local level and slope factors, for each one of the four countries. They find that for all countries and maturities, variation in the global factor is responsible for a large share of variation in yields, the global share tends to increase with maturity and verify the links of the two global factors (level and slope) to the global macroeconomy.

Similar to or following Diebold *et al.* (2008), several studies have shown strong dependencies of interest rates across countries and have found systematic global factors in international yield curves, for example, Pérignon *et al.* (2007), Modugno & Nikolaou (2009), Bae & Kim (2011), Moench (2010), Dahlquist & Hasseltoft (2013), Kaminska *et al.* (2013), Bai & Wang (2015), Jotikasthira *et al.* (2015), Abbritti *et al.* (2018)), Coroneo *et al.* (2018), Byrne *et al.* (2019), Stagnol (2019) and Kobayashi (2020).

All the aforementioned studies use a relatively small set of countries owning to data availability, coverage focus and difficulties that arise with explicit parametric dynamic factor estimation and modeling. A priori, a hierarchical linkage factor model needs to be set up. In addition, although parametric model identification is enforced, it is not certain that the "true" global factors have been identified particularly when US does not participate in the set of countries or when regional commonalities dominate global ones.

Choi *et al.* (2018), Choi *et al.* (2021) overcome these problems and develop the procedures to appropriately estimate the number of global and local factors in parsimonious multilevel factor models and to consistently estimate the global and local factors. In their setup, global factors refer to unobserved factors that affect all individuals in the world while the unobserved country factors influence only those in one specific country. Kim *et al.* (2017) apply this methodology to U.S. treasury zero coupon bonds log yield data, for maturities 1, 2 and 3 years and a set of macroeconomic series in order to extract two total (economy-wise) and two sectoral factors using a large US dataset.

We contribute to the literature in the following ways. We use the multi-level factor model and estimation approach of Choi *et al.* (2018) and Choi *et al.* (2021), in order to examine and understand the co-movements of the yield curves across a wide set of eleven countries. To that purpose, we employ the readily available ten countries dataset of Wright (2011). The dataset is expanded using newly constructed series on the term structure of constant-maturity, zero-coupon interest rates for Greece. Open-source code[1] and the dataset are provided to facilitate replication and results comparison.

We confirm that global factors are dominant contributors to international yield variability albeit country heterogeneity is observed and needs further examination. We estimate a maximum number of three global and three local factors. Global factors are contemporaneously linked to global inflation (level factor), global real activity (slope factor) and global systemic risks (curvature) reflected mostly by the St. Louis Fed's financial stress index. All our results are scrutinized for robustness using alternative identification pairs with respect to the initial global factors consistent estimator. We find that the US-Germany pair is the one that mostly conforms with contemporaneous co-movements of US factor proxies and global macroeconomic fundamentals.

The rest of the paper is organized as follows. In section 2, we briefly describe the data set while section 3 presents the multi-level factor model and the details of subsequent econometric analysis. In section 4, we present and discuss the main results of the paper including careful estimation of the number of global and local factors, identification of the global factors, the variance contributions of global and local factors and contemporaneous correlations between selected global macro series and the three extracted global factors. Finally, section 5 offers some concluding remarks.

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[1] We use the open source econometric software gretl (https://gretl.sourceforge.net/) and its native scripting language "Hansl" to write code for all estimation procedures followed in this paper. Replication material can be found at https://sites.google.com/site/ioannisavenetis/research.

2 Data and preliminary analysis

We adopt the widely used and readily available monthly nominal zero-coupon bond yields dataset[2] constructed by Wright (2011), which covers 10 countries, namely: U.S, Canada, U.K., Germany, Sweden, Norway, Switzerland, Japan, Australia and New Zealand, with varying spans, for the period: November 1971 (earliest) to May 2009 (latest). For each country in this dataset, zero coupon yields are constructed for 60 maturities running from 3 months to 15 years (180 months), except for New Zealand that runs with 40 maturities, from 3 months to 10 years (120 months). As such, term structure information from a wide range of maturities is evoked.

We expand this dataset to incorporate Greek zero-coupon bond yields. The official prices and yields of Greek Government benchmark bonds traded in the Electronic Secondary Securities Market (HDAT) operated by the Bank of Greece are available on a daily basis from March 1999.[3]

Estimated zero-coupon yields are provided for seven maturities: 36, 60, 84, 120, 180, 240 and 360 months. We use the last day of each month to compact the daily dataset and we construct the monthly Greek yield curve for all 60 maturities - 3 months, 6 months, ..., to 180 months - using the Nelson & Siegel (1987), Svensson (1994) and Diebold & Li (2006) models. The zero-coupon bond yields are highly correlated across models and without loss of generality, in our empirical analysis, we adopt data produced by the Diebold & Li (2006) dynamic model. Robustness checks did not reveal essential quantitative or any qualitative differences on our results following the aforementioned choice.

Thus, in our empirical analysis, we employ a balanced panel for all 11 countries, covering the period March 1999 - May 2009 with $T = 123$ observations and $N = 640$ series in total.

Figure 1 depicts the time series evolution of the term structure of yields for four countries (to conserve space): US, Germany, Japan and Greece. It reveals significant level movements over the sample while, although less marked, variation in the slope and curvature is also evident. Cross-country commonalities - less pronounced in the case of Japan - suggest the presence

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[2] For example, see Bai & Wang (2015) and Abbritti *et al.* (2018). This dataset is available by Prof. Jonathan Wright on his website at (last access 20/12/2019): https://econ.jhu.edu/directory/jonathan-wright/. Alternatively, the data can be downloaded at https://www.aeaweb.org/articles.php?doi=10.1257/aer.101.4.1514

[3] We obtained daily clean bond prices and yields, for the period 2/3/1999 to 5/1/2021. See the Bank of Greece web-page on Greek Government Securities:
https://www.bankofgreece.gr/en/statistics/financial-markets-and-interest-rates/greek-government-securities/

of underlying global factor(s).

The preliminary assessment of cross-country yield curve commonalities, is complemented by principal component (PC) analysis following Diebold *et al.* (2008, section 3.3). In detail, we conduct a "double" PC analysis: first, for each country, we estimate the first four PCs and their variance share (Table 1, Panel A) and second, for each of the four sets of estimated principal components (there are 11 series per set), we compute the variance share attributed to the first two PCs denoted by $PC1^p$ and $PC2^p$ (Table 1, Panel B). Further, Panel B "names" the PC1,...,PC4 estimates as Level, Slope, Curvature and Curvature_2. The naming choice as well as the choice of the first four PCs rests on the assumption of four representative factors in zero-coupon yields, namely: level, slope, curvature, curvature_2[4] which is supported by our results; the fourth PC in Panel A accounts for a maximum of 0.35% of yields variation in the case of Switzerland (CH) while the variability explained by the first four PCs sums to no less than 99.92% across all countries indicating an excellent fit of a four factor model.

