Global house prices since 1950*

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Abstract

What drives house prices? Applying a parsimonious structural model to house prices in 12 advanced economies since 1950, we show that expectations about future fundamentals were the key driver behind some major house price movements. In the model, the price of housing services is determined by the housing stock, population, income per capita, and housing consumption heterogeneity across age groups. These fundamentals contain persistent predictable components, inferred from data, affecting expectations. The estimated model accounts for the spectacular boom and bust in Japan, the boom starting in many countries in the early 1990s, and the recurrent cycles in house prices in Switzerland. A decomposition into the contributing factors is carried out.

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1 Introduction

What drives house prices? The boom and bust in the US housing market in the 2000s has firmly placed this question in mainstream macroeconomics. During the boom (2000-2006), US real house prices grew on average by 5.4% per annum, while during the bust (2006-2012) the market suffered average annual decline in real house prices of −5.1%. The tremendous volume of academic work that followed has taught us important lessons about the role of mortgage markets, household heterogeneity, and financial factors in house price determination.[1]

The global financial crisis added an element of urgency in our understanding of the US boom-bust period. However, in terms of house prices alone, the US experience is not extraordinary when viewed from a longer international perspective (documented in the next section). For instance, in the mid-1990s many advanced economies embarked on a path of real house price appreciation that was roughly at par with the growth rates observed during the US boom and more than twice as high as in the previous decades since WWII. The tremendous growth led contemporary commentators to speculate whether house price bubbles were forming around the world (see Case and Shiller, 2003). The most dramatic changes in house prices in the post-WWII history, however, occurred in Japan. After WWII, Japan experienced an unprecedented four-decade-long house price bonanza, with real house prices growing at 9.3% per year on average. That is almost double the growth rate during the US boom. In 1991, however, the boom in Japan suddenly turned into two decades of a sustained house price bust, with the average growth rate of −3.2% per year. The house price movement in Japan is so stark that successfully accounting for it must inevitably bring valuable insights into the factors driving house prices at the aggregate level. At the other end of the spectrum is Switzerland, where house prices have modest long-run growth, but exhibit pronounced recurrent cycles.

[1] For instance, Favilukis, Ludvigson and Van Nieuwerburgh (2017), Garriga, Manuelli and Peralta-Alva (2019), Kaplan, Mitman and Violante (2020), Garriga and Hedlund (2020), and Albanesi, Giorgi and Nosal (2022). For a review of the literature on housing in macroeconomics see Davis and Van Nieuwerburgh (2015), Guerrieri and Uhlig (2016) and Piazzesi and Schneider (2016).

The goal of this paper is to further advance our understanding of house price determination by accounting for the above patterns of house prices since WWII in a common theoretical framework. Our sample includes 12 countries and annual data for the period 1950-2019.[2] Viewing the housing stock as an asset providing shelter services over time, we price the aggregate housing stock of each country using the interest rate and a simple optimizing model of demand for housing services. The resulting aggregate demand for housing services depends on total population, income per capita, and the age distribution of the population, jointly referred to as 'fundamentals'. Importantly, we allow the exogenous stochastic processes for the growth rates of these variables to contain predictable components (Barsky and DeLong, 1993; Bansal and Lundblad, 2002; Bansal and Yaron, 2004) and estimate the processes and their components from the data by Bayesian state space methods. The equilibrium house prices, derived from a standard asset pricing relation, depend on the expectations inferred from these processes. Any remaining parameters affecting the endogenous house price process—related mainly to people's preferences for housing and non-housing consumption—are estimated by Bayesian methods from the individual country house price and age distribution data.[3]

The approach taken here abstracts from financial and other frictions. While such frictions matter for house prices, as the research on the US boom-bust period has shown, given the long-run perspective of this paper, the goal is to explore the role of fundamentals alone.[4] Due to limitations on sufficiently long data on the housing stock, the supply of housing services is assumed to grow at a constant growth rate. However, where the required data are available, a process like the one for the elements of housing demand is also estimated for the housing stock. This extension does not change the results and is contained in an Online Appendix.[5]

[2]The sample consists of Australia, Belgium, Canada, Denmark, Finland, France, Japan, the Netherlands, Sweden, Switzerland, the United Kingdom, and the United States.

[3]The annual frequency, dictated by the data availability, precludes estimation of time-varying prices of risk, or time-varying volatility, with an acceptable degree of precision. We therefore abstract from these complications and work under risk neutrality.

[4]We also abstract from the possibility of bubbles.

[5]Knoll, Schularick and Steger (2017) argue that due to the introduction of zoning and land control restrictions, residential land can be considered a fixed factor in the post-WWII period, relative to earlier decades. Their work also shows that across countries the bulk of house price movements after WWII is due

The estimated model accounts well for the three aforementioned house price patterns since 1950. Specifically, it reproduces almost exactly the decades-long boom and bust in Japan. The model also accounts for the fact that between 1993 and 2007 most countries experienced house price growth twice as fast as in the preceding decades. Finally, the model generates the recurrent fluctuations in house prices, in the absence of long-run growth, observed in Switzerland. We are not aware of another study that would successfully account for these patterns.[6]

The main takeaway is that expectations about future fundamentals are crucial in accounting for the three patters of house prices in the post-WWII period. Without changes in expectations, house prices would exhibit a relatively stable 'trend' path. In the case of Japan, the boom would be nowhere near as strong as in the data and there would be no bust, only a leveling-off of house prices. Changes in expectations generate sizable and persistent house price swings around the trend. We stress that the changes in expectations in our framework are changes in expectations about future fundamentals, as derived from the estimated state space based on observables. Expectations about future house prices are endogenous.[7]

Which factors were the most important ones? In the case of Japan, the most important driver of the boom-bust period was expected future per-capita income (GDP) growth, followed by expected future population growth. These two factors reproduce the boom-bust period almost exactly. Japan experienced a phenomenal growth in GDP per capital and population after WWII. According to the model, expectations of such advances in prosperity continuing into the future got reflected in the rapid growth of house prices. As the growth in the fundamentals stalled (and in the case of population even switched the sign), the resulting shifts in expectations turned the boom into a bust.

to residential land prices, as opposed to the replacement costs of structures; see also the seminal paper by Davis and Heathcote (2007) for the United States and Braun and Lee (2021) for German counties, reaching the same conclusion.

[6]We have results for all 12 individual countries. However, to draw general conclusions, we organize the paper in terms of the three house price patterns.

[7]Some authors work directly with house price expectations to get sufficiently volatile house prices (eg, Landvoigt, Piazzesi and Schneider, 2015). This strategy may be more relevant than our approach for some markets and periods, subject to data availability.

In the case of the countries that experienced the strong acceleration in house price growth from around 1993 (all countries in the sample except Japan and Switzerland), the main driver until the year 2000 was expected future per-capita GDP growth. Afterwards, between 2000 and 2007, the fast house price growth came from expectations of future population growth. These expectations reflected, respectively, fast underlying growth in GDP per capita during the 1990s, which was followed by a surge in population growth in the 2000s. Finally, in the case of Switzerland, the cyclical nature of house prices typical for this country is mainly due to recurrent shocks to expected population growth, reflecting net migration.

A pertinent question concerns the role of interest rates, especially in the decade since the global financial crises. Has loose monetary policy inflated house prices? Our findings support this view. In all countries, house prices would be lower between 2009 and 2019 if interest rates stayed at their post-WWII average. The gap in 2019 is about 12%. The effect of interest rates is weaker in Japan and Switzerland than in the other countries.[8]

Finally, the model is used to gauge the marginal contribution to house prices of the changes in housing demand due to changes in the age distribution, given the realized path of total population. All countries in the sample experienced significant population aging between 1950 and 2019. For five broad age groups, the largest losses were in the age group 0-24 and the largest gains in the age groups 55-69 and 70+. The shares of the middle groups, 25-39 and 40-54, remained relatively unchanged. Starting with Japan, *expectations* of future population ageing had a positive effect on house prices until the mid-1990s, as the mass of the distribution was slowly moving towards the age categories 40-54 and 55-69, which (according to the estimated parameters) are the largest consumers of housing services. After the mid-1990s, expectations of population ageing progressing further into the category 70+ started to weight down on house prices.[9] The rest of the countries appear to be in 2019 where Japan was before the mid-1990s, with expectations of population ageing still having

[8]The difference between Japan and Switzerland on one hand and the rest of the countries on the other is in the size of the decline in the real interest rate between 2009 and 2019.

[9]Relative to the two main drivers of the house price boom and bust in Japan (the growth rates of real GDP per capita and population) this effect is less important.

a positive effect on house prices. Taking into account also the effect of population ageing on the trend in house prices—due to the effect on *current* demand for housing services—population ageing had, so far, a positive effect on house prices in all countries in the sample. If the age structure of the population stayed at the 1950 distribution, house prices in 2019 would be 14 percent lower (cross-country median).

In terms of the literature, as noted above, most of the recent work on house prices has focused on the US boom-bust period and the role of financial frictions. Our paper is related to three (overlapping) strands of the earlier literature, which mostly abstract from financial frictions. In comparison with both the recent and the earlier literatures, the distinguishing feature of our model is the central role of expectations about future fundamentals.[10] First, the paper follows a long tradition, going back to Swan (1984) and Topel and Rosen (1988), that ties house prices to demand for housing services and the supply of the housing stock. Davis and Heathcote (2005) carry out such analysis in a real business cycle model with sectoral productivity shocks calibrated to the US economy. Case and Shiller (2003) establish a regression-based relationship between house prices and per-capita income in a cross-section of US states for the period 1985-2002, but stress the importance of expectations of future house price growth.[11] Our approach ties such expectations to fundamentals in a theoretically coherent way. Knoll et al. (2017) collect and analyze house price data for a number of countries going back to 1870. They describe a 'hockey stick' pattern, whereby house prices were approximately flat until the 1950s, before embarking on an upward trend, and relate the change to residential land becoming a scarce factor. We focus in more detail on the post-1950 period.[12]

[10] Kaplan et al. (2020) have an element of this mechanism. They consider an unobserved shock to expected future utility of housing that is chosen to reproduce survey-based house price growth expectations during the US boom.

[11] See also Poterba (1991), McCarthy and Peach (2004), and Glaeser and Gyourko (2007).

[12] In addition, a number of authors have approached the relationship between house prices and fundamentals (typically income per capita) from the perspective of a time series cointegrating relationship, using US national, state and city data (eg, Gallin, 2006; Holly, Paseran and Yamagata, 2010). Arestis and González (2014) and Geng (2018) carry out such an exercise at the aggregate level for OECD countries for the periods 1970-2011 and 1990-2016, respectively. As cointegration only detects a relationship between the variables along a stochastic trend, given the length of the data, persistent deviations of house prices from the trend contributed to inconclusive findings across the different studies.

Second, the paper is related to an asset valuation approach to house prices. This literature has focused on three aspects of asset valuation: a variance decomposition of house prices into expected future returns and rent growth (Campbell, Davis, Gallin and Martin, 2009; Plazzi, Torous and Valkanov, 2010), testing the predictability of house price growth and excess returns in a cross-section and time series (for instance, Case and Shiller, 1990; Capozza and Seguin, 1996; Gallin, 2008; Demers and Eisfeldt, 2021), and deriving house prices based on the Poterba (1984) user cost theory. In the latter case, authors typically make ad-hock assumptions about expected future house prices (see, eg, André, 2010, for OECD countries, 1970-2009).[13]

Finally, as we take the age distribution explicitly into account, the paper is related to Mankiw and Weil (1989), Hamilton (1991), Green and Hendershott (1996), and Martin (2005). We contrast our results for the United States with the predictions of the classic paper by Mankiw and Weil (1989).

The paper proceeds as follows, Section 2 documents real house prices in the sample countries, Section 3 introduces the model, Section 4 describes estimation, Section 5 presents the findings, and Section 6 concludes. Online Appendix provides further details.

2 Three house price patterns

This section discusses the observed patterns in house prices in the post-WWII period. Whenever we speak of house prices, we mean *real* house prices. The sample consists of 12 countries: Australia, Belgium, Canada, Denmark, Finland, France, Japan, the Netherlands, Sweden, Switzerland, the United Kingdom, and the United States. The sample period is 1950-2019, except Canada, which is for 1957-2019. The data are annual. For the period 1970-2019, the data come from the OECD database. For 1950-1969, the data source is Knoll et al. (2017).[14]

[13]In their application to the US national and metropolitan area data, 1975-2007, Campbell et al. (2009) highlight the importance of expected excess returns (a 'housing premium') for house price variation over time. However, for the sub-period 1997-2007, they find that expected future rent growth was the dominant factor in house price movements. This would be consistent with shifts in expectations about fundamentals.

