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Simulating historical inflation-linked bond returns☆

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ABSTRACT

Empirical research on the benefits of investing in inflation-linked bonds usually relies on a limited number of observations due to the relatively recent introduction of these assets. We estimate models for the break-even inflation rate and use these to create hypothetical inflation-linked bond returns. We compare these with the return on actual inflation-linked bond returns on a recent sample and find that surveys of professional forecasters and moving average models perform best. We confirm these findings for a sample of 19 international inflation-linked bond markets. Using surveys of professional forecasters, we create hypothetical inflation-linked bond return series for 41 countries starting in 1987 or later depending on the availability of nominal bond markets. These simulated series can be used by asset allocation researchers, but an average correlation of 0.7 means that the simulated series are at best reasonable proxies for real data on inflation-linked bond returns. This cautionary note is also relevant to appreciate existing research using simulated inflation-linked bond returns.

1. Introduction

Asset allocation studies typically use historical data on asset classes as inputs for expected returns, standard deviations, or correlations. In addition, models for asset liability management make direct or indirect use of real interest rates or inflation-linked bond returns when pension liabilities contain cost-of-living adjustments.

Unfortunately, inflation-linked bonds have only been introduced relatively recently as investment opportunities for the public, which limits the available historical return series that can be used for empirical analyses.[1] The longest inflation-linked bond return data series produced by Bloomberg Barclays are available for the United Kingdom (May 1981), Australia (January 1997), Canada (January 1997) the United States (February 1997), and France (September 1998). Since then, many other governments, both from developed and emerging markets, have started issuing inflation-linked bonds; see Swinkels (2012) and King and Low (2014). The existence of inflation-linked bond markets helps economists determine the real interest rates across countries; see Mishkin (1984) and Barro and Sala-i Martin (1990) for historical estimates of real interest rates for developed countries.

The available inflation-linked bond return series of developed markets are not well-suited to determine the potential advantage that inflation-linked bonds have in an asset allocation problem, as inflation has been relatively constant around two percent. Brière and Signori (2009) investigate the benefits of inflation-linked bonds using historical data on the U.S. and France over the period

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[1] Shiller (2005) indicates that inflation-linked bonds have existed in the U.S. at least since 1780. However, only recently they have become mainstream investment instruments. Roll (1996) explains trade-offs between asset characteristics in the design of US TIPS.

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1997 to 2007. They conclude that inflation-linked bonds did not add much value in an investor's asset allocation after 2003. Cartea et al. (2012) find that inflation-linked bonds can be attractive to US long-term investors with a real investment objective. In order to determine the asset allocation benefits of inflation-linked bonds in times of inflation, Kothari and Shanken (2004) simulate historical inflation-linked bond returns starting in 1953. It does not become clear from their study what the quality of the simulated return series is relative to actual inflation-linked bond returns. Their sample period ends in December 2000, just after the introduction of inflation-linked bonds in the U.S., so called Treasury Inflation-Protected Securities (TIPS). Perhaps the short sample period is the reason they do not compare their simulated returns with observed returns on U.S. inflation-linked bonds.[2] We aim to fill this gap in the literature.

The use of extended time-series by historical simulation allows researchers to also include inflationary periods in their analyses. Another possibility is to increase the cross-section with observed inflation-linked bond returns. Swinkels (2012) extends the cross-section of inflation-linked bond returns to 9 emerging and 11 developed markets. Inflation in emerging markets has been markedly higher and more volatile than for developed markets, which is a good environment to investigate the benefits of inflation-linked bonds. Unsurprisingly, for samples with more inflation variability than in Brière and Signori (2009), inflation-linked bonds turn out to be a more attractive asset class for investors, mainly because of increased diversification with nominal bond returns in these environments. Barnes et al. (2010) advocate the use of index-linked bonds as an effective hedge against changes in the real yield or inflation shocks, especially for longer holding periods.

Since many countries only started issuing inflation-linked bonds over the past decade, they all share the global financial crisis, a peculiar time for the pricing of inflation-linked bonds; see Campbell et al. (2009) and D'Amico, Kim, and Wei (2014). Therefore, it might be a valuable extension to have available inflation-linked bond time-series both for a large cross-section of countries and a long sample period, even though this line of research is hampered by the difficulty to model the risk premia embedded in inflation-linked bonds, such as the inflation and liquidity risk premiums; see Driessen et al. (2017).

Methods described in, e.g. Pástor and Stambaugh (2002), Agarwal and Naik (2004) and Page (2013) make it possible to combine information from assets with long and short data histories. The methods in these papers typically assume that correlations or covariances with other asset classes in the period that both assets are available are the same in the period that one asset class was not traded. This makes it potentially problematic when covariances are expected to be time-varying, for example because nominal bonds and inflation-linked bonds have a high return correlation when inflation is stable around an expected level, but low when inflation unexpectedly increases or decreases. This expected covariance dynamics leads us to model the inflation-linked bond returns using a model for break-even inflation instead of extrapolation of returns using observed covariances in periods that all assets are traded.

Our paper contributes to the literature in two ways. First, we estimate the model accuracy of the model by Kothari and Shanken (2004) by comparing it to the returns of actual inflation-linked bonds in the United States over the period 1997 to 2017. Second, we develop a more accurate and less data intensive method to simulate historical inflation-linked bond returns. This allows asset allocation researchers to use long-run data series on inflation-linked bonds without having to estimate complicated simulation models.

Our main findings are threefold. First, no matter whether we use the coefficient estimates of Kothari and Shanken (2004) or the coefficients from expanding or rolling window regressions, or even the out-of-sample period only, the correlation between simulated and realized inflation-linked bond returns is about 0.6 to 0.7. The volatility of the return differences between the simulated and realized bond returns is larger than the volatility of the realized bond returns themselves, with respectively 5.5 and 5.0 percent. This suggests a relatively poor performance of this model during the period that inflation-linked bonds exist. Second, using survey of professional forecasters' inflation estimates as a proxy for break-even inflation produces correlations above 0.8 with a return difference volatility of 3.1 percent. When inflation surveys are not available, a moving average of realized inflation produces a correlation of 0.7 and return difference volatility of 4.0 percent. This is a closer match than the more data intensive Kothari and Shanken (2004) method. Third, we confirm for an international sample of realized inflation-linked bond returns that the simulations using inflation surveys has a correlation above 0.7 and a volatility of return differences below 5 percent. These simulated series, which are available online, can be used by asset allocation researchers, but an average correlation of 0.7 means that the simulated series are at best reasonable proxies for real data on inflation-linked bond returns. This cautionary note is also relevant to appreciate existing research using simulated inflation-linked bond returns.

The remainder of this paper is organized as follows. In Section 2, we explain the models we use to estimate the break-even inflation rates. Section 3 contains the empirical results of our comparison of each of the models for the US. In Section 4, we simulate inflation-linked bond returns for 19 countries that have issued inflation linked bonds. Section 5 contains the summary statistics of the simulated inflation-linked bond series for 41 countries starting in 1987 or later depending on the availability of nominal bond markets. Finally, Section 6 concludes.

2. Estimating break-even inflation

A historical simulation of inflation-linked bond returns that we have in mind is equivalent to historical simulation of the break-even inflation. The break-even inflation is defined as the difference between the nominal and real yield on an inflation-linked bond, and its most important components are the expected inflation, the inflation risk premium, and the liquidity risk premium. It is often

[2] Note that Kothari and Shanken (2004) do include analyses on observed inflation-linked bond returns over the period February 1997 to July 2003. Roll (2004) also empirically analyses the asset allocation benefits of TIPS using historical data from February 1997 to September 2003 and concludes that TIPS are a valuable asset class. D'Amico, Kim, and Wei (2014) find that before 2003 liquidity in TIPS was poor and pricing therefore included a substantial liquidity premium, up to 100 basis points.

assumed that the latter two are partially offsetting and quantitatively less relevant than expected inflation, which is why they are often ignored.[3] Trying to model these premia is a challenging issue, since the global financial crisis is basically the only period where the liquidity risk premium is elevated when the US market was developed. Due to the relatively constant inflation rates over the past decades, it is a hopeless task to use realized inflation-linked bond data to develop a model for the inflation risk premium that is likely to would have worked well during the inflationary shocks in the 1970s. Moreover, there is no possibility to verify the accuracy, as actual inflation-linked bonds were not around back then.

In this section, we start by explaining the methods to estimate the break-even inflation that we use for our historical simulation of inflation-linked bond returns. We start by explaining the method by Kothari and Shanken (2004). We then describe two alternative models. The first alternative makes use of historical series of inflation forecasts by professional forecasters. The second alternative model is a moving average model, with the random walk as a special case.