Indeed, results reported in Table 1, Panel A, support previous evidence - well documented in the literature - that the magnitudes of a few common components adequately represent the monthly term structure. The variance proportion explained by the first factor in each country group is above 80% with the second factor proportion lying within 2.93% - 17.21%. Table 1 Panel B results, suggest the existence of global factors as in Diebold *et al.* (2008). Specifically, the first principal component, $PC1^p$, explains 71% of the "levels" variation, 66.35% of the "slope" variation while, 41.5% of the "curvature" variation and 23.44% of the "Curvature_2" variation.

This PC analysis highlights the presence of one global level and one global slope as dominant factors while points to the significance of one global curvature factor.

3 Multilevel factor model and global factors identification

Following closely the Choi *et al.* (2018) notation, our applied analysis will build on the multilevel factor model

$$X_{mt} = \Gamma_m G_t + \Lambda_m F_{mt} + e_{mt} \tag{3.1}$$

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[4] A popular extension of the Nelson & Siegel (1987) model was put forth by Svensson (1994). Svensson's fourth factor, introduces a second medium-term (curvature) component to the model. With four factors, the Nelson-Siegel model can fit term structure shapes with more that one local maximum or minimum along the maturity spectrum.

Table 1. Principal components analysis for each country group (Panel A) and for each PC group (Panel B)

Panel A	N_m	PC1	PC2	PC3	PC4
US	60	90.52	9.13	0.25	0.07
CAN	60	89.71	9.63	0.44	0.18
UK	60	87.84	10.75	1.14	0.19
DE	60	88.90	10.39	0.63	0.06
SE	60	92.11	7.00	0.78	0.08
NO	60	96.59	2.93	0.41	0.05
CH	60	90.50	8.41	0.71	0.34
JP	60	89.58	9.44	0.97	0.00
AUS	60	90.78	8.66	0.46	0.10
NZ	40	82.45	17.21	0.34	0.00
GR	60	89.57	9.94	0.49	0.00
Panel B		Level	Slope	Curv.	Curv$_2$.
PC1^p		71.04	66.35	41.52	23.44
PC2^p		11.76	12.30	16.17	15.55

Notes. Panel A: For eleven country groups (each having N_m series), we report the variance proportion associated with the first four principal components, $PC1, ..., PC4$. **Panel B:** principal component analysis of the estimated PC1,...,PC4 factor groups. Each factor group has 11 common component series. The first four factors are named "Level", "Slope", "Curvature" and "Curvature$_2$". We report the variance proportion of these eleven series explained by the first (PC1^p) and second (PC2^p) principal components.

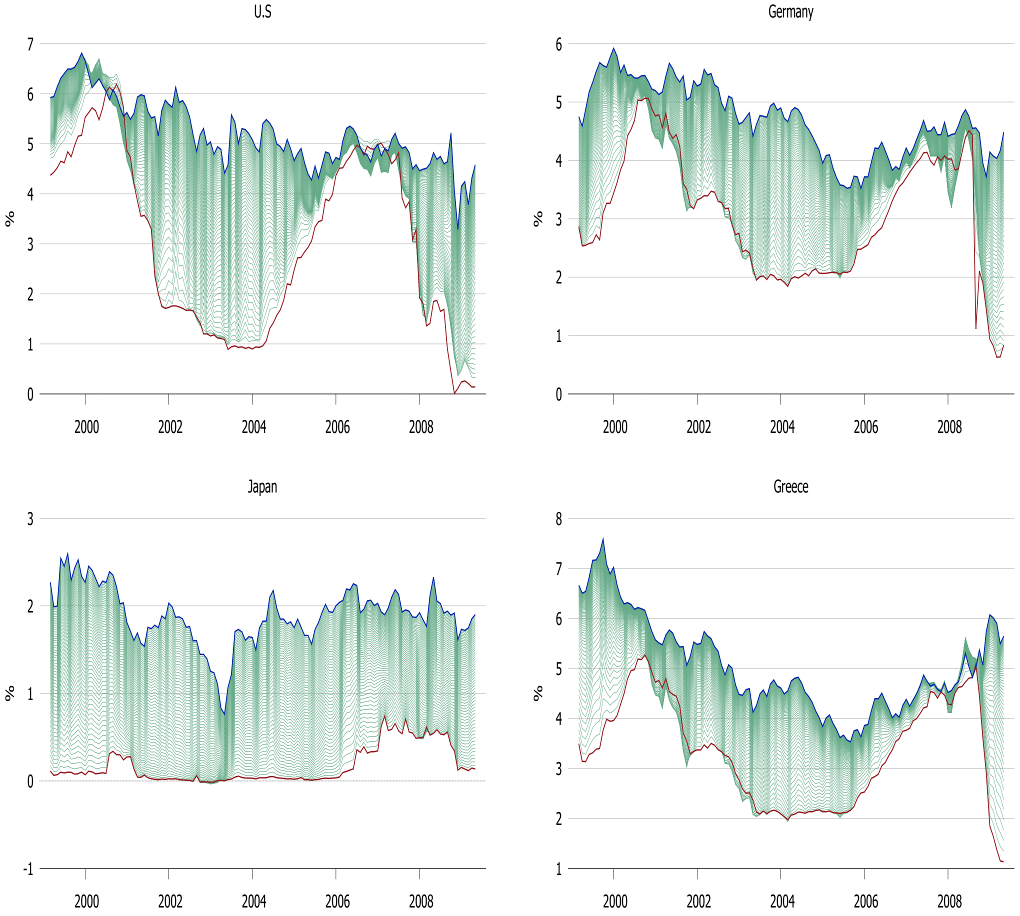

Figure 1. Evolution of monthly yields for 60 fixed maturities of 3, 6, 9,...,180 months. The blue shaded curve stands for the largest maturity of 180 months while the red shaded curve denotes the shortest maturity yield rate (3 months). All "in-between" maturities, 6-177 months, are shown with a green shade.

where $m = 1, ..., M$ is the country index (more generally group or block index), $t = 1, ..., T$ denotes time, G_t is an $s \times 1$ vector of unobserved global factors that affects individuals in all the countries, F_{mt} is an $r_m \times 1$ vector of unobserved country factors that affects individuals only in country m, Γ_m and Λ_m are unobserved factor loadings matrices with dimensions $N_m \times s$ and $N_m \times r_m$ respectively (each country is allowed to have a different number of individuals N_m) and e_{mt} is an idiosyncratic country vector error. Let $i = 1, ..., N_m$ denote individual country series, it is assumed that $E\left(e_{mit}\right) = 0$ for all m, i, t suggesting the use of demeaned data in model (3.1) while mild serial and cross-sectional dependency among $\{e_{mit}\}$ is allowed to obtain valid asymptotics for factor estimation. The $N_m \times 1$ vector X_{mt} contains standardized yields for country m at time t of maturities $i = 1, ..., N_m$.