[14]The house price data of Knoll et al. (2017) coincide with the OECD data in the post-1970 period.

The data are expressed as an index (set to 100 in 1957) and are plotted in Figure 1. Visual inspection reveals three broad patterns.

First, the time path of house prices in Japan stands out. It exhibits spectacular four-decade-long growth between 1950 and 1991 (with a small boom-bust period in the early 1970s). As a result, in 1991, house prices in Japan were 39 times higher than in 1950. That is equivalent to an annual growth rate of 9.3%. From 1991, however, house prices steadily declined for almost two decades until 2009, at an average rate of −3.2% per annum. In 2009, house prices were at the same level as in 1978. No other country in the sample experienced such a long-lasting decline. In terms of the post-WWII house price boom, France comes second to Japan. But even in France, which had tremendous house price growth between 1950 and 1967, house prices in 1967 were 'only' 7.9 times higher than in 1950, compared with 16.4 times higher in Japan. And in 1991, house prices in France were only 12.5 times higher than in 1950, compared with the aforementioned 39 fold increase in Japan. Both the boom and bust in house prices in Japan are unprecedented in the post-WWII history.

Second, most countries seem to exhibit a house price pattern characterized by a faster average growth in the period after mid-1990s then in the previous decades after WWII. This is more apparent in the bottom chart of Figure 1, which is a zoom-in of the upper chart by removing France and Japan. To confirm and formalize this pattern, we carry out principal component (PC) analysis of the 12 data series, using the method of Barigozzi, Lippi and Luciani (2021), which extends the PC decomposition to non-stationary data. The 1st PC of the 12 data series is plotted in both charts of Figure 1 as the thick blue line.[15] The loadings of the individual series on the 1st PC reveal that Japan and Switzerland are different from the other countries. The loading for Japan is essentially zero while the loading for Switzerland, while positive, is much smaller than for the other countries; see Table 1. Re-doing the PC decomposition without Japan and Switzerland produces essentially the same 1st PC (not plotted).[16] We will refer to the group of countries excluding Japan and Switzerland as the

[15]The 1st PC is quantitatively the most important common component in the 12 data series.

[16]Computing the unweighted average or median of the ten countries reveals the same pattern as the 1st PC.

'G10 countries' and summarize their *common* house price experience by the 1st PC of the 10 data series.[17] Based on the 1st PC, these countries experienced moderate house price growth of 1.7% per year on average during 1951-1993 and fast growth of 4.8% per year on average during 1993-2007, not too different from the growth rates witnessed during the US boom in the 2000s.[18] The difference in the growth rates led many contemporary commentators to speculate that house price bubbles were forming in these countries (Case and Shiller, 2003).[19] Including the global financial crisis, the average growth rate for 1993-2019 based on the 1st PC is 3.1%, which is still almost double the average growth rate prior to 1993.

Third, as already follows from the previous discussion, we treat Switzerland separately. This country is characterized by the lowest long-run growth rate of house prices among the 12 countries, of only 1.1% per year on average (for instance, house prices in 2019 are only slightly above their 1989 levels). House prices in Switzerland, however, exhibit recurrent fluctuations, with about three complete 'cycles' in the post WWII period. In terms of a change from peak to trough, the magnitudes of the cycles are as follows: 1960-1962 a decline of 12%, 1973-1977 a decline of 27%, and 1989-1997 a decline of 36%.

Although we have results for all 12 countries in the sample (contained in the online Appendix), to draw some general lessons, we organize the paper in terms of the house price patterns for Japan, the 1st PC of the G10 countries, and Switzerland. Our goal is to account for these three patterns in a common theoretical framework and understand the main driving forces. As a final note, observe that in light of the international experience, the US house price movements in the post-WWII history are quite modest.

[17] A common component has been also detected by Hirata, Kose, Otrok and Terrones (2012) and Jackson, Kose, Otrok and Owyang (2016).

[18] For the purposes of describing the data, we choose 1993 as the year in which we split the sample as 1993 is the starting point of uninterrupted growth of house prices until 2007, based on the 1st PC.

[19] If the first subperiod was cut short in 1979 (ie, excluding the 1980s recession experienced by essentially all ten countries), the average growth rate for 1950-1979 based on the 1st PC would be 2.5%.

3 The model

The theoretical framework is a standard asset pricing model, adapted to the housing market, allowing for predictable components in the driving processes of the fundamentals, similar to Barsky and DeLong (1993), Bansal and Lundblad (2002), and Bansal and Yaron (2004). A state variable contains information about a persistent change in the expected growth rate of a fundamental. Due to such changes in expectations, house prices can be volatile and persistently deviate from trend.

3.1 Pricing the aggregate housing stock

The housing stock is considered to be an asset providing a stream of one-dimensional homogenous services (eg, shelter services of a square footage). There is no distinction in the model between whether housing is rented or owned; there is a single price of a unit of aggregate housing services. The period-t price of a unit of the aggregate housing stock—the *house price*—is assumed to satisfy the standard asset pricing condition

$$q_t = E_t \left[m_{t+1}(q_{t+1} + d_{t+1}) \right],$$

where q_t is the period-t house price, d_{t+1} is the period $t+1$ price of housing services, m_{t+1} is a pricing kernel, and E_t is the expectation operator conditional on the state space in period t. The asset pricing model we work with belongs in the class of log-normal models with a risk-neutral pricing kernel, $-\log m_{t+1} = \delta + r_t$, where r_t is a one-period interest rate and δ is a parameter picking up a 'housing premium', the return on housing in excess of the interest rate.[20]

To allow for non-stationary data, the above asset pricing condition is expressed as

$$x_t = E_t \left[m_{t+1} \exp(\upsilon_{t+1})(x_{t+1} + 1) \right], \tag{1}$$

[20]The annual frequency, dictated by the data availability, precludes estimation of a process for time-varying prices of risk, or time-varying volatility, with an acceptable degree of precision. Consequently, we adopt a risk neutral pricing kernel and treat the housing premium as a parameter.

where $x_t \equiv q_t/d_t$ and $\upsilon_{t+1} \equiv \log d_{t+1} - \log d_t$ is the continuously compounded growth rate of the price of housing services. The term $(x_{t+1}+1)$ on the right-hand side of equation (1) makes the equation unsuitable for a closed-form solution for x_t in terms of the model's state variables. The standard way to proceed is to rewrite the equation in logs

$$\log x_t = \log E_t \left[\exp(\log m_{t+1} + \upsilon_{t+1} + \log(x_{t+1}+1)\right]$$

and adopt the Campbell and Shiller (1988) approximation

$$\log x_t \approx \log E_t \left[\exp(\log m_{t+1} + \upsilon_{t+1} + \kappa_0 + \kappa_1 \log x_{t+1})\right], \tag{2}$$

where $\kappa_0 \equiv \log(\overline{x}+1) - \kappa_1 \log \overline{x}$ and $\kappa_1 \equiv \overline{x}/(\overline{x}+1)$, with $\overline{x}$ being the unconditional mean of x_t. Equation (2) can be solved analytically by the method of undetermined coefficients for $\log x_t$ as a linear function of the model's state variables.[21]

3.2 Demand for housing services

We use a simple model to relate the price of housing services to fundamentals. Specifically, to total population, income per capita, and the age distribution of the population (and the housing stock). As noted in the Introduction, this strategy has a long tradition in the literature. There are also practical reasons for this approach when pricing the aggregate housing stock, especially in an international long-run context. Some of the reasons, related to problems with measurement of the price of housing services (rental price), have been pointed out by, eg, Crone and Nakamura (2004), Smith and Smith (2006), Glaeser and Gyourko (2007), and Hill and Syed (2016). For instance, data on rental prices pertain only to rented properties, not owner-occupied properties (owner occupiers pay implicit rents to themselves). With the exception of Switzerland, in the countries in our sample the bulk of the aggregate housing

[21] An alternative approach would be to work with equation (1) and approximate the state space by discretization. For our purposes, the advantage of the Campbell-Shiller approximation is that it allows more efficient estimation of the model in terms of computing time.

stock is owner occupied (see Forrest, Kennett and Izuhara, 2003; Scanlon and Whitehead, 2004; Andrews and Caldera-Sanchez, 2011, for home ownership rates in the twelve countries in our sample). While statistical bureaus attempt to impute rental prices of owner-occupied properties, published data unfortunately do not extend much beyond the 1990s in most cases.[22] Further, the imputation methodology differs across countries and has changed over time. Crone and Nakamura (2004) provide an overview and critique of the various approaches. Finally, rental prices are affected by various time-varying government regulations, which do not apply to owner-occupied properties, making any extrapolation from observed rental prices to owner-occupied properties problematic.[23] A benefit of a model-based approach is that it can be applied to the entire sample, providing a consistent method across countries and over time.

Consider an economy in which people differ in their needs/preferences for housing services. We approach the problem of the allocation of housing services across agents as a planner's problem. Denoting by $j \in J$ the heterogenous agents, the planner's problem in any period t is

$$\max_{\{a_j, c_j\}_{j \in J}} \int_J u_j(a_j, c_j) d\mu_j \quad \text{subject to} \quad \int_J a_j d\mu_j = a \quad \text{and} \quad \int_J c_j d\mu_j = c.$$

Here, $u_j(.,.)$ is a per-period utility function of agent j, a_j is the agent's consumption of housing services, c_j is the agent's consumption of a non-housing good, and a and c are the current-period per-capita aggregate quantities of housing services and the non-housing good, respectively. Evoking the results of Maliar and Maliar (2001) and Maliar and Maliar (2003), we assume

$$u_j(a_j, c_j) = \psi_j \frac{a_j^{1-\varepsilon_1}}{1-\varepsilon_1} + \frac{c_j^{1-\varepsilon_2}}{1-\varepsilon_2}, \quad \varepsilon_1, \varepsilon_2 \geq 0,$$

where ψ_j is a preference parameter. This utility function admits explicit aggregation that summarizes the effects of the changes in the distribution of the population in terms of a

[22]For instance, the Haver Analytics database contains data on imputed rental prices of owner-occupied properties extending back to the 1950s only for Australia and the United States. Data for Denmark and Finland go back to late 1970s, for Canada to the 1980s.

[23]See Kettunen and Ruonavaara (2020) and Weber and Lee (2020) for the evolution of government regulations in the rental market in an international context.

single variable resembling a preference shock for housing.[24] Specifically, the aggregation results lead to a problem of a stand-in consumer

$$\max_{a,c} \left\{ \Psi \frac{a^{1-\varepsilon_1}}{1-\varepsilon_1} + \frac{c^{1-\varepsilon_2}}{1-\varepsilon_2} \right\} \quad \text{subject to} \quad da + c = y,$$

where y is per-capita aggregate income and

$$\Psi \equiv \left[\int_J \psi_j^{1/\varepsilon_1} d\mu_j \right]^{\varepsilon_1} \tag{3}$$

summarizes the effects of heterogeneity. In our case, heterogeneity is in terms of age. The price of housing services d then satisfies the first-order condition of the stand-in consumer. In logs: $\log d_t = \log \Psi_t + \varepsilon_2 \log c_t - \varepsilon_1 \log a_t$. In an equilibrium of the market for housing services: $a_t = H_t/N_t$, where H_t is the aggregate housing stock and N_t is population. The equilibrium price of housing services can thus be expressed as

$$\log d_t = \log \Psi_t + \varepsilon_2 \log c_t - \varepsilon_1 \log H_t + \varepsilon_1 \log N_t, \tag{4}$$

with potentially different elasticities with respect to $\log \Psi_t$, $\log c_t$, and $(\log H_t - \log N_t)$. The variable Ψ_t summarizes the effect of heterogeneity on aggregate demand for housing services.

3.3 The equilibrium equations

Substituting equation (4) into $\log x_t = \log q_t - \log d_t$ gives

$$\log x_t = \log q_t - \log \Psi_t - \varepsilon_2 \log c_t + \varepsilon_1 \log H_t - \varepsilon_1 \log N_t. \tag{5}$$

[24]The results of Maliar and Maliar (2001) and Maliar and Maliar (2003) are different from the Gorman (1953) aggregation and hold for some non-homothetic utility functions, such as the one assumed here, which do not conform with the Gorman (1953) class. The results of Maliar and Maliar (2001) and Maliar and Maliar (2003) do not lead to individual demand functions that would allow aggregation as in Gorman (1953) but generate a utility function of a stand-in consumer in which heterogeneity is summarized by a single variable.