Once we have estimated break-even inflations and observed nominal interest rates, we can derive log nominal inflation-linked bond returns of a zero-coupon bond with maturity or duration D in the following way. The price of a zero-coupon bond with principle amount $PRINC$ needs to be discounted by the real yield over D time periods:

$$P_{D,t} = \frac{PRINC}{\left(1 + Y_{t,t+D}\right)^{D}}.$$

Taking the natural log of this price, gives

$$p_{D,t} = princ - D \times y_{t,t+D}.$$

where lower-case letters indicate natural logs of the upper-case letters. The real return that follows is:

$$r_{D,t+1} = p_{D-1,t+1} - p_{D,t} = princ - (D-1) \times y_{t+1,t+D} - princ + D \times y_{t,t+D},$$

and for the nominal return the realized inflation π_{t+1} has to be added.[4]

2.1. Kothari and Shanken (2004)

Information from the term structure of interest rates and realized inflation is used to model break-even inflation. The three regression equations that they estimate for a five-year zero coupon inflation-linked bond are

$$\pi_{t+1} = \alpha_0 + \alpha_1 \times y_{t,t+1} + \alpha_2 \times \left(y_{t,t+5} - y_{t,t+1}\right) + \alpha_3 \times \pi_t + \alpha_4 \times rreal_t + \varepsilon_{t+1} \quad (1)$$

$$\pi_{t+2} - \pi_{t+1} = \beta_0 + \beta_1 \times \left(f_{t+1,t+2} - y_{t,t+1}\right) + \beta_2 \times \pi_t + \beta_3 \times rreal_t + \theta_{t+2} \quad (2)$$

$$\pi_{t+3} - \pi_{t+2} = \gamma_0 + \gamma_1 \times \left(f_{t+2,t+3} - f_{t+1,t+2}\right) + \gamma_2 \times \pi_t + \gamma_3 \times rreal_t + \varphi_{t+3} \quad (3)$$

where π_t is the inflation in period t defined as the relative change of the Consumer Price Index between time t and $t-1$, $y_{t,t+k}$ the yield-to-maturity known at time t for a k-year bond, $rreal_t$ is the realized real return on Treasury bills over the past 12 months, and $f_{s,t}$ the forward interest rate between time s and t. These predictive variables are due to the early work of Fama (1975), Fama and French (1989), Nelson and William Schwert (1977), and Fama and Gibbons (1984), for the short-interest rate, the yield curve, prior inflation, and the real Treasury bill return, respectively. Note, however, that Anari and Kolari (2016) find that there are both causal relationships from inflation to interest rates and vice versa. In order to obtain an estimate for the three-year ahead inflation, we need the predictions of each of the three equations above, which can be interpreted as the one-year (break-even) inflation level, and the expected changes in the level in the two years afterwards.

The motivation for using these equations is to estimate the empirical information contained in the term structure and realized inflation about expected future inflation. Kothari and Shanken (2004) note that this is not a true out-of-sample forecast as the entire sample is used to estimate the parameters. It is not clear whether investors would have known the estimated model at each point of the sample. This leaves us with the question whether we should use the regression parameters from Kothari and Shanken (2004) or the regression parameters on our updated sample. The advantage of using the updated sample is that it includes more data and hence, if the model is stable over time, should give more accurate parameter estimates. A disadvantage is that due to the parameter update the expected inflation and hence the return series in the past will be affected, and conclusions may possibly change even when returns over the same sample period are analysed. We estimate the regression model on both samples to gauge the differences between the estimated model parameters quantitatively. We also add expanding and rolling window versions of the model, as well as a model that is estimated only on the out-of-sample period.

Even though the ultimate goal is to model the break-even inflation for longer histories, the predictive relation ends at a three-year horizon. The idea is that inflation predictions further than three years in the future are constant. This means that the adjusted R-squared of the regression model above with an additional year of change would be approximately zero.

[3] Chen et al. (2010) estimate the term structure of the inflation risk premium, and find that this is almost zero at the short end, but nearly 80 basis points at the 20-year point of the US yield curve over the period 1996 to 2007. Madureira (2007) finds an inflation premium of up to 25 basis points for UK yield curve over the period 1983 to 2000. De Roode (2013) finds that the financial crisis has had a substantial impact on the estimation of inflation risk premia for the UK and US. Swinkels (2012) finds that nominal and inflation-linked bonds have had similar average returns over the periods they existed, suggesting that realized liquidity risk and inflation risk premiums have offset each other.

[4] We abstract here from time lags between realized inflation and compensated inflation in the inflation-linked bond asset.

2.2. Professional forecasters' inflation forecasts

Perhaps the most direct way to forecast (break-even) inflation is to use actual inflation forecasts from professional forecasters. This is a similar approach as Chernov and Mueller (2012) use to find the term structure of inflation expectations from 1971 onwards. Ang et al. (2007) find that the professional forecasters have the best inflation forecasting ability. Bauer and McCarthy (2015) also indicate that professional forecasters beat predictions from the inflation-swap market when it comes to predicting U.S. inflation. Bardong and Lehnert (2004) and Andonov et al. (2010) find that trading strategies on the break-even inflation that use surveys of professional forecasters or statistical models on inflation are profitable, both for French and US break-even inflation markets. The goal for our application, however, is not to predict realized inflation, but to predict break-even inflation without using its own past. Our approach here is to predict break-even inflation with forecasted inflation from professional forecasters. This approximation should be unbiased when risk premiums, such as the inflation-risk premium and the liquidity risk premium, on inflation-linked bonds are expected to be zero on average. Jochmann et al. (2010) argue that most of the literature assumes that the inflation expectations component will dominate, and therefore use the terms break-even inflation and expected inflation interchangeably.

Professional forecasters could include statistical models, as long as they are known at the point the forecast is made, in their own forecast. However, models such as Kothari and Shanken (2004) use future information, which makes professional forecasters a more realistic out-of-sample forecast. The use of future information, the estimated model parameters in Section 2.1 and the one-year ahead realized inflation in Section 2.3, can be interpreted as a proxy for the information that forecasters have, but is difficult to obtain in an econometric model.[5]

The inflation forecast is then defined as:

$$\pi_t^{PROF} = \mu_t^{PROF}$$

where μ_t^{PROF} the average forecast of the cross-section of professional forecasters. We only have forecasts for this and the next calendar year, as well as 10 years ahead. As we are predicting break-evens of bond returns, we disregard this calendar year's inflation forecast, which is partially based on inflation realizations. The next calendar year means that the prediction is sometimes over the period 1 to 12 months ahead (in December), and sometimes 12 to 23 months ahead (in January). This may create some discontinuities around the year-end, when the forecast switches from one year to the next. This is a disadvantage of the structure of the data available to us. We choose not to smooth this data, but this could lead to further improvements. We also use the 10-year forecast. The disadvantage of this forecast seems to be that it is much more stable than the break-even inflations. One possibility is that forecasters are doing a *bad* job, for example because they do not spend enough effort on the 10-year forecast or anchor it more than market participants to central bank inflation targets.[6] Another possibility is that the forecasters are doing a *good* job, and time-varying liquidity or inflation risk premiums make the break-even inflation more time-varying than the expected inflation component. We analyse both next calendar year's inflation forecast and the 10-year forecast to determine which forecast is best to predict the break-even inflation. We do not include information on disagreement about inflation expectations, as Ehling et al. (2018) suggest that this only impacts the level of the real and nominal interest rates, but not the wedge between the two.

2.3. Random walk and moving average inflation

The models described above requires data on professional forecasters or on the term structure of interest rates, which might not be easily obtainable. In addition, complex models might contain considerable estimation error leading to poor estimates. Hence, we choose a simple model that does not require any estimation. We take the average inflation of the past two years and the next year:

$$\pi_t^{MA} = \frac{1}{3} \times \left(\pi_{t-1} + \pi_t + \pi_{t+1}\right)$$

An advantage is that no estimation is required. The one-year ahead realized inflation, which is unknown at time t when the historical inflation forecast is made, serves as a proxy for information available to inflation-linked bond investors about the future path of inflation. Its 33 percent weight makes sure that the use of future information limited compared to observable inflation data. The main reason to include this forecast is that it can be used for countries or time-periods when no information is available on forecasts by professional forecasters. We also include an estimate in which the realized one-year ahead inflation rate is replaced by the inflation forecast by professional forecasters. This moving average measure also leads to a smoother estimate compared to using only the last observed inflation rate π_t, as used by Chen and Terrien (2001) to historically simulate inflation-linked bond returns.[7] Disadvantages of these moving average methods are that they are ad hoc. We might use too much unknown future information to arrive at our estimates. Moreover, we cannot use it for an estimate as of today, as we do not yet know next year's inflation rate. Note that this model results in a flat term structure of inflation expectations, or stated differently, the estimate above is used for each prediction horizon.

[5] For example, a Value Added Tax increase in the future may lead to a predictable change in inflation that is difficult to capture with statistical models that only use historical information, although the term structure of interest rates could potentially incorporate that information. Chu et al. (2011) find that inflation-linked bond prices both react during the period in which retail prices are surveyed, as well as on the announcement date of the CPI, suggesting that some information is already incorporated in the price before the actual data release.