This is a model that requires the group structure and factor strengths to be known to the practitioner a priori. Choi *et al.* (2018) provide a methodology that consistently estimates, up to an invertible matrix, the factors and the loadings and successfully identifies (separates) global and local factors. Their underlying assumptions include that: global and local factors are zero-mean, stationary processes that satisfy (and their self- and cross-products) the conditions for the law of large numbers and the central limit theorem; all factors are contemporaneously uncorrelated although in Choi *et al.* (2021) non-zero correlation between the local factors is allowed; no country (or group) should have a dominantly large or small number of series. Consistency of factor loadings and factor estimates is shown under the realistic condition of a fixed number of blocks, M (though their approach is still valid asymptotically as M tends to infinity).

The identification (separation up to an invertible matrix) of the global factors is the cornerstone for multilevel models like (3.1) particularly when structural analysis is required. Yet, even if variance ratio decompositions or forecasting are in the center of focus, a challenging theme confronted is the estimation of the number of global and local factors, simultaneously, that is, without assuming a priori either of these two numbers.

Choi *et al.* (2021) propose a two-step procedure to estimate the number of global and local factors and Choi *et al.* (2018) put forth a sequential multi-step approach to estimate consistently the global and local factors and loadings. The just mentioned steps are set out in more detail below:

Step 1, using two consistent selection criteria, the canonical correlations difference (CCD) and the modified canonical correlations (MCC), proposed by Choi *et al.* (2021)[5], the number s of global factors is estimated.[6]

Step 2, once s is consistently estimated by CCD and MCC, the global factors G_t are concentrated out of the full data panel using an initial global factor(s) estimator[7] $\hat{G}_t^{(1)}$ and existing criteria, such as those proposed by Bai & Ng (2002) and Ahn & Horenstein (2013),[8] are then employed to consistently estimate the number of local factors r_m for $m = 1, ..., M$, where local factors are allowed to be mutually correlated.

Steps 3-4-5, presented in detail[9] in Choi *et al.* (2018) involve an initial estimate of Λ_m, F_{mt} by principal components, the final estimation of Γ_m and G_t (denoted by $\hat{\Gamma}_m^{(2)}$, $\hat{G}_t^{(2)}$) based on the previous estimates $\hat{\Lambda}_m^{(1)}$, $\hat{F}_{mt}^{(1)}$ and, lastly, estimation of Λ_m, F_{mt} (denoted by $\hat{\Lambda}_m^{(2)}$, $\hat{F}_{mt}^{(2)}$) given the consistent estimator $\hat{\Gamma}_m^{(2)}$, $\hat{G}_t^{(2)}$ of global factor loadings and global factors.

4 An application to international yield curves

4.1 Estimation of the number of global factors

In order to estimate the number of global factors and initiate step 1 above, we should select a sufficiently large number of maximum (common) factors r^*_{max}, that satisfies the inequality

$$r^*_{max} \geq \max\{s + r_1, ..., s + r_M\}$$

with s the number of global factors and r_m the number of local factors in the m^{th} country group.

To this end, we apply ten standard factor selection criteria - namely ER, GR, IC_{p1}, IC_{p2}, IC_{p3}, BIC_3, PC_{p1}, PC_{p2}, PC_{p3} and ED - for each data

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[5] These authors provide further guidance for the empirical selection of the common maximum number of factors that improve the selection precision of CCD and MCC in finite samples.

[6] Alternative consistent selection criteria for the number of global factors can be found in Chen (2012), Andreou *et al.* (2019) and Han (2021).

[7] The superscript "(1)" is employed to distinguish the initial estimate of the global factors vector G_t from the final estimator, $\hat{G}_t^{(2)}$, obtained in a later step (both are consistent).

[8] Choi *et al.* (2021) propose the use of BIC_3 by Bai & Ng (2002) and ER by Ahn & Horenstein (2013). Even so, we report results from the ER, GR procedures of Ahn & Horenstein (2013), all PC, IC criteria along with BIC_3 developed by Bai & Ng (2002) and the ED (edge distribution) procedure developed by Onatski (2010). We rely primarily on ER, GR and then IC_{p2} and BIC_3. Among others, one advantage of these estimators is their reduced sensitivity to the (common) maximum number of factors r_{max} allowed in each block.

[9] They correspond to steps 2, 3 and 4 in Choi *et al.* (2018).

block (each country) with a predetermined upper bound r_{max} and obtain consistent estimates of $s + r_m$ for $m = 1, ..., M$. We, then, pick out the common maximum number of factors as

$$r^*_{max} = \max\left\{\widehat{s + r_1}, ..., \widehat{s + r_M}\right\} \tag{4.1}$$

We set a "sufficiently" large upper bound $r_{max} = 20$ although we record the outcome of the aforementioned procedure for all $r_{max} = 2, ..., 20$ to guard against sensitivity induced by the initial upper bound choice.

Table 2 reports the results for two selected upper bounds $r_{max} = \{6, 15\}$ that demonstrate the performance of all selection criteria and their dependence (in our sample) on the preselected upper bound r_{max}. The general picture emerging from the results with $r_{max} = 2, ..., 20$ and, of course, those reported in Table 2 for $r_{max} = \{6, 15\}$, is that only the ER and GR are relatively conservative in their upper bound choice while only ER achieves upper bound insensitivity for sufficiently large preselected values of r_{max}. The estimated maximum number of factors r^*_{max} equals the preselected upper bound value r_{max} when $r_{max} = 2, ..., 15$ while, only for the ER selection criterion, it is stabilized at $r^*_{max} = 15$ for upper bound choices of $r_{max} = 15, ..., 20$ or larger.

Table 3 reports the (**step 1**) results for CCD and MCC obtained by applying the common $r_{max} = 2, ..., 15$ for each term structure block, $m = 1, ..., M$. Both criteria select two global factors, in almost all different values of $r_{max} = 2, ..., 15$ with an exception of three global factors selected by MCC for $r_{max} = 12, ..., 15$. Thus, the impact of varying the value of r_{max} on the performance of CCD and MCC is minimal.