Equation (4) can also be used to derive the growth rate of the price of housing services in terms of the growth rates of the fundamentals

$$\upsilon_{t+1} = z_{t+1} + \varepsilon_2 g_{t+1} - \varepsilon_1 h_{t+1} + \varepsilon_1 n_{t+1}, \tag{6}$$

where $z_{t+1} \equiv \log \Psi_{t+1} - \log \Psi_t$, $g_{t+1} \equiv \log c_{t+1} - \log c_t$, $h_{t+1} \equiv \log H_{t+1} - \log H_t$, and $n_{t+1} \equiv \log N_{t+1} - \log N_t$.

Equations (2), (5), and (6), together with the stochastic processes specified below and the pricing kernel $-\log m_{t+1} = \delta + r_t$, constitute the asset pricing model for the aggregate housing stock, where the process for the log of the house price, $\log q_t$, is the endogenous object.

3.4 Exogenous processes

Stationary stochastic processes are specified for r_t, g_t, n_t, and z_t. In principle, we could also specify a stochastic process for the growth rate of the aggregate housing stock, h_t. However, data on the housing stock for the countries and periods under investigation are available only for the United States and, under some assumptions, can be constructed for Japan. For our main results we therefore proceed under the assumption that the growth rate of the housing stock is constant but, in the Online Appendix, carry out robustness checks for the United States and Japan using the available housing stock data.[25]

The interest rate is assumed to follow a standard AR(1) process

$$r_{t+1} = \nu_r + \phi_r r_t + \sigma_r \xi_{r,t+1}, \tag{7}$$

where $\phi_r \in (0, 1)$ and $\xi_{r,t+1}$ is iid $N(0, 1)$. For g_t we follow Bansal and Yaron (2004). Specif-

[25] Data on residential investment that could potentially be used to construct housing stock data are available for most countries in our sample at best only from the 1970s and in many cases even only the 1990s (see the supplementary material to Kydland, Rupert and Šustek, 2016). As noted in the Introduction, Knoll et al. (2017) argue that land, which makes up a bulk of movements in house prices, can be considered a relatively fixed factor in the post-WWII period. A constant growth rate of the housing stock thus seems like a reasonable approximation, making the movements in the price of housing services demand determined.

ically,

$$g_{t+1} = \nu_g + s_{g,t} + \sigma_g \xi_{g,t+1}, \tag{8}$$

$$s_{g,t+1} = \theta_g s_{g,t} + \varsigma_g \zeta_{g,t+1},$$

where $\theta_g \in (0,1)$ and $\xi_{g,t+1}$ and $\zeta_{g,t+1}$ are iid $N(0,1)$. The point made by Bansal and Yaron (2004) is that such a process can generate significant movements in asset prices, while producing autocorrelations of g_t that are close to zero, as observed in the data; see also Barsky and DeLong (1993) and Bansal and Lundblad (2002). This is because the process allows for a persistent predictable component $s_{g,t}$ (a conditional mean of g_{t+1}), which has a large impact on asset prices, as shown below, but a small effect on the observed autocorrelation of the growth rate itself. This occurs when θ_g is large and σ_g is sufficiently larger than ς_g.

Unlike growth rates of per-capita consumption (income or GDP), population growth rates exhibit persistent smooth movements. Both population growth rates and *changes* in population growth rates are persistent. That is, increases in the growth rate tend to be followed by further increases and declines tend to be followed by further declines (in other words, population growth rates exhibit a 'momentum').[26] We capture this behavior by a parsimonious process

$$n_{t+1} = \nu_n + \phi_n n_t + s_{n,t} + \sigma_n \xi_{n,t+1}, \tag{9}$$

$$s_{n,t+1} = \theta_n s_{n,t} + \varsigma_n \zeta_{n,t+1},$$

where $\phi_n, \theta_n \in (0,1)$ and $\xi_{n,t+1}$ and $\zeta_{n,t+1}$ are iid $N(0,1)$.[27] Observe that re-writing the first equation as

$$\Delta n_{t+1} = \nu_n + (\phi_n - 1) n_t + s_{n,t} + \sigma_n \xi_{n,t+1},$$

and for $\phi_n \to 1$, the shock $s_{n,t}$ has an approximate interpretation as the conditional mean of

[26] Statistical tests of stationarity of population growth rates are inconclusive and in the samples of the length used here have low power. However, it is theoretically difficult to justify population growth rates that can grow (or decline) without bounds.

[27] The process for n_t has a representation as ARMA(2,2).

the change in n_{t+1}, or a predictable component in the momentum of the population growth rate.

Finally, the properties of the process for z_t, the growth rate of the distributional variable Ψ_t, are determined by the properties of the time series of the age distribution. Movements in the age distribution are smooth and persistent, although first-differencing and aggregation contained in (3) may alter these properties. We proceed under the assumption that z_t follows the process

$$z_{t+1} = \nu_z + \phi_z z_t + s_{z,t} + \sigma_z \xi_{z,t+1}, \tag{10}$$

$$s_{z,t+1} = \theta_z s_{z,t} + \varsigma_z \zeta_{z,t+1},$$

where $\phi_z, \theta_z \in (0,1)$ and $\xi_{z,t+1}$ and $\zeta_{z,t+1}$ are iid $N(0,1)$. Note that, unlike in the above three processes, the estimates of the process (10) are conditional on the estimates of the parameters used in the aggregation equation (3), as discussed further below.

In theory, the processes for z_t, n_t, g_t, and r_t are to some extent interconnected. For instance, gains in longevity affect z_t by increasing the fraction of the elderly in the population. At the same time they increase n_t by reducing mortality rates, reduce g_t by increasing the number of economically inactive people in the population, and reduce r_t by increasing saving for pension age (see, eg, Cooley and Henriksen, 2018; Aksoy, Basso, Smith and Grasl, 2019). Similarly, g_t and r_t may be driven by a common third factor, such as technology shocks or monetary policy. Thus, in principle, the four variables could be characterized by a joint stochastic process with many non-zero off-diagonal elements in the transition and covariance matrices. However, such a specification would substantially increase the number of parameters to be estimated and reduce the precision of the estimates. We therefore opt for the more parsimonious structure (7)-(10) and leave the investigation of such interactions for future research for which a more structural model than the one used here is more appropriate.

3.5 Equilibrium house prices

The equilibrium process for house prices is determined by the pricing kernel, equations (2), (5), and (6), and the above stochastic processes for the exogenous variables (assuming $h_t = h$). Given the log-normal structure of the model, the process for $\log x_t$ satisfying equation (2) is linear in the state variables z_t, $s_{z,t}$, n_t, $s_{n,t}$, $s_{g,t}$, and r_t. We therefore guess

$$\log x_t = \gamma + \gamma_z z_t + \gamma_{sz} s_{z,t} + \gamma_n n_t + \gamma_{sn} s_{n,t} + \gamma_{sg} s_{g,t} + \gamma_r r_t \tag{11}$$

and obtain the equilibrium coefficients by the method of undetermined coefficients. This procedure yields

$$\gamma_z = \frac{\phi_z}{1 - \kappa_1 \phi_z}, \quad \gamma_{sz} = \frac{1 + \kappa_1 \gamma_z}{1 - \kappa_1 \theta_z}, \tag{12}$$

$$\gamma_n = \frac{\varepsilon_1 \phi_n}{1 - \kappa_1 \phi_n}, \quad \gamma_{sn} = \frac{\varepsilon_1 + \kappa_1 \gamma_n}{1 - \kappa_1 \theta_n}, \tag{13}$$

$$\gamma_{sg} = \frac{\varepsilon_2}{1 - \kappa_1 \theta_g}, \quad \gamma_r = -\frac{1}{1 - \kappa_1 \phi_r}. \tag{14}$$

Equilibrium house prices are then obtained from equation (5) as

$$\log q_t = \underbrace{\log \Psi_t + \varepsilon_2 \log c_t - \varepsilon_1 (\log H_0 + ht) + \varepsilon_1 \log N_t}_{\log d_t} + \log x_t. \tag{15}$$

As $\log d_t$ depends only on the current levels of the fundamentals, whereas $\log x_t$ depends on expectations (and the interest rate), we can think of the log of equilibrium house prices as the sum of a log trend determined by current fundamentals and log deviations from trend driven by expectations and the interest rate.[28]

Observe that the equilibrium coefficients (12)-(14) are increasing, in absolute value, in the persistence of the shocks and (for κ_1 close to one, which is quantitatively the case) the responses to $s_{z,t}$ and $s_{n,t}$ are larger than to z_t and n_t, respectively. In the case of the

[28] For instance, in the empirical literature (noted in the Introduction) that ties house prices to fundamentals through cointegration, a cointegrating relationship would refer to $\log d_t$, while $\log x_t$ would be a part of an error correction mechanism picking up short-term deviations of house prices from a stochastic trend.

Bansal and Yaron (2004) process for g_t, the loading is only on the predictable component $s_{g,t}$. The iid part of the process for g_t affects the stochastic trend but not the deviations from trend. Finally, γ subsumes all constants and conditional variances and is given by

$$\gamma = \frac{-\delta - \varepsilon_1 h + (1+\kappa_1\gamma_z)\nu_z + (\varepsilon_1 + \kappa_1\gamma_n)\nu_n + \varepsilon_2\nu_g + \kappa_1\gamma_r\nu_r + \kappa_0 + 0.5\Sigma}{1-\kappa_1} \tag{16}$$

where

$$\Sigma = (1+\kappa_1\gamma_z)^2\sigma_z^2 + (\varepsilon_1+\kappa_1\gamma_n)^2\sigma_n^2 + (\varepsilon_2)^2\sigma_g^2 + (\kappa_1\gamma_r)^2\sigma_r^2 + (\kappa_1\gamma_{sz})^2\varsigma_z^2 + (\kappa_1\gamma_{sn})^2\varsigma_n^2 + (\kappa_1\gamma_{sg})^2\varsigma_g^2.$$

The fact that the variances increase γ reflects the standard Jensen's inequality effect of variance terms on asset prices.

Given the estimates of the latent state variables ($s_{z,t}$, $s_{n,t}$, $s_{g,t}$) and data on the observable part of the state space (z_t, n_t, r_t), equation (11) is used to generate equilibrium $\log x_t$. Equilibrium house prices $\log q_t$ are then generated by equation (15) using the distributional variable Ψ_t, constructed from the observed age distribution, and the observed levels of c_t and N_t. The data on the levels and the growth rates in the state space are mutually consistent by construction, as described in Section 3.3.

As noted above, Ψ_t and z_t are observable conditional on the estimates of the parameters entering the aggregation equation (3). This point can be summarized by the notation $\Psi_t = \Psi(\varepsilon_1, \psi; d\mu_t)$ and $z_t = \log\Psi_t - \log\Psi_{t-1} = z(\varepsilon_1, \psi; d\mu_t, d\mu_{t-1})$, where ψ is a vector of the age-specific preference parameters and $d\mu_t$ is the observed period-t age distribution.

4 Estimation

4.1 Data

As already noted, the sample period is 1950-2019, except Canada, which is for 1957-2019. House price data have already been discussed. To estimate the model, we complement the house price data with annual data on real GDP per capita, total population, the age distribution of the population, and the real interest rate (obtained as a simple difference between the 10-year nominal interest rate and the inflation rate realized in the same period).[29] Real GDP data are from Penn World Table, version 9.1. The PWT data end in 2017. The last two years are taken from the St Louis Fed FRED database. The GDP data are converted into per capita terms by dividing by total population. Population data come from the United Nations, World Population Prospects 2019. The growth rates of GDP per capita and population are derived from the respective levels as log differences. The data on age distribution (available by year from ages 0 to 100) also come from the United Nations, World Population Prospects 2019. The data on long-term nominal interest rates and CPI inflation come from the dataset accompanying Jordá, Schularick and Taylor (2017) and, where necessary, are complemented with data from the St Louis Fed FRED database. We have already mentioned the limitations regarding the housing stock data for the countries in our sample. We calibrate h, the constant growth rate of the housing stock, setting it equal to 0.02 for all countries.[30]

To proceed, the theoretical construct Ψ needs to be made operational. This is done by splitting the population into J groups. The operational Ψ^* is then given by

$$\log \Psi_t^* = \varepsilon_1 \log \left(\sum_{j=1}^{J} \psi_j^{1/\varepsilon_1} \mu_{j,t} \right),$$

where $\mu_{j,t}$ is the fraction of age group j in a country's population in period t, as reported in World Population Prospects 2019. As is apparent, $\log \Psi_t^*$ is conditional on the estimates of ε_1 and $\psi = \{\psi_j\}_{j=1}^{J}$. The growth rate z_t is then constructed as $z_t = \log \Psi_t^* - \log \Psi_{t-1}^*$. In the application, we opt for $J = 5$: ages 0-24, 25-39, 40-54, 55-69, 70+.

