

Risk Matters: Breaking Certainty Equivalence

**Juan Carlos Parra-Alvarez, Hamza Polattimur and
Olaf Posch**

CREATES Research Paper 2020-02

Risk Matters: Breaking Certainty Equivalence*

Juan Carlos Parra-Alvarez^{(a,c,d)†}, Hamza Polattimur^(b), and Olaf Posch^(b,c)

^(a)Aarhus University, ^(b)Universität Hamburg, ^(c)CREATES,

^(d)Danish Finance Institute

March 2020

Abstract

In this paper we use the property that certainty equivalence, as implied by a first-order approximation to the solution of stochastic discrete-time models, breaks in its equivalent continuous-time version. We study the extent to which a first-order approximated solution built by perturbation methods accounts for risk. We show that risk matters economically in a real business cycle (RBC) model with habit formation and capital adjustment costs and that neglecting risk leads to substantial pricing errors. A first-order approximation in continuous time reduces pricing errors by 90 percent relative to the certainty equivalent linear solution.

Keywords: Certainty equivalence, Perturbation methods, Pricing errors

JEL classification: C02, C61, C63, E13, E32, G12.

*We thank Serguei Mailiar, Johannes Pfeiffer, Alexander Meyer-Gohde, participants at the 23rd International Conference in Computing in Economics and Finance (New York, 2017), the 13th Dynare Conference (Tokyo, 2017), the 11th International Conference on Computational and Financial Econometrics (London, 2017), the 26th Annual SNDE Symposium (Tokyo, 2018), the 23rd Annual LACEA Meeting (Guayaquil, 2018), the 6th International Conference on Economics of the Turkish Economic Association (Antalya, 2018); and seminar participants for their valuable comments and discussions. We appreciate financial support from the German Research Foundation (DFG, Project No. 268475812).

[†]Corresponding author: Juan Carlos Parra-Alvarez (Email address: jparra@econ.au.dk, Address: Aarhus University, Department of Economics and Business Economics, Fuglesangs Allé 4, 8210, Aarhus V, Denmark.)

1 Introduction

There is a consensus among economists that uncertainty affects the consumption-saving decision of individuals. Neglecting the effects of risk in macroeconomics and finance often generates substantial pricing errors. Hence, recent research is concerned with the ability of local approximations of non-linear stochastic macroeconomic models to account for risk, with a particular focus on perturbation methods originally introduced in economics by [Judd and Guu \(1993\)](#). Although perturbation-based methods only provide local precision around a particular point, usually the model’s deterministic steady state, many authors suggest that they can generate high levels of accuracy, comparable to that delivered by global approximation techniques, as the order of the approximation is increased (see [Judd, 1998](#); [Aruoba et al., 2006](#); [Caldara et al., 2012](#); [Parra-Alvarez, 2018](#)). In many applications, however, we are interested in the first-order perturbation and the resulting linear approximation of the equilibrium conditions.

A known limitation of the first-order perturbation around the deterministic steady state is that the approximate solution in discrete time typically exhibits certainty equivalence (see [Simon, 1956](#); [Theil, 1957](#)). In other words, the first-order approximation to the solution of stochastic economic models with forward-looking agents is identical to the solution of the same model under perfect foresight. The direct implication is that the solution becomes invariant to higher-order moments of the underlying shocks. An open question this paper studies relates to the costs of neglecting the effects of risk. In particular, what errors do we make when not accounting properly for risk in linear approximations? How can we interpret these errors in an economically meaningful way?

Certainty equivalence prevails in the classical linear-quadratic optimal control problem, popularized in economics by [Kydland and Prescott \(1982\)](#) and [Anderson et al. \(1996\)](#). In the early 1950s the introduction of certainty equivalent stochastic control problems with quadratic utility and linear constraints aimed at providing a practical solution for decision problems under uncertainty. Even today, if risk is negligible for the research question at hand, certainty equivalent solutions are still useful. In this case, one may conclude that “certainty equivalence is a virtue” (see [Kimball, 1990a](#)). Conversely, when there is a reason to believe that the effects of uncertainty are important, one notices that “certainty equivalence is a vice”. Put differently, if risk matters, breaking certainty equivalence is desired in order to account for the effects of risk. As discussed in [Fernandez-Villaverde et al. \(2016\)](#), the approximated solution of the model under certainty equivalence (i) makes it difficult to talk about the welfare effects of uncertainty; (ii) cannot generate any risk premia for assets; and (iii) prevents analyzing the consequences of changes in volatility.

To break the property of certainty equivalence in the class of perturbation methods, economists have restored to the computation of higher-order Taylor expansions, the

underlying apparatus behind any perturbation method, which translate into non-linear approximations of the model's solution. Originally proposed in [Judd and Guu \(1993\)](#), higher-order approximations became popular with the work of [Schmitt-Grohe and Uribe \(2004\)](#) for second-order approximations, [Andreasen \(2012\)](#) and [Ruge-Murcia \(2012\)](#) for third-order approximations, and [Levintal \(2017\)](#) for fifth-order approximations. However, the use of high-order approximations for medium-scale macroeconomic models (i) is computationally expensive, (ii) often results in explosive solutions, and (iii) requires computationally demanding non-linear estimation methods, such as the particle filter, for the estimation of the model's structural parameters.

In contrast to stochastic discrete-time models, certainty equivalence breaks in the first-order perturbation when time is assumed to be continuous. This result, originally mentioned in [Judd \(1996\)](#) and [Gaspar and Judd \(1997\)](#), allows us to account for risk in a linear world. In discrete time the approximation is built inside the system of expectational equations that summarize the equilibrium of the economy, while in continuous time it is possible to compute those expectations with the use of stochastic calculus (Itô's lemma) before building the perturbation-based approximation.

In this paper we revisit the ability of a first-order approximation to capture the effects of risk. Using as a benchmark an RBC model with habit formation and capital adjustment costs *à la* [Jermann \(1998\)](#), we compare how the effects of uncertainty are internalized by perturbations built around the model's deterministic steady state relative to a more accurate solution obtained by projection methods. First, we build approximated solutions to the continuous-time model and show that the certainty equivalence property already breaks in the first order such that the obtained linear approximation is risk-sensitive. We then calibrate the parameters of the model to values that are standard in the literature and compare, along different dimensions, the first-order certainty equivalent (CE) solution to the first- and second-order approximations obtained from perturbation. We show that each of the approximations converges to different long-run equilibria or fixed points in the absence of shocks. While the first-order CE converges to the deterministic steady state, risk-adjusted solutions converge to their respective risky steady states. This property is reflected in the policy and impulse response functions.

We find that the risk effects captured by the first-order approximation in continuous time are economically significant. When relying on the linear CE solution the pricing errors are about 1 dollar for each 100 dollar spent. The risk-adjustment of the first-order approximation leads to errors of about 10 cents for each 100 dollar spent, reducing pricing errors by about 90%. In the second-order approximation, pricing errors fall further to about 3 cents. We also find that the continuous-time first-order approximation is especially useful in situations in which risk matters but nonlinearities are negligible. In general, its main advantage is that it avoids the above-mentioned shortcomings associated with CE on the one hand and with non-linear models on the other hand.

Our work relates to that of [Collard and Juillard \(2001\)](#), [Coeurdacier et al. \(2011\)](#), [de Groot \(2013\)](#), [Meyer-Gohde \(2015\)](#) and [Lopez et al. \(2018\)](#), who compute first-order approximations around the model’s risky steady state instead of the deterministic steady state in order to break certainty equivalence in discrete-time models. [Collard and Juillard \(2001\)](#) consider a bias reduction procedure to compute the approximation around the risky steady state; [Coeurdacier et al. \(2011\)](#), whose approach is generalized by [de Groot \(2013\)](#), approximate the risky steady state based on the second-order solution. [Meyer-Gohde \(2015\)](#) constructs a risk-sensitive linear approximation using policy functions resulting from higher-order perturbations. [Lopez et al. \(2018\)](#) differ from the previous studies as they consider lognormal affine approximations, often used in macro-finance, which are shown to be a special case of a first-order perturbation around the risky steady state. We argue that it is possible to account for risk in an economically meaningful way using *standard* first-order (linear) perturbations around the *deterministic* steady state when time evolves continuously.

The rest of the paper is organized as follows. In [Section 2](#), we introduce our model and define the equilibrium conditions used in the perturbation method to approximate the solution. [Section 3](#) summarizes the perturbation approach and revisits the property of certainty equivalence in linear models. [Section 4](#) derives the pricing implications of the approximated solution and introduces a pricing error measure that can be used to evaluate the accuracy of the approximation. [Section 5](#) discusses the main results by comparing policy functions, impulse-response functions, and pricing errors for different degrees of approximation. Finally, [Section 6](#) concludes.

2 A prototype RBC model

For illustration, we use a continuous-time version of the real business cycle model (RBC) introduced in [Jermann \(1998\)](#) with some minor modifications. There is a single good in the economy that is produced using a constant-returns-to-scale production technology that is subject to random shocks in productivity. Changes in the economy’s aggregate capital stock are subject to adjustment costs, and the household preferences exhibit intertemporal non-separabilities due to internal habit formation in consumption. A discrete-time version of the model can be found in accompanying web appendix.

Preferences. The economy is inhabited by a large number of identical households that maximize their expected discounted lifetime utility from consumption, C_t ,

$$U_0 \equiv \mathbb{E}_0 \left[\int_0^\infty e^{-\rho t} u(C_t, X_t) dt \right], \quad (1)$$

where $\mathbb{E}_0[\cdot]$ is the expectation operator conditional on the information available at time $t = 0$, $\rho \geq 0$ is the household’s subjective discount rate, and u is the instantaneous utility

function. For simplicity we assume that

$$u(C, X) = \frac{(C - X)^{1-\gamma}}{1-\gamma}, \quad (2)$$

where γ measures the curvature of the utility function (together with the consumption surplus ratio) so, *ceteris paribus*, a higher value of γ yields higher risk aversion. In what follows, we assume that the consumption choice is non-negative, $C_t \geq 0$, and does not fall below a subsistence level of consumption, $C_t \geq X_t$, where X_t denotes habits in consumption. Hence, the instantaneous utility in (1) is said to exhibit adjacent complementarity in consumption (see [Ryder and Heal, 1973](#)), where an increase in consumption today increases the marginal utility of consumption at adjacent dates relative to the marginal utility of consumption at distant ones. The habit level in consumption is defined endogenously (internal habit) in the model, in contrast to the relative consumption model or ‘catching up with the Joneses’ (external habit), where the habit is aggregate consumption and thus exogenous to the households. In particular, the habit process is given by

$$X_t = e^{-at}X_0 + b \int_0^t e^{a(s-t)} C_s ds, \quad X_0 \geq 0,$$

or equivalently,

$$dX_t = (bC_t - aX_t)dt. \quad (3)$$

Hence, X_t is a weighted sum of past consumption, with weights declining exponentially into the past. The larger is b , the less weight is given to past consumption in determining X_t and vice versa. The special case $b = X_0 = 0$ corresponds to the case of time-separable utility with constant relative risk aversion (see [Constantinides, 1990](#)). The parameter a measures the degree of persistence in the habit stock.

Technology. The one good in the economy is produced according to a Cobb-Douglas production function

$$Y_t = \exp(A_t) K_t^\alpha L_t^{1-\alpha}, \quad 0 < \alpha < 1, \quad (4)$$

where K_t is the aggregate capital stock, L_t is the perfectly inelastic labor supply (normalized to one for all $t \geq 0$), and A_t is a stochastic process representing random total factor productivity (TFP). The aggregate capital stock in the economy increases if effective investment exceeds depreciation

$$dK_t = (\Phi(I_t/K_t) - \delta)K_t dt, \quad K_0 > 0, \quad (5)$$

where $\delta \geq 0$ is the depreciation rate, and I_t is aggregate investment. Following [Jermann \(1998\)](#), the capital adjustment cost function is defined by

$$\Phi(I_t/K_t) = \frac{a_1}{1 - 1/\xi} (I_t/K_t)^{1-1/\xi} + a_2, \quad (6)$$

where $\xi > 0$ denotes the elasticity of the investment-to-capital ratio with respect to Tobin's q , and $a_1 \geq 0$ and $a_2 \geq 0$ are parameters. In line with [Boldrin et al. \(2001\)](#), we set $a_1 = \delta^{1/\xi}$ and $a_2 = \delta/(1 - \xi)$ such that the steady state is invariant to ξ , and hence the long-run investment-to-capital ratio equals the depreciation rate¹. On the other hand, TFP is assumed to follow an Ornstein-Uhlenbeck process with mean reversion $\rho_A > 0$ and variance $\sigma_A > 0$

$$dA_t = -\rho_A A_t dt + \sigma_A dB_{A,t}, \quad (7)$$

where $B_{A,t}$ is a standard Brownian motion. In equilibrium, the economy satisfies the aggregate resource constraint

$$Y_t = C_t + I_t. \quad (8)$$

Optimality conditions. Consider the problem faced by a social planner who has to choose the path for consumption that maximizes (1) subject to the dynamic constraints (3), (5), and (7), and the static constraints (4), (6), and (8)

$$V(K_0, X_0, A_0) = \max_{\{C_t \geq X_t \in \mathbb{R}^+\}_{t=0}^\infty} U_0 \quad \text{s.t.} \quad (3) - (8), \quad (9)$$

in which C_t is the control variable at time $t \in \mathbb{R}^+$, and $V(K_0, X_0, A_0) \equiv V_0$ is the value of the optimal plan (value function) from the perspective of time $t = 0$, i.e., when the state of the economy is described by the time $t = 0$ values for the capital stock, K_0 , the stock of habits, X_0 , and the total factor productivity, A_0 .

As shown in [Appendix A](#), for any $t \in [0, \infty)$, a necessary condition for optimality is given by the *Hamilton-Jacobi-Bellman* (HJB) equation

$$0 = \max_{C \geq X \in \mathbb{R}^+} \left\{ \frac{(C - X)^{1-\gamma}}{1 - \gamma} + (\Phi((\exp(A)K^\alpha - C)/K)K - \delta K)V_K \right. \\ \left. + (bC - aX)V_X - \rho_A A V_A + \frac{1}{2}\sigma_A^2 V_{AA} - \rho V \right\}, \quad (10)$$

where $V_K \equiv \partial V(K, X, A)/\partial K$, $V_X \equiv \partial V(K, X, A)/\partial X$ and $V_A \equiv \partial V(K, X, A)/\partial A$, and $V_{AA} \equiv \partial^2 V(K, X, A)/\partial A^2$ denote, respectively, the first-order partial derivatives and the second-order partial derivative of the value function with respect to the states of the economy². The first order condition for any interior solution reads

¹Given this parameterization it can be shown that in the steady state: $\Phi(\bar{I}/\bar{K}) = \Phi(\delta) = \delta$, $\Phi'(\bar{I}/\bar{K}) = \Phi'(\delta) = 1$, and $\Phi''(\bar{I}/\bar{K}) = \Phi''(\delta) = -1/(\xi\delta)$, i.e. the slope of Φ' depends negatively on ξ and δ .