[6] See Strosal and Winkelmann (2015) for an analysis of anchoring of break-even inflation to central bank targets.

[7] Note that Chen and Terrien (2001) also include an inflation-risk premium, while we assume that the inflation-risk premium and liquidity premium, together with possible other premiums, equal zero.

Table 1
Regression models to estimate historical US break-even inflation.

Variable	KS2004 Coefficient	Replication Coefficient	Out-of-sample Coefficient	Full Coefficient
A. Forecast of one-year-ahead inflation				
Intercept	0.98	1.00	1.78	0.79
Int($t+1$)	0.53	0.54	0.85	0.61
Yld($t, t+5$) −Int($t+1$)	−0.21	−0.27	0.18	−0.19
Inf(t)	0.18	0.18	−0.77	0.10
Realbill(t)	−0.63	−0.64	−0.48	−0.61
Adjusted R^2	71.0%	70.8%	32.5%	65.5%
B. Forecast of change in two-year-ahead inflation over one-year-ahead inflation				
Intercept	0.88	0.92	−0.88	0.40
Fint($t+2$) −Int ($t+1$)	0.80	0.80	0.99	0.78
Inf(t)	−0.25	−0.25	0.15	−0.18
Realbill(t)	−0.13	−0.14	−0.15	−0.07
Adjusted R^2	25.3%	25.9%	11.0%	17.3%
C. Forecast of change in three-year-ahead inflation over two-year-ahead inflation				
Intercept	0.10	0.12	−0.72	−0.14
Fint($t+3$) −Fint ($t+2$)	0.83	0.84	0.65	0.74
Inf(t)	−0.07	−0.07	0.17	−0.04
Realbill(t)	0.04	0.02	0.10	0.06
Adjusted R^2	9.5%	9.5%	2.2%	6.1%

The column "KS2004" refers to Kothari and Shanken (2004)'s coefficient estimates over the period June 1953 to December 2000. The column "Replication" refers to our coefficient estimates over the period June 1953 to December 2000. The column "Out-of-sample" refers to the sample January 2001 to December 2017. The column "Full" refers to our coefficient estimates over the full sample from June 1953 to December 2017. Panel A contains the regression results of Eq. (1), Panel B of Eq. (2), and Panel C of Eq. (3).

3. Comparing hypothetical and actual inflation-linked bond returns

In this section, we gauge the accuracy of the historical simulation method relative to actually observed returns of inflation-linked bonds. Such quality assessment is not undertaken in Kothari and Shanken (2004), probably because inflation-linked bonds were just introduced in the United States when their sample ends in December 2000. First, we re-estimate the model with the same data over the same sample period, modelling annual returns at the monthly frequency. Next, we estimate the model over the out-of-sample period from January 2001 to December 2017. We also estimate the model over the entire sample period, to see how robust the parameter estimates are. The data from the one-month bill returns, the consumer price index, and zero-coupon yields (the so-called Fama–Bliss monthly yield series; see Fama and Bliss, 1987) are from the Center for Research in Securities Prices (CRSP) obtained through Wharton Research Data Services (WRDS). Table A.1 in the Appendix A contains our descriptive statistics and compares this with the descriptive statistics reported by Kothari and Shanken (2004). Table 1 contains the regression estimates over the original sample, our replication, and over our entire sample period from June 1953 to December 2017.

The first two columns indicate that our methodology and data is virtually identical to Kothari and Shanken (2004), as regression coefficients and adjusted R-squares are extremely close. The third column shows that the regression results are different over time. Especially, the explanatory power of the regression over the out-of-sample period January 2001 to December 2017 are substantially lower. For example, Panel A shows that the R-squared is 71.0 percent for the original sample, while this is only 32.5 percent for the out-of-sample period. Column four shows that adding 17 years of data to a sample of 48 years leads to important differences in the regression coefficients, especially the intercepts. In addition, the explanatory power (as measured by the R-squared) is lower for each of the regression equations when estimated over the full sample or out-of-sample instead of the sample by Kothari and Shanken (2004).

Fig. 1 graphically summarizes the first contribution of our paper, which is the comparison of the modelled break-even inflation with the realized break-even inflation for the U.S. using the parameters from the sample until 2000. We see that the break-even inflation of Kothari and Shanken (2004) tends to be higher and more volatile than the break-even inflation predicted by the other models, except the random walk. The figure also shows that the 10-year break-even inflation rate itself has hovered around two percent, with exceptions the first years after the introduction and the start of the global financial crisis, when it was substantially below two percent. Inflation forecasts by professional forecasters as well as a simple moving average inflation are smooth and relatively close to two percent.[8]

Our comparison of actual with simulated inflation-linked bond returns depends crucially on the model for the break-even inflation, as we are using the same nominal interest rates in each case. In some sense, we are testing our ability to predict the break-even inflation without using past values of the break-even inflation, as those are not observed in the historical sample for which we want to simulate inflation-linked bond returns.

[8] In the Appendix A, Fig. A.1—Panel A, we plot the cumulative forecast errors of the break-even inflation over time, so it becomes clear how the forecast accuracy changes over time.

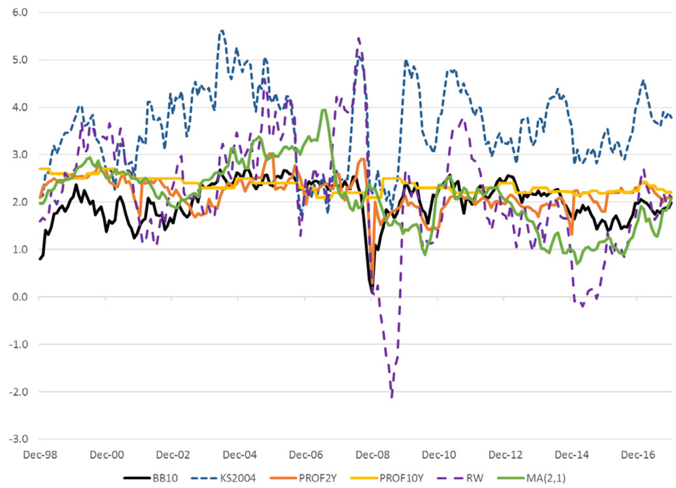


Fig. 1. Comparison of prediction models with realized break-even inflation for the U.S. The black line "BB10" is the 10 year break-even inflation from the swap market, sourced from Bloomberg. The blue dotted line "KS2004" is the break-even inflation from the model by Kothari and Shanken (2004). The orange line "PROF2Y" and the yellow line "PROF10Y" are inflation forecasts from professional forecasters. The purple dotted line "RW" is the random walk, and the green line "MA(2,1)" the moving average looking back two years and one year ahead. The *y*-axis is in percentages per annum.

Table 2
Simulated inflation-linked bond returns, 1999 to 2017.

	Actual		Simulated returns KS					Simulated returns Other				
	ILB	BB10	KS	Fixed InS	Fixed OoS	Expanding	Rolling	PF2	PF10	MA(2,1)	MA(2,1)*	RW
Mean	5.12	5.12	3.87	3.86	4.82	3.98	3.65	4.78	4.52	4.71	4.85	5.28
Median	4.92	4.71	2.71	2.96	3.88	3.15	2.71	3.33	3.44	4.22	3.69	4.35
Maximum	16.76	16.50	29.67	30.23	19.41	29.41	30.57	16.62	17.35	15.41	19.62	29.75
Minimum	−6.21	−4.07	−11.67	−12.39	−3.25	−12.55	−13.43	−3.14	−4.27	−5.47	−6.00	−25.94
Standard deviation	5.01	4.78	7.31	7.48	4.64	7.35	7.85	4.94	4.97	4.55	5.76	9.86
Skewness	0.11	0.47	0.69	0.65	1.02	0.59	0.63	0.71	0.81	0.14	0.68	0.00
Kurtosis	−0.44	−0.40	0.75	0.72	0.68	0.66	0.62	−0.32	0.02	−0.25	−0.18	0.36
Correl Act	1.00	0.95	0.66	0.66	0.44	0.66	0.67	0.81	0.75	0.66	0.73	0.67
Correl BB10	0.95	1.00	0.75	0.74	0.60	0.74	0.76	0.87	0.85	0.73	0.79	0.65
Tr.error Act	0.00	1.56	5.48	5.59	5.10	5.51	5.82	3.07	3.54	3.97	3.98	7.50
Tr.error BB10	1.56	0.00	4.89	5.06	4.22	4.97	5.25	2.49	2.64	3.46	3.55	7.67

The column "ILB" is based on monthly returns of the Barclays 1–10 year US Inflation-linked Bond Index. The column "BB10" uses as a proxy for break-even inflation of the bond index the 10 year break-even inflation from the swap market, sourced from Bloomberg. The next set of columns uses various forms of the regression model by Kothari and Shanken (2004). The column labelled "KS" uses the regression coefficients published in their paper, while the column "Fixed InS" uses our estimates over the period 1953–2000 for the entire period. The column "Fixed OoS" uses the regression coefficients over the out-of-sample period 2001–2017. The "Expanding" window uses more data to estimate the regression coefficients as we go along, while "Rolling" uses deletes the oldest observation when we add a new one. The columns based on other estimates are "PF2Y" and "PF10Y" the average 2 and 10 year forecast of the professional forecasters, sourced from Consensus Economics, Bloomberg, and the Survey of Professional Forecasters. The column "MA(2,1)" uses the moving average form the past two years and the future one year, while "MA(2,1)*" replaces the future year with the two-year ahead survey-based inflation forecast. Finally, the column "RW" contains the last annual inflation as a proxy for the break-even inflation.