Notice that the choice of either one, two or, at most, three global factors is in line with a number of empirical works. Pérignon *et al.* (2007) assume the presence of one global and one local factor driving government bond returns. Dahlquist & Hasseltoft (2013) provide evidence that risk premia are driven by one global and one local factor. Bai & Wang (2015) assume one global and one local factor driving government bond yields (albeit as an empirical illustration to a seminal contribution on model identification of dynamic factor models). Diebold *et al.* (2008) and Bae & Kim (2011) adopt two global and two local factors while two global factors explain a large fraction of international yields variation in Jotikasthira *et al.* (2015), Byrne *et al.* (2019) and Kaminska *et al.* (2013). Three global and three local factors are allowed in Modugno & Nikolaou (2009), Abbritti *et al.* (2018), Coroneo *et al.* (2018), Kobayashi (2020), Stagnol (2019).

Given that MCC performs particularly well when correlations among the local factors are allowed, we adopt the estimate of $\hat{s} = 3$ global factors.

Table 2. Selection of the Maximum Number of Factors r^*_{max}

$r_{max} = 6$	ER	GR	ICp1	ICp2	ICp3	BIC3	PCp1	PCp2	PCp3	ED
US	2	2	6	6	6	6	6	6	6	6
CAN	2	2	6	6	6	6	6	6	6	6
UK	2	2	6	6	6	6	6	6	6	6
DE	2	2	6	6	6	6	6	6	6	6
SE	1	3	6	6	6	6	6	6	6	6
NO	1	1	6	6	6	6	6	6	6	6
CH	2	2	6	6	6	6	6	6	6	6
JP	6	6	6	6	6	6	6	6	6	6
AUS	6	6	6	6	6	6	6	6	6	6
NZ	3	3	6	5	6	4	6	5	6	4
GR	3	3	6	6	6	4	6	6	6	3
$\mathbf{r^*_{max}}$	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**	**6**

$r_{max} = 15$	ER	GR	ICp1	ICp2	ICp3	BIC3	PCp1	PCp2	PCp3	ED
US	2	2	11	11	13	11	11	11	15	11
CAN	10	10	12	11	12	11	12	12	12	12
UK	10	10	15	15	15	15	15	15	15	15
DE	15	15	15	15	15	15	15	15	15	15
SE	15	15	15	15	15	15	15	15	15	15
NO	1	1	15	15	15	15	15	15	15	15
CH	15	15	15	15	15	15	15	15	15	15
JP	6	6	15	15	15	11	15	15	15	7
AUS	11	10	15	15	11	13	15	15	15	13
NZ	3	3	14	5	15	8	15	14	15	4
GR	3	3	15	15	15	11	15	15	15	3
$\mathbf{r^*_{max}}$	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**

Notes. Estimated number of factors by ten selection criteria for each country along with the estimated maximum number of factors r^*_{max}. **Top panel** reports the results when the preselect upper bound is set at $r_{max} = 6$ and **bottom panel** for the upper bound choice of $r_{max} = 15$.

Table 3. Results from CCD and MCC global factor selection criteria

		CCD													
r_{max}	:	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\hat{s}$	:	2	2	2	2	2	2	2	2	2	2	2	2	2	2
		MCC													
r_{max}	:	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\hat{s}$	:	1	2	2	2	2	2	2	2	2	2	3	3	3	3

Notes. The canonical correlations difference (CCD) and the modified canonical correlations (MCC) criteria for selection/estimation of the number of global factors s obtained by applying the common maximum number of factors $r_{max} = 2, ..., 15$ for each block.

4.2 Estimation of the number of local factors

Once the number of global factors has been consistently estimated, **step 2** of section 3 calls for the estimation of the number of local factors r_m, $m = 1, ..., M$ in each country data block. A crucial element of step 2 (and of subsequent steps 3, 4 and 5) is the (initial) estimator $\hat{G}_t^{(1)}$ for the global factors which, following Choi *et al.* (2018), is based on the block-pair that yields the maximum canonical correlation.

Table 4 reports the squared sample correlation coefficients between arbitrary linear combinations of the principal components estimates, for all possible pairs of countries in our sample, when three global $s = 3$ and three local factors $r_m = 3$ are - a priori - assumed. Table 4 results imply that the initial estimator $\hat{G}_t^{(1)}$ of the global factors should be based on the North-American pair USA-Canada (US-CAN is the pair of countries with the maximum sample mean of the eigenvalues). The second and third largest correlations come from the European pairs of Germany-Switzerland (DE-CH) and Germany-Sweden (DE-SE), respectively. A regional character emerges implying that the strength of the correlation of countries' yield movements depends on the relative importance of global and regional components. If the regional component of a country's yield is stronger than the global and idiosyncratic country component, the country may appear more correlated with its neighbors than with the world as a whole.

Table 4 results are based on the estimated $\hat{s} = 3$ and the preset choice of $r_m = 3$. Identification considerations compel the use of alternative choices, at

Table 4. Sample canonical correlations between all possible pairs of countries.

	US	CAN	UK	DE	SE	NO	CH	JP	AUS	NZ	GR
US	1	**0.746**	0.664	0.638	0.601	0.591	0.665	0.564	0.592	0.483	0.542
CAN		1	0.593	0.643	0.626	0.583	0.645	0.577	0.607	0.534	0.573
UK			1	0.645	0.604	0.562	0.653	0.505	0.643	0.553	0.540
DE				1	**0.707**	0.605	**0.729**	0.542	0.581	0.549	0.635
SE					1	0.604	0.658	0.538	0.576	0.588	0.618
NO						1	0.596	0.469	0.503	0.478	0.537
DE							1	0.559	0.556	0.515	0.620
JP								1	0.529	0.456	0.499
AUS									1	0.605	0.538
NZ										1	0.505
GR											1

Notes. Sample canonical correlation coefficients between all possible pairs of countries derived from our sample. The three largest correlation coefficients are presented in bold types and correspond to the pairs US-CAN (largest), DE-CH (second-largest) and DE-SE (third-largest).

least, for the number of local factors. Thus, we repeat the estimation of Table 4 for $s = \{1, 2, 3\}$ and $r_m = 1, ..., 15$. The outcomes are shown in Table 5 where the top three pairs (maximum sample mean of the eigenvalues) between country yields are depicted. To conserve space, the first three columns correspond to $r_m = \{1, 2, 3\}$ and the last column to the maximum number of local factors $r_m = 15$. Table 5 documents the dependence of the initial pair choice on the s, r_m selection while a "regional dependence" pattern emerges, for example, pairs US-CAN, DE-SE, DE-CH appear most frequently or we note the appearance of AUS-NZ (Pair 2 for $s = 1, r_m = 1$).