[29] For the countries in our sample, data on long-term nominal interest rates are longer in coverage than data on short-term nominal interest rates.

[30] This calibration is based on the average growth rate of the aggregate housing stock during the available samples for Japan and the United States. A long-run average growth rate of about 2% is also implied by the quantity index for shelter consumption in Denmark and Finland (OECD data) and the United States (BEA data) and by available data on the housing stock for Ireland (Central Statistics Office Ireland).

4.2 Estimation method

Observe from the equilibrium coefficients (12)-(14) that only eight parameters affect the deviations of house prices from the stochastic trend: the persistence parameters of the exogenous processes $(\phi_z, \theta_z, \phi_n, \theta_n, \theta_g, \phi_r)$ and the two elasticities $(\varepsilon_1, \varepsilon_2)$. The vector of the age-dependent preference parameters (ψ) affects the deviations only indirectly, by affecting Ψ_t^* and thus the state variables z_t and $s_{z,t}$ in equation (11). The stochastic trend (the $\log d_t$ part in equation (15)) depends on ψ, through its effect on Ψ_t^*, and the two elasticities. All remaining parameters (δ, ν_z, ν_n, ν_g, ν_r, σ_z, σ_n, σ_g, σ_r, ς_z, ς_n, ς_g) show up only in γ and thus do not affect house price dynamics, neither the deviations nor the stochastic trend.[31]

The model allows recursive estimation. The parameters are split into two sets, whereby parameters in set Υ_1 are estimated first and then parameters in set Υ_2 are estimated conditionally on Υ_1.

The set of parameters Υ_1 concerns the stochastic processes for the exogenous variables and can be estimated independently from the rest of the model. Specifically, this set consists of the parameters of the stochastic processes for the observables g_t, n_t, and r_t: $\Upsilon_1 = \{\nu_g, \theta_g, \sigma_g, \varsigma_g; \nu_n, \phi_n, \theta_n, \sigma_n, \varsigma_n; \nu_r, \phi_r, \sigma_r\}$. Note that Υ_1 includes four of the eight parameters showing up in the equilibrium coefficients (12)-(14): the persistence parameters θ_g, ϕ_n, θ_n, and ϕ_r. For each of the three observables we estimate the parameters of their respective processes using Bayesian state-space methods. The latent state variables $s_{g,t}$ and $s_{n,t}$ are obtained by the Kalman filter. As we are attempting to estimate potentially highly persistent processes, to improve the precision of the estimates, the parameters are estimated on a panel of all 12 countries. Specifically, in the panel estimation, the persistence parameters and variances of a given process are common across countries but the intercept is allowed to be country specific. The details of the panel estimation, including the priors, are contained in the Online Appendix.

The set Υ_2 consists of the remaining parameters: the housing premium, the two elastici-

[31] Through κ_1, the deviations also depend on the steady-state $\overline{x}$, but for reasonable values of $\overline{x}$, this constant has only a small effect on the dynamics.

ties, the age-dependent preference parameters for housing consumption, and the parameters of the stochastic process for the growth rate of the distributional variable Ψ_t^*. That is, $\Upsilon_2 = \{\delta, \varepsilon_1, \varepsilon_2, \psi, \nu_z, \phi_z, \theta_z, \sigma_z, \varsigma_z\}$, where $\psi = \{\psi_1, \psi_2, \psi_3, \psi_4, \psi_5\}$, with $\psi_2 = 1$ as a normalization. Four of the parameters in Υ_2 show up in the equilibrium coefficients (12)-(14). These are ε_1, ε_2, ϕ_z, and θ_z. The parameters in Υ_2 are estimated for each country separately, using the limited information Bayesian approach described in detail by Chernozhukov and Hong (2003); see also Christiano, Trabandt and Walentin (2010). Specifically, given (i) a country's data on c_t (proxied by real GDP per capita), N_t, n_t, r_t, and $\{\mu_t\}_{j=1}^J$, (ii) the estimated latent states $s_{g,t}$ and $s_{n,t}$ obtained in the previous step, and (iii) the parameters Υ_1 estimated in the previous step, the parameters Υ_2 are chosen so that the distance between the time path of the model-implied house prices, $q(\Upsilon_2)$, and the actual data, q^{data}, is as small as possible. The actual data are for 1951-2019 and the model-implied house prices are given by equation (15). The data points give us 69 moments for the quasi-likelihood function.[32] The quasi-likelihood function is given by

$$F(q^{data}|\Upsilon_2) = \left(\frac{1}{2\pi}\right)^{\frac{T}{2}} |V|^{-\frac{1}{2}} \exp\left(-\frac{1}{2}\left(q^{data} - q(\Upsilon_2)\right)' V^{-1}\left(q^{data} - q(\Upsilon_2)\right)\right),$$

where T denotes the number of elements in q^{data} and V is a weighting matrix. In our application, V is chosen to be the identity matrix. The quasi-posterior distribution is defined as

$$F\left(\Upsilon_2|q^{data}\right) \propto F(q^{data}|\Upsilon_2)p(\Upsilon_2)$$

where $p(\Upsilon_2)$ denotes the prior distribution. In the presence of a potentially very persistent unobserved state $s_{z,t}$, the limited information approach is better behaved in finite samples than a full-information likelihood approach.

We use a random walk Metropolis-Hastings algorithm to approximate the posterior distri-

[32]In addition to the house price data, the vector q^{data} includes, as an additional moment, the long-run price-rent ratio, which is set equal to 20 for all countries in the sample. The model vector $q(\Upsilon_2)$ contains its model counterpart. This ratio helps pin down the housing premium parameter δ and the long-run value is based on Jordá et al. (2017). There are thus in total 70 moments in the quasi-likelihood function.

bution. In each iteration, the algorithm consists of the following steps. First, we draw a candidate parameter vector from the normal density $\Upsilon_2^{new} \sim N\left(\Upsilon_2^{old}, \Omega\right)$ where $\Omega = \lambda \times \text{var}\left(\Upsilon_2\right)$ and $\text{var}\left(\Upsilon_2\right)$ is an estimate of the variance of the parameters.[33] Second, we accept the draw with probability

$$\alpha = \min\left(1, \frac{F\left(\Upsilon_2^{new}|q^{data}\right)}{F\left(\Upsilon_2^{old}|q^{data}\right)}\right).$$

The total number of iterations is set to 505,000 and we save every 50th draw after a burn-in of 5,000. The unobserved state $s_{z,t}$ is obtained by the Kalman filter.

4.3 Parameter estimates

Table 2, panel A, contains the results of the panel estimation of parameters Υ_1. For space constraints, we report only the common persistence and variance parameters; the country-specific intercepts, which do not affect house price dynamics, are not reported. The 90% error bands are reported in the parentheses. The estimates show that the predictable component in the process for g_t is persistent, with the median of the posterior distribution of θ_g equal to 0.9387. The process for the population growth rate is also persistent, with the medians of the posterior of ϕ_n and θ_n equal to 0.8694 and 0.9852, respectively. Referring back to the discussion in Section 3.4, the estimates of the population growth process imply that $s_{n,t}$ can be approximately interpreted as a momentum in the population growth rate and that the momentum is very persistent. That is, *changes* in the population growth rate are followed by similar *changes* next period.

Panel B of Table 2 contains the results of the estimation of parameters Υ_2 based on the country-specific quasi-likelihood function. In the table we report the priors (common across the countries) and the cross-country median and standard deviation of the medians of the country-specific posterior distributions. The medians of the country-specific posterior distributions, and the 90% error bands, are contained in the Online Appendix.

[33] The starting values of the parameters are obtained by maximising the log posterior using the covariance matrix adaption algorithm (CMA-ES). Then, an initial run of the Metropolis-Hastings algorithm is used to approximate $\text{var}\left(\Upsilon_2\right)$. We choose the scaling factor λ so that the acceptance rate is about 20%.

The mean of the prior distribution of δ is set equal to 0.06 to reflect that long-run total housing return in many countries is about 7% per year (Jordá et al., 2017) and that the long-run real interest rate is about 1%. The means of the prior distributions of ε_1 and ε_2 are set equal to one, implying a log utility function. The mean of the prior for ψ approximates the typical housing consumption profile over the life-cycle (eg, Mankiw and Weil, 1989; Eichholtz and Lindenthal, 2014; Lisack, Sajedi and Thwaites, 2017).[34] As noted above, ψ_2 is normalized to equal to one. The priors for δ, ε_1, ε_2, and ψ are loose, as can be seen from the lower and upper bounds and the variances reported in the table; gamma distribution is assumed for these parameters to ensure positive values. The priors for the parameters of the stochastic process for z_t are tight and are based on a simple pre-estimation of the process; beta distribution is assumed to ensure they lie between zero and one.[35]

In the resulting posteriors, the cross-country median of the medians of the country-specific distributions of δ is equal to 0.052. The change relative to the common prior reflects differences in the country-specific real interest rates and housing capital gains. For the elasticities, we obtain cross-country medians $\varepsilon_1 = 0.67$ and $\varepsilon_2 = 1.17$. These estimates imply increasing share of housing expenditures in total consumption as income increases. Thus, as countries get richer over time, the share of housing expenditures increases. Knoll et al. (2017) report that this has been the case in many countries since 1950.[36] The estimates of ψ yield a life-cycle pattern with a peak at the age category 55-69. This is similar to Eichholtz and Lindenthal (2014) and Lisack et al. (2017) and could reflect, for

[34]This is a profile for housing consumption, not necessarily home ownership (for instance, the estimates of Eichholtz and Lindenthal, 2014, are based on floor space). Although in our simple model housing consumption over the life-cycle is strictly speaking determined by preferences, it is more appropriate to think about the parameter vector ψ as a projection of housing consumption on age that picks up various other factors, such as credit constraints. This is the interpretation of Mankiw and Weil (1989). To keep the estimation manageable and the degrees of freedom reasonable, we assume that ψ is time-invariant. To map the housing consumption into household space, housing consumption of the category 0-24 would need to be assigned in some proportions to the "adult" categories.

[35]In the pre-estimation, Ψ_t^* is constructed at the priors of ε_1 and ψ. Then, z_t is derived as a log difference of Ψ_t^* and $s_{z,t}$ is constructed as a moving average of z_t. The parameter estimates of the process used as priors are then obtained by OLS.

[36]As in the case of the age-dependent preference parameters, the elasticities may be picking up factors not modeled explicitly. Interestingly, the cross-country median of ε_1 is in the ballpark of a regression-based estimate of Takáts (2012) obtained on a panel of 22 OECD countries 1970-2009. The relative magnitudes of the two elasticities also conform with Chambers, Garriga and Schlagenhauf (2009).

instance, inheritance received by people in this age category. Based on European data, Wind, Dewilde and Doling (2020) report that a non-negligible fraction of households of such age have a secondary property not used for rental purposes. The peak at the age category 55-69 could also reflect the effect of empty nests. Once children leave the parents' house, each parent occupies more space per person.[37] Finally, the estimates of the parameters of the process for z_t imply that the predictable component $s_{z,t}$ is persistent, although z_t itself is not. The interpretation of this property is that there are predictable changes in the growth rate of the aggregate preference for housing related to the age structure of the population.

5 Results

This section first provides summary statistics of the model-implied house price movements for the individual countries in the sample. It then compares the model with the three patterns of house prices highlighted in Section 2. After that, it shows the importance of expectations about fundamentals in accounting for the three house price patterns and carries out a decomposition into the contribution of the individual factors. Finally, it considers a counterfactual intended to gauge the effect of population ageing on house prices since 1950.