Table 2 contains the descriptive statistics of the actual inflation-linked bond returns of the Barclays US Treasury Inflation-linked Bond Index with 1 to 10-year maturity, alongside those of the simulated inflation-linked bond returns. In addition, it contains the tracking error of the hypothetical with the actual return series. The tracking error is defined as the standard deviation of the annual return differences, measured at the monthly frequency. For a good approximation, the tracking error is close to zero, while the mean returns of both series are close to the same.

In Table 2, we see the descriptive statistics from August 1998 to December 2017 of the actual inflation-linked bond index returns and simulated inflation-linked bond returns when using the 10-year break-even inflation index, several variations of the Kothari and Shanken (2004) model, the forecasts from the survey of professional forecasters, the moving average, and random walk models. Since we know from Fig. 1 that the break-even inflation is highest in the Kothari and Shanken (2004) model, it comes as no surprise that the average return of that model is lowest with 3.87 percent per annum, compared to 5.12 percent for the actual series. The standard deviation is with 7.31 percent per annum also markedly higher than the 5.02 percent of the actual series, as are the maximum and minimum. The correlation with the returns on an actual inflation-linked bond index is 0.66. This gives a tracking error of 5.48 percent per annum. Note that the magnitude of the tracking error is larger than the volatility of the actual series that the model tries to proxy. This is due to the high volatility of the simulated series. In addition to the coefficients published in Kothari and Shanken (2004), we also include other variations. The next column labelled "Fixed InS" uses our estimates over the period 1953–2000 for the entire period. The column "Fixed OoS" uses the regression coefficients over the out-of-sample period 2001–2017. The "Expanding"

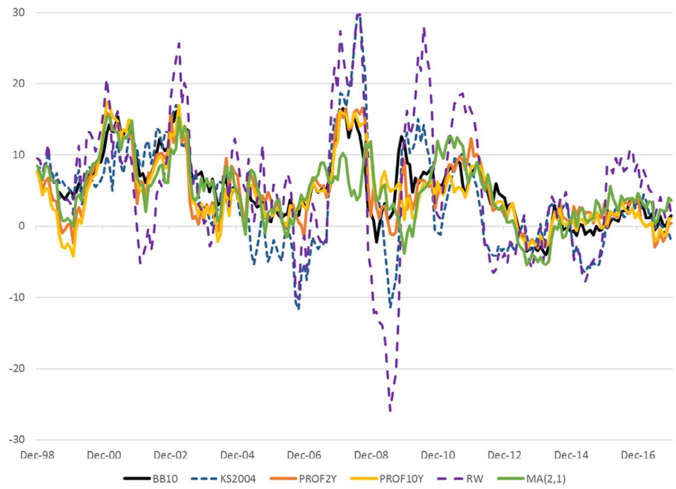


Fig. 2. Comparison of annual inflation-linked bond returns for the U.S. This figure contains monthly moving windows of annual inflation-bond returns (*y*-axis, in percentages per annum) based on different models for break-even inflation. The black line "BB10" is the 10 year break-even inflation from the swap market, sourced from Bloomberg. The blue dotted line "KS2004" is the break-even inflation from the model by Kothari and Shanken (2004). The pink line "PROF2Y" and the yellow line "PROF10Y" are inflation forecasts from professional forecasters. The purple dotted line "RW" is the random walk, and the green line "MA(2,1)" the moving average looking back two years and one year ahead.

window uses more data to estimate the regression coefficients as we go along, while "Rolling" deletes the oldest observation when we add a new one. Each of these versions lead to similar estimates. Most of these variations lead to similar correlations and tracking errors. The "FixedOoS" has the lowest correlation, 0.44, even though it can fit the data purely on the most recent data. Apparently, the estimation error in the relationships between the variables is large on this relatively short sample. In summary, it seems that the model for break-even used by Kothari and Shanken (2004) has not performed well over the recent period when inflation-linked bonds existed. This is by no means a proof that the model was a poor fit historically, but it indicates that there are periods that their simulation model does not work that well.

The other models are close to each other and closer to the actual return series. The average return of the model with two year forecasted inflation is somewhat lower with 4.78 compared to 5.12. The maximum, minimum, and standard deviation are close to the actual series. The correlation with the actual series is 0.81, which leads to a tracking error of 3.07. Although this is still a considerable tracking error relative to the standard deviation of the series it tries to mimic, it is far better than the alternative proposed by Kothari and Shanken (2004). As motivated before, the moving average model is potentially attractive because it can be used without survey data on professional inflation forecasts. We see that this model has a correlation of 0.66 and a tracking error of 3.97. Hence, it is clear that the survey model is better than the moving average model, but that the moving average model comparable to the Kothari and Shanken (2004) method. We also include a variation of the moving average model, in which we replace the future one-year inflation with the survey forecast. This leads to somewhat better results as the moving average model, but has the disadvantage that we need survey data. It seems better to only use survey data (see column "PF2Y") instead of mixing this information with historical inflation data. The random walk model has a much too high volatility, and hence too high tracking error. Smoothing the inflation series seems to be preferred to avoid this.

In Fig. 2, we see Table 2 in graphical format, by displaying the rolling one-year total return series. The black line is the target, while the other lines are predictions from the models.[9] We see that each of the models follows a similar pattern, but that the Kothari and Shanken (2004) and random walk model are more volatile and have considerably larger deviations from the series it aims to mimic. The other forecasting models lead to similar returns. The correlation of the Kothari and Shanken (2004) model with the forecast from professional forecasters is 0.72. Together with the substantially different volatility, these numbers suggest that asset allocation studies using these series might yield different insights on the attractiveness of inflation-linked bonds.

As mentioned before, Chernov and Mueller (2012) also simulate real yields going back to 1971, by using macro-economic information as well as nominal yields and inflation. The five-year yields of their preferred model are available at quarterly frequency and displayed in Fig. 3, along with the real yields that follow from our historical simulations.[10] We cannot compare their model simulation over the period that inflation-linked bonds existed, as they recommend to use the real yields of the TIPS and do not disclose the simulated values after 2002 when TIPS turned reasonably liquid.

We observe that the models have similar behaviour, but the extent to which real yield estimates change can be at times substantially different. For example, the model by Chernov and Mueller (2012) jumps up in 1982, but "only" to 6 percent. The real yield of the simulation by Kothari and Shanken (2004) jumps to even 10 percent, while the moving average, and professional forecaster model increase to about 8 percent. The series for professional forecasters is at the quarterly level here, as we use the US Survey of Professional

[9] In the Appendix A, Fig. A.1—Panel B, we plot the cumulative forecast errors of the inflation-linked bond returns over time, so it becomes clear how the forecast accuracy changes over time.

[10] The data from Chernov and Mueller (2012) is at http://personal.lse.ac.uk/muellerp/RealYieldAOT5.xls.

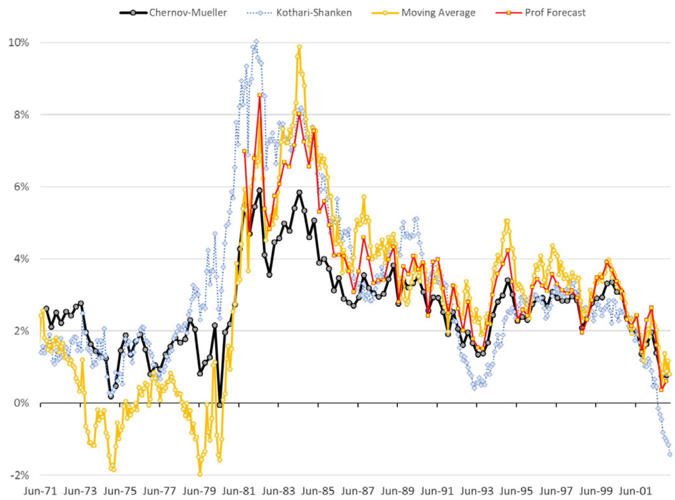


Fig. 3. Comparison with real rates from Chernov and Mueller (2012). We plot the estimated real yields (quarterly frequency) from Chernov and Mueller (2012) together with estimates from (a) the Kothari and Shanken (2004) model, (b) estimates from the moving average (two years back, one year ahead) realized inflation model, and (c) with the Survey of Professional Forecasters. For the latter, we use the Survey of Professional Forecasters, which starts in the third quarter of 1981, since this has a longer history then our primary source that we use in the rest of the paper, Consensus Economics.