²A formal introduction and derivation of the dynamic programming equation for continuous-time problems can be found in [Chang \(2009\)](#). In what follows, we omit the use of the time index given the recursive structure of the HJB equation.

$$(C - X)^{-\gamma} + bV_X = \Phi' \left(\frac{\exp(A)K^\alpha - C}{K} \right) V_K, \quad (11)$$

making optimal consumption an implicit function of the state variables, $C^* = C(K, X, A)$. The function $C(\cdot)$ maps every possible values of the states of the economy at time t into the optimal consumption at time t . The maximized HJB equation reads

$$0 = \frac{(C(K, X, A) - X)^{1-\gamma}}{1-\gamma} + (\Phi((\exp(A)K^\alpha - C(K, X, A))/K)K - \delta K)V_K + (bC(K, X, A) - aX)V_X - \rho_A AV_A + \frac{1}{2}\sigma_A^2 V_{AA} - \rho V, \quad (12)$$

which together with the first order condition (11) determine the unknown functions $V(K, X, A)$ and $C(K, X, A)$ that define the equilibrium in the economy.

Equilibrium dynamics. A solution to the continuum of problems formed by (11) and (12) can be characterized in the *time-space domain* by a sequence $\{V_{K,t}, V_{X,t}, K_t, X_t, A_t\}_{t=0}^\infty$ that solves the boundary value problem (with appropriate transversality conditions) characterized by the system of equilibrium stochastic differential equations (SDEs)

$$\begin{aligned} dV_{K,t} = & (\rho - \Phi((\exp(A_t)K_t^\alpha - C_t)/K_t) - \Phi'((\exp(A_t)K_t^\alpha - C_t)/K_t) \\ & \times [(\alpha - 1)\exp(A_t)K_t^{\alpha-1} + C_t/K_t] + \delta)V_{K,t}dt + V_{KA,t}\sigma_A dB_{A,t} \end{aligned} \quad (13)$$

$$dV_{X,t} = ((\rho + a)V_{X,t} + (C_t - X_t)^{-\gamma})dt + V_{XA,t}\sigma_A dB_{A,t} \quad (14)$$

$$dK_t = (\Phi((\exp(A_t)K_t^\alpha - C_t)/K_t)K_t - \delta K_t)dt \quad (15)$$

$$dX_t = (bC_t - aX_t)dt \quad (16)$$

$$dA_t = -\rho_A A_t dt + \sigma_A dB_{A,t}, \quad (17)$$

together with initial conditions $K(0) = K_0$, $X(0) = X_0$, and $A(0) = A_0$ and where C_t solves the non-linear algebraic equation in (11).

Alternatively, we may eliminate time and shocks from the system of equilibrium SDEs in (13)-(17) and define the solution to the optimal control problem in the *state-space domain* as the triple $\{V_K(K, X, A), V_X(K, X, A), C(K, X, A)\}$ for admissible values of the state space (K, X, A) that solves the system of partial differential equations (PDEs)

$$\begin{aligned} 0 = & (\rho - \Phi((\exp(A)K^\alpha - C)/K) - \Phi'((\exp(A)K^\alpha - C)/K)((\alpha - 1)\exp(A)K^{\alpha-1} \\ & + C/K) + \delta)V_K - (\Phi((\exp(A)K^\alpha - C)/K)K - \delta K)V_{KK} \\ & - (bC - aX)V_{XK} + \rho_A AV_{AK} - \frac{1}{2}\sigma_A^2 V_{AAK} \end{aligned} \quad (18)$$

$$\begin{aligned} 0 = & (\rho + a)V_X + (C - X)^{-\gamma} - (\Phi((\exp(A)K^\alpha - C)/K)K - \delta K)V_{KX} \\ & - (bC - aX)V_{XX} + \rho_A AV_{AX} - \frac{1}{2}\sigma_A^2 V_{AAX} \end{aligned} \quad (19)$$

$$0 = (C - X)^{-\gamma} + bV_X - \Phi'((\exp(A)K^\alpha - C)/K)V_K. \quad (20)$$

A complete derivation of both the equilibrium system of SDEs in the time-space domain, and its PDE representation in the state-space domain can be found in Appendix A.

Deterministic steady state. In the absence of uncertainty (i.e. $\sigma_A = 0$), the economy converges over time to a fixed point or steady-state equilibrium in which all variables are idle. Given the assumptions on the capital adjustment cost function in (6), the deterministic steady state of the model is fully characterized by

$$\bar{A} = 0 \quad (21)$$

$$\bar{K} = [\alpha/(\rho + \delta)]^{\frac{1}{1-\alpha}} \quad (22)$$

$$\bar{C} = \bar{K}^\alpha - \delta\bar{K} \quad (23)$$

$$\bar{X} = (b/a)\bar{C} \quad (24)$$

$$\bar{V}_X = -[1/(\rho + a)] (\bar{C} - \bar{X})^{-\gamma} \quad (25)$$

$$\bar{V}_K = [1 - b/(\rho + a)] (\bar{C} - \bar{X})^{-\gamma}, \quad (26)$$

where \bar{V}_X and \bar{V}_K are the deterministic steady state values of the costate variables for the capital stock and the habit formation. For a detailed derivation of the model's deterministic steady state see Appendix A.

3 Approximate solution

Most dynamic economic models do not admit an analytical solution, so it usually has to be approximated using numerical methods (see Fernandez-Villaverde et al., 2006). Perturbation methods are fast and reliable, and provide an approximate solution to the stochastic optimal control problem in (9) based on the implicit function theorem and the Taylor's series expansion theorem. The perturbed solution consists of a polynomial that approximates the true solution of the problem locally in a neighborhood of an *a priori* known solution. In what follows, we build the perturbation solution to the equilibrium system of PDEs in (18)-(20) around the deterministic steady state given by (21)-(26).

Let $\eta > 0$ denote a *perturbation parameter* that rescales the amount of uncertainty in the economy. In our prototype model, η controls the absolute magnitude of the variance of the shocks to TFP (see Judd, 1996; Gaspar and Judd, 1997; Fernandez-Villaverde et al., 2016). Therefore, the exogenous stochastic processes (7) may be rewritten as

$$dA_t = -\rho_A A_t dt + \sqrt{\eta \sigma_A^2} dB_{A,t},$$

where the case $\eta = 0$ makes the model deterministic, and $\eta = 1$ recovers the true TFP process in (7)³. Following Judd (1998), the perturbation method can be summarized as

³Note that alternative definitions of the perturbation parameter can be found in the literature (cf.

follows:

1. Express the problem of interest as a continuum of problems parameterized by the added perturbation parameter η , with the $\eta = 0$ case known.
2. Differentiate the continuum of problems with respect to the state variables and the perturbation parameter η .
3. Solve the resulting equation for the implicitly defined derivatives at the known solution of the state variables and $\eta = 0$.
4. Compute the desired order of approximation by means of Taylor's theorem. Set $\eta = 1$ to recover the approximation to the original model.

In what follows, we introduce a general framework for the perturbation method for continuous-time models. We then provide an illustrative example of the method by using a simplified version of our prototype model⁴. Subsequently, we explain why the property of certainty equivalence that usually results from any first-order perturbation approximation to discrete-time models breaks in continuous-time models. Finally, we introduce the notion of the risky steady state, which will become relevant for understanding transition paths from the model.

3.1 Solving the model: A general framework

In continuous time, the general equilibrium can be represented by the functional equation

$$\mathcal{H}(\mathbf{y}, \mathbf{y}_{\mathbf{x}}, \mathbf{y}_{\mathbf{xx}}, \mathbf{x}; \eta) = \mathbf{0}, \quad (27)$$

where \mathbf{y} denotes the vector of control variables (or costates), $\mathbf{y}_{\mathbf{x}}$ and $\mathbf{y}_{\mathbf{xx}}$ the matrices of first- and second-order partial derivatives of the control variables with respect to the vector of state variables \mathbf{x} , η is the perturbation parameter, and \mathcal{H} is a functional operator collecting the model's equilibrium conditions. The state vector \mathbf{x} evolves over time according to the controlled stochastic differential equation

$$d\mathbf{x}_t = \mathbf{f}(\mathbf{x}_t, \mathbf{y}_t) dt + \sqrt{\eta} \mathbf{G}(\mathbf{x}_t) d\mathbf{B}_t, \quad (28)$$

where $\mathbf{f}(\cdot)$ is the drift vector, $\mathbf{G}(\cdot)$ is a diffusion matrix, potentially dependent on the current value of the state vector, and \mathbf{B}_t is the vector of exogenous shocks.

A solution to the functional equation in (27) takes the form

$$\mathbf{y} = \mathbf{g}(\mathbf{x}; \eta), \quad (29)$$

[Kogan and Uppal, 2001](#); [Chacko and Viceira, 2005](#); [Hansen et al., 2008](#)).

⁴A summary of the perturbation method for discrete-time models can be found in the accompanying web appendix and the references therein.

where $\mathbf{g}(\cdot)$ is a vector of policy functions that maps every possible value of \mathbf{x} into \mathbf{y} .

The deterministic steady state of the model in (27) is defined as the tuple $(\bar{\mathbf{y}}, \bar{\mathbf{y}}_{\mathbf{x}}, \bar{\mathbf{y}}_{\mathbf{xx}}, \bar{\mathbf{x}})$ that satisfies

$$\mathcal{H}(\bar{\mathbf{y}}, \bar{\mathbf{y}}_{\mathbf{x}}, \bar{\mathbf{y}}_{\mathbf{xx}}, \bar{\mathbf{x}}; 0) = \mathbf{0}. \quad (30)$$

Accordingly, it follows that in the steady state $\bar{\mathbf{y}} = \mathbf{g}(\bar{\mathbf{x}}; 0)$.

A perturbation-based approximation to the solution of the problem in (27) starts by building a k -th order Taylor series expansion of the unknown policy function \mathbf{g} in (29) around the deterministic steady state obtained from (30). We then substitute the approximated policy functions into \mathcal{H} to obtain the new operator

$$F(\mathbf{x}; \eta) := \mathcal{H}(\mathbf{g}(\mathbf{x}; \eta), \mathbf{g}_{\mathbf{x}}(\mathbf{x}; \eta), \mathbf{g}_{\mathbf{xx}}(\mathbf{x}; \eta), \mathbf{x}; \eta) = \mathbf{0}, \quad (31)$$

where $\mathbf{g}_{\mathbf{x}}$ is the matrix of first-order partial derivatives of the policy function, and $\mathbf{g}_{\mathbf{xx}}$ is the matrix of second-order partial derivatives⁵.

To compute the coefficients of the approximated solution we exploit the fact that if $F(\mathbf{x}; \eta) = \mathbf{0}$ for any admissible values of \mathbf{x} and η , then its derivatives must also be zero. That is, $F_{x^k, \eta^j}(\mathbf{x}; \eta) = \mathbf{0}$, for all $x \in \mathbf{x}, \eta, k, j$, where $F_{x^k, \eta^j}(\mathbf{x}; \eta)$ denotes the k -th derivative of F with respect to the state variable $x \in \mathbf{x}$, and with respect to η taken j times, evaluated at $(\mathbf{x}; \eta)$.

Let $k = 1$. Then, the *First-Order* approximation around the deterministic steady state to the policy functions is defined by

$$\mathbf{g}(\mathbf{x}; \eta) \approx \mathbf{g}(\bar{\mathbf{x}}; 0) + \mathbf{g}_{\mathbf{x}}(\bar{\mathbf{x}}; 0)(\mathbf{x} - \bar{\mathbf{x}}) + \mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0), \quad (32)$$

where $\mathbf{g}_{\mathbf{x}}(\bar{\mathbf{x}}; 0)$ corresponds to the stable solution to the quadratic matrix-equation that results from solving $F_x(\bar{\mathbf{x}}; 0) = \mathbf{0}$ for each state variable $x \in \mathbf{x}$. Similarly, $\mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0)$ is computed by solving $F_{\eta}(\bar{\mathbf{x}}; 0) = \mathbf{0}$. As opposed to perturbation of discrete-time models, this constant is not necessarily zero (see also Judd, 1996). Therefore, the First-Order approximation includes a correction term that captures the effects of risk, i.e., is risk-sensitive, and hence it does *not* exhibit certainty equivalence. By setting $\mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0) = \mathbf{0}$ in (32) we define the corresponding *First-Order Certainty Equivalent* (CE) approximation.

Now let $k = 2$. Then, the *Second-Order* approximation to the unknown policy function around the deterministic steady state is defined by

⁵As opposed to discrete-time models, the solution to the type of continuous-time models considered here does not require the approximation of a policy function for the next period state variables. However, their values at a given point in time can be recovered, *ex-post*, by solving the corresponding (controlled) differential equations in (28).

$$\begin{aligned} \mathbf{g}(\mathbf{x}; \eta) &\approx \mathbf{g}(\bar{\mathbf{x}}; 0) + \mathbf{g}_{\mathbf{x}}(\bar{\mathbf{x}}; 0)(\mathbf{x} - \bar{\mathbf{x}}) + \mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0) \\ &\quad + \frac{1}{2}\mathbf{g}_{\mathbf{xx}}(\bar{\mathbf{x}}; 0)(\mathbf{x} - \bar{\mathbf{x}}) \otimes (\mathbf{x} - \bar{\mathbf{x}}) + \mathbf{g}_{\mathbf{x}\eta}(\bar{\mathbf{x}}; 0)(\mathbf{x} - \bar{\mathbf{x}}) + \frac{1}{2}\mathbf{g}_{\eta\eta}(\bar{\mathbf{x}}; 0) \end{aligned} \quad (33)$$

where the remaining unknown coefficients are obtained as the solution to the linear system of equations formed by $F_{x_i x_j}(\bar{\mathbf{x}}; 0) = \mathbf{0}$ for all $x_i, x_j \in \mathbf{x}$, $F_{x_i \eta}(\bar{\mathbf{x}}; 0) = \mathbf{0}$ for all $x_i \in \mathbf{x}$, and $F_{\eta\eta}(\bar{\mathbf{x}}; 0) = \mathbf{0}$. In contrast to the discrete-time case, all the coefficients from the Second-Order approximation are different from zero. Hence, it provides an additional source of risk corrections beyond that already introduced through $\mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0)$. While the latter, together with $\mathbf{g}_{\eta\eta}(\bar{\mathbf{x}}; 0)$, only affect the level of the policy functions, $\mathbf{g}_{\mathbf{x}\eta}(\bar{\mathbf{x}}; 0)$ adjusts their slopes, introducing in this way a time-varying risk correction component already in a second-order approximation.