Previous studies, e.g. as early as Chuhan *et al.* (1998), have documented that country-specific developments are at least as important as global factors (in certain contexts) for explaining capital inflows in both equity and bond markets. In addition, the importance of regional factors in sovereign bond yield co-movements has been documented, e.g. Bae & Kim (2011) provide evidence on the existence of regional commonality in yield curve dynamics of Asian Countries while Bhatt *et al.* (2017) argue on the importance of regional factors that can be attributed to the systemic importance (macroeconomic factors such as dept/GDP ratio) of currency union members.

If we can separate global factors from local factors, the methodology developed by Choi *et al.* (2018) and Choi *et al.* (2021) can yield consistent estimates of both global and local factors. If the two groups to which canonical correlation anaysis (CCA) is applied not only share global factors but also have pairwise common factors, CCA cannot distinguish which factors are true global factors and which are only common to the two groups. Thus, the

Table 5. Country-pairs with largest (top three) canonical correlations.

$s = 1$	$r_m = 1$		$r_m = 2$		$r_m = 3$		$r_m = 15$	
Pair1	DE	CH	DE	SE	US	CAN	DE	CH
Pair2	AUS	NZ	DE	CH	DE	SE	US	UK
Pair3	DE	SE	US	CAN	DE	CH	UK	DE
$s = 2$	$r_m = 1$		$r_m = 2$		$r_m = 3$		$r_m = 15$	
Pair1	DE	SE	US	CAN	US	CAN	DE	CH
Pair2	DE	CH	DE	SE	DE	SE	US	UK
Pair3	US	CAN	DE	CH	DE	CH	UK	DE
$s = 3$	$r_m = 1$		$r_m = 2$		$r_m = 3$		$r_m = 15$	
Pair1	US	CAN	US	CAN	US	CAN	DE	CH
Pair2	DE	SE	DE	SE	DE	CH	US	UK
Pair3	DE	CH	DE	CH	DE	SE	UK	DE

Notes. The first three pairs of countries with the maximum sample mean of the eigenvalues, when the number of global factors is set at $s = 1, 2, 3$ and the number of local factors at $r_m = 1, 2, 3$. These pairs have been computed for all choices in the range $r_m = 1, 2, ..., 15$. As an example, the last column reports results for $r_m = 15$.

pairwise maximum CCA approach fails to securely identify the true global factors and we attribute the results in Table 4 and Table 5 to this difficulty. The same identification issue (with respect to the global factors) arises in all previous literature that employs dynamic factor models where identification of the model and consequently of the nature of factors (level, slope, curvature) is achieved with parametric constraints however identification/distinction of the true underlying global factors remains an issue.

In order to avoid regional interactions (geographical proximity, increasing macroeconomic and financial integration that ease bond capital flows, or other), we select the USA-Germany pair (US-DE), as the pair of countries to initiate the global factors estimation and select the number of local factors. Table 6 reports the results for r_m produced by all criteria endorsed. We will adopt the varying selection from ER - first column in Table 6 - and the selection of the ED criterion which suggests the use of $r_m = 3$ local factors for all countries, in order to compare results. Notice that the role of local factors is greatly diminished when three $s = 3$ global factors are taken into consideration so that the ED choice overfits with local factors of minor-to-near-zero economic importance. All our subsequent results where unaffected with respect to an increase in the number of local factors (from those supported by ER to the number $r_m = 3$ supported by ED or the rest of the criteria). Stock & Watson (2011) point out that, when dealing with empirical systems, different methods frequently determine a different number of factors and they suggest to augment statistical estimators with judgment informed by the application at hand.

Finally, in the following subsection 4.3, we make clear that the identifying choice of US-DE - as the pair to produce the global factor estimates - was appropriate since it maximizes correlation of the global factor estimates with proxy measures of level, slope and curvature factors based on US yields and also maximizes (i) correlation between the first global factor and global year-over-year inflation rates (ii) correlation amongst the second global factor and year-over-year global industrial production growth rates and (iii) correlation amongst the third global factor (curvature) and economic policy uncertainty measures.

4.3 Multi-level factor model results

In this section, we confirm that global factor estimates correspond to the familiar level, slope and curvature factors typically retrieved with more involved dynamic factor methods, we evaluate the relative importance of global and local factors and explore contemporaneous macroeconomic linkages of the estimated global factors.

Table 6. Selection of the number of local factors r_m

	ER	GR	ICp1	ICp2	ICp3	BIC3	PCp1	PCp2	PCp3	ED
US	1	1	3	3	3	3	3	3	3	3
CAN	2	2	3	3	3	3	3	3	3	3
UK	1	1	3	3	3	3	3	3	3	3
DE	1	3	3	3	3	3	3	3	3	3
SE	1	1	3	3	3	3	3	3	3	3
NO	1	1	3	3	3	3	3	3	3	3
CH	1	1	3	3	3	3	3	3	3	3
JP	3	3	3	3	3	3	3	3	3	3
AUS	1	1	3	3	3	3	3	3	3	3
NZ	3	3	3	3	3	3	3	3	3	3
GR	3	3	3	3	3	3	3	3	3	3

Notes. Number of local factors proposed by alternative criteria for each country following elimination of global factors based on the pair US-DE. The maximum upper bound for local factors was set at $r_{m,max} = 3$.

Overall, our estimates $\hat{G}_t^2$ of the three global yield curve latent factors should describe a historical evolution of the yield curve shape that is coherent across the factors and consistent with the main known facts on the long run, short run and medium run characteristics of the yield curve. We consider US yields as representative of the global factor movements, and we compute the following empirical proxies (see Diebold & Li (2006), Diebold *et al.* (2006) and Afonso & Martins (2012)) for each of the yield curve latent factors:

$$\begin{aligned} \text{Level} &:= X_{US,t}(120) \\ \text{Slope} &:= X_{US,t}(3) - X_{US,t}(120) \\ \text{Curvature} &:= 2 \cdot X_{US,t}(36) - X_{US,t}(3) - X_{US,t}(120) \end{aligned}$$

where $X_{US,t}(h)$ refers to US standardized zero-coupon bond yields of maturity h (in months). Positive values of the slope proxy imply an inverted yield shape and negative values are associated with steeper ascending curves. Given the international focus of our study, we use the 36 months maturity as proxy for the mid-point of the curvature, instead of the 24 months yield typically employed for US data. Larger negative values of the curvature proxy are associated with increased convexity and pronounced exposure to systemic risk.