Forecasters second year information forecast, which is available since the third quarter of 1981 at the quarterly frequency. We use this alternative data source, as our default data source for professional forecasters, Consensus Economics, does not have data going back that far. The moving average model's real yield spikes to 10 percent in 1984, while the Kothari and Shanken (2004) and the professional forecaster model remains at 8 percent and Chernov and Mueller (2012) is still 6 percent. Such differences obviously have a major impact on the inflation-linked bond returns derived from these series.

The period 1971–1981, when we do not have data on professional forecasters, the estimated real yield of Kothari and Shanken (2004) is closer to Chernov and Mueller (2012) than the moving average rule, which leads to negative real yields close to −2 percent. As we do not have data on the actual realized real yields over this historical sample period, we cannot draw any firm conclusions on which of the real yield estimates was closest to reality during this period.

We now turn to a sample of international inflation-linked bond returns to examine whether we find a similar fit using inflation forecasts by professional forecasters.

4. Estimating international inflation-linked bond returns

In this section, we evaluate whether using surveys of professional forecasters to estimate break-even inflation rates in other markets leads to similar quantitative findings as for the U.S. market that we described above.

Barclays calculates market-capitalization weighted country indexes for governments that issue inflation-linked bonds available to the public. For a subset of countries, Barclays also calculates so-called "comparator indexes", which are essentially indexes that try to mimic the maturity profile of each country's inflation-linked bond index with nominal bonds issues by the same government. Hence, the differential return between these indexes can be used to compare nominal and inflation-linked investments, controlled for differences in maturity profile.

We use the nominal yields and durations of the "comparator indexes" and subtract next year's forecasted inflation obtained from Consensus Economics over the period October 1989 to March 2015 and Bloomberg Consensus Estimates for April 2015 to October 2017 as a proxy for the break-even inflation.[11] From these real yields and durations, we calculate nominal returns on inflation-linked bonds of each of these countries, in the same way as we did for the US in Section 3. We obtained consumer price indexes (for the UK the retail price index) to calculate the nominal returns from the OECD (primary) or IMF (Australia, Hong Kong, Malaysia, New Zealand, Singapore, and Thailand), or local bureaus of statistics (Eurozone and Taiwan). We use the Eurozone HICP excluding tobacco from Eurostat. For Australia and New Zealand inflation is only available with quarterly frequency. We then compare the simulated returns with the realized inflation-linked bond returns.

Table 3 shows that the results we found for the US are quantitatively similar for many other countries that have issued inflation-linked bonds. The average correlation is 0.74 while this is 0.75 for the US inflation-linked bond market.[12] The correlation between

[11] The Barclays inflation-linked and comparator data series are not available from Barclays Live, our data source for this series, after October 2017. The splicing of these two professional forecaster's series is necessary because we do not have access to this data source for the period after March 2015. Bloomberg's Consensus Estimates (ECPIxx yy Index, with xx the two-letter country code, e.g. US for the United States, and yy the year, e.g. 17 for 2017) are available only with a few years of history. For the short period that we have data on both sources, we see that the data is very similar. We do not have access to the Consensus Economics forecasted inflation for the Eurozone. We use the Survey of Professional forecasters for the Harmonized Index of Consumer Prices (HICP) available from the European Central Bank (ECB). Glas and Hartmann (2016) analyse inflation forecasts from this survey in more detail, focusing on uncertainty and disagreement between the individual forecasts. We use the average of the forecasts and leave the potential information from individual forecasts for further research.

[12] Note that the 0.75 refers to the entire US inflation-linked bond market, while the 0.81 reported in Table 2 refers to the 1- to 10-year segment of the same market.

Table 3
Simulated international inflation-linked bond returns, 1996 to 2017.

Country	Start	End	Obs	Duration	Average		St deviation		Correlation	Tracking
					Simulated	Actual	Simulated	Actual		error
Australia	Apr-97	Oct-17	235	6.7	6.45	7.09	6.30	5.14	0.80	3.77
Canada	Dec-96	Oct-17	239	12.0	7.24	7.28	7.18	7.54	0.69	5.80
Denmark	May-12	Oct-17	54	8.1	1.40	1.34	4.75	5.07	0.88	2.39
France	Sep-98	Oct-17	218	7.7	4.95	4.96	4.73	4.83	0.75	3.40
Germany	Mar-06	Oct-17	128	5.7	2.88	3.40	4.24	3.62	0.75	2.85
Greece	Mar-03	Oct-17	96	11.4	−5.71	−5.64	19.84	19.31	0.92	7.74
Israel	June-08	Oct-17	101	6.5	4.05	4.84	3.95	4.23	0.80	2.58
Italy	Sep-03	Oct-17	158	6.8	4.44	4.89	5.33	8.15	0.85	4.59
Japan	Mar-04	Oct-17	152	6.7	1.44	1.60	4.71	5.20	0.34	5.71
New Zealand	Jan-97	Oct-17	238	6.5	6.89	7.05	6.33	5.62	0.65	5.04
Poland	Oct-04	Oct-17	141	6.2	5.21	5.47	4.99	5.52	0.75	3.74
Russia	July-15	Oct-17	16	5.4	5.43	6.74	7.67	4.07	0.81	5.01
South Africa	Mar-00	Oct-17	200	7.4	11.29	11.59	9.66	6.93	0.66	7.29
South Korea	Mar-07	Oct-17	116	5.8	4.99	5.76	4.47	5.37	0.77	3.47
Sweden	Dec-96	Oct-17	239	7.1	4.98	5.63	5.22	4.65	0.71	3.81
Thailand	July-11	Oct-17	64	7.8	1.01	1.71	4.15	5.02	0.75	3.31
Turkey	Feb-07	Oct-17	117	3.7	14.77	15.95	10.32	13.03	0.81	7.64
United Kingdom	Dec-96	Oct-17	239	10.9	7.56	8.23	8.50	6.66	0.68	6.25
United States	Feb-97	Oct-17	237	7.5	5.29	5.75	5.82	5.85	0.75	4.16
Average			157	7.4	4.98	5.46	6.75	6.62	0.74	4.66

For each market the start date, end date, number of observations, and average duration is displayed. In addition, it contains the simulated and actual average return and standard deviation of the market capitalization weighted inflation-linked bond markets for each country with a nominal "comparator" bond index. The last two columns contain the correlation and tracking error for the simulated and actual inflation-linked bond series.

the actual inflation-linked bonds and the simulated bonds varies from 0.34 (Japan) to 0.88 (Denmark) and 0.92 (Greece). For Greece the high correlation may be due to the credit events during the sample period. The particularly good fit for Denmark might be due to the relatively short sample period that excludes the financial crisis, in which liquidity effects may have dominated the returns on inflation-linked bonds more than expected inflation; see Campbell et al. (2009). For many countries, the correlation is around 0.7.[13] The particularly poor fit for Japan, which has only data since 2004, is mainly due to the crisis period, but also due to a jump in inflation forecast when moving from 2013 to 2014; see Appendix A Fig. A.2 for more details. For most series the tracking error, defined as the standard deviation of differential returns between the simulated and actual return series, is substantial. In 3 out of 19 cases the tracking error is even larger than the volatility of the actual series, mostly due to a relatively high volatility of the simulated series. In Appendix A Table A.2 we present the same table as Table 3, but using the moving average rule with two years past and one year ahead realized inflation, as we did in the previous section. The results are slightly worse, with average correlations at 0.65 instead of 0.74.[14]

In summary, the international sample has a goodness-of-fit comparable to the U.S. that was presented in the previous section. Although an average correlation of 0.74 is decent, it also indicates that it is difficult to find indicators that correlate well with break-even inflation. This is also evidenced by the substantial tracking errors between the simulated and actual series.

5. Creating long histories of international inflation-linked bonds

The methodology used above does not require that inflation-linked bonds exist to simulate the returns. In this section, we estimate the inflation-linked bond returns for each of the 41 countries in the Barclays Global Treasury Index in the same way as in Section 4. Here we display the summary statistics, but the simulated bond returns on the monthly frequency are available online for analysts or researchers who would like to use this in future analyses. Note that we create 'comparator' series in the sense that we take the duration of the nominal bond market as a starting point, and create hypothetical inflation-linked bond return with that duration. However, researchers may use our method to create inflation-linked bond return with the duration that is relevant for their application. For real pension liabilities this may be considerably longer than the market-based duration that we have used here. Also note that in this section for countries in the Eurozone, we use their local inflation rates. In the previous section we used the Eurozone inflation that is used in most of the Eurozone inflation-linked bond market, to create as close a proxy to the actual inflation-linked bond returns. Hence, the Eurozone inflation-linked bond returns in this section are proxies for the returns as if the bonds were linked to local inflation. Arnold (2015) argues that local inflation-linked bonds could be more useful for investors than Eurozone inflation-linked bonds. For the time that Eurozone inflation-linked bonds exist, it may also be possible to use real yields from these markets to derive the returns on inflation-linked bonds linked to local inflation. How to best use Eurozone inflation-linked bond data to best simulate local inflation-linked bonds is beyond the scope of this paper.