3.2 An illustration: The stochastic growth model

To illustrate how the procedure described above works, consider the stochastic neoclassical growth model which results from setting $X_0 = b = 0$ and letting $\xi \rightarrow \infty$ in the prototype model of Section 2. The HJB equation to the planner's problem is

$$\rho V(K, A; \eta) = \max_{C \in \mathbb{R}^+} \left\{ \frac{C^{1-\gamma}}{1-\gamma} + \frac{1}{dt} \mathbb{E}_t \left[dV(K, A; \eta) \right] \right\}$$

where the aggregate capital stock and TFP evolve according to:

$$dK_t = (\exp(A_t)K_t^\alpha - C_t - \delta K_t) dt, \quad K_0 > 0, \quad (34)$$

$$dA_t = -\rho_A A_t dt + \sqrt{\eta \sigma_A^2} dB_{A,t}, \quad A_0 > 0. \quad (35)$$

Using Itô's lemma together with the properties of stochastic integrals, we can write the HJB equation as

$$\begin{aligned} \rho V(K, A; \eta) = \max_{C \in \mathbb{R}^+} \left\{ \frac{C^{1-\gamma}}{1-\gamma} + (\exp(A)K^\alpha - C - \delta K)V_K(K, A; \eta) \right. \\ \left. - \rho_A A V_A(K, A; \eta) + \frac{1}{2}\eta \sigma_A^2 V_{AA}(K, A; \eta) \right\}. \end{aligned} \quad (36)$$

A complete derivation can be found in Appendix B. The equilibrium of the economy can be characterized in the time-space domain by the sequence $\{C_t, K_t, A_t\}_{t=0}^\infty$ that solves the

system of SDEs formed by the Euler equation for consumption

$$\frac{dC_t}{C_t} = \left[\frac{\alpha \exp(A_t) K_t^{\alpha-1} - \delta - \rho}{\gamma} + \frac{1}{2}(1 + \gamma) \left(\frac{C_{A,t}}{C_t} \right)^2 \eta \sigma_A^2 \right] dt + \frac{C_{A,t}}{C_t} \sqrt{\eta \sigma_A^2} dB_{A,t}, \quad (37)$$

where $C_{A,t} \equiv \partial C(K_t, A_t; \eta) / \partial A_t$, together with (34) and (35). The deterministic steady-state values of \bar{A} , \bar{K} , and \bar{C} are given by (21), (22), and (23), respectively.

Alternatively, the equilibrium of the economy can be characterized in the state-space domain by the PDE

$$\begin{aligned} & (\alpha \exp(A) K^{\alpha-1} - \delta - \rho) C / \gamma + \frac{1}{2}(1 + \gamma) C (C_A / C)^2 \eta \sigma_A^2 \\ & - C_K (\exp(A) K^\alpha - C - \delta K) + C_A \rho_A A - \frac{1}{2} C_{AA} \eta \sigma_A^2 = 0, \end{aligned} \quad (38)$$

which defines our functional operator $\mathcal{H}(C, C_K, C_A, C_{KK}, C_{AA}, C_{KA}, C_{AK}, K, A; \eta) = 0$, with unknown solution $C = C(K, A; \eta)$. Substituting the policy function into (38) yields the functional equation

$$F(K, A; \eta) \equiv \mathcal{H}(C(K, A; \eta), C_K(K, A; \eta), C_A(K, A; \eta), C_{AA}(K, A; \eta), K, A; \eta) = 0,$$

where we have already used the fact that in equilibrium $C_{KK} = C_{KA} = C_{AK} = 0$ since the capital stock is not affected directly by any exogenous shocks.

Let us first consider a first-order perturbation to the unknown policy function around the deterministic steady state

$$C(K, A; \eta) \approx \bar{C} + \bar{C}_K (K - \bar{K}) + \bar{C}_A (A - \bar{A}) + \bar{C}_\eta \eta,$$

where $\bar{C}_i = C_i(\bar{K}, \bar{A}; 0)$ denotes partial derivatives of the policy function with respect to $i = \{K, A, \eta\}$ evaluated at the deterministic steady state. The constants \bar{C}_K and \bar{C}_A result from the solution to the quadratic system of equations formed by

$$\begin{aligned} \bar{C}_K &= \frac{1}{2}(\alpha \exp(\bar{A}) \bar{K}^{\alpha-1} - \delta) \pm \left[\frac{1}{4}(\alpha \exp(\bar{A}) \bar{K}^{\alpha-1} - \delta)^2 - \alpha(\alpha - 1) \exp(\bar{A}) \bar{K}^{\alpha-2} \bar{C} / \gamma \right]^{\frac{1}{2}}, \\ \bar{C}_A &= (\bar{C}_K + \rho_A)^{-1} \left[\bar{C}_K \exp(\bar{A}) \bar{K}^\alpha - \alpha \exp(\bar{A}) \bar{K}^{\alpha-1} \bar{C} / \gamma \right]. \end{aligned}$$

For the stochastic growth model we pick the positive root, $\bar{C}_K > 0$, since it is the one that is consistent with a concave value function (see Parra-Alvarez, 2018). The remaining constant, \bar{C}_η , corresponds to the solution of the stochastic component of the approximation, and is given by

$$\bar{C}_\eta = -(\bar{C}_K)^{-1} \frac{1}{2} (1 + \gamma) \bar{C} (\bar{C}_A / \bar{C})^2 \sigma_A^2. \quad (39)$$

Hence, (39) shows that $\overline{C}_\eta \neq 0$, suggesting that a first-order approximation includes a constant correction for risk. The latter is captured by σ_A . Note that \overline{C}_η turns out to be negative, reflecting that risk averse agents will consume less in the presence of risk due to precautionary savings. However, certainty equivalence will still hold if the underlying assumptions of the economic model imply such property – e.g. in cases of (i) zero volatility, $\sigma_A = 0$, and/or (ii) quadratic utility, $(1 + \gamma) = 0$ (see Judd, 1996).

3.3 An intuition: Why does certainty equivalence break?

The solution to stochastic economic models is said to be certainty equivalent if the resulting policy functions are invariant to higher order moments of the model's underlying exogenous shocks. In other words, the solution of an economic model under uncertainty is identical to the solution of the same model under certainty.

For discrete-time stochastic models certainty equivalence holds for any first-order (linear) approximation around the deterministic steady state. In general, the optimality conditions that characterize economic equilibria in these models can be summarized by a system of stochastic difference equations, where expectations regarding the future value of the control variables need to be formed. Given that the policy functions are *a priori* unknown, the computation of such expectations can only be done *ex-post* once the optimal controls have been approximated. Hence, for a first-order perturbation this is equivalent to calculating the expected value of a set of linear functions which, according to the linearity property of the expectation operator, implies that only first order moments will enter the approximated solution.

However, as exemplified by equation (39), this is not the case for continuous-time stochastic models. To illustrate this point consider the non-linear HJB equation in (36), where the expected continuation value $(1/dt)\mathbb{E}_t[dV]$ has been already computed using the tools from stochastic calculus. Having computed expectations in the HJB, the resulting Euler equation in (37) includes some features that account for the model's underlying risk. In particular, let us consider the quadratic term $\frac{1}{2}(1+\gamma)(C_A/C)^2\eta\sigma_A^2$, which also appears in the correction in (39). The first thing to note is that it contains the marginal response of optimal consumption to changes in the exogenous driving force of the model, C_A , which is closely related to risk aversion. To see this recall that in equilibrium the optimal consumption function, C , is related to the marginal utility of consumption, $u'(C)$, and thus C_A is related to the first order derivative of the marginal utility, $u''(C)$. Also note that it contains the perturbation and the variance parameters which jointly capture the amount of risk in the model, $\eta\sigma_A^2$. Finally, note that the term $1+\gamma$ can be shown to be the coefficient of relative prudence for the case of CRRA utility functions. In contrast, as expected values cannot be computed *a priori* for discrete-time models, the Euler equation for consumption in that case will only include terms related to the marginal utility of consumption, $u'(C)$.

| Risk effects on: | $\partial^n u / (\partial c)^n$ | related to: | Cont. Time | | Discrete Time | | |
|------------------|---------------------------------|---------------------------|------------|-----|---------------|-----|-----|
| | | | 1st | 2nd | 1st | 2nd | 3rd |
| — | $n = 2$ | risk aversion: $-u''/u'$ | ✓ | ✓ | ✓ | ✓ | ✓ |
| level of C | $n = 3$ | prudence: $-u'''/u''$ | ✓ | ✓ | | ✓ | ✓ |
| slope of C | $n = 4$ | temperance: $u^{(4)} < 0$ | | ✓ | | | ✓ |

Table 1. Effects of risk in perturbation solutions. The table indicates the order of the derivative of the utility function $\partial^n u / (\partial c)^n$ necessary to account for a particular effect of risk on optimal consumption, as well as the order of approximation needed to capture it both in continuous-time and discrete-time stochastic models.

How this relates to certainty equivalence becomes clear when taking a closer look at the precautionary motive, or prudence, that describes the optimal reaction of consumption to risk. Prudence is related to the third derivative of the utility function, $u'''(C)$ ⁶, and its absence leads to certainty equivalence. Hence, a policy function that only contains $u''(C)$ will account for risk aversion, i.e., how much an agent dislikes risk, but not for prudence and, thus, will be certainty equivalent. If in addition, the policy function involves the fourth derivative of the utility function, $u^{(4)}(C) < 0$, then it will also account for temperance, i.e., how the marginal propensity to consume responds to risk. Thus, while the effects of risk on the level of consumption are captured by $u'''(C)$, the effects on the slope are captured by $u^{(4)}(C)$ (see [Kimball, 1990a](#) and [Zeldes, 1989](#)).

In terms of the approximation method note that a first-order (linear) perturbation to the unknown consumption function requires computing the first derivative of the Euler equation. Since its discrete-time version only contains $u'(C)$, a first-order approximation will just include terms up to the second derivative of the utility function and hence it will account for risk aversion but not for prudence. Therefore, a first-order approximation in discrete time will be certainty equivalent. In contrast, the continuous-time Euler equation (37) already includes terms related to $u'(C)$ and $u''(C)$, so its first-order approximation will account for both risk aversion *and* prudence. The resulting policy functions in continuous time will not only depend on the mean of the exogenous shock but also on its variance – *breaking certainty equivalence*. To break certainty equivalence in discrete time, a second-order approximation is needed, which in continuous time already leads to correction terms in the slopes. Table 1 summarizes the discussion above by indicating which order of approximation is required in order to account for a given risk effect. Note that when only the second-order derivative enters the Euler equation (the case $n = 2$), optimal consumption will not be affected by risk, i.e., certainty equivalence will prevail.

⁶Absolute prudence is defined as $-u'''(C)/u''(C)$, while relative prudence is defined as $-u'''(C)C/u''(C)$ (see [Kimball, 1990b](#)).

3.4 Risky steady state

Similar to the concept of the deterministic steady state, we may define the risky or stochastic steady state as the fixed point to which the dynamic economic system converges to in the absence of shocks, but where $\sigma_A > 0$. As discussed in [Coeurdacier et al. \(2011\)](#), the risky steady state is of utmost relevance to the extent that it incorporates relevant information regarding the future risk prospects of risk-averse economic agents.

Unfortunately, the computation of the risky steady state is not straightforward. Following its definition, we require information about how risk, as measured by the variance of economic shocks, affects the policy functions, $\mathbf{g}(\mathbf{x}; \eta)$, which, *ex-ante*, are also unknown. However, it is still possible to approximate its value by using the perturbation-based approximation of the policy functions around the deterministic steady state.

In particular, we define the risky steady state value of the state variables, $\hat{\mathbf{x}}$, as the solution to the system of (non-linear) equations formed by

$$\mathbf{f}(\hat{\mathbf{x}}, \mathbf{g}(\hat{\mathbf{x}}; \eta = 1)) = \mathbf{0}, \quad (40)$$

where $\mathbf{f}(\cdot)$ is the drift in (28) that results from (i) replacing the vector of controls \mathbf{y} by its perturbation-based approximation evaluated at the unknown risky steady state; (ii) setting any future realization of economic shocks to zero, i.e. $d\mathbf{B}_t = \mathbf{0}$; and (iii) imposing the stationarity condition $d\mathbf{x}_t/dt = \mathbf{0}$. Once $\hat{\mathbf{x}}$ is computed, it is possible to compute the risky steady state value for the control vector as $\hat{\mathbf{y}} = \mathbf{g}(\hat{\mathbf{x}}; \eta = 1)$.

Since it is already possible to account for risk in continuous time using a first-order approximation, the approach in (40) can be used to build an approximation to the risky steady state in a linear framework⁷. Hence, the first-order approximation of the risky steady state is given by the solution to

$$\mathbf{0} = \mathbf{f}(\hat{\mathbf{x}}, \mathbf{g}(\bar{\mathbf{x}}; 0) + \mathbf{g}_{\mathbf{x}}(\bar{\mathbf{x}}; 0)(\hat{\mathbf{x}} - \bar{\mathbf{x}}) + \mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0)) \quad (41)$$

$$\hat{\mathbf{y}} = \mathbf{g}(\bar{\mathbf{x}}; 0) + \mathbf{g}_{\mathbf{x}}(\bar{\mathbf{x}}; 0)(\hat{\mathbf{x}} - \bar{\mathbf{x}}) + \mathbf{g}_{\eta}(\bar{\mathbf{x}}; 0). \quad (42)$$

A similar procedure can be used to build a k -th order approximation of the risky steady state, for $k > 1$.

4 Asset pricing

This section investigates the economic implications of the approximated solutions by measuring the pricing errors made when using the First-Order CE approximation, the

⁷A similar methodology is available for the case of discrete-time models for perturbations of order 2 and higher (see [de Groot, 2013](#)). A summary of this procedure is described in the accompanying web appendix.

First-Order approximation, and the Second-Order approximation defined in Section 3.1. The pricing mismatch is computed relative to a benchmark that is obtained using a global non-linear projection method based on a Chebyshev polynomial approximation of the unknown value function (see Parra-Alvarez, 2018; Posch, 2018). This approach delivers highly accurate solutions but is costly in terms of computational efficiency. By comparing the different pricing errors we can study how risk matters quantitatively for asset pricing.