5.1 Summary statistics of house price movements in the model

The left-hand-side chart of Figure 2 plots the standard deviation of the percentage deviations of house prices from the stochastic trend. The standard deviation is plotted for each of the 12 countries in the sample. For each country, it is calculated using the posterior distribution of the parameter estimates and the data on the observable exogenous variables. The chart thus plots a distribution of the standard deviation for each country. The right-hand-side chart does the same for the first-order autocorrelation of the percentage deviations. Together, the two charts demonstrate that the model exhibits volatile and persistent house price swings

[37]For the United States, the means of the posterior distributions for the categories 40-54 and 55-69 are similar (see the Online Appendix), which conforms with the estimates of Mankiw and Weil (1989).

around the stochastic trend.

For the standard deviation, the cross-country median of the medians of the country-specific posterior distributions is 15%. Deviations of house prices of 20% from trend are thus not uncommon and three standard deviations lead to almost 50% change in house prices relative to trend. The lowest median of the standard deviation, 8%, is generated for the United States, whereas the highest median, 48%, is generated for Japan, followed by France, 25%. The high values for Japan and France reflect the house price boom in these countries in the decades after WWII, as well as the house price bust after 1991 in the case of Japan (refer back to Figure 1). Observe also that in terms of the standard deviation, Switzerland looks just like the majority of the countries, even though it exhibits only a modest long-run trend.

For the autocorrelation, the cross-country median of the medians of the country-specific posterior distributions is 0.91. This implies half-life of seven years and eight months. The lowest median of the autocorrelation, 0.69, is generated for the United States, while the highest, 0.97, is generated for Japan.

5.2 The three house price patterns in the model

Figure 3 compares the three patterns of house prices described in Section 2 with their model counterparts. Specifically, it plots house prices for Japan, the G10 countries, and Switzerland against the respective house prices generated by the model. For the model, we plot the median and the 90% error bands based on the posterior distribution of the model estimates. For the G10, both the data and the model are represented by the 1st PC of the ten countries. The loadings on the 1st PC in the model are comparable to those in the data. At the median, the loadings are: 0.30 (AUS), 0.34 (BEL), 0.34 (CAN), 0.31 (DNK), 0.26 (FIN), 0.32 (FRA), 0.23 (NLD), 0.34 (SWE), 0.37 (GBR), 0.33 (USA). See Table 1 for the data counterparts.

In the case of Japan, the model succeeds in generating both the long-lasting boom and bust and tracks the data closely. The 90% error bands are narrow, reflecting the fact that the unprecedented movements of house prices in Japan allow tight estimation of the model parameters. A deficiency of the model for Japan is the period after the global financial crises, during which Japan finally experienced a mild recovery of house prices. The model generates a faster recovery (and a subsequent decline).

For the G10, the model succeeds in generating the pick up in house price growth in the early 1990s. The timing of the fast growth period is slightly different, starting in 1992 and ending in 2005, compared with 1993-2007 in the data. In the model, based on the median path, the average growth rates are 2.2% during 1951-1992 and 4.2% during 1992-2005. This compares with 1.7% during 1951-1993 and 4.8% during 1993-2007 in the data. The model also generates the double-dip in house prices in the early and late 1980s, as well as a decline in house prices (and subsequent recovery) around the global financial crisis in 2007, although the magnitudes in the model and the data somewhat differ.[38]

Finally, the model generates the recurrent fluctuations in house prices in Switzerland, in the absence of a pronounced long-run growth. The model tracks the fluctuations relatively closely, except in the period 2000-2010.

Overall, the model accounts for the main patterns in global house prices in the post-WWII period, even though it does not reproduce the data exactly. The discrepancies between the model and the data should not be surprising, given that the model abstracts from financial frictions, risk premia, and other factors.

5.3 Decomposition

As explained in Section 3.5, the deviations from the stochastic trend depend only on the interest rate and expectations about future fundamentals, whereas the stochastic trend depends only on current fundamentals. To demonstrate the role of the interest rate and expectations in accounting for the three house price patterns, Figure 4 plots the model house prices together with the model stochastic trends. The plots are based on the median paths

[38]The fast-growth period starts off from a higher level of house prices in the model than in the data because the double-dip in the 1980s in the model is not as large as in the data.

of house prices; for the G10, the chart plots the 1st PC of the median house prices for the ten countries and the 1st PC of the corresponding stochastic trends. It is apparent that the stochastic trends alone are unable to account for the key features of the three house price patterns. Based on the trend alone, the boom in Japan would be nowhere near as strong as in the data and there would be no bust, just flattening out of house prices. In the case of the G10 countries, the trend misses the period of the fast house price growth from the early 1990s till the global financial crisis. And in the case of Switzerland, on the basis of the stochastic trend alone, there would be no recurrent house price swings.

Next we turn to a decomposition of the three house price patterns into the contributions of the interest rate and expectations about the individual fundamentals. The decomposition is again applied to the median paths of house prices (the 1st PC of the medians in the case of the G10). In the decomposition, we start off with only the state variables z_t and $s_{z,t}$ affecting the *deviations* of house prices from the stochastic trend. That is, in this experiment, the deviations are determined only by the state variables driving expectations about the growth rate of the distributional variable Ψ_t (aggregate demand for housing related to the age structure of the population). Then we add the state variables n_t and $s_{n,t}$, which are related to expectations about population growth. After that we add $s_{g,t}$, the state variable driving expectations about income per capita. And finally we add the interest rate r_t, which reproduces the median house prices in the model. These experiments thus measure the marginal contribution of each additional variable to the deviations of house prices from the stochastic trend.

5.3.1 Japan

Figure 5 shows the decomposition for Japan. When only expectations about the growth rate of the distributional variable Ψ_t affect the deviations of house prices from the stochastic trend (the upper-left chart), the figure shows that until about 1996, these expectations had a mild positive effect on house prices. However, after that, the effect turned negative, although not sufficiently enough to account for a significant share of the bust. These effects in the model reflect the dynamics of population ageing in the data. Japan experienced pronounced population ageing since 1950, with the distribution gradually shifting towards older categories, as discussed in more detail in Section 5.4. Until about 1996, expectations of population ageing had a positive effect on house prices, as the share of the middle aged kept increasing. After that, however, expectations of population ageing worsening going forward started to push house prices down, as the the share of the middle aged started to decline and the increase in the share of the 70+ group accelerated.[39]

The upper-right chart shows the effect of expectations about both demographic variables, the age structure and the population growth rate, together. Expectations about future population growth had a positive marginal effect on house prices between 1962 and 1976 and, together with expectations about population ageing, account for about half of the bust after 1991. The expectations in the model reflect the dynamics of the population growth rate in the data. After a decline in population growth in the aftermath of WWII, population growth gradually increased throughout the 1960s, reaching a peak in the early 1970s. After that, however, population growth embarked on a sustained decline lasting until the end of the sample period.

The lower-left chart shows the marginal contribution of expectations about the growth rate of income per capita. The chart shows that this effect essentially closes the gap between the full model and the effect of the two demographic variables. Expectations about future growth of income per capita were the single most important factor behind the house price boom and make up about half of the bust. These expectations reflect fast underlying growth in GDP per capita, picked up by the state variable $s_{g,t}$, that reached its peak in the second half of the 1960s. By the early 1970s, the growth rate dropped and stayed roughly constant until the second half of the 1980s. By 1992, however, it dropped further to close to zero and stayed in that region until the end of the sample period.

The real interest rate played a substantial role only during a couple of years in the early

[39] Recall that according to the life-cycle demand for housing in Table 2, demand for housing at the age category 70+ is lower than at the categories 40-54 and 55-69. Although the Table shows only the cross-country medians, the lower demand at the 70+ category applies to Japan as well (see the Online Appendix).

1970s, when a drop in the real rate pushed temporarily house prices up, and after 2013, when low interest rates also contributed positively to house prices; see the lower-right chart.

5.3.2 G10 countries

Figure 6 carries out the decomposition for the G10 countries. The upper-left chart shows the contribution of expectations about growth of the aggregate demand for housing related to the age structure of the population. We see that since the 1980s, the contribution has been mildly positive. This seems similar to the situation in Japan prior to 1996 noted above. Indeed, as further discussed in Section 5.4, Japan is ahead of the G10 in terms of population ageing.

The upper-right chart shows the joint contribution of expectations about population ageing and population growth. It shows that expectations about population growth had a positive marginal contribution to house prices for most of the period since the mid-1980s. In particular, these expectations are important in accounting for the second half of the fast-growth period, having a strong positive effect on house prices between 2000 and 2007. This reflects a rebound in the population growth rate in the data that in most of the G10 countries reached a peak around 2009. At the peak, the growth rate was at the highest level since the late 1960s.[40]

The lower-left chart shows the marginal contribution of expectations about growth of income per capita. This variable closes most of the gap between the full model and the path generated by expectations about the two demographic variables only. In particular, expectations about the growth rate of income per capita generate the double-dip in house prices in the 1980s and account for the first half, 1992-1999, of the fast growth period. In addition, the effect of these expectations around the global financial crisis is strongly negative and the recovery is much milder than in the full model. The positive contribution to the fast-growth period in house prices is due to a 1990s rebound in the underlying growth rate of GDP per capita, picked up by the state variable $s_{g,t}$, that in most of the G10 countries

[40]This description of the growth rate is based on the cross-country average in the data.

reached a peak around 1997. At the peak, the growth rate was at its highest level since the end of the 1960s.[41]

Regarding the marginal contribution of the interest rate, the most interesting part is the period after the global financial crisis. Many commentators posed the question whether the increase in house prices since the start of the recovery from the global financial crisis is due to loose monetary policy. To the extent that the real interest rate used in our analysis reflects monetary policy, the decomposition supports this view. At the end of our sample period, the gap between the full model and the version without the interest rate for the G10 countries is about 12%.

5.3.3 Switzerland

Finally, Figure 7 carries out the decomposition for Switzerland. Expectations about the growth rate of the aggregate demand for housing related to the age structure of the population have essentially no effect on house prices. However, expectations about population growth do. In fact, these expectations account for a bulk of the recurrent house price swings in Switzerland. They reflect cyclical movements in the population growth rate in the data that are strongly positively correlated (0.80) with net migration rates. The fluctuations in house prices due to these expectations are quantitatively interesting, leading to up to 20% in deviations from the stochastic trend in 1960 and 1975, 12% in 1990, and 14% in 1995. Expectations about growth of income per capita close most of the remaining gap between the full model and the path generated by the two demographic variables. In appears that the recurrent fluctuations in house prices in Switzerland are related to the general business cycle, but the key factor is not as much the resulting expectations about growth of income per capita as expectations about net migration. The interest rate played a quantitatively interesting role in the early 1980s and towards the end of the sample period. At the end of the sample period, it contributes 6.5% to house prices in the full model, which, however, is less than the 12% in the G10.

[41] This description of the growth rate is based on the cross-country average in the data.

5.4 A demographic counterfactual

In the previous section we have seen the contribution to house prices of expected future demand for housing driven by expected changes in the age structure of the population. According to the model, the G10 resemble what Japan looked like before 1996 in the sense that expected population ageing still has a moderate positive contribution to house prices. This section explores the contribution of population ageing to house prices through the *combined* effect of expectations (deviations from trend) and the stochastic trend.

In this experiment, we fix the age structure of the population at the 1950 distribution and generate house prices with all the other state variables taking on the values as before (a consequence of fixing the age distribution is that z_t and $s_{z,t}$ are now equal to zero).[42] The results of this experiment, at the medians of the posterior distributions, are contained in Table 3.

First, for each country, the table shows data on the change in the share of each age group in the population between 1950 and 2019. Population ageing in the 12 countries is immediately apparent. The largest losses in all countries are in the age category 0-24, while the largest gains are in the categories 55-69 and 70+. In addition, between the last two categories, only in Canada is the gain in the group 55-69 larger than in the group 70+. The shares of the categories 25-39 and 40-54 remained relatively unchanged in all countries. The most dramatic change occurred in Japan, which experienced a decline of 33 percentage points in the category 0-24 and an increase of 11 and 18 percentage points, respectively, in the categories 55-69 and 70+.

The right-most column in Table 3 reports the change in house prices, which according to the model, results from the change in the population distribution between 1950 and 2019. In all 12 countries the contribution of aging population to house prices has so far been positive. When the age structure of the population is kept at the 1950 distribution, house prices in 2019 are, in the sense of the cross-country median, 14% lower. The largest positive

[42] Feeding in the data on the age distribution but assuming homogenous consumption across age groups ($\psi_j = 1 \; \forall j$) would, up to a constant, have the same effect.

contribution is generated for Canada, where at the 1950 distribution house prices would be 28% lower.[43] As noted above, Canada is the only country that had, across the five age groups, the biggest gain in the category 55-69, which is the largest consumer of housing services according to the estimated parameters. Japan has the second largest contribution of population ageing to house prices, where house prices would otherwise be 24% lower. The contribution in Japan is lower than in Canada as the biggest change in the distribution has already shifted further into the category 70+, which consumes less housing services than the category 55-69. The smallest contribution is generated for Sweden and the United States, where house prices at the 1950 distribution would be only 9% and 10% lower, respectively.