[13] We follow the approach by Kothari and Shanken (2004) to estimate rolling-window annual returns in our base case. In the Appendix A, Table A.3, we also display the statistics based on monthly returns. These results are substantially weaker with an average correlation of 0.51 compared to 0.74 for annual returns.

[14] South Africa seems to be an outlier with a large tracking error of 13 percent. This is due to the volatile realized inflation in South Africa, while forecasted inflation is much more stable, as is break-even inflation.

Table 4
Descriptive statistics from simulated inflation-linked bond returns, investment grade 1987–2017.

	Index inclusion			Duration	Simulated inflation-linked bond returns			
	Enter	Exit	Obs		Average	Volatility	Min	Max
Australia	Apr-88	Dec-17	345	4.6	6.6	5.3	−9.9	23.3
Austria	Jan-87	Dec-17	360	6.0	5.9	5.1	−4.5	18.1
Belgium	Jan-87	Dec-17	360	5.7	6.4	5.3	−5.6	19.8
Canada	Jan-87	Dec-17	360	6.0	6.3	5.4	−9.5	20.9
Chile	Jan-05	Dec-17	145	3.5	6.1	3.2	−2.3	14.0
Czech	Jan-05	Dec-17	145	5.7	3.2	4.3	−8.0	13.8
Denmark	Jan-87	Dec-17	360	5.6	6.0	5.4	−7.5	21.6
Finland	July-91	Dec-17	306	4.8	5.1	6.2	−6.3	29.8
France	Jan-87	Dec-17	360	6.0	6.1	5.9	−6.9	24.4
Germany	Jan-87	Dec-17	360	5.5	5.4	4.8	−5.2	18.0
Greece	June-01	July-10	97	5.7	3.6	5.5	−22.9	15.5
Hong Kong	Sep-04	Dec-17[a]	117	3.3	2.2	4.0	−4.4	13.5
Hungary	Jan-05	Dec-17[b]	72	3.9	9.7	8.3	−8.0	33.0
Ireland	Jan-87	Dec-17	360	5.8	7.1	10.6	−27.2	49.9
Israel	Jan-12	Dec-17	61	5.3	1.0	2.9	−4.4	6.3
Italy	Jan-87	Dec-17	360	5.0	7.3	6.2	−9.5	31.4
Japan	Jan-87	Dec-17	360	6.4	3.0	5.4	−11.4	22.2
Latvia	Feb-14	Dec-17	36	7.0	2.1	2.9	−2.0	10.0
Lithuania	Jan-15	Dec-17	25	8.5	2.5	2.6	−1.4	8.2
Luxembourg	Jan-10	Dec-17	85	6.2	1.4	5.1	−11.6	10.2
Malaysia	Jan-06	Dec-17	133	5.0	3.4	4.1	−8.9	16.9
Mexico	Jan-05	Dec-17	145	5.1	7.9	4.5	−3.2	22.8
Netherlands	Jan-90	Dec-17	324	6.0	5.8	5.7	−6.9	19.3
New Zealand	Jan-87	Dec-17	360	4.1	7.3	5.8	−5.3	26.8
Norway	Apr-91	Dec-17	309	4.5	5.7	6.1	−14.7	25.8
Poland	Jan-05	Dec-17	145	4.1	4.7	3.0	−2.9	11.1
Portugal	Aug-91	Dec-17[c]	231	4.6	5.0	7.8	−31.0	18.9
Russia	Apr-14	Dec-17	34	4.1	13.1	9.4	2.8	37.3
Singapore	Jan-02	Dec-17	181	5.5	2.0	6.5	−10.8	20.4
Slovakia	Jan-05	Dec-17	145	5.4	3.2	4.6	−6.1	19.8
Slovenia	Jan-05	Dec-17	145	6.1	4.0	6.2	−11.1	21.6
South Africa	Jan-05	Oct-17	143	6.0	8.4	6.0	−4.8	25.7
South Korea	Jan-02	Dec-17	181	4.2	4.1	3.2	−2.1	13.2
Spain	Jan-89	Dec-17	336	5.1	6.9	6.2	−6.2	28.5
Sweden	Jan-87	Dec-17	360	5.0	6.1	6.2	−9.9	23.5
Switzerland	Jan-10	Dec-17	85	9.2	0.8	2.9	−4.1	8.7
Taiwan	Jan-06	Dec-11	60	7.3	3.0	5.2	−6.7	16.2
Thailand	Jan-02	Dec-17[d]	153	6.4	2.8	3.9	−7.0	15.0
Turkey	Apr-14	Sep-16	18	3.7	9.0	4.5	1.5	17.1
United Kingdom	Jan-87	Dec-17	360	7.7	7.7	7.1	−13.8	29.7
United States	Jan-87	Dec-17	360	5.3	5.5	5.3	−5.1	17.0

For each market in the Barclays Global Treasury Index, the start date, end date, number of observations, and average duration is displayed. In addition, it contains the simulated average return, standard deviation, and minimum and maximum annual return.

[a] Hong Kong left the index from July-2008 to Feb-2010.

[b] Hungary left the index from Dec-2011 to Feb-2017.

[c] Portugal left the index from Dec-2011 to Nov-2017.

[d] Thailand left the index from Mar-07 to June-2008.

Table 4 shows that the typical volatility of the simulated inflation-linked bond indexes is close to 6 percent per annum.[15] The minimum is typically close to −10 percent in a year, with for a few countries below −20 percent, while the maximum is typically above 10 percent, with a few countries above 30 percent. Our sample that starts in 1987 is characterized by declining interest rates, which contributes to the high average and maximum returns.

6. Conclusion

Asset allocation researchers may want to use inflation-linked bond return data for asset allocation or liability modelling studies. Realized return series on this asset class are relatively short and characterized by a low and stable inflation environment. It is possible to simulate returns on inflation-linked bonds for periods when they did not yet exist. Our empirical results indicate that using the two year ahead inflation forecast of professional forecasters may work better than other methods that have been proposed in the literature, such as those by Kothari and Shanken (2004) or Chen and Terrien (2001). Simulation performance for 19 international bond markets is similar to that on the U.S. market.

[15] We follow the approach by Kothari and Shanken (2004) to estimate monthly rolling-window annual returns in our base case. In the Appendix A, Table A.4, we also display the statistics based on monthly returns. From Table A.3 we know that these series tend to contain more noise and correlation with observed inflation-linked bond return series is substantially lower. However, we include these series because for some applications monthly data may be preferred over annual data.

We make the simulated historical inflation-linked bond series online available. Hence, our results can be used by (asset allocation) researchers. However, we have to caution for using these simulated series as if they were actual data. The uncertainty around the simulation results needs to be taken into account, as the correlation is approximately 0.7 with realized series. Although perhaps better than nothing—it is unfortunately not a close substitute for realized data. Our results also put the claims of existing research that uses simulated inflation-linked bond returns in perspective.

Appendix A

See Tables A.1–A.4 and Figs. A.1 and A.2.

Table A.1
Descriptive statistics for basic annual series computed at monthly intervals.

	1-Year Inflation				1-Year Expected Inflation			
	KS2004 1953–2000	Repl 1953–2000	OoS 2001–2017	Full 1953–2017	KS2004 1953–2000	Repl 1953–2000	OoS 2001–2017	Full 1953–2017
Mean	4.04	4.04	2.11	3.53	4.08	4.01	2.40	3.59
Median	3.27	3.26	2.07	2.90	3.32	3.29	2.33	2.98
Maximum	14.76	14.80	5.61	14.80	15.34	14.79	5.43	14.79
Minimum	−0.74	−0.79	−2.11	−2.11	0.18	0.21	−1.21	−1.21
Standard deviation	3.06	3.06	1.31	2.85	2.57	2.49	1.18	2.33
Skewness	1.33	1.33	−0.25	1.56	1.41	1.38	−0.10	1.56
Kurtosis	4.55	4.58	3.57	5.74	4.90	4.83	3.14	5.88
	1-Year Spot Rate				1-Year Riskless Real Rate			
	KS2004 1953–2000	Repl 1953–2000	OoS 2001–2017	Full 1953–2017	KS2004 1953–2000	Repl 1953–2000	OoS 2001–2014	Full 1953–2014
Mean	6.19	6.18	1.61	4.98	2.06	2.11	−0.76	1.35
Median	5.77	5.77	1.05	4.91	1.57	1.67	−1.11	1.25
Maximum	17.13	17.13	5.34	17.13	8.97	8.87	3.05	8.87
Minimum	0.63	0.64	0.10	0.10	−2.28	−2.19	−3.68	−3.68
Standard deviation	3.03	3.03	1.62	3.39	2.08	2.03	1.50	2.28
Skewness	0.96	0.96	1.00	0.75	1.12	1.11	0.63	0.70
Kurtosis	4.18	4.21	2.67	3.68	4.18	4.20	3.58	3.80

The columns “KS2004” refer to Kothari and Shanken (2004)'s descriptive statistics over the period June 1953–December 2000. The columns “Repl” refer to our data over the period June 1953 to December 2000. The columns “OoS” refer to our out-of-sample data over the period January 2001 to December 2017. The columns ”Full” refer to our full sample from June 1953 to December 2017. The four variables are the one-year inflation, the one-year expected inflation from the Kothari and Shanken (2004) model, the one-year nominal spot rate, and the one-year past riskless real rate.