4.1 Stochastic discount factor

We define the stochastic discount factor (SDF) as the process m_s/m_t , such that, for any security with price P_t , and a single payoff χ_s at some future date $s \geq t$, we obtain

$$m_t P_t = \mathbb{E}_t [m_s \chi_s] \quad \Rightarrow \quad 1 = \mathbb{E}_t [(m_s/m_t) R_s], \quad (43)$$

where $R_s \equiv \chi_s/P_t$ is the security's return, and m_t is the present (discounted) value of a unit of consumption in period t . Hence, the condition (43) can be used to discount expected payoffs on *any* asset with a single payoff to find their equilibrium prices. In other words, investors will be indifferent between investing into the various assets only if (43) is satisfied.

From the definition of expected discounted life-time utility (1), the instantaneous utility function (2), and the first-order condition (11), we obtain the SDF for $s > t$ following Detemple and Zapatero (1991) as (see Appendix A)

$$m_s/m_t = e^{-\rho(s-t)} \frac{(C_s - X_s)^{-\gamma} + bV_{X,s}}{(C_t - X_t)^{-\gamma} + bV_{X,t}} \quad \text{for } s > t, \quad (44)$$

where $m_t = e^{-\rho t} (C_t - X_t)^{-\gamma} + bV_{X,t}$ is the present discounted value of a unit of consumption at instant $t \geq 0$.

4.2 Pricing errors

In what follows we define pricing errors as (see Lettau and Ludvigson, 2009)

$$\varepsilon_i \equiv \mathbb{E}_t [(m_s/m_t) R_{i,s}] - 1, \quad (45)$$

based on the gross return on any tradable asset i with instantaneous return, $R_{i,s}$.

Risk-free asset. Consider a zero-coupon bond with sure payoff $\chi_{f,t+N} = 1$ at period $t + N$. From (43) we obtain the price of this zero-coupon bond as $P_{f,t}^{(N)} = \mathbb{E}_t [(m_{t+N}/m_t)]$ such that the return of this asset is $R_{f,t}^{(N)} = 1/P_{f,t}^{(N)}$, conditional on the information set at time t . Unfortunately, we do not readily observe an *instantaneous* risk-free asset for $N \rightarrow 0$ with corresponding yield $r_t^f \equiv \lim_{N \rightarrow 0} R_{f,t}^{(N)}$. Any equilibrium return from a

risk-free sovereign bond carries a term premium for a given time-to-maturity $N \equiv s - t$.

Zero-coupon bonds. To compute the price of a zero-coupon bond for a given time-to-maturity N we use the partial differential equation (PDE) approach (see [Posch, 2018](#)). Hence, in the absence of arbitrage opportunities, the fundamental price of a zero-coupon bond with maturity N , $P_{f,t}^{(N)}$, satisfies

$$\mathbb{E}_t \left(\frac{dP_{f,t}^{(N)}}{P_{f,t}^{(N)}} \right) - \left(\frac{1}{P_{f,t}^{(N)}} \frac{\partial P_{f,t}^{(N)}}{\partial N} + r_t^f \right) dt = -\mathbb{E}_t \left(\frac{dP_{f,t}^{(N)}}{P_{f,t}^{(N)}} \frac{dm_t}{m_t} \right), \quad (46)$$

with boundary condition $P_{f,t}^{(0)} = 1$, and where the SDF evolves according to

$$\frac{dm_t}{m_t} \equiv \mu_{m,t} dt + \sigma_{m,t} dB_{A,t}, \quad (47)$$

where the drift, $\mu_{m,t}$, and diffusion, $\sigma_{m,t}$, terms in (47) are functions of the policy functions. Hence, they depend on the approximation method used (see [Appendix A](#)).

Assuming that the market price yields the efficient price under the physical probability measure \mathbb{P} , the fundamental pricing equation can be written as

$$\frac{\partial P_{f,t}^{(N)}}{\partial N} = \frac{1}{dt} \mathbb{E}_t^{\mathbb{P}} \left(\frac{dm_t}{m_t} \right) P_{f,t}^{(N)} + \frac{1}{dt} \mathbb{E}_t^{\mathbb{P}} \left(dP_{f,t}^{(N)} \right) + \frac{1}{dt} \mathbb{E}_t^{\mathbb{P}} \left((dP_{f,t}^{(N)}) \left(\frac{dm_t}{m_t} \right) \right),$$

where we used the fact that $r_t^f = -\frac{1}{dt} \mathbb{E}_t^{\mathbb{P}} [dm_t/m_t]$. The physical probability measure is defined in terms of the (true) policy function for consumption from the economic model. In what follows, we assume that the latter is approximated accurately (in a global sense) by means of projection methods. Note that the covariance of the prices with the SDF on the right-hand side of (46) gives rise to a term premium.

Since in equilibrium all the time dependence of the zero-coupon bond price with given time-to-maturity N comes through the state variables that drive the economy, i.e., $P_{f,t}^{(N)} = P_f^{(N)}(K_t, X_t, A_t)$, an application of Itô's lemma shows that the dynamics of the bond's price is given by

$$dP_{f,t}^{(N)} = \frac{\partial P_{f,t}^{(N)}}{\partial K_t} dK_t + \frac{\partial P_{f,t}^{(N)}}{\partial X_t} dX_t + \frac{\partial P_{f,t}^{(N)}}{\partial A_t} dA_t + \frac{1}{2} \frac{\partial^2 P_{f,t}^{(N)}}{\partial A_t^2} (dA_t)^2. \quad (48)$$

Hence, the fundamental pricing equation can now be written as

$$\begin{aligned}
\frac{\partial P_{f,t}^{(N)}}{\partial N} = & \mu_{m,t} P_{f,t}^{(N)} + \frac{\partial P_{f,t}^{(N)}}{\partial K_t} (\Phi((\exp(A_t) K_t^\alpha - C(K_t, X_t, A_t))/K_t) - \delta) K_t \\
& + \frac{\partial P_{f,t}^{(N)}}{\partial X_t} (bC(K_t, X_t, A_t) - aX_t) - \rho_A A_t \frac{\partial P_{f,t}^{(N)}}{\partial A_t} \\
& + \frac{1}{2} \frac{\partial^2 P_{f,t}^{(N)}}{\partial A_t^2} \sigma_A^2 + \frac{\partial P_{f,t}^{(N)}}{\partial A_t} \sigma_A \sigma_{m,t}.
\end{aligned} \tag{49}$$

The functional form of the solution to (49) is unknown. We use collocation methods to approximate the price function with the polynomial $P_{f,t}^{(N)} \approx \phi(N, K_t, X_t, A_t) \mathbf{c}$, in which \mathbf{c} is a vector of unknown coefficients and $\phi(\cdot)$ denotes the Chebyshev basis matrix with associated Chebyshev nodes. We extend the approximated PDE in (49) with the boundary condition $\phi(0, K_t, X_t, A_t) \mathbf{c} = \mathbf{1}_p$, where p denotes the degree of the approximation. The collocation approach provides accurate results and allows us to avoid tedious numerical simulations.

Let $\varepsilon_{f,a}^{(N)}$ represent a measure of *ex-ante* pricing errors on a zero-coupon bond with time-to-maturity N , defined as the (absolute) percentage deviation of the price under the subjective probability measure \mathbb{S} relative to the physical probability measure \mathbb{P}

$$\varepsilon_{f,a}^{(N)} \equiv \mathbb{E}_t^{\mathbb{S}}[(m_N/m_t)] / \mathbb{E}_t^{\mathbb{P}}[(m_N/m_t)] - 1. \tag{50}$$

We define \mathbb{S} to be the probability measure used by an investor that uses the perturbation approach to approximate the model's policy function for consumption instead of the true solution (i.e. it employs either the First-Order CE, the First-Order, or the Second-Order approximation) in both the SDF dynamics in (47) and the bond-price PDE in (48). Let $P_{f,a}^{(N)}$ denote the price that solves (49) under the subjective probability measure \mathbb{S} .

By using the PDE approach it is possible to shed light on the sources of pricing errors. First, the risk-free rate is poorly approximated. Second, the covariance of the price dynamics with the SDF is poorly captured. And third, the approximation to the consumption function alone is inaccurate. Hence, we can decompose the pricing errors into misspecification of: (i) the risk-free rate (or drift of the SDF), $r_t^f = -\mu_{m,t}$; (ii) the term premium that arises from the covariance component, $(\partial P_{f,t}^{(N)} / \partial A_t) \sigma_A \sigma_{m,t}$; and (iii) the price dynamics $\mathbb{E}_t(dP_{f,t}^{(N)}) / P_{f,t}^{(N)}$.

To analyze the different sources of pricing mismatch, we define the *ex-post* pricing errors as the (absolute) percentage deviation of the price under the subjective probability measure \mathbb{S} relative to the physical measure \mathbb{P} , but where the investor can observe the correct/true SDF dynamics either partially

$$\varepsilon_{f,b}^{(N)} \equiv \mathbb{E}_t^{\mathbb{S}}[(m_N/m_t) | \mu_{m,t}^{\mathbb{S}} \equiv \mu_{m,t}] / \mathbb{E}_t^{\mathbb{P}}[(m_N/m_t)] - 1, \tag{51}$$

| Parameter | Value | Source / Target |
|-----------------------------------|--------|--|
| Discounting, ρ | 0.0410 | Jermann (1998) |
| Risk aversion, γ | 2.0000 | Aruoba et al. (2006) |
| Depreciation rate, δ | 0.0963 | Jermann (1998) |
| Capital share in output, α | 0.3600 | Jermann (1998) |
| Persistence TFP, ρ_A | 0.2052 | Aruoba et al. (2006) |
| Volatility TFP, σ_A | 0.0307 | U.S. real GDP growth volatility |
| Adjustment cost, ξ | 0.3261 | Short-term return on government bonds reported in Jermann (1998) |
| Habit current cons., b | 0.8200 | Jermann (1998) |
| Habit past cons., a | 1.0000 | Jermann (1998) |

Table 2. Parameter values. The parameters of the model are calibrated to an annual frequency and their values should be interpreted accordingly.

or completely

$$\varepsilon_{f,c}^{(N)} \equiv \mathbb{E}_t^{\mathbb{S}} [(m_N/m_t) | \mu_{m,t}^{\mathbb{S}} \equiv \mu_{m,t}, \sigma_{m,t}^{\mathbb{S}} \equiv \sigma_{m,t}] / \mathbb{E}_t^{\mathbb{P}} [(m_N/m_t)] - 1. \quad (52)$$

Hence, the measures in (51) and (52) focus on the pricing error reduction obtained by providing further information on the SDF dynamics. For example in (52), the investor infers the correct SDF from the data, and solves the corresponding PDE

$$\frac{\partial P_{f,c}^{(N)}}{\partial N} = \mu_{m,t} P_{f,c}^{(N)} + \frac{1}{dt} \mathbb{E}_t^{\mathbb{S}} (dP_{f,c}^{(N)}) + \left(\frac{\partial P_{f,c}^{(N)}}{\partial A_t} \right) P_{f,c}^{(N)} \sigma_A \sigma_{m,t},$$

with the approximated price $P_{f,c}^{(N)}$ (in the same way we define $P_{f,b}^{(N)}$). This enables us to study the hypothetical error an investor would face ex-post when trading the asset at the subjective (approximated) price instead of true $P_{f,t}^{(N)}$, yet knowing the SDF dynamics.

5 Results

5.1 Calibration

To quantitatively evaluate the extent to which the First-Order approximation can account for the effects of risk we proceed to calibrate the prototype model of Section 2 to an annual frequency. Therefore, all the parameter values should be interpreted accordingly. Many of the parameter values are chosen to replicate the parameterization to the U.S. economy used in the discrete-time models of [Jermann \(1998\)](#) and [Aruoba et al. \(2006\)](#). A complete summary of the model's calibration is provided in Table 2.

In particular, we set the risk aversion parameter and the share of capital income to $\gamma = 2$ and $\alpha = 0.36$, respectively. The values for the subjective discount rate, the depreciation

| Model version | σ_C/σ_Y | | σ_I/σ_Y | | $R_{f,t}^{(0.25)}$ | |
|--------------------------|---------------------|--------|---------------------|--------|--------------------|-------------|
| | Pert. | Global | Pert. | Global | Pert. | Global |
| Benchmark | 0.45 | 0.44 | 2.65 | 2.69 | 0.37 (4.99) | 0.68 (5.17) |
| No habits, no adj. costs | 0.34 | 0.34 | 3.00 | 3.01 | 4.09 (0.19) | 4.11 (0.19) |
| Habit, no adj. costs | 0.13 | 0.14 | 3.72 | 3.72 | 3.86 (0.26) | 4.10 (0.19) |
| Adj. costs, no habits | 1.12 | 1.11 | 0.68 | 0.66 | 3.77 (0.60) | 3.85 (0.61) |
| U.S. Data (1954-1989) | 0.51 | | 2.65 | | 0.80 (5.67) | |

Table 3. Moments from simulated data. The different moments are computed using 100,000 draws starting at the deterministic steady state. The policy functions are computed using both a first-order perturbation (Pert.) and a global method (Global). For comparison, U.S. data moments correspond to those in [Jermann \(1998\)](#). We report the standard deviation (sd) of quarterly growth rates for output, σ_Y , consumption, σ_C , and investment, σ_I after 10 years; and the three-month yield $R_{f,t}^{(0.25)}$ with sd in brackets (annualized, percentage terms).

rate and the habit process are set to $\rho = 0.041$, $\delta = 0.0963$, and $a = 1$ and $b = 0.82$, respectively. These parameter values are consistent with steady-state values for the capital-output ratio, and the consumption and investment shares in aggregate output of around 2.5, and 76% and 24%, respectively. We fix the adjustment cost parameter to $\xi = 0.3261$ such that the model produces an average real return on short term government bonds close to that reported in [Jermann \(1998\)](#). Finally, the persistence of TFP is set to $\rho_A = 0.2052$ which corresponds to the continuously compounded value of that in [Aruoba et al. \(2006\)](#), while its volatility is set to $\sigma_A = 0.0307$ to target the relative growth volatilities (relative standard deviations) of consumption and investment to output, and which is consistent with the observed volatility of real GDP growth in the U.S. for the period 1954-1989.