For the United States, the classic paper by Mankiw and Weil (1989) predicted a peak in the growth rate of housing demand—due to changes in the age distribution alone—in the late 1970s to early 1980s. Their model then forecasts a continuous decline in the growth rate of housing demand and, given a historical reduced-form relationship between housing demand and house prices, a substantial decline in house prices starting in the 1990s. The measure of aggregate demand for housing in their paper is our Ψ_t^* with $\varepsilon_1 = 1$. The authors split the population by year and estimate the age-dependent ψ's from micro data. We have five age groups and estimate the coefficients from the aggregate time series, as described in Section 4.2, using a profile similar to the Mankiw-Weil estimates as a prior. The resulting estimates are comparable to those of Mankiw and Weil (1989).[44] Our model, however, generates a peak in the growth rate of Ψ_t (ie, a peak in z_t) in 2000, two decades later than predicted by Mankiw and Weil (1989). As the age-dependent housing consumption profile is similar across our and their studies, the difference comes from the United States experiencing a less dramatic shift towards the category 70+ than predicted by the authors on the basis of the 1983 Census Bureau's fertility and mortality forecasts.

[43] To be precise, for Canada the starting period is 1957, due to the data span discussed in Section 2.

[44] See the Online Appendix for the estimates for the United States. The corresponding estimates in Mankiw and Weil (1989) are in their Figure 3. Unlike in the cross-country median in Table 2, the posterior for the United States exhibits similar values for the age groups 40-54 and 55-69.

6 Concluding remarks

We have applied a simple asset pricing model to country-level house price indexes for the period 1950-2019 in a sample of 12 advanced economies. The model ties house prices to a small number of fundamentals. The key elements of the model are stochastic processes for the growth rates of the fundamentals, which allow for persistent predictable components. Shocks to the predictable components result in large and persistent changes in expectations about future fundamentals, and thus future house prices, generating large and persistent house price swings around a stochastic trend. According to the model, deviations of house prices of 20% from trend are common in most countries. And in Japan, even a 50% departure from trend lies within just one standard deviation of the model fluctuations. On average, the half-life of the deviations is almost eight years. Expectations-driven departures of house prices from the levels dictated by current fundamentals can thus be large and persistent.

The model accounts for three key patterns of house prices in the post-WWII period that, separately, characterize Japan, a group of 10 advanced economies (the G10), and Switzerland. The most remarkable result is that the model almost exactly replicates the spectacular decades-long boom and bust in Japan. The model also generates the boom that started in the G10 in the early 1990s, as well as the cyclical fluctuation around almost a zero trend in Switzerland. Expectations about future growth of income per capita and population are the two most important factors accounting for the three house price patterns. Expectations about future population ageing (demand for housing services due to the age structure of the population) also play a role, but less important one than the other two factors. In Japan, such expectations are already having a negative effect on house prices, while in the G10 the effect is still moderately positive. When the effect of population ageing on both expectations and the trend is taken into account, in all countries in the sample, ageing population had, so far, a positive effect on house prices.

The model abstracts from a number of factors affecting house prices. In particular, we have intentionally abstracted from financial market frictions to focus squarely on the fundamentals. In the model, future fundamentals are discounted by a real interest rate on government bonds. The implicit assumption behind this discount rate is that agents purchasing residential properties have unconstrained, period-by-period, access to financial markets at that interest rate. That is not the case in reality. A natural extension, therefore, is to take into account borrowing constraints and nominal long-term mortgage loans. Long-term mortgages interacting with persistent predictable components in the growth rates of the fundamentals could generate further amplification of house price movements. We would expect such interaction to show up as a volatile and persistent wedge in the Euler equation for housing, resembling time-varying expected excess returns on housing (a housing premium), relative to the interest rate on government bonds. However, such an application runs into a problem with widespread availability of data on mortgage credit in the 1950s and 1960s in many countries.

Our focus has been on country-level house prices. However, there is no reason why the same mechanism could not be present at a more local level. Such an application would be a further test of the theory.

The recent literature on housing markets has paid special attention to household heterogeneity. The large house price swings generated in our model by, for instance, shocks to expected future income growth, may affect different households differently. In the presence of heterogeneity, this mechanism may bring together, in an internally consistent way, shocks to fundamentals, realistic house price movements, tenure choice, and redistribution. We hope our findings will be useful to researchers working in this area.

Finally, age heterogeneity has been incorporated into the model in a heuristic way. For practical econometric reasons, we have also abstracted from any dynamic interactions between the fundamentals under consideration (and the real interest rate), which can be jointly affected by the dynamics of the age distribution. Nonetheless, our results suggest that if the age distribution should account for the key patterns of the data highlighted in this paper, it would have to do so through a significant impact on the estimated predictable components in income and population growth rates. We leave these avenues for future work.

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Table 1: Loadings of house price data on the 1st principal component, 1950-2019

AUS	BEL	CAN	DNK	FIN	FRA	JPN	NLD	SWE	CHE	GBR	USA
0.21	0.32	0.32	0.35	0.22	0.35	-0.04	0.23	0.35	0.12	0.41	0.34

Notes: Based on the method of Barigozzi et al. (2021) for non-stationary data.

Table 2: Parameter estimates

A. Panel estimation of the exogenous processes (Υ_1)

ϕ_r	σ_r	θ_g	σ_g	ς_g	ϕ_n	θ_n	σ_n	ς_n
0.6620	0.0233	0.9387	0.0188	0.0085	0.8694	0.9852	2.71e-5	3.14e-4
[0.6211,	[0.0224,	[0.9038,	[0.0176,	[0.0070	[0.8645,	[0.9724,	[2.23e-05,	[3.02e-04
0.7036]	0.0243]	0.9639]	0.0200]	0.0103]	0.8771]	0.9975]	3.35e-05]	3.28e-04]

B. Country-specific quasi-likelihood estimation (Υ_2)

	Common prior distribution					Median of the posterior dist.	
	Type	Mean	Variance	LB	UB	Cross-country Median	Std
δ	Gamma	0.06	0.001	0.01	0.1	0.052	0.0058
ε_1	Gamma	1.0	0.3	0.01	10.0	0.67	0.131
ε_2	Gamma	1.0	0.3	0.01	10.0	1.17	0.370
ψ_1	Gamma	0.5	0.1	0.01	10.0	0.40	0.049
ψ_2 *		1.0				1.0	
ψ_3	Gamma	2.0	0.5	0.01	10.0	1.76	0.75
ψ_4	Gamma	2.0	0.5	0.01	10.0	2.15	0.61
ψ_5	Gamma	1.5	0.5	0.01	10.0	1.46	0.32
ϕ_z	Beta	0.3	0.01	0.01	0.999	0.28	0.012
θ_z	Beta	0.9	0.01	0.01	0.999	0.95	0.025
ν_z	Normal	0	0.1	-1.0	1.0	0.014	0.0077
σ_z	Log-normal	0.004	3e-5	1e-9	7.34	0.0026	0.00087
ς_z	Log-normal	0.0006	5e-7	1e-9	7.34	0.00029	0.00011

$^*\psi_2$ is normalized to equal to one.

Notes: In panel A, the 90% error bands are reported in the parentheses. The constant terms in the stochastic processes (ν_r, ν_g, ν_n) are allowed to be country-specific. They are unimportant for the dynamics of the model and for space constraints are not reported. In panel B, only the cross-country median and standard deviation of the medians in the country-specific posterior distributions are reported. The medians and the 90% error bands of the country-specific posterior distributions are reported in the Online Appendix. The age categories are: 0-24 (group 1), 25-39 (group 2), 40-54 (group 3), 55-69 (group 4), 70+ (group 5). The growth rate of the housing stock, h, is calibrated to 0.02 for all countries.

Table 3: The effect of ageing population on house prices, 1950-2019

	1950-2019 change in the share of					Ratio of 2019 house prices under 1950 distribution to under actual distribution
	0-24	25-39	40-54	55-69	70+	
AUS	-0.10	-0.02	0.01	0.04	0.06	0.86
BEL	-0.07	-0.01	-0.02	0.04	0.07	0.87
CAN	-0.20	0.00	0.03	0.10	0.07	0.72
DNK	-0.11	-0.04	0.01	0.05	0.09	0.86
FIN	-0.19	-0.02	0.00	0.09	0.12	0.79
FRA	-0.08	-0.01	-0.01	0.04	0.07	0.88
JPN	-0.33	-0.03	0.07	0.11	0.18	0.76
NLD	-0.18	-0.03	0.03	0.09	0.10	0.80
SWE	-0.07	-0.03	-0.02	0.03	0.09	0.91
CHE	-0.13	-0.01	0.00	0.05	0.08	0.89
GBR	-0.06	-0.02	-0.02	0.03	0.07	0.87
USA	-0.10	-0.02	0.00	0.06	0.06	0.90

Notes: The table shows the combined effect of the age distribution on the stochastic trend and the deviations of house prices. The results are computed at the medians of the posterior distributions. The change in the age distribution may not add up to zero due to rounding.

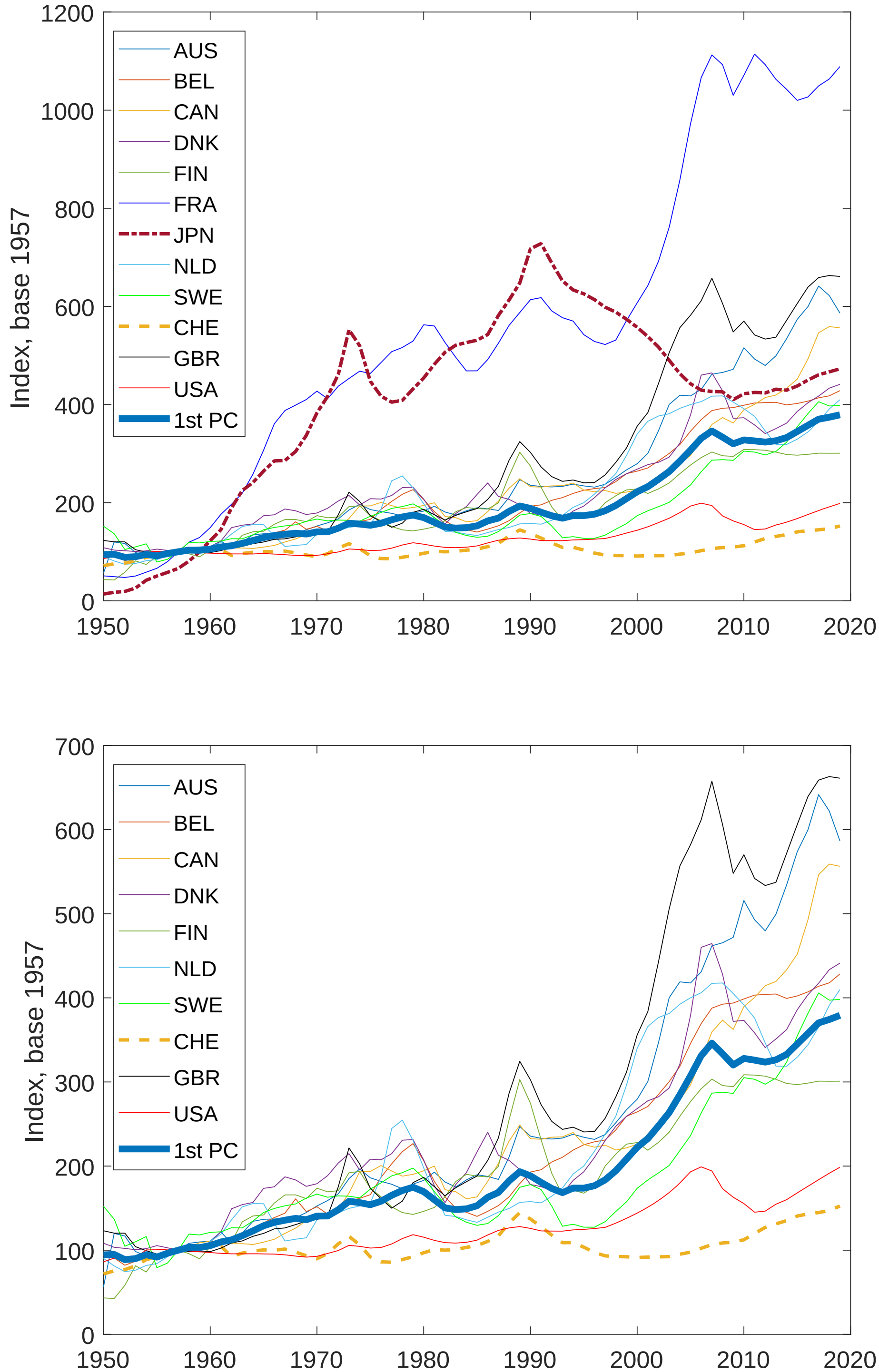

Figure 1: Real house price index, 1957 = 100. The sample is 1950-2019, except CAN, which is from 1957. The thick blue line is the 1st principal component of the countries in the sample, computed using the method of Barigozzi et al. (2021), which extends the principal component analysis to non-stationary data. The 1st principal component is representative of house prices in AUS, BEL, CAN, DNK, FIN, FRA, NLD, SWE, GBR, and USA (the 'G10 countries'). The bottom chart is a zoom-in of the upper chart by removing FRA and JPN.