Table A.2
Simulated international inflation-linked bond returns, using moving average rule.

Country	Start	End	Obs	Duration	Average		St deviation		Correlation	Tracking
					Simulated	Actual	Simulated	Actual		error
Australia	Apr-97	Oct-17	235	6.7	6.98	7.09	6.48	5.14	0.65	5.00
Canada	Dec-96	Oct-17	239	12.0	7.34	7.28	7.44	7.54	0.55	7.08
Denmark	May-12	Oct-17	54	8.1	1.00	1.34	6.17	5.07	0.90	2.78
FranMA	Sep-98	Oct-17	218	7.7	4.76	4.96	5.01	4.83	0.60	4.43
Germany	Mar-06	Oct-17	128	5.7	2.72	3.40	4.24	3.62	0.65	3.34
GreeMA	Mar-03	Oct-17	96	11.4	−5.62	−5.64	20.07	19.31	0.93	7.39
Israel	June-08	Oct-17	101	6.5	2.93	4.84	3.58	4.23	0.62	3.47
Italy	Sep-03	Oct-17	158	6.8	4.17	4.89	4.20	8.15	0.79	5.48
Japan	Mar-04	Oct-17	152	6.7	1.45	1.60	3.43	5.20	0.31	5.28
New Zealand	Jan-97	Oct-17	238	6.5	7.18	7.05	5.94	5.62	0.72	4.34
Poland	Oct-04	Oct-17	141	6.2	5.03	5.47	5.03	5.52	0.42	5.71
Russia	July-15	Oct-17	16	5.4	0.58	6.74	10.81	4.07	0.82	7.83
South Africa	Mar-00	Oct-17	200	7.4	12.18	11.59	14.43	6.93	0.48	12.65
South Korea	Mar-07	Oct-17	116	5.8	4.64	5.76	3.78	5.37	0.68	3.96
Sweden	Dec-96	Oct-17	239	7.1	6.20	5.63	6.66	4.65	0.58	5.47
Thailand	July-11	Oct-17	64	7.8	0.34	1.71	4.35	5.02	0.64	4.04
Turkey	Feb-07	Oct-17	117	3.7	12.47	15.95	11.28	13.03	0.86	6.74
United Kingdom	Dec-96	Oct-17	239	10.9	7.13	8.23	9.47	6.66	0.56	7.96
United States	Feb-97	Oct-17	237	7.5	5.30	5.75	5.84	5.85	0.56	5.49
Average			157	7.4	4.57	5.46	7.27	6.62	0.65	5.71

For each market the start date, end date, number of observations, and average duration is displayed. In addition, it contains the simulated and actual average return and standard deviation of the market capitalization weighted inflation-linked bond markets for each country with a nominal “comparator” bond index. The last two columns contain the correlation and tracking error for the simulated and actual inflation-linked bond series. In contrast to Table 3 in the main text, the break-even inflation rate is here estimated with two-year historical and one-year ahead realized inflation.

Table A.3
Simulated international inflation-linked bond returns, monthly, 1994–2017.

Country	Start	End	Obs	Duration	Professional forecasters						Moving average					
					Average		St deviation		Correlation	Tracking error	Average		St deviation		Correlation	Tracking error
					Simulated	Actual	Simulated	Actual			Simulated	Actual	Simulated	Actual		
Australia	Apr-97	Oct-17	246	6.7	6.75	7.11	7.64	4.90	0.56	6.36	7.31	7.11	7.12	4.90	0.61	5.66
Canada	Dec-96	Oct-17	250	12.0	7.40	6.85	8.66	7.49	0.53	7.88	7.32	6.85	9.00	7.49	0.39	9.23
Denmark	May-12	Oct-17	65	8.1	1.16	1.47	6.42	5.03	0.66	4.90	0.27	1.47	5.45	5.03	0.67	4.28
France	Sep-98	Oct-17	229	7.7	4.85	4.81	5.62	4.99	0.64	4.57	4.74	4.81	5.25	4.99	0.63	4.41
Germany	Mar-06	Oct-17	139	5.7	2.81	3.24	4.49	4.13	0.59	3.93	2.88	3.24	4.05	4.13	0.55	3.89
Greece	Mar-03	Oct-17	107	11.4	−11.09	−8.74	20.97	21.81	0.83	12.60	−11.00	−8.74	20.40	21.81	0.82	12.58
Israel	June-08	Oct-17	112	6.5	4.75	4.47	7.17	5.03	0.58	5.89	4.59	4.47	6.05	5.03	0.54	5.38
Italy	Sep-03	Oct-17	169	6.8	4.50	4.92	6.44	8.34	0.78	5.22	4.24	4.92	6.24	8.34	0.80	5.02
Japan	Mar-04	Oct-17	163	6.7	1.45	1.79	5.31	4.71	0.10	6.73	1.32	1.79	3.70	4.71	0.07	5.77
New Zealand	Jan-97	Oct-17	249	6.5	6.59	6.75	7.06	4.71	0.51	6.15	6.94	6.75	6.32	4.71	0.57	5.31
Poland	Oct-04	Oct-17	152	6.2	5.32	5.30	7.14	5.01	0.26	7.59	5.81	5.30	6.70	5.01	0.22	7.41
Russia	July-15	Oct-17	27	5.4	13.35	9.02	13.80	4.00	0.43	12.62	4.79	9.02	13.86	4.00	0.21	13.59
South Africa	Mar-00	Oct-17	211	7.4	11.40	10.98	13.12	4.96	0.23	12.90	11.23	10.98	11.29	4.96	0.27	11.06
South Korea	Mar-07	Oct-17	127	5.8	4.56	5.20	5.02	6.35	0.39	6.36	4.63	5.20	4.84	6.35	0.28	6.80
Sweden	Dec-96	Oct-17	250	7.1	5.22	5.37	7.02	4.47	0.54	5.92	5.99	5.37	6.23	4.47	0.59	5.08
Thailand	July-11	Oct-17	75	7.8	1.87	2.41	6.69	4.89	0.31	6.93	1.79	2.41	6.32	4.89	0.33	6.60
Turkey	Feb-07	Oct-17	128	3.7	15.48	14.81	12.83	9.95	0.68	9.49	13.31	14.81	12.80	9.95	0.68	9.43
United Kingdom	Dec-96	Oct-17	250	10.9	7.65	7.85	10.66	7.63	0.48	9.67	7.53	7.85	9.07	7.63	0.59	7.66
United States	Feb-97	Oct-17	248	7.5	5.23	5.43	7.45	5.61	0.61	6.01	5.47	5.43	7.08	5.61	0.54	6.23
Average			168	7.4	5.22	5.21	8.61	6.53	0.51	7.46	4.69	5.21	7.99	6.53	0.49	7.13

Same as Table 3, but now based on simulated return series on a monthly basis. Numbers in the table are annualized.

Table A.4
Descriptive statistics from simulated inflation-linked bond returns, investment grade, monthly, 1987–2017.