Table 3 reports some of the moments implied by different parameterizations of our RBC model when solved by a first-order perturbation and a global approximation method based on collocations. Along with the prototype model of Section 2 (Benchmark), we report the moments for the model without habit formation and no capital adjustment cost of Section 3.2 (No habits, no adj. costs, i.e. $b = X_0 = 0$ and $\xi \rightarrow \infty$), no capital adjustment cost (Habit, no adjustment costs, i.e. $\xi \rightarrow \infty$), and without habits (Adjustment costs, no habits, i.e., $b = X_0 = 0$). The last row in the table shows the moments reported by [Jermann \(1998\)](#) for U.S. data from 1954-1989. The relative standard deviations for quarterly consumption and investment growth correspond to averages over 100,000 samples generated through a Euler-Maruyama discretization scheme with precision $\Delta = 0.0125$, each of them consisting of 10 years of simulated data, initialized at the deterministic steady state. Finally, the table also includes the three-month simulated yield-to-maturity for a zero-coupon bond and the standard deviation of its simulated distribution.

We confirm that only the model with both habit formation and capital adjustment costs generates the historical consumption and investment volatility relative to output, and three-month bond yields with sufficient variability. Hence, in this model risk matters

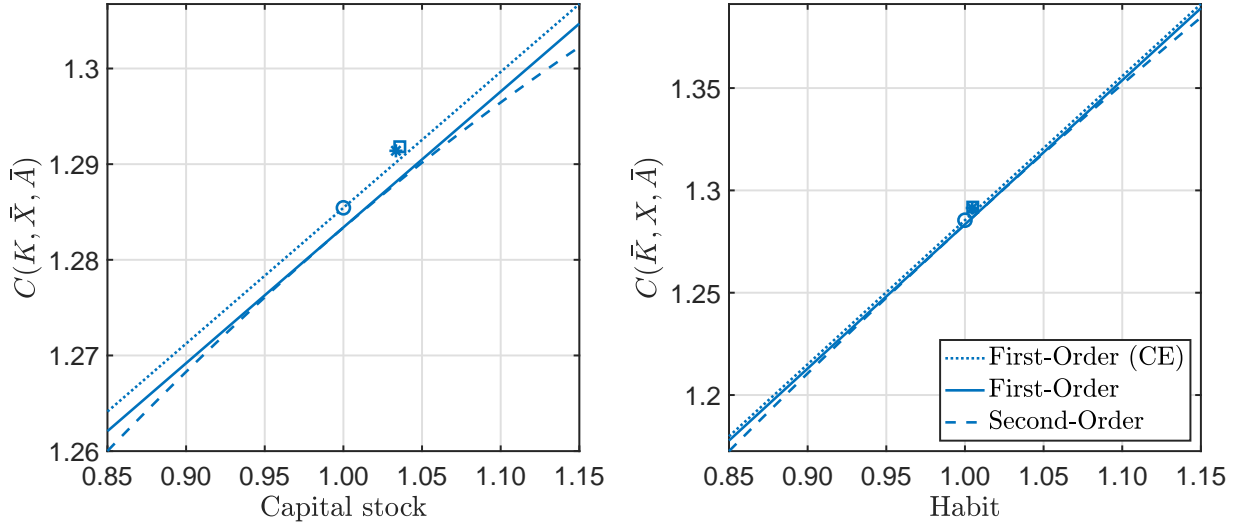


Figure 1. Approximated policy function for consumption: First- and second-order approximations to the policy function for consumption around the deterministic steady state along the capital stock lattice (left panel) and the habit lattice (right panel), while keeping the remaining state variables at their corresponding deterministic steady-state values. Values on the horizontal axis represent deviations from deterministic steady-state values. A circle denotes the deterministic steady state, a star denotes the first-order approximation to the risky steady state, and a square denotes the second-order approximation to the risky steady state.

quantitatively and we can use the parameterization in Table 2 to investigate the asset pricing errors for the different solution methods (at the deterministic steady state).

5.2 Approximated policy functions

Figure 1 shows the first- and second-order perturbation approximations to the policy function for consumption around the deterministic steady state for our prototype model using the calibration in Table 2. The left panel shows optimal consumption along the capital stock lattice for values 15% below and above its deterministic steady state, while keeping the remaining state variables fixed at their deterministic steady state values. The right panel plots optimal consumption along the habit formation lattice covering values that are 15% above and below its deterministic steady state value. The figures also indicate the deterministic and risky steady state values for consumption, capital stock and habit. Their values are reported in Table 4, where we have also included a measure of the risky steady state computed from a global approximation based on projection methods⁸.

The plot depicts two types of a first-order (linear) approximation to the optimal consumption function. First, it shows the First-Order (CE) by the dotted line, which resembles the first-order approximation one would obtain from a discrete-time version of the model. By construction, this approximation is invariant to the amount of volatil-

⁸The second-order risky steady-state values for the corresponding discrete-time model approximated with the approach in de Groot (2013) are very close to the second-order risky-steady state values that we report in Table 4.

| Variable | Deterministic | Mean | Risky | | |
|----------|---------------|--------|-------------|--------------|--------|
| | | | First-Order | Second-Order | Global |
| A | 0 | 0 | 0 | 0 | 0 |
| X | 1.0541 | 1.0533 | 1.0589 | 1.0593 | 1.0592 |
| K | 4.5077 | 4.5662 | 4.6582 | 4.6693 | 4.6655 |
| C | 1.2854 | 1.2847 | 1.2914 | 1.2918 | 1.2917 |

Table 4. Steady states values. The table reports steady-state values for all the variables in the model. It includes the exact deterministic steady-state values, the simulated ergodic mean (global solution), as well as the first- and second-order approximated risky steady-state values. A global approximation to the risky steady state is included as a benchmark.

ity in the model, and hence is certainty equivalent. Second, the solid line depicts the First-Order approximation that corresponds to the first-order perturbation solution that breaks certainty equivalence as it includes the (constant) risk correction term $\bar{C}_\eta \equiv C_\eta(\bar{K}, \bar{X}, \bar{A}; 0) \neq 0$. Hence, while still being a linear approximate solution, it is risk sensitive as its intercept depends on the amount of uncertainty in the model. As a comparison, we plot the Second-Order approximation (dashed line) to illustrate the additional risk correction attainable when using higher orders of approximation.

Two things are worth mentioning at this point. First, note that the First-Order (CE) policy function for consumption, which by construction passes through the deterministic steady state, lays above the other two alternative approximations. The reason is that the latter account for the effects of risk, and hence imply lower consumption levels along the entire state space. In particular, the First-Order approximation is parallel to the First-Order (CE), and for values of the state space in a neighborhood of the deterministic steady state, it will imply levels of consumption that are relatively close to those suggested by the Second-Order, and hence, a non-linear approximation. Second, the risky steady states computed from the First- and Second-Order approximations command higher values for the capital stock, habits, and consumption over the long-run, relative to those implied by the deterministic case. This result can be confirmed by looking at Table 4. The higher risky steady-state values result from households that consume less and save more in the short run due to precautionary motives and hence imply higher levels of capital stock and consumption over the long run.

A detailed summary of the approximated policy function for consumption is presented in Table 5, where we report the loadings from the first- and second-order perturbations associated to each of the state variables. Columns 2 and 4 show the coefficients for the continuous-time model, while columns 3 and 5 do the same for its discrete-time version⁹. Comparing the first-order approximations in columns 2 and 3 confirms that we break certainty equivalence when time is continuous. Following our previous discussion, the

⁹The first- and second-order approximations to the policy functions that solve the corresponding discrete-time model are computed using `Dynare`.

| | First-Order | | Second-Order | |
|--------------------------------------|----------------|------------|----------------|----------------|
| | Cont. time | Disc. time | Cont. time | Disc. time |
| \bar{C} | 1.2854 | 1.2854 | 1.2854 | 1.2854 |
| \bar{C}_η | -0.0020 | 0 | -0.0020 | 0 |
| $(K - \bar{K})$ | 0.0315 | 0.0290 | 0.0315 | 0.0290 |
| $(X - \bar{X})$ | 0.6680 | 0.7042 | 0.6680 | 0.7042 |
| $(A - \bar{A})$ | 0.5370 | 0.4899 | 0.5370 | 0.4899 |
| $\bar{C}_{\eta\eta}$ | - | - | -0.0000 | -0.0025 |
| $(K - \bar{K}) \times \eta$ | - | - | -0.0003 | 0 |
| $(X - \bar{X}) \times \eta$ | - | - | 0.0020 | 0 |
| $(A - \bar{A}) \times \eta$ | - | - | -0.0063 | 0 |
| $(K - \bar{K})^2$ | - | - | -0.0049 | -0.0046 |
| $(X - \bar{X})^2$ | - | - | -0.1930 | -0.2089 |
| $(A - \bar{A})^2$ | - | - | -0.3119 | -0.3663 |
| $(K - \bar{K}) \times (X - \bar{X})$ | - | - | 0.0402 | 0.0389 |
| $(K - \bar{K}) \times (A - \bar{A})$ | - | - | -0.0282 | -0.0286 |
| $(A - \bar{A}) \times (X - \bar{X})$ | - | - | 0.6508 | 0.6942 |

Table 5. Loadings of policy function for consumption. The table reports the coefficients from first- and second-order approximations to the policy function for consumption, $C = C(K, X, A; \eta)$, around the deterministic steady state $(\bar{C}, \bar{K}, \bar{A})$ for the model in Section 2 and its equivalent discrete-time version.

constant risk correction of -0.0020 implied by our calibration, which is otherwise absent in the solution to the discrete-time model, suggests that a First-Order (CE) approximation overestimates optimal consumption in the presence of uncertainty along the entire state space. Note how a similar risk correction of -0.0025 is obtained in a discrete-time framework when using a second-order, and hence non-linear, approximation. Comparing columns 4 and 5 reveals that a second-order perturbation in continuous-time includes not only an additional adjustment in the constant term of the approximation, $\bar{C}_{\eta\eta} \neq 0$, but also in the slopes of the policy function implying a time-varying risk correction. As suggested in [Andreassen \(2012\)](#), these two additional effects can only be achieved in discrete-time models by computing third-order approximations (see Table 1).

5.3 Impulse response functions

Having approximated the unknown policy function, we now compute the impulse-response functions (IRF) in order to compare how the different degrees of approximation capture the amplification and propagation mechanisms of the prototype economy to a temporary shock on the level of TFP. The results are presented in Figure 2, where we plot the transitional dynamics of consumption, capital stock, habits, and output over the course of 60 years after a one-time unexpected increase in TFP equal to σ_A . Prior to the shock, all the variables are assumed equal to their respective stationary values. Thus, while the

First-Order (CE) solution is initially resting at the deterministic steady state, the First- and Second-Order solutions are resting at their respective (approximate) risky steady states. Again, the CE solution can be thought of as a proxy for the IRF one would obtain from a first-order perturbation to an equivalent discrete-time model. For comparison purposes we report the first- and second-order IRFs for the discrete-time model in the accompanying web appendix.

Note that the IRFs for the First-Order (CE) lay below the risk-sensitive approximations in Figure 2. Intuitively, since the constant correction term for the First-Order approximation is negative, $\bar{C}_\eta < 0$, one may expect that the consumption response approximated by a First-Order will be below the one approximated by First-Order (CE). However, as shown in Figure 1 and Table 4, the risk-correction reduction in consumption induced by the former will in fact lead to a higher risky steady-state capital stock and, thereby, a higher risky steady-state level of consumption. Thus, the fact that the First-Order (CE) is below the First-Order and Second-Order responses is explained by the differences in their fixed points, or long-run convergence levels, hence cannot readily be interpreted as an indication that certainty equivalent approximations underestimate the response of macroeconomic variables to aggregate shocks. Furthermore, note that the additional risk-corrections provided by the Second-Order approximation (and hence non-linear) have only minor effects on the optimal reaction of consumption to a TFP shock. In other words, the risk-correction in the first-order perturbation approach provides a sensible approximation to the effects of risk in continuous-time models.

5.4 Asset pricing implications

In this section we investigate the ability of the different approximations to account for risk when pricing assets. While others focus on accuracy measures based on the computation of Euler equation errors (cf. Judd, 1998; Aruoba et al., 2006; Parra-Alvarez, 2018), we are more interested in the implications that each of the approximations have on the pricing mismatch incurred by an investor that does not have/use the ‘true’ solution of the model.

In what follows, we use the PDE approach introduced in Section 4 to assess to what extent our first-order approximation can account for risk. Table 6 reports the absolute pricing errors of a zero-coupon bond for different time-to-maturities when the economy is at its deterministic steady state, $\varepsilon_f^{(N)} \equiv \varepsilon_f^{(N)}(\bar{K}, \bar{X}, \bar{A})$. We show the results for risk-free bonds with a 3-month, 1 year and 5 years time-to-maturity. Column 2 (Global) provides errors under the true probability measure \mathbb{P} as obtained from a global approximation using collocation methods; columns 3 – 5 report errors resulting from First-Order (CE), First-Order, and Second-Order perturbation. Moreover, for each time-to-maturity, we report errors for the cases in which the SDF dynamics are (a) not observed as in (50), (b) partially observed (drift only) as in (51), or (c) fully observed (drift and diffusion) as