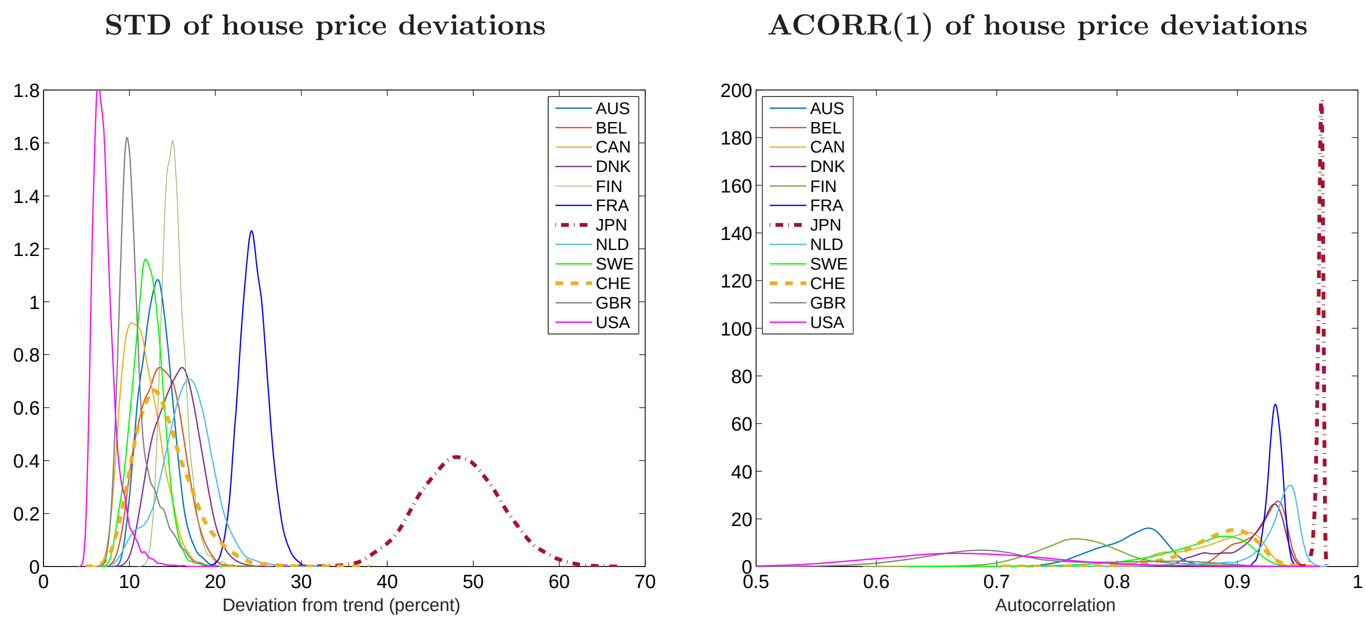

Figure 2: Properties of the model. The standard deviation and the first-order autocorrelation of the percentage deviations of house prices from trend. The distributions of STD and ACORR(1) are based on the posterior distributions of the parameter estimates.

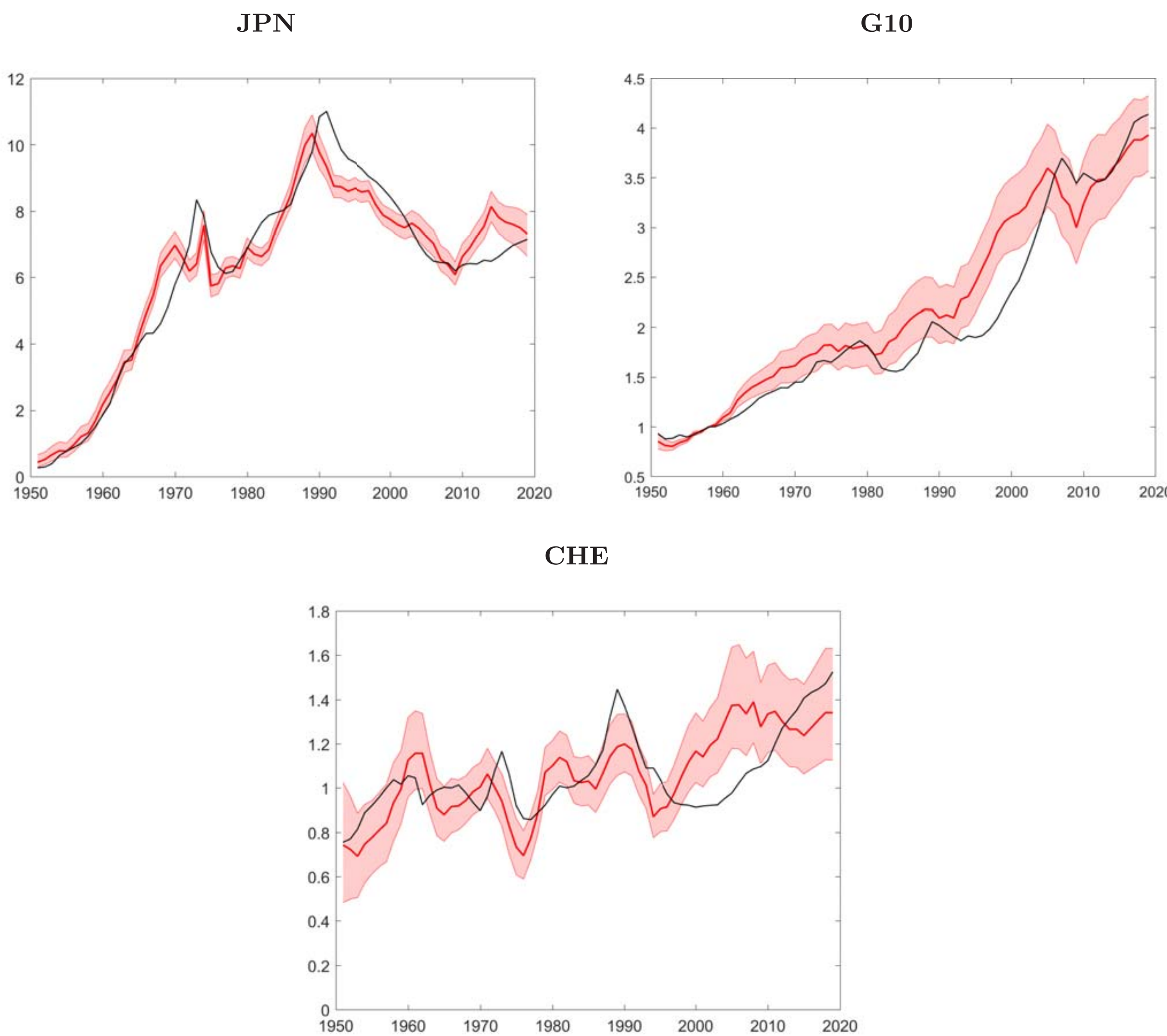

Figure 3: Model vs. data. The thick red line is the median and the shaded areas are the 90% error bands obtained from the posterior distribution of the parameter estimates. The black line is the data. The data are a real house price index, 1957 = 1. For the G10, both the data and the model are based on the 1st principal component of the ten countries.

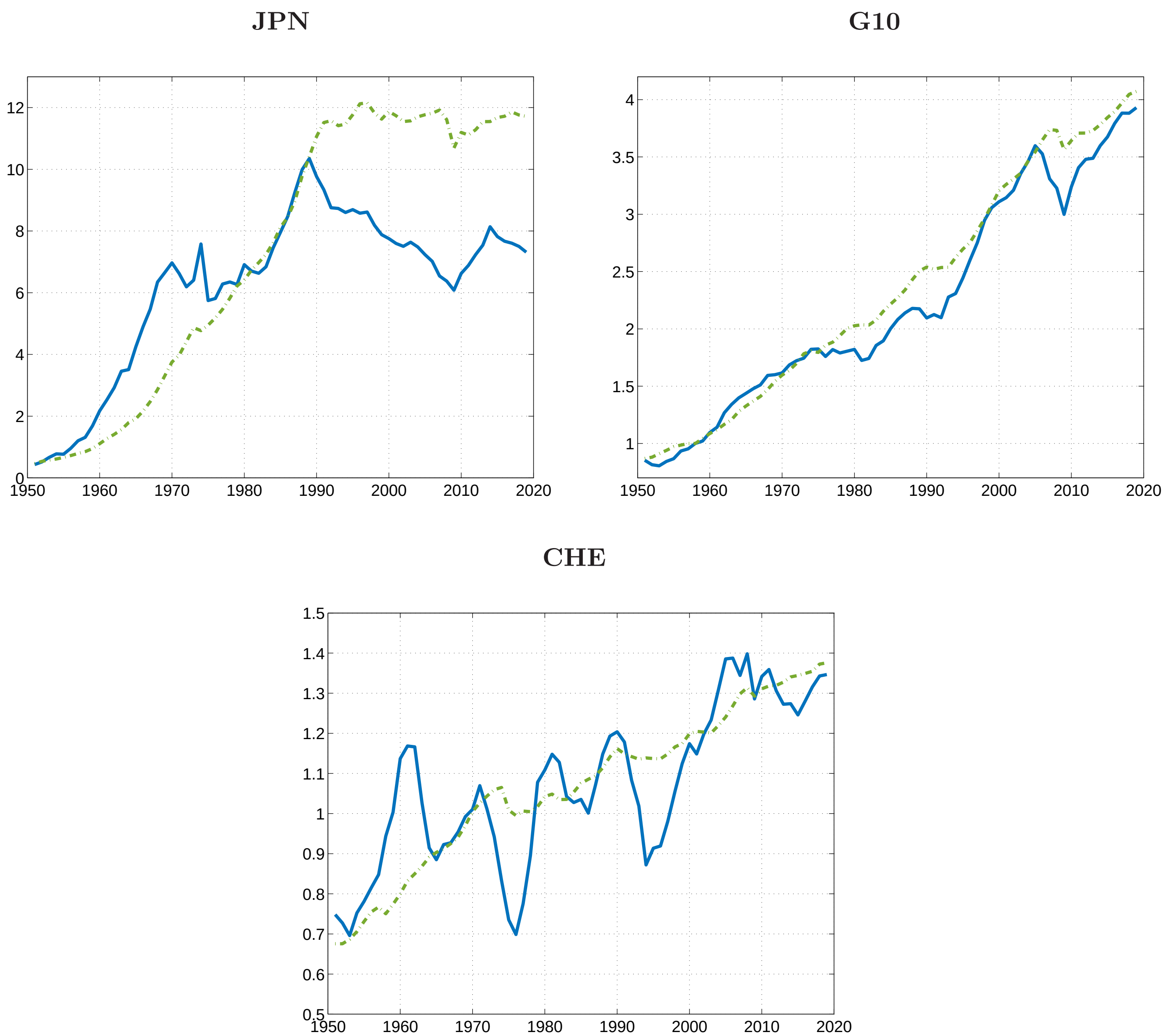

Figure 4: The role of expectations and the interest rate. The median of the model house prices (solid line) and the median of the model stochastic trend (dash-dotted line). The stochastic trend does not depend on expectations and the interest rate. For the G10 countries, the chart plots the 1st principal component of the medians.