Figure 2 shows the estimated global factors, $\hat{G}_{1,t}^2, \hat{G}_{2,t}^2, \hat{G}_{3,t}^2$ (blue curves) along with the adopted empirical proxies. Sign identification refers to ensuring that estimated global $\hat{G}_t^2$ factors are positively correlated with the respective empirical proxy. The correlation between the global level $\hat{G}_{1,t}^2$ and the level proxy is 0.93, the correlation between $\hat{G}_{2,t}^2$ and the slope proxy is 0.81 while the correlation between $\hat{G}_{3,t}^2$ and the curvature proxy is much lower at 0.29, indicative of a wider behavior of the curvature factor not fully captured by the US-based proxy across the sample span. Only after 2004, the curvature proxy is strongly correlated with the estimated curvature factor (correlation of 0.80) indicative of common exposure on global market risk. Further, the curvature proxy implicitly requires the same decay at long and short maturities of the yield curve, a characteristic that might not be supported across a decade of data.

Figure 2. Top left: US 10-year bond yield acting as the level proxy (red curve) along with the estimated and sign identified level factor (blue curve).Top right: US 10-year bond yield acting as the level proxy (red curve) along with the estimated and sign identified slope factor (blue curve). Bottom left: The curvature proxy (red curve) along with the estimated and sign identified curvature factor (blue curve).

Table 7 reports the proportion of variance of zero coupon bond yields, for each country, driven separately by global and local (country specific) factors and three main results clearly arise. First, for all eleven countries - except Japan - variation in the global factors is responsible for the larger share of variation in yields (row sum of Table 7 results). The global share is never less than half (only for JP equals 45%), typically between 55% - 75% and in four countries even above 80% (US, CAN, DE, SE). Hence, it is confirmed that global yield factors are important drivers of country bond yields. Second, the global share of bond yield variation is smallest for Japan, consistent with relative independence of the JP market. In addition, the global slope factor dominates the global level factor for JP where also the local level dominates the global level proportion. Finally, it is interesting to note that the global level factor contributes less for the UK than for the US and Germany. Third, the global curvature factor has the lesser contemporaneous contribution. Only Greece seems to distinguish, with an almost 11% contribution, revealing significant exposure to global systemic risks.

The first result is similar to the one found by the seminal study of Diebold *et al.* (2008) and others. The third result, with respect to Greece, is novel (to the best of our knowledge). However, the second hinges on correctly identifying global factors from potential preeminent regional commonalities. Adopting the US-CAN as the initial pair of countries would result in a decrease of the global level contribution for DE close to the ones we observe know (and under the US-CAN pair) for UK. Adopting the pair DE-CH or DE-SE would result to a much lesser global level contribution to US yields and no global level effects for the JP yields.

A more detailed picture of variance decompositions and the relative contribution of global and local factors is shown in Figure 3 where variance proportions across all maturities (in months) $3, 6, ..., 180$ are depicted. For all countries - except Japan - and maturities, variation in the global factors is responsible for the larger share of variation in yields. Further, the global share increases with maturity while the country factor shows the opposite pattern. Exceptions are the UK and Japan where the global share, after the 36 months maturity starts to decrease and Greece where after the maturity of 36 months the global and local factors share stabilize at around 60% and 40% respectively.

It is also evident that global factors have become more important over time. Finally, Table 8 results expose global factor linkages to the macroeconomy. Diebold *et al.* (2006) and Diebold *et al.* (2008) provide a macroeconomic interpretation for the estimated term structure factors of level and slope. Their analysis suggests that the first two latent factors from the stan-

Table 7. Global and local factors: variance ratios

factor type	Country	factor 1	factor 2	factor 3	factor 1	factor 2	factor 3
global	US	0.7250	0.1045	0.0220	0.7252	0.1045	0.0225
local	US	0.1332			0.1412	0.0043	0.0021
global	CAN	0.7476	0.0907	0.0429	0.7477	0.0922	0.0432
local	CAN	0.0867	0.0171		0.0918	0.0198	0.0034
global	UK	0.6057	0.0609	0.0386	0.6055	0.0566	0.0352
local	UK	0.2638			0.2650	0.0289	0.0071
global	DE	0.7227	0.0923	0.0053	0.7222	0.0862	0.0054
local	DE	0.1654			0.1645	0.0156	0.0053
global	SE	0.7043	0.1244	0.0088	0.7035	0.1200	0.0085
local	SE	0.1459			0.1452	0.0168	0.0051
global	NO	0.5548	0.0226	0.0263	0.5548	0.0222	0.0262
local	NO	0.3815			0.3756	0.0181	0.0024
global	CH	0.6610	0.0740	0.0239	0.6610	0.0700	0.0237
local	CH	0.2211			0.2199	0.0170	0.0062
global	JP	0.1363	0.2767	0.0362	0.1364	0.2804	0.0356
local	JP	0.4699	0.0646	0.0093	0.4714	0.0665	0.0093
global	AUS	0.4767	0.0799	0.0167	0.4764	0.0772	0.0169
local	AUS	0.4004			0.4050	0.0198	0.0044
global	NZ	0.4553	0.1343	0.0144	0.4555	0.1358	0.0149
local	NZ	0.3372	0.0394	0.0031	0.3463	0.0444	0.0031
global	GR	0.4204	0.0542	0.1087	0.4205	0.0550	0.1094
local	GR	0.3666	0.0403	0.0036	0.3648	0.0456	0.0037

Notes. Proportion of variance in country bond yields separately explained by global and local factors. Columns 3-5 use country varying local factors numbers r_m proposed by the ER criterion while columns 6-8 use $r_m = 3$ for all countries $m = 1, ..., 11$. In both cases: factor 1 corresponds to the level factor, factor 2 corresponds to the slope factor and factor 3 corresponds to the curvature factor.