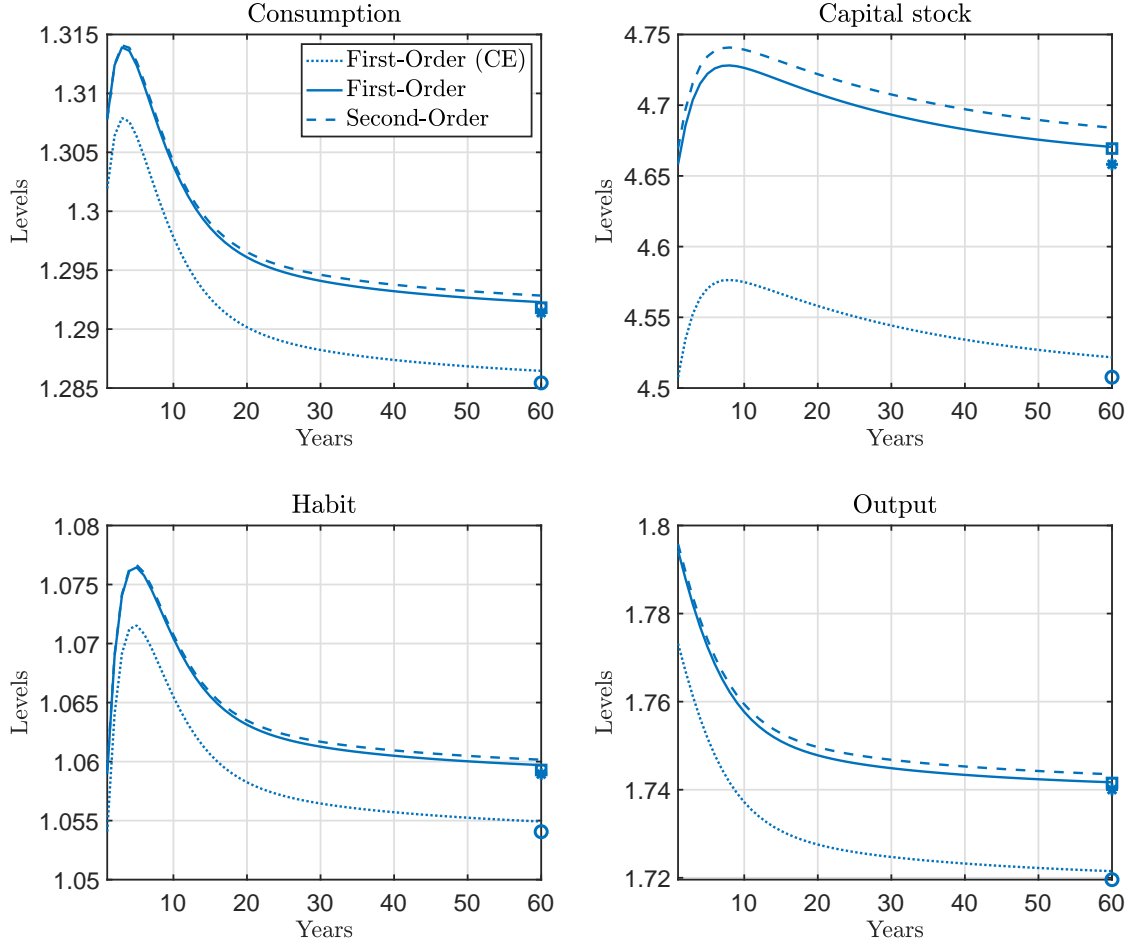


Figure 2. Impulse-Response function to a one s.d. shock in TFP: Responses for the annual levels of consumption, capital stock, habit formation and output to a one time shock in TFP equivalent to one standard deviation, σ_A . All the variables are assumed to be in their corresponding steady states before the shock. A circle denotes the deterministic steady state, a star denotes the first-order approximation to the risky steady state, and a square denotes the second-order approximation to the risky steady state.

in (52). This means that in (a) we approximate the policy function as well as the drift and diffusion of the SDF, in (b) we approximate the policy function and diffusion of the SDF, and finally in (c) we only approximate the policy function.

Our results suggest that there are substantial gains from using the (risk-sensitive) First-Order relative to the First-Order (CE) version. Consider the case of a three-month zero-coupon bond with effective price of $P_f^{0.25} = 0.9983$. An investor relying on the certainty equivalent linear solution (First-Order (CE)), not just to approximate the policy function but also the drift and diffusion of the SDF, will incur in pricing errors of about 1 dollar for each 100 dollar spent ($\varepsilon_{f,a}^{(0.25)} = 0.95\%$ in Column 3). If instead the investor uses the First-Order approximation, the pricing error will be of the order of 10 cents for each 100 dollars spent ($\varepsilon_{f,a}^{(0.25)} = 0.14\%$ in Column 4). Hence, breaking certainty equivalence reduces the potential price mismatch by nearly 90% while still remaining in the linear world. The Second-Order approximation further reduces pricing errors which fall

| | Global | First-Order (CE) | First-Order | Second-Order |
|------------------------------|--------|------------------|---------------|---------------|
| $\varepsilon_{f,a}^{(0.25)}$ | 0.0000 | 0.0095 | 0.0014 | 0.0003 |
| $\varepsilon_{f,b}^{(0.25)}$ | | 0.0001 | 0.0001 | 0.0000 |
| $\varepsilon_{f,c}^{(0.25)}$ | | 0.0001 | 0.0000 | 0.0000 |
| $\varepsilon_{f,a}^{(1)}$ | 0.0000 | 0.0494 | 0.0065 | 0.0009 |
| $\varepsilon_{f,b}^{(1)}$ | | 0.0017 | 0.0009 | 0.0001 |
| $\varepsilon_{f,c}^{(1)}$ | | 0.0018 | 0.0000 | 0.0000 |
| $\varepsilon_{f,a}^{(5)}$ | 0.0000 | 0.4269 | 0.1742 | 0.0050 |
| $\varepsilon_{f,b}^{(5)}$ | | 0.0243 | 0.0096 | 0.0069 |
| $\varepsilon_{f,c}^{(5)}$ | | 0.0302 | 0.0017 | 0.0000 |

Table 6. Asset pricing implications for zero-coupon bonds. The table reports the absolute pricing errors induced by different approximation methods on risk-free zero-coupon bonds with time-to-maturity of three months, one year and five years when the SDF dynamics are (a) are not observed, (b) partially observed (drift only) and (c) completely observed (drift and diffusion).

to about 3 cents per 100 dollars ($\varepsilon_{f,a}^{(0.25)} = 0.03\%$ in Column 5). Sizable gains are also observed for bonds with longer time-to-maturities or from inferring the dynamics of the SDF (drift and diffusion) from the data.

We find that although pricing errors increase as N increases, they can be substantially reduced if the investor uses the true risk-free rate (or drift of the SDF), which is case (b). In fact, the pricing error for the First-Order approximation is below 10 cents ($\varepsilon_{f,b}^{(1)} = 0.09\%$ in Column 4) for the one year ahead zero-coupon bond. Relative to the First-Order (CE) solution, the risk-adjusted First-Order approximation reduces pricing errors by about 50 percent for one year maturities when using the true risk-free rate. If the investor further knows the true diffusion of the SDF, case (c), i.e., when only the policy functions are approximated, then the First-Order approximation also performs well for a maturities of 5 years. Here, the error is about 20 cents ($\varepsilon_{f,c}^{(5)} = 0.17\%$ in Column 4), which is 90% lower than the error from First-Order (CE) ($\varepsilon_{f,c}^{(5)} = 3.02\%$ in Column 3).

Figure 3 confirms our results for the case of *ex-ante* absolute pricing errors. Investors using a First-Order (CE) solution, when the true data generating process (DGP) is the global solution, would accept large and persistent pricing errors (see Lettau and Ludvigson, 2009): they range between one to five percent for bonds with time-to-maturities from a quarter to a year ($\varepsilon_{f,a}^{(0.25)} = 0.95\%$, $\varepsilon_{f,a}^{(1)} = 4.94\%$). On the contrary, those using the First-Order approximation can reduce these pricing errors by more than 85 percent ($\varepsilon_{f,a}^{(0.25)} = 0.14\%$, $\varepsilon_{f,a}^{(1)} = 0.65\%$).

To better understand the sources of the pricing errors, the right panel of Figure 3 decomposes the pricing mismatch made when using the First-Order (CE) solution into: (i) the error stemming from linearization in the presence of uncertainty; and (ii) the error stemming from imposing certainty equivalence in the linear world. As (i) is given

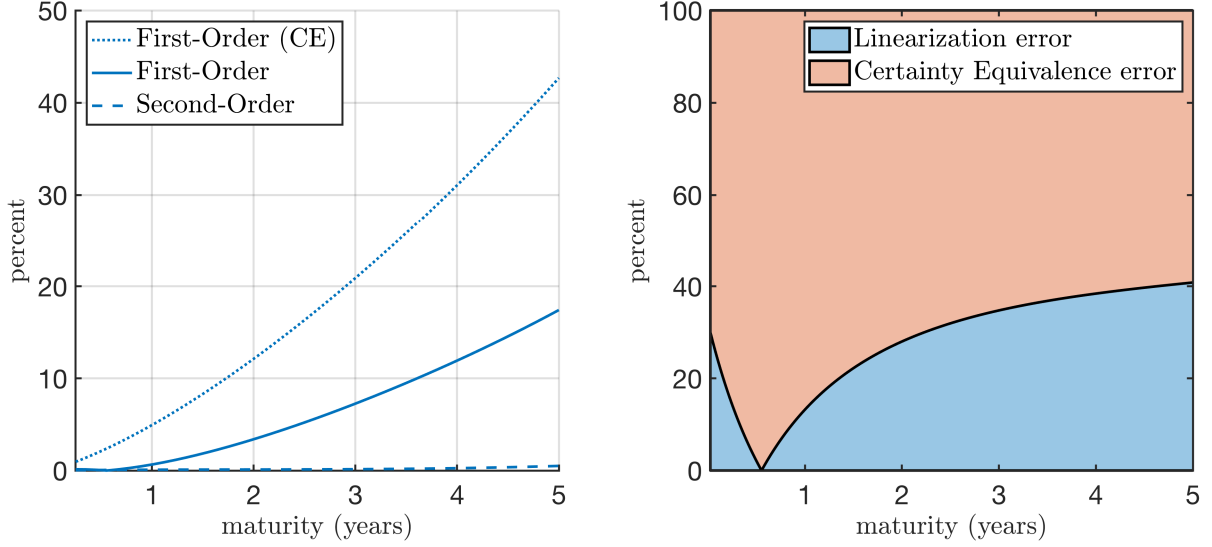


Figure 3. Pricing errors: The left panel plots the absolute pricing errors for different approximations. The right panel decomposes the pricing error incurred by using the CE solution into a certainty equivalence component and a linearization component, where the line represents $|(\text{First-Order})/(\text{First-Order (CE)}) - 1|$.

by the error resulting from the First-Order approximation, (ii) results as the (absolute) difference of the errors from the First-Order and the First-Order (CE) approximation, and hence provides a measure of pricing error reduction (relative to the true solution)¹⁰. Therefore, the red area measures the pricing error that can be attributed to imposing certainty equivalence in the First-Order (CE) solution, while the blue area measures the error that can be attributed to its linearization. As the red area suggests, between 60% and 100% of the error stemming from the certainty equivalence solution for maturities below five years can be reduced by the risk adjustment of the First-Order solution. For a maturity of 1 year, for instance, 86% of the error in the First-Order (CE) solution can be attributed to the presence of certainty equivalence itself and hence reduced by the First-Order approximation. The remaining error resulting from the First-Order solution, as indicated by the blue area, is inevitable in linear models.

Our results shed light on the key source of the weakness of the linear approximation from perturbation in discrete-time models which results from its certainty equivalence property rather than linearization. Thus, we can conclude that once the vice of certainty equivalence is discarded, similar to the First-Order approximation in continuous time, one may stay with linear models and at the same time account for risk in a reasonable manner.

¹⁰The accompanying web appendix presents an alternative decomposition according to which we break the pricing mismatch into: (i) the error stemming from certainty equivalence in the non-linear world, which would result from a non-linear certainty equivalent solution; and (ii) the error stemming from linearization under certainty equivalence. We conclude that the errors induced by certainty equivalence and those by linearization are similar under both decompositions, which suggests that the entire error stemming from certainty equivalence is removed by the First-Order approximation.

6 Conclusions

In this paper we use the fact that certainty equivalence (CE) breaks in continuous-time stochastic non-linear models when their rational expectation solution is approximated by first-order perturbations. To this end, we use a production economy with stochastic shocks to productivity, extended with habit formation and capital adjustment costs, which are known to generate substantial risk effects (see [Jermann, 1998](#)). We study the economic effects of breaking certainty equivalence in the linear approximation to the continuous-time model and compare them to the associated effects obtained using a CE solution, which is similar to that obtained using a first-order perturbation to the solution of discrete-time models. The reason that CE already breaks in first order is that the continuous-time formulation allows us to compute expectations before building the perturbation solution, which is not possible in discrete time. We shed light and illustrate the differences in the perturbation solution of equivalent models in continuous and discrete time and find substantial effects of risk.

To quantify the effects economically, we compute the asset pricing implications and pricing errors for the continuous-time model and show that the first-order already captures about 90 percent relative to the CE solution which, by construction, neglects the effects of risk. The correction in slopes from the second-order approximation in continuous time turns out to be small compared to the constant correction obtained in first order. Therefore, the first-order approximation turns out to be especially useful in this environment in which risk matters but nonlinearities are negligible.

We provide intuition why the first-order perturbation solution in continuous time accounts for prudence and hence is not certainty equivalent. In fact, the risk effects captured by continuous-time perturbations materialize with lower orders of approximation than those required by their (standard) discrete-time counterparts. Most prominent is that the continuous-time perturbation solution has a constant correction in the first-order approximation, which appears only in a second-order approximation in the discrete-time model. Similarly, the correction in slopes appears in second-order approximation in the continuous-time version, while it only appears in the third-order approximation in the discrete-time model.

We show that the (constant) risk adjustment in the first-order approximation does not only reduce pricing errors. First, we illustrate the effects for the resulting policy functions and compare them to the numerically more costly nonlinear approach. While the coefficients that are not associated with risk are close in discrete and continuous-time depending on the order of approximation, the risk corrections differ substantially. Second, we show how the risk adjustment affects the IRFs, which also reveals considerable differences mainly in the levels and for the computation of fixed points.

Our results encourage the use of continuous-time perturbations to account for risk in

the class of (approximate) linear models. We believe this helps in the computation and estimation of large-scale macroeconomic models. Given the advantages of the continuous-time perturbation, future work should make these advantages more accessible by developing a toolbox that automates perturbation in continuous-time models.

References

- ANDERSON, E. W., E. R. MCGRATTAN, L. P. HANSEN, AND T. J. SARGENT (1996): “Mechanics of Forming and Estimating Dynamic Linear Economies,” in *Handbook of Computational Economics*, ed. by H. M. Amman, D. A. Kendrick, and J. Rust, Elsevier, vol. 1 of *Handbook of Computational Economics*, chap. 4, 171–252.
- ANDREASEN, M. (2012): “On the Effects of Rare Disasters and Uncertainty Shocks for Risk Premia in Non-Linear DSGE Models,” *Review of Economic Dynamics*, 15, 295–316.
- ARUOBA, S. B., J. FERNANDEZ-VILLAVERDE, AND J. RUBIO-RAMIREZ (2006): “Comparing Solution Methods for Dynamic Equilibrium Economies,” *Journal of Economic Dynamics and Control*, 30, 2477–2508.
- BOLDRIN, M., L. J. CHRISTIANO, AND J. D. M. FISHER (2001): “Habit Persistence, Asset Returns, and the Business Cycle,” *American Economic Review*, 91, 149–166.
- CALDARA, D., J. FERNANDEZ-VILLAVERDE, J. RUBIO-RAMIREZ, AND W. YAO (2012): “Computing DSGE Models with Recursive Preferences and Stochastic Volatility,” *Review of Economic Dynamics*, 15, 188–206.
- CHACKO, G. AND L. M. VICEIRA (2005): “Dynamic Consumption and Portfolio Choice with Stochastic Volatility in Incomplete Markets,” *Review of Financial Studies*, 18, 1369–1402.
- CHANG, F.-R. (2009): *Stochastic Optimization in Continuous Time*, Cambridge University Press, second ed.
- COEURDACIER, N., H. REY, AND P. WINANT (2011): “The Risky Steady State,” *American Economic Review*, 101, 398–401.
- COLLARD, F. AND M. JUILLARD (2001): “A Higher-Order Taylor Expansion Approach to Simulation of Stochastic Forward-Looking Models with an Application to a Nonlinear Phillips Curve Model,” *Computational Economics*, 17, 125–139.
- CONSTANTINIDES, G. M. (1990): “Habit Formation: A Resolution of the Equity Premium Puzzle,” *Journal of Political Economy*, 98, 519–543.
- DE GROOT, O. (2013): “Computing the Risky Steady State of DSGE Models,” *Economics Letters*, 120, 566–569.
- DETEMPLE, J. B. AND F. ZAPATERO (1991): “Asset Prices in an Exchange Economy with Habit Formation,” *Econometrica*, 59, 1633–1657.