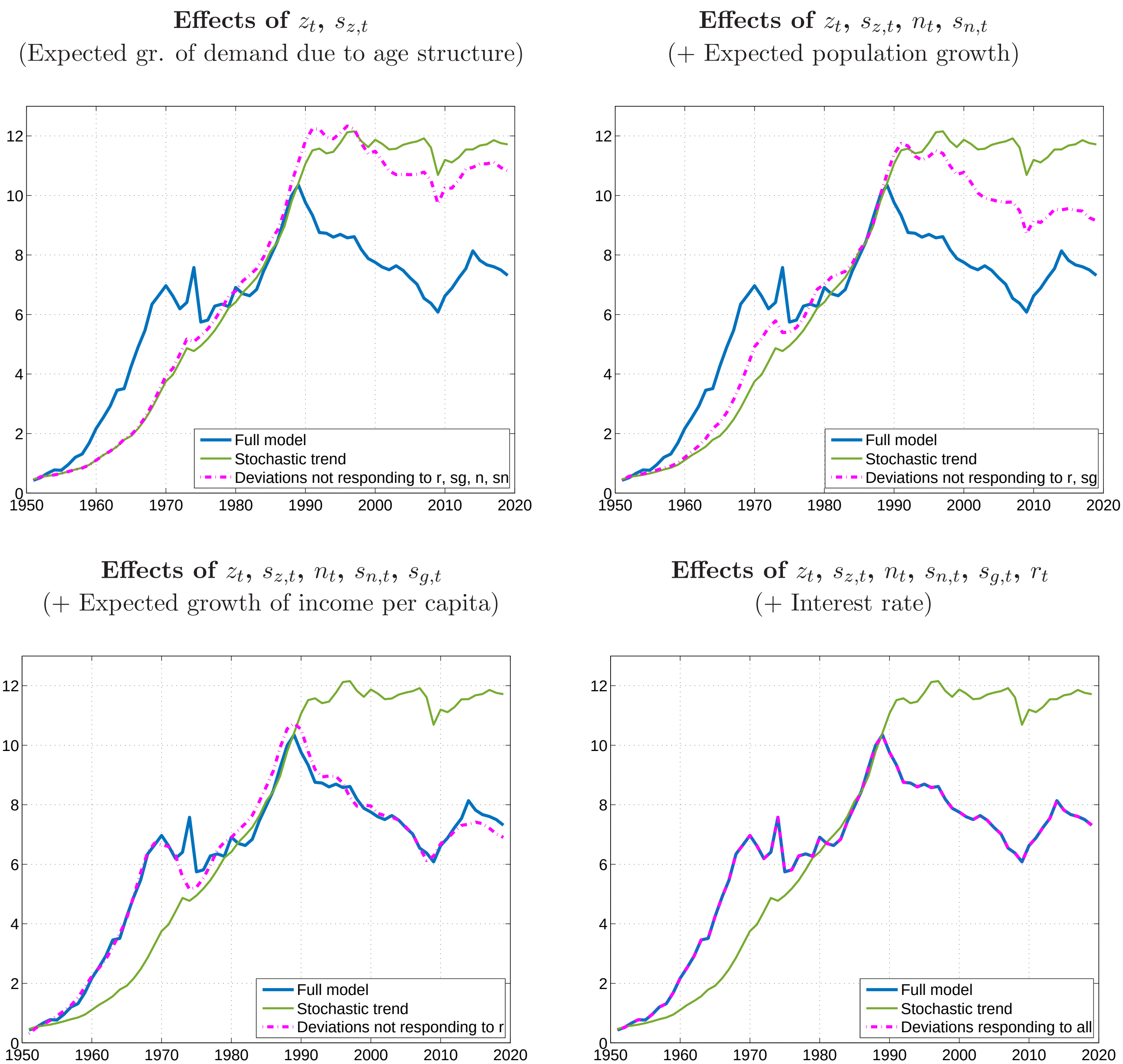

Figure 5: Japan—the marginal contribution of the state variables to the deviations of house prices from the stochastic trend. The solid thick line = the full model; the solid thin line = stochastic trend only; the dash-dotted line = the model with only the state variables in the respective chart title affecting the deviations from trend.

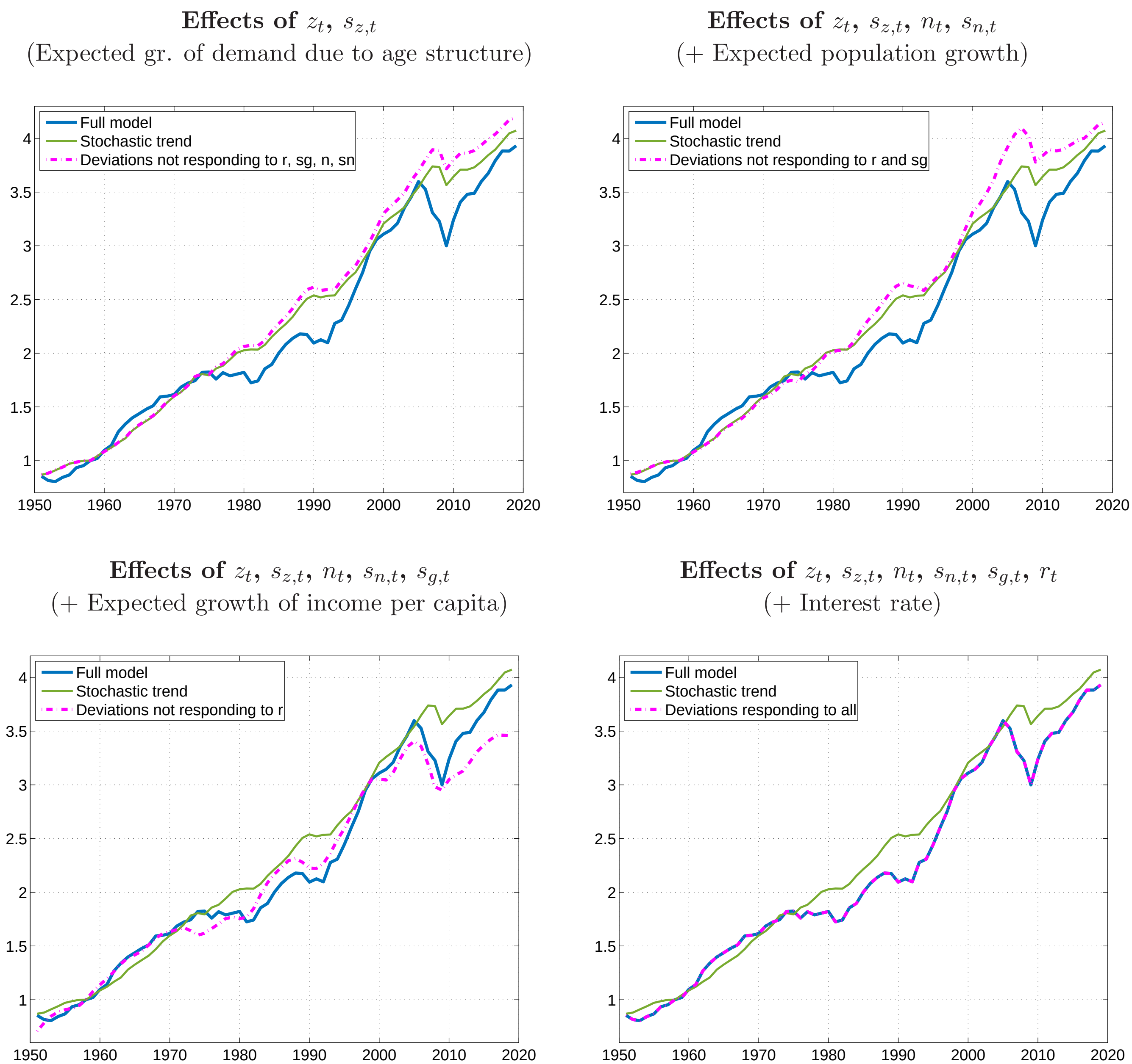

Figure 6: G10 countries—the marginal contribution of the state variables to the deviations of house prices from the stochastic trend. The solid thick line = the full model; the solid thin line = stochastic trend only; the dash-dotted line = the model with only the state variables in the respective chart title affecting the deviations from trend. Based on the 1st principal component of the medians.

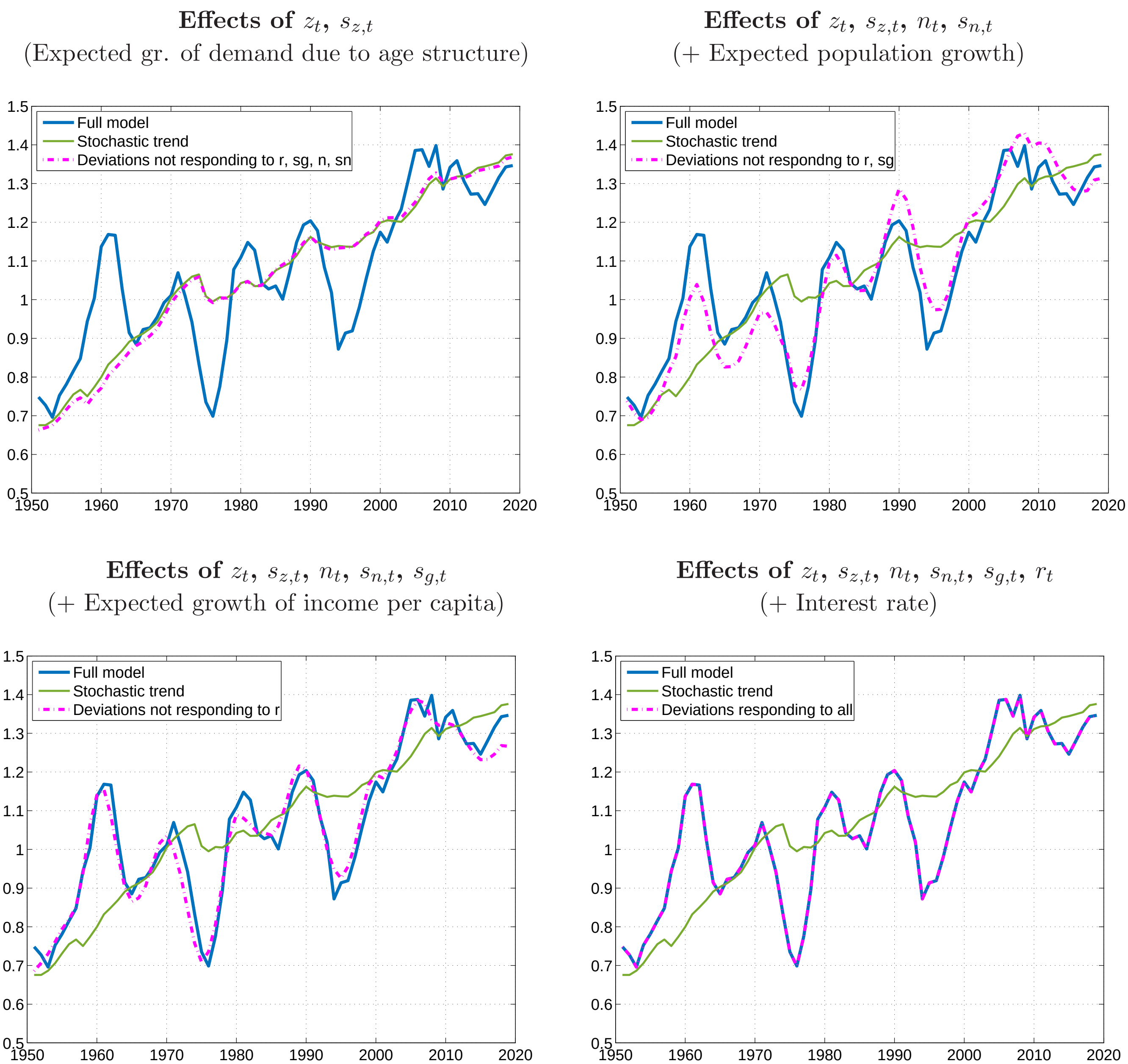

Figure 7: Switzerland—the marginal contribution of the state variables to the deviations of house prices from the stochastic trend. The solid thick line = the full model; the solid thin line = stochastic trend only; the dash-dotted line = the model with only the state variables in the respective chart title affecting the deviations from trend.