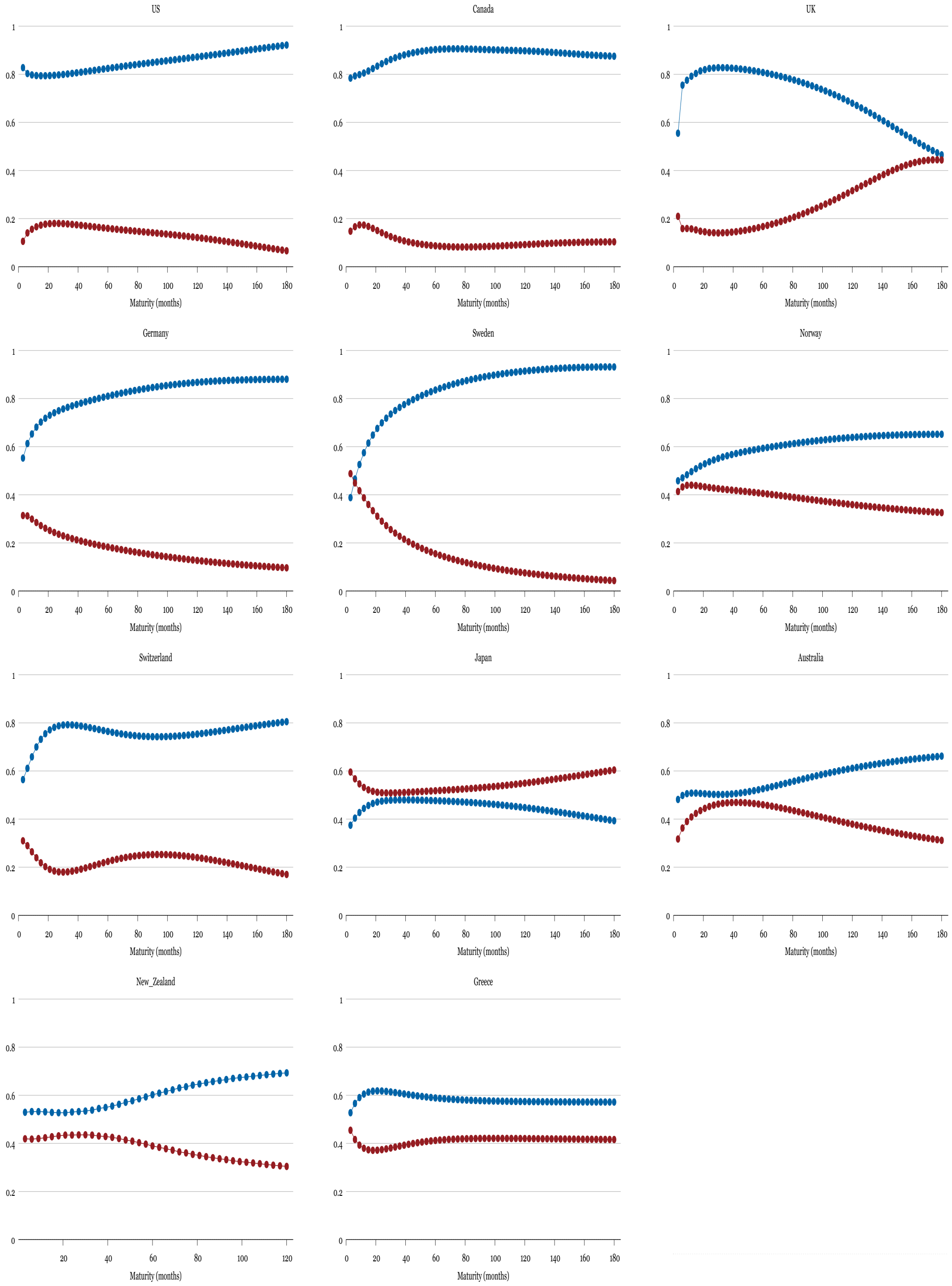

Figure 3. Blue curves denote the share of yield variance explained by global factors at each maturity while red curves denote the share of yield variance explained by local factors.

dard finance term structure model do have macroeconomic underpinnings.[10] We note that a number of robustness checks were performed to crosscheck the subsequent contemporaneous correlation results. Many possible pairs of countries were adopted as candidates for initial global factor estimation, e.g. US-CAN, DE-SE, DE-CH US-JP, JP-US. Table 8, based on the US-DE couple, reports the highest correlations found across all these trials.

Following he empirical analysis in Abbritti *et al.* (2018), we construct a "global inflation series" as the first principal component extracted from a matrix containing year-over-year CPI inflation of the following countries (nine out of eleven) in our sample: US, CAN, UK, DE, SE, NO, CH, JP, GR and also employ G7, G20 and OECD inflation series to proxy for global inflation.[11] Similarly, we construct a "global real activity indicator" as the first principal component extracted from a matrix containing industrial production[12] growth for eight of the countries in our sample along with G7 and OECD industrial production growth.

With respect to the estimated global curvature links with the macroeconomy, we note that Diebold *et al.* (2006) did not find associations to macroeconomic fundamentals[13] and for this reason Diebold *et al.* (2008) confined their analysis to the level and slope factors. Recently, Abbritti *et al.* (2018) and Kobayashi (2020) uncover a key role for the third global factor in explaining the dynamics of the interest rates.The curvature turns out to be especially important for explaining long-run variations in interest rates and the term premium and is related to financial and policy risks; especially during the outset of the recent global financial crisis of 2007.

As such, we exploit contemporaneous correlations of our estimated global curvature factor with economic, financial and policy risk measures. We employ two versions of the monthly index of Global Economic Policy Uncer-

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[10] For an early review of macro-finance models of interest rates see Rudebusch (2010). Stolyarov & Tesar (2021) further provide a review on statistical models for interest rate forecasting and the important role of certain macroeconomic variables as determinants of long-run interest rates.

[11] All series are country aggregates or group aggregates from the OECD main economic indicators (MEI) database and refer to growth rates same period previous year. G7 includes: Canada, France, Germany, Italy, Japan, United Kingdom and United States. The G20 aggregate is calculated taking the fifteen individual country members (Argentina, Australia, Brazil, Canada, China, India, Indonesia, Japan, Korea, Mexico, the Russian Federation, Saudi Arabia, South Africa, Turkey, the United States) plus the European Union as an aggregate. OECD includes 37 countries.

[12] We use OECD monthly data on total industry excluding construction (seasonally adjusted index, 2015=100). Due to data availability, we obtained industrial production series for eight countries in our sample: US, CAN, UK, DE, SE, NO, JP and GR.

[13] They employ manufacturing capacity utilization, the federal funds rate, and annual price inflation for the US.