- FERNANDEZ-VILLAVERDE, J., J. RUBIO-RAMIREZ, AND M. SANTOS (2006): “Convergence Properties of the Likelihood of Computed Dynamic Models,” *Econometrica*, 74, 93–119.
- FERNANDEZ-VILLAVERDE, J., J. RUBIO-RAMIREZ, AND F. SCHORFHEIDE (2016): “Solution and Estimation Methods for DSGE Models,” in *Handbook of Macroeconomics*, ed. by J. B. Taylor and H. Uhlig, Elsevier, vol. 2 of *Handbook of Macroeconomics*, chap. 9, 527 – 724.
- GASPAR, J. AND K. JUDD (1997): “Solving Large-Scale Rational-Expectations Models,” *Macroeconomic Dynamics*, 1, 45–75.
- HANSEN, L. P., J. C. HEATON, AND N. LI (2008): “Consumption Strikes Back? Measuring Long-Run Risk,” *Journal of Political Economy*, 116, 260–302.
- JERMANN, U. J. (1998): “Asset Pricing in Production Economies,” *Journal of Monetary Economics*, 41, 257–275.
- JUDD, K. L. (1996): “Approximation, Perturbation, and Projection Methods in Economic Analysis,” in *Handbook of Computational Economics*, ed. by H. M. Amman, D. A. Kendrick, and J. Rust, Elsevier, vol. 1 of *Handbook of Computational Economics*, chap. 12, 509–585.
- (1998): *Numerical Methods in Economics*, MIT Press Books, The MIT Press.
- JUDD, K. L. AND S.-M. GUU (1993): “Perturbation Methods for Economic Growth Models,” in *Economic and financial modeling with Mathematica*, ed. by H. R. Varian, Springer-Verlag, chap. 2, 80–103.
- KIMBALL, M. S. (1990a): “Precautionary Saving and the Marginal Propensity to Consume,” NBER Working Papers 3403, National Bureau of Economic Research, Inc.
- (1990b): “Precautionary Saving in the Small and in the Large,” *Econometrica*, 58, 53–73.
- KOGAN, L. AND R. UPPAL (2001): “Risk Aversion and Optimal Portfolio Policies in Partial and General Equilibrium Economies,” NBER Working Papers 8609, National Bureau of Economic Research, Inc.
- KYDLAND, F. E. AND E. C. PRESCOTT (1982): “Time to Build and Aggregate Fluctuations,” *Econometrica*, 50, 1345–70.
- LETTAU, M. AND S. LUDVIGSON (2009): “Euler Equation Errors,” *Review of Economic Dynamics*, 12, 255–283.

- LEVINTAL, O. (2017): “Fifth-order Perturbation Solution to DSGE Models,” *Journal of Economic Dynamics and Control*, 80, 1–16.
- LOPEZ, P., D. LOPEZ-SALIDO, AND F. VAZQUEZ-GRANDE (2018): “Risk-Adjusted Linearizations of Dynamic Equilibrium Models,” Tech. rep.
- MEYER-GOHDE, A. (2015): “Risk-Sensitive Linear Approximations,” Annual Conference 2015 (Muenster): Economic Development - Theory and Policy 113057, Verein für Socialpolitik / German Economic Association.
- PARRA-ALVAREZ, J. C. (2018): “A comparison of numerical methods for the solution of continuous-time DSGE models,” *Macroeconomic Dynamics*, 22, 1555 – 1583.
- POSCH, O. (2018): “Resurrecting the New-Keynesian Model: (Un)conventional Policy and the Taylor rule,” *Working Paper*, <https://dx.doi.org/10.2139/ssrn.3130903>.
- RUGE-MURCIA, F. (2012): “Estimating Nonlinear DSGE Models by the Simulated Method of Moments: With an Application to Business Cycles,” *Journal of Economic Dynamics and Control*, 36, 914 – 938.
- RYDER, H. E. AND G. M. HEAL (1973): “Optimal Growth with Intertemporally Dependent Preferences,” *Review of Economic Studies*, 40, 1–31.
- SCHMITT-GROHE, S. AND M. URIBE (2004): “Solving Dynamic General Equilibrium Models Using a Second-order Approximation to the Policy Function,” *Journal of Economic Dynamics and Control*, 28, 755–775.
- SIMON, H. A. (1956): “Dynamic Programming Under Uncertainty with a Quadratic Criterion Function,” *Econometrica*, 24, 74–81.
- THEIL, H. (1957): “A Note on Certainty Equivalence in Dynamic Planning,” *Econometrica*, 25, 346–349.
- ZELDES, S. P. (1989): “On the Concavity of the Consumption Function,” *The Quarterly Journal of Economics*, 104, 275–298.

Appendix

A Stochastic optimal control problem

A.1 The HJB equation and the first-order conditions

The benevolent planner chooses a path for consumption in order to maximize the expected discounted life-time utility of a representative household. Define the value of the optimal program as

$$V(K_0, X_0, A_0) = \max_{\{C_t \geq X_t \in \mathbb{R}^+\}_{t=0}^\infty} U_0 \quad \text{s.t.} \quad (3) - (8)$$

in which $C_t \geq X_t \in \mathbb{R}^+$ denotes the control variable at instant $t \in \mathbb{R}^+$.

As a first step, we define the *Hamilton-Jacobi-Bellman equation* (HJB) for any $t \in [0, \infty)$

$$0 = \max_{C \geq X \in \mathbb{R}^+} \left\{ \frac{(C - X)^{1-\gamma}}{1-\gamma} + \frac{1}{dt} \mathbb{E}_t dV(K, X, A) - \rho V(K, X, A) \right\}.$$

Itô's lemma imply

$$\begin{aligned} dV(K, X, A) &= V_K(K, X, A)dK + V_X(K, X, A)dX \\ &\quad + V_A(K, X, A)dA + \frac{1}{2}V_{AA}(K, X, A)\sigma_A^2 dt \end{aligned}$$

where $V_i(K, X, A) \equiv \frac{\partial V(K, X, A)}{\partial i}$, and $V_{ij}(K, X, A) \equiv \frac{\partial^2 V(K, X, A)}{\partial i \partial j}$ for $i, j = K, X, A$. Using the martingale difference properties of stochastic integrals, we arrive at

$$\begin{aligned} 0 = \max_{C \geq X \in \mathbb{R}^+} \left\{ \frac{(C - X)^{1-\gamma}}{1-\gamma} + \left(\Phi \left(\frac{\exp(A)K^\alpha - C}{K} \right) - \delta \right) KV_K(K, X, A) \right. \\ \left. + (bC - aX)V_X(K, X, A) - \rho_A AV_A(K, X, A) \right. \\ \left. + \frac{1}{2}\sigma_A^2 V_{AA}(K, X, A) - \rho V(K, X, A) \right\}. \end{aligned}$$

The first-order condition for any interior solution reads

$$(C - X)^{-\gamma} + bV_X(K, X, A) = \Phi' \left(\frac{\exp(A)K^\alpha - C}{K} \right) V_K(K, X, A), \quad (53)$$

making optimal consumption an implicit function of the state variables, $C = C(K, X, A)$,

where $\Phi'(\cdot) = a_1(\cdot)^{-1/\xi}$. The maximized (concentrated) HJB equation is then

$$0 = \frac{(C(K, X, A) - X)^{1-\gamma}}{1-\gamma} + \left(\Phi \left(\frac{\exp(A)K^\alpha - C(K, X, A)}{K} \right) - \delta \right) KV_K(K, X, A) \\ + (bC(K, X, A) - aX)V_X(K, X, A) - \rho_A AV_A(K, X, A) \\ + \frac{1}{2}\sigma_A^2 V_{AA}(K, X, A) - \rho V(K, X, A). \quad (54)$$

A.2 Equilibrium in the time-space domain

Let $V_{ijl} \equiv \partial^3 V(K, X, A) / (\partial i \partial j \partial l)$ for any $i, j, l = K, X, A$. Then, using the maximized HJB equation in (54) together with the envelope theorem we obtain the associated costate variable with respect to capital, $V_{K,t}$,

$$\rho V_K = \left(\Phi((\exp(A)K^\alpha - C)/K)K - \delta K \right) V_{KK} \\ + \left(\Phi((\exp(A)K^\alpha - C)/K) + \Phi'((\exp(A)K^\alpha - C)/K)((\alpha - 1)\exp(A)K^{\alpha-1} \right. \\ \left. + C/K) - \delta \right) V_K + (bC - aX)V_{XK} - \rho_A AV_{AK} + \frac{1}{2}\sigma_A^2 V_{AAK}. \quad (55)$$

On the other hand, the application of Itô's Lemma yields the evolution of (off-equilibrium) $V_{K,t}$ as

$$dV_K = \left(\Phi((\exp(A)K^\alpha - C)/K) - \delta \right) KV_{KK} + (bC - aX)V_{KX} \\ - \rho_A AV_{KA} + \frac{1}{2}\sigma_A^2 V_{KAA} \Big) dt + \sigma_A V_{KA} dB_A. \quad (56)$$

Combining equations (55) and (56) we arrive at the following optimal/equilibrium stochastic differential equation (SDE) for V_K

$$dV_K = \left(\rho - \Phi((\exp(A)K^\alpha - C)/K) - \Phi'((\exp(A)K^\alpha - C)/K) \right. \\ \left. \times ((\alpha - 1)\exp(A)K^{\alpha-1} + C/K) + \delta \right) V_K dt + \sigma_A V_{KA} dB_A. \quad (57)$$

Similarly, the optimal costate variable with respect to the habit level, $V_{X,t}$, reads

$$\rho V_X = -(C - X)^{-\gamma} + \left(\Phi((\exp(A)K^\alpha - C)) - \delta \right) KV_{KX,t} \\ + (bC - aX)V_{XX} - aV_X - \rho_A AV_{AX} + \frac{1}{2}\sigma_A^2 V_{AAX}. \quad (58)$$

Using Itô's Lemma, the evolution of the (off-equilibrium) costate variable with respect

to the habit level is given by

$$dV_X = \left(\left(\Phi(\exp(A)K^\alpha - C/K) - \delta \right) KV_{XK} + (bC - aX)V_{XX} - \rho_A AV_{XA} + \frac{1}{2}\sigma_A^2 V_{XAA} \right) dt + \sigma_A V_{XA} dB_A. \quad (59)$$

Combining equations (58) and (59) we arrive at the optimal/equilibrium SDE for V_X

$$dV_X = \left((\rho + a)V_X + (C - X)^{-\gamma} \right) dt + \sigma_A V_{XA} dB_A. \quad (60)$$

Then, the equilibrium of the economy in the time-space domain can be characterized by the sequence $\{V_{K,t}, V_{X,t}, K_t, X_t, A_t\}_{t=0}^\infty$ that solves the following system of SDEs

$$\begin{aligned} dV_{K,t} &= \left(\rho - \Phi((\exp(A_t)K_t^\alpha - C_t)/K_t) - \Phi'((\exp(A_t)K_t^\alpha - C_t)/K_t) \right. \\ &\quad \left. \times ((\alpha - 1)\exp(A_t)K_t^{\alpha-1} + C_t/K_t) + \delta \right) V_{K,t} dt + \sigma_A V_{KA,t} dB_{A,t} \\ dV_{X,t} &= \left((\rho + a)V_{X,t} + (C_t - X_t)^{-\gamma} \right) dt + \sigma_A V_{XA,t} dB_{A,t} \\ dK_t &= \left(\Phi((\exp(A_t)K_t^\alpha - C_t)/K_t) - \delta \right) K_t dt \\ dX_t &= (bC_t - aX_t) dt \\ dA_t &= -\rho_A A_t dt + \sigma_A dB_{A,t}, \end{aligned}$$

together with initial conditions $K(0) = K_0$, $X(0) = X_0$, and $A(0) = A_0$, and where C_t is the solution to the non-linear algebraic equation:

$$(C_t - X_t)^{-\gamma} + bV_{X,t} = \Phi' \left(\frac{\exp(A_t)K_t^\alpha - C_t}{K_t} \right) V_{K,t}.$$

A.3 Equilibrium in the state-space domain

Following [Posch \(2018\)](#), the equilibrium can be alternatively defined in the space of states by simply using the equilibrium partial differential equations (PDEs) for the costate variables in (55) and (58). Together with the first order condition in (53) they form a system of non-linear functional equations in the unknown policy functions $\{V_K, V_X, C\} = \{V_K(K, X, A), V_X(K, X, A), C(K, X, A)\}$

$$\begin{aligned}
0 &= \left(\rho - \Phi\left(\frac{\exp(A)K^\alpha - C}{K}\right) - \Phi'\left(\frac{\exp(A)K^\alpha - C}{K}\right) \left(\frac{(\alpha - 1) \exp(A)K^{\alpha-1} + C}{K} \right) + \delta \right) V_K \\
&\quad - \left(\Phi\left(\frac{\exp(A)K^\alpha - C}{K}\right) - \delta \right) K V_{KK} - (bC - aX) V_{XK} + \rho_A A V_{AK} - \frac{1}{2} \sigma_A^2 V_{AAK} \\
0 &= (\rho + a) V_X + (C - X)^{-\gamma} - \left(\Phi\left(\frac{\exp(A)K^\alpha - C}{K}\right) - \delta \right) K V_{KX} \\
&\quad - (bC - aX) V_{XX} + \rho_A A V_{AX} - \frac{1}{2} \sigma_A^2 V_{AAX} \\
0 &= (C - X)^{-\gamma} + b V_X - \Phi'\left(\frac{\exp(A)K^\alpha - C}{K}\right) V_K
\end{aligned}$$

where the dynamics of the state variables are given by the controlled SDEs

$$\begin{aligned}
dK_t &= \left(\Phi((\exp(A_t)K_t^\alpha - C_t(K_t, X_t, A_t))/K_t) - \delta \right) K_t dt \\
dX_t &= (bC_t(K_t, X_t, A_t) - aX_t) dt \\
dA_t &= -\rho_A A_t dt + \sigma_A dB_{A,t}
\end{aligned}$$

subject to the initial conditions $K(0) = K_0$, $X(0) = X_0$ and $A(0) = A_0$.