Monthly	Index inclusion			Duration	Simulated inflation-linked bond returns			
	Enter	Exit	Obs		Average	Volatility	Min	Max
Australia	Apr-88	Dec-17	356	4.6	6.44	6.05	−5.3	8.4
Austria	Jan-87	Dec-17	371	6.0	5.83	5.30	−7.7	13.0
Belgium	Jan-87	Dec-17	371	5.7	6.27	6.10	−10.2	13.9
Canada	Jan-87	Dec-17	371	6.0	6.14	6.65	−10.9	7.4
Chile	Jan-05	Dec-17	156	3.5	5.73	3.97	−3.0	6.9
Czech	Jan-05	Dec-17	156	5.7	3.15	5.90	−7.2	5.9
Denmark	Jan-87	Dec-17	371	5.6	6.00	5.66	−6.8	7.4
Finland	July-91	Dec-17	317	4.8	4.89	5.73	−10.3	11.8
France	Jan-87	Dec-17	371	6.0	5.95	5.90	−11.4	16.4
Germany	Jan-87	Dec-17	371	5.5	5.30	5.10	−9.0	13.1
Greece	June-01	July-10	108	5.7	2.54	10.19	−21.5	14.7
Hong Kong	Sep-04	Dec-17[a]	139	3.3	2.49	3.27	−3.5	3.1
Hungary	Jan-05	Dec-17[b]	92	3.9	8.35	10.85	−10.3	13.5
Ireland	Jan-87	Dec-17	371	5.8	7.31	9.88	−14.0	19.9
Israel	Jan-12	Dec-17	72	5.3	1.30	4.81	−3.9	5.6
Italy	Jan-87	Dec-17	371	5.0	7.18	6.46	−7.0	12.1
Japan	Jan-87	Dec-17	371	6.4	3.04	6.10	−6.5	15.8
Latvia	Feb-14	Dec-17	47	7.0	3.80	5.52	−2.8	5.8
Lithuania	Jan-15	Dec-17	36	8.5	4.71	5.97	−3.1	4.4
Luxembourg	Jan-10	Dec-17	96	6.2	1.30	4.85	−3.9	4.9
Malaysia	Jan-06	Dec-17	144	5.0	3.38	3.99	−5.0	4.9
Mexico	Jan-05	Dec-17	156	5.1	7.53	6.23	−8.3	7.6
Netherlands	Jan-90	Dec-17	335	6.0	5.65	5.60	−10.7	12.2
New Zealand	Jan-87	Dec-17	371	4.1	7.45	6.73	−10.3	14.6
Norway	Apr-91	Dec-17	320	4.5	5.75	5.68	−12.5	10.9
Poland	Jan-05	Dec-17	156	4.1	4.75	4.29	−3.1	6.7
Portugal	Aug-91	Dec-17[c]	242	4.6	4.34	7.86	−8.3	12.1
Russia	Apr-14	Dec-17	45	4.1	12.20	10.90	−9.8	9.1
Singapore	Jan-02	Dec-17	192	5.5	2.04	5.50	−4.6	8.3
Slovakia	Jan-05	Dec-17	156	5.4	2.87	5.68	−4.7	7.2
Slovenia	Jan-05	Dec-17	156	6.1	3.67	6.79	−8.8	6.2
South Africa	Jan-05	Oct-17	154	6.0	7.67	9.33	−7.1	13.0
South Korea	Jan-02	Dec-17	192	4.2	4.14	3.49	−2.5	4.8
Spain	Jan-89	Dec-17	347	5.1	7.01	6.51	−7.8	11.6
Sweden	Jan-87	Dec-17	371	5.0	6.12	6.42	−5.8	12.4
Switzerland	Jan-10	Dec-17	96	9.2	1.38	7.18	−5.8	9.7
Taiwan	Jan-06	Dec-11	71	7.3	1.87	6.53	−8.1	7.0
Thailand	Jan-02	Dec-17[d]	175	6.4	3.34	6.15	−4.1	8.8
Turkey	Apr-14	Sep-16	29	3.7	13.18	8.42	−3.4	5.9
United Kingdom	Jan-87	Dec-17	371	7.7	7.53	7.72	−9.8	10.8
United States	Jan-87	Dec-17	371	5.3	5.30	5.43	−4.5	7.5

Same as Table 4, but now estimated at the monthly frequency. Numbers for average and volatility are annualized, while minimum and maximum refer to the monthly frequency.

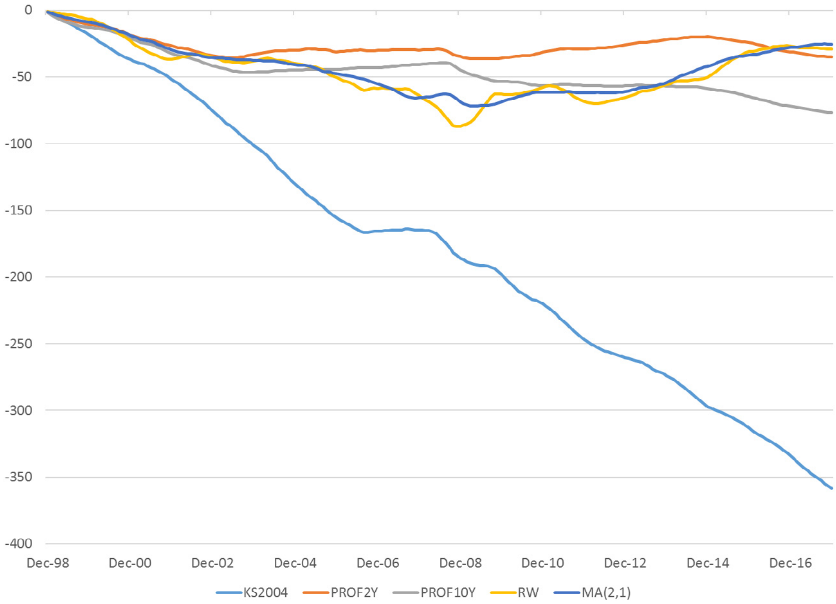
[a] Hong Kong left the index from July-2008 to Feb-2010.

[b] Hungary left the index from Dec-2011 to Feb-2017.

[c] Portugal left the index from Dec-2011 to Nov-2017.

[d] Thailand left the index from Mar-07 to June-2008.

Panel A: Break-even inflation



Panel B: Inflation-linked bond returns

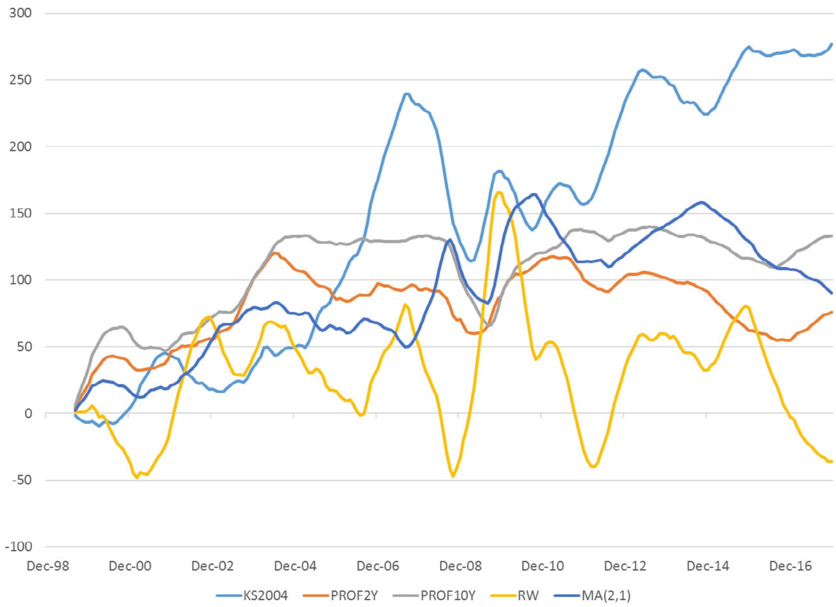


Fig. A.1. Cumulative forecast errors for the United States.

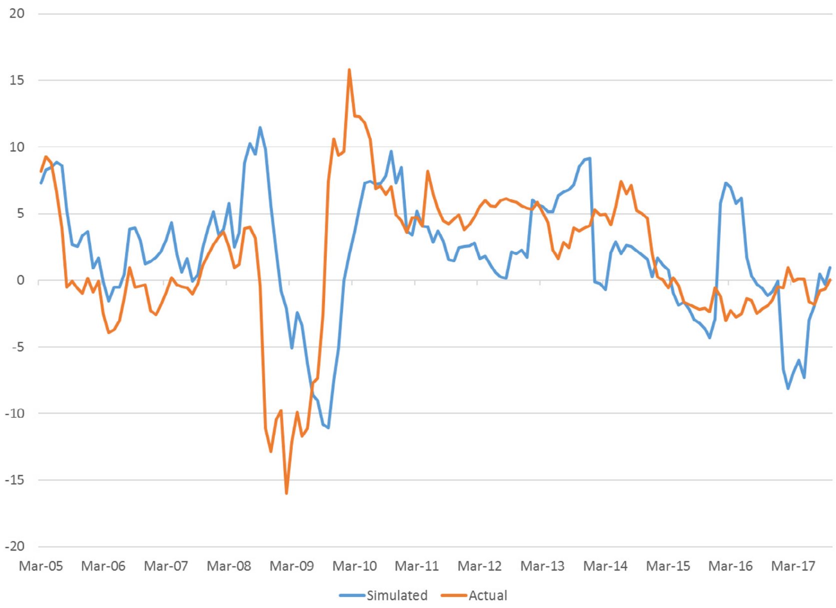


Fig. A.2. Simulated and actual inflation-linked bond returns in Japan, 2005–2017.

Appendix B. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jempfin.2018.06.005.

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