Table 8. Contemporaneous correlation amongst macro-series and global factors

	$\hat{G}^{(2)}_{1,t}$: level	$\hat{G}^{(2)}_{2,t}$: slope	$\hat{G}^{(2)}_{3,t}$: curvature
"global" inflation factor	0.0355		
G7 inflation rate	0.0428		
G20 inflation rate	**0.4383**		
OECD inflation rate	**0.6082**		
"global" IP factor		**0.3209**	
G7 IP Growth rate		**0.3384**	
OECD IP Growth rate		**0.3484**	
GEPU current-price GDP			**-0.4866**
GEPU PPP-adjusted GDP			**-0.5156**
"global" EPU factor			**-0.4984**
FS			**-0.6041**
EMV1			**-0.7161**
EMV2			-0.1748
STLFS			**-0.7835**

Notes. Contemporaneous correlation coefficients between macroeconomic series and estimated global factors $\hat{G}^{(2)}_{i,t}$ for $i = 1, 2, 3$. Macroeconomic series proxying for (a) global inflation rates, (b) global real activity growth rates and (c) economic/financial uncertainty/risk/stress indices. Full sample, Mar 1999 - May 2009, 123 monthly observations. Bold types denote statistical significance (at the 1% significance level in all cases).

tainty (GEPU) put together by Baker *et al.* (2016).[14] We also construct a "global EPU factor" as the first principal component factor extracted from a matrix containing EPU series for 21 countries, namely: Australia, Brazil, Canada, Chile, China, Colombia, France, Germany, Greece, India, Ireland, Italy, Japan, Korea, Netherlands, Russia, Spain, UK, US, Sweden and Mexico. Further, the newspaper-based equity market volatility (EMV) tracker of Baker *et al.* (2019) - overall EMV and 44 different sub-indices- were employed. We estimated 45 EMV correlations with the curvature factor and found that the "Financial Crises EMV Tracker" (EMV1) and the "Competition Matters EMV Tracker" (EMV2) were statistically and quantitatively significant. Thus, the later two indices were selected amongst all EMV indices published at http://www.policyuncertainty.com/. Finally, a newspaper-based financial stress indicator (FS) for the United States developed by Püttmann (2018) was adopted along with the St. Louis Fed Financial Stress Index (STLFS).[15]

The first column of Table 8 shows the contemporaneous correlation coefficients of the global level factor $\hat{G}^{(2)}_{1,t}$ with global inflation variables. The estimated factor is strongly correlated with global inflation as measured by the OECD weighted countries average. The global inflation proxy based on a sub-sample of the countries in our study and the G7 inflation shows zero contemporaneous correlation, an indication that the small country span of these variables is not successful in capturing global inflation trends and variation in $\hat{G}^{(2)}_{1,t}$. Correlation suddenly rises to measurable and statistical significant levels when the G20 inflation is considered and the maximum correlation value is attained for global inflation captured by the OECD countries average.

The second column of Table 8 shows that the estimated global slope factor $\hat{G}^{(2)}_{2,t}$ mimics adequately global growth as approximated by industrial production growth rates. Interestingly, the correlation with global growth rates based on the sub-sample of the countries in our study, G7 growth rates and OECD growth rates is almost equal but the maximum value of 0.3484 is attained by the OECD variable. Thus, wide country coverage is not an issue implying the leading role of G7 countries.

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[14] More information and data on http://www.policyuncertainty.com/. The GEPU Index is a GDP-weighted average of national Economic Policy Uncertainty indices for 21 countries: Australia, Brazil, Canada, Chile, China, Colombia, France, Germany, Greece, India, Ireland, Italy, Japan, Mexico, the Netherlands, Russia, South Korea, Spain, Sweden, the United Kingdom, and the United States. There are two available versions of the GEPU Index: one based on current-price GDP measures, and one based on PPP-adjusted GDP. The 21 countries that enter into the GEPU Index account for about 71% of global output on a PPP-adjusted basis and roughly 80% at market exchange rates as the GEPU authors report in their site.

[15] Data available at https://fred.stlouisfed.org/series/STLFSI4.

Table 9. Sub-sample contemporaneous correlation amongst macro-series and estimated curvature

	Mar 1999 - Dec 2005	Jan 2006 - May 2009
GEPU current-price GDP	-0.1096	**-0.8651**
GEPU PPP-adjusted GDP	-0.0846	**-0.8632**
“global” EPU factor	-0.0848	**-0.8888**
FS	**-0.2557**	**-0.8963**
EMV1	0.0527	**-0.8765**
EMV2	**-0.2915**	**-0.4115**
STLFS	**-0.4279**	**-0.9217**

Notes. Contemporaneous correlation coefficients between economic and financial uncertainty/risk/stress macro-series and the estimated global curvature factor $\hat{G}_{3,t}^{(2)}$ for two distinct sub-samples: Mar 1999 - Dec 2005 with 82 monthly observations and Jan 2006 - May 2009 with 42 monthly observations. Bold types denote statistical significance (at the 1% significance level in all cases).

Importantly, we also uncover a key contemporaneous correlation for the estimated global curvature factor displayed at the third column of Table 8. Full sample (March 1999 to May 2009) correlations between risk measures and the estimated global curvature factor $\hat{G}_{3,t}^{(2)}$ are all - but EMV2 - statistically significant with levels equal or exceeding the ones observed for the well established link of the level factor with inflation. The maximum observed correlations are attained for EMV1 (Financial Crises EMV Tracker) -0.71 and the St. Louis Fed Financial Stress Index (STLFS) -0.78, attaching economic interpretation to the third global factor.

Moreover, Table 9 uncovers an interesting time-varying behavior to the aforementioned correlations. For the first half of our sample (1999-2005, 82 monthly observations) FS and STLFS retain correlation with global curvature albeit milder whereas EMV1 (Financial Crises EMV Tracker) looses correlation in contrast to the more economic grounded EMV2 index (Competition Matters EMV Tracker) that exhibits mild to low correlation. For the second sub-sample, all indices are significantly correlated with global curvature, the maximum correlation of -0.92 observed for the St. Louis Fed Financial Stress Index (STLFS). This is an important finding, as long as the St. Louis Fed's Financial Stress index measures systemic risk in the U.S. financial system. It corroborates to the leading role of the US as a risk exporter following the 2007 financial crisis.

5 Concluding remarks

We use a multilevel factor setting to analyze the co-movement contributions of global and local factors to international government zero coupon bond yields. We employ the readily available non-proprietary dataset by Wright (2011) (10 countries) which we expand to include the Greek term structure, using the Diebold & Li (2006) approach. Based on the novel methodologies of Choi *et al.* (2018) and Choi *et al.* (2021), we are able to estimate the number of global (three) and local factors (country varying, at most three) and, following careful identification, we consistently estimate global and local factors.

We confirm that global term structure factors embed several macroeconomic driving forces such as global inflation (level factor) and global real activity growth (slope factor). Moreover, the third global factor (curvature) reflects the progression of economic/financial uncertainty/risk/stress indices whose effect is strongly reflected in the post 2006 era by the St. Louis Fed's financial stress index measuring systemic risk in the U.S. financial system.

This study opens a new window into how policy makers or global bond portfolio traders should appraise the information content within the global term structure of sovereign bonds. Further future research includes sample update extension, dynamic linkages examination following a structural VAR approach on estimated global and local factors, forecasting and thorough investigation on the structural interpretation of shock transmission channels as in Chin *et al.* (2022).

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