A.4 Deterministic steady state

The deterministic steady state of the economy is given by the values $\{\bar{C}, \bar{I}, \bar{V}_K, \bar{V}_X, \bar{K}, \bar{X}, \bar{A}\}$ that solve the following system of equations

$$\rho - \Phi(\bar{I}/\bar{K}) - \Phi'(\bar{I}/\bar{K})((\alpha - 1) \exp(\bar{A})\bar{K}^{\alpha-1} + \bar{C}/\bar{K}) + \delta = 0 \quad (61)$$

$$(\rho + a)\bar{V}_X + (\bar{C} - \bar{X})^{-\gamma} = 0 \quad (62)$$

$$\Phi(\bar{I}/\bar{K}) - \delta = 0 \quad (63)$$

$$b\bar{C} - a\bar{X} = 0 \quad (64)$$

$$(\bar{C} - \bar{X})^{-\gamma} + b\bar{V}_X - \Phi'(\bar{I}/\bar{K})\bar{V}_K = 0 \quad (65)$$

$$\bar{I}/\bar{K} - \frac{\exp(\bar{A})\bar{K}^\alpha - \bar{C}}{\bar{K}} = 0 \quad (66)$$

$$\bar{A} = 0, \quad (67)$$

which results from imposing $\sigma_A = 0$ together the idle condition $dK_t/dt = dX_t/dt = dA_t/dt = 0$ on the equilibrium PDEs (55) and (58).

The solution to this system of non-linear equations is entirely determined by the steady state value of the investment-capital ratio, \bar{I}/\bar{K} . Given the values of a_1 and a_2 , it

is possible to show that for any value of ξ

$$\bar{I}/\bar{K} = \delta.$$

Note that for the steady-state value of the investment-capital ratio, $\Phi(\delta) = \delta$, $\Phi'(\delta) = 1$, and $\Phi''(\bar{I}/\bar{K}) = \Phi''(\delta) = -1/(\xi\delta)$. From (61) and (66) we find the steady-state value of the capital stock as

$$\bar{K} = \left[\frac{\alpha \exp(\bar{A})}{(\rho + \delta)} \right]^{\frac{1}{1-\alpha}}. \quad (68)$$

Using (66) we find the steady-state value of consumption

$$\bar{C} = \exp(\bar{A})\bar{K}^\alpha - \delta\bar{K}. \quad (69)$$

From (64) we pin down the steady-state value of the habit as

$$\bar{X} = \frac{b}{a}\bar{C}. \quad (70)$$

Finally using (62) and (65) we find the steady-state values for the costate variables

$$\bar{V}_X = -\frac{1}{\rho + a} (\bar{C} - \bar{X})^{-\gamma} \quad (71)$$

$$\bar{V}_K = \left(1 - \frac{b}{\rho + a} \right) (\bar{C} - \bar{X})^{-\gamma}. \quad (72)$$

A.5 Stochastic discount factor

When the habit is internal the agent takes into account the effect of today's consumption decisions on the future levels of habits. Following [Detemple and Zapatero \(1991\)](#),

$$m_t = k e^{-\rho t} \left\{ (C_t - X_t)^{-\gamma} - b \mathbb{E}_t \left[\int_t^\infty e^{-(\rho+a)(s-t)} (C_s - X_s)^{-\gamma} ds \right] \right\}, \quad (73)$$

for some given constant k .

Using the (linear) equilibrium SDE for V_X in (60) we may write

$$e^{-(\rho+a)t} dV_{X,t} = e^{-(\rho+a)t} \left((\rho + a) V_{X,t} + (C_t - X_t)^{-\gamma} \right) dt + e^{-(\rho+a)t} V_{XA,t} \sigma_A dB_{A,t},$$

or equivalently

$$e^{-(\rho+a)t} (dV_{X,t} - (\rho + a) V_{X,t} dt) = e^{-(\rho+a)t} (C_t - X_t)^{-\gamma} dt + e^{-(\rho+a)t} V_{XA,t} \sigma_A dB_{A,t}.$$

Note that Itô's formula yields

$$d(e^{-(\rho+a)t}V_{X,t}) = -(\rho+a)e^{-(\rho+a)t}V_{X,t} + e^{-(\rho+a)t}dV_{X,t}$$

such that

$$d(e^{-(\rho+a)t}V_{X,t}) = e^{-(\rho+a)t} (C_t - X_t)^{-\gamma} dt + e^{-(\rho+a)t}V_{XA,t}\sigma_A dB_{A,t}.$$

Integrating both sides yields

$$\begin{aligned} \int_t^T d(e^{-(\rho+a)s}V_{X,s}) &= \int_t^T e^{-(\rho+a)s} (C_s - X_s)^{-\gamma} ds + \int_t^T e^{-(\rho+a)s}V_{XA,s}\sigma_A dB_{A,s} \\ \Leftrightarrow V_{X,t} &= e^{-(\rho+a)(T-t)}V_{X,T} - \int_t^T e^{-(\rho+a)(s-t)} (C_s - X_s)^{-\gamma} ds \\ &\quad - \int_t^T e^{-(\rho+a)(s-t)}V_{XA,s}\sigma_A dB_{A,s}. \end{aligned}$$

Applying the expectation operator (assuming existence of the integrals) implies

$$\mathbb{E}_t[V_{X,t}] = e^{-(\rho+a)(T-t)}\mathbb{E}_t[V_{X,T}] - \mathbb{E}_t\left[\int_t^T e^{-(\rho+a)(s-t)} (C_s - X_s)^{-\gamma} ds\right].$$

Further, by letting $\lim_{T \rightarrow \infty} e^{-(\rho+a)(T-t)}\mathbb{E}[V_{X,T}] = 0$, we may write

$$V_{X,t} \equiv \lim_{T \rightarrow \infty} \mathbb{E}_t[V_{X,t}] = -\mathbb{E}_t\left[\int_t^\infty e^{-(\rho+a)(s-t)} (C_s - X_s)^{-\gamma} ds\right]$$

such that (73) can be written as

$$m_t = e^{-\rho t} \left[(C_t - X_t)^{-\gamma} + bV_{X,t} \right] \tag{74}$$

so that the SDF, as defined in Section 4, is

$$m_s/m_t = e^{-\rho(s-t)} \frac{(C_s - X_s)^{-\gamma} + bV_{X,s}}{(C_t - X_t)^{-\gamma} + bV_{X,t}}.$$

Using Itô's lemma, the dynamics of m_t is given by

$$\frac{dm_t}{m_t} = \mu_{m,t}dt + \sigma_{m,t}dB_{A,t}, \tag{75}$$

where the drift and diffusion coefficients are

$$\begin{aligned} \mu_{m,t} = & -\rho - \frac{(C_t - X_t)^{-\gamma}}{(C_t - X_t)^{-\gamma} + bV_{X,t}} \left[\gamma (C_t - X_t)^{-1} \left(\mu_{C,t} - (bC_t - aX_t) \right) \right. \\ & \left. - b (C_t - X_t)^\gamma \mu_{V_{X,t}} - \frac{1}{2} \gamma (\gamma + 1) (C_t - X_t)^{-2} \sigma_{C,t}^2 \right] \end{aligned} \quad (76)$$

and

$$\sigma_{m,t} = -\frac{(C_t - X_t)^{-\gamma}}{(C_t - X_t)^{-\gamma} + bV_{X,t}} \left[\gamma (C_t - X_t)^{-1} \sigma_{C,t} - b (C_t - X_t)^\gamma \sigma_{V_{X,t}} \right]. \quad (77)$$

Note that (76) and (77) depend on the drift and diffusion coefficients of the policy functions for consumption and the habit costate variable. Using Itô's lemma we can show that they are given by

$$\begin{aligned} \mu_{C,t} &= \frac{\partial C_t}{\partial K_t} \left[\Phi \left(\frac{\exp(A_t) K_t^\alpha - C_t}{K_t} \right) - \delta \right] K_t + \frac{\partial C_t}{\partial X_t} (bC_t - aX_t) - \frac{\partial C_t}{\partial A_t} \rho_A A_t + \frac{1}{2} \frac{\partial^2 C_t}{(\partial A_t)^2} \sigma_A^2 \\ \mu_{V_{X,t}} &= (\rho + a) V_{X,t} + (C_t - X_t)^{-\gamma} \\ \sigma_{C,t} &= \frac{\partial C_t}{\partial A_t} \sigma_A \\ \sigma_{V_{X,t}} &= \frac{\partial V_{X,t}}{\partial A_t} \sigma_A. \end{aligned}$$

B The stochastic growth model

By letting $X_0 = b = 0$ and $\xi \rightarrow \infty$, the model in Section 2 collapses to

$$V(K_0, A_0) = \max_{\{C_t\}_{t=0}^{\infty}} \mathbb{E}_0 \left[\int_0^{\infty} e^{-\rho t} \frac{C_t^{1-\gamma}}{1-\gamma} dt \right]$$

subject to

$$\begin{aligned} dK_t &= (\exp(A_t)K_t^\alpha - C_t - \delta K_t) dt, \quad K_0 > 0 \\ dA_t &= -\rho_A A_t dt + \sqrt{\eta \sigma_A^2} dB_{A,t}, \quad A_0 > 0, \end{aligned}$$

where we have included explicitly the perturbation parameter, η , that rescales the amount of variance in the model. The associated HJB equation reads

$$\begin{aligned} \rho V(K, A; \eta) = \max_C \left\{ \frac{C^{1-\gamma}}{1-\gamma} + (\exp(A)K^\alpha - C - \delta K)V_K(K, A; \eta) \right. \\ \left. - \rho_A A V_A(K, A; \eta) + \frac{1}{2} \eta \sigma_A^2 V_{AA}(K, A; \eta) \right\}. \end{aligned}$$

The first order condition for an interior solution is

$$C^{-\gamma} = V_K(K, A; \eta),$$

making optimal consumption a function of the state variables and the perturbation parameter, $C^\star = C(K, A; \eta)$. Substituting back, the maximized (concentrated) HJB equation reads

$$\begin{aligned} \rho V(K, A; \eta) = \frac{C(K, A; \eta)^{1-\gamma}}{1-\gamma} + (\exp(A)K^\alpha - C(K, A; \eta) - \delta K)V_K(K, A; \eta) \\ - \rho_A A V_A(K, A; \eta) + \frac{1}{2} \eta \sigma_A^2 V_{AA}(K, A; \eta) \end{aligned}$$

from which we can obtain the costate variable (using the envelope theorem) as

$$\begin{aligned} \rho V_K(K, A; \eta) &= (\exp(A)K^\alpha - C(K, A; \eta) - \delta K)V_{KK}(K, A; \eta) \\ &\quad (\alpha \exp(A)K^{\alpha-1} - \delta)V_K(K, A; \eta) - \rho_A A V_{AK}(K, A; \eta) + \frac{1}{2} \eta \sigma_A^2 V_{AAK}(K, A; \eta) \end{aligned}$$

such that

$$\begin{aligned} (\rho - \alpha \exp(A)K^{\alpha-1} + \delta)V_K(K, A; \eta) &= (\exp(A)K^\alpha - C(K, A; \eta) - \delta K)V_{KK}(K, A; \eta) \\ &\quad - \rho_A A V_{AK}(K, A; \eta) + \frac{1}{2} \eta \sigma_A^2 V_{AAK}(K, A; \eta). \end{aligned}$$

Using Itô's Lemma, the evolution of the costate variable is given by

$$\begin{aligned} dV_K(K, A; \eta) &= V_{KK}(K, A; \eta)dK + V_{KA}(K, A; \eta)dA + \frac{1}{2}\eta\sigma_A^2 V_{KAA}(K, A; \eta)dt \\ &= (\rho - \alpha \exp(A)K^{\alpha-1} + \delta)V_K(K, A; \eta)dt + V_{KA}(K, A; \eta)\sqrt{\eta\sigma_A^2}dB_A. \end{aligned}$$

Using once again the first-order condition, we may alternatively write

$$dC_t^{-\gamma} = (\rho - \alpha \exp(A_t)K_t^{\alpha-1} + \delta)C_t^{-\gamma}dt - \gamma C_t^{-\gamma-1}C_{A,t}\sqrt{\eta\sigma_A^2}dB_{A,t}$$

or

$$\frac{dC_t}{C_t} = \left[\frac{1}{\gamma} (\alpha \exp(A_t)K_t^{\alpha-1} - \delta - \rho) + \frac{1}{2}(1 + \gamma) \left(\frac{C_{A,t}}{C_t} \right)^2 \eta\sigma_A^2 \right] dt + \left(\frac{C_{A,t}}{C_t} \right) \sqrt{\eta\sigma_A^2}dB_{A,t},$$

which is the Euler equation for consumption in (37). Together with (34) and (35), they define the equilibrium of the economy in the time-space domain.

Alternatively, the equilibrium of this economy can be characterized in the space of states by eliminating time and stochastic shocks from the previous equilibrium system. To do so, note that Itô's lemma implies

$$\begin{aligned} dC_t &= C_{K,t}dK_t + C_{A,t}dA_t + \frac{1}{2}C_{AA,t}\eta\sigma_A^2dt \\ &= C_{K,t}(\exp(A_t)K_t^\alpha - C_t - \delta K_t)dt \\ &\quad - C_{A,t}\rho_A A_t dt + C_{A,t}\eta\sigma_A dB_{A,t} + \frac{1}{2}C_{AA,t}\eta\sigma_A^2dt. \end{aligned} \quad (78)$$

Combining (37) and (78) yields

$$\begin{aligned} \frac{1}{\gamma} (\alpha \exp(A_t)K_t^{\alpha-1} - \delta - \rho) C_t + \frac{1}{2}(1 + \gamma)C_t \left(\frac{C_{A,t}}{C_t} \right)^2 \eta\sigma_A^2 \\ - C_{K,t}(\exp(A_t)K_t^\alpha - C_t - \delta K_t) + C_{A,t}\rho_A A_t - \frac{1}{2}C_{AA,t}\eta\sigma_A^2 = 0 \end{aligned}$$

which corresponds to the functional equation

$$\mathcal{H}(C, C_K, C_A, C_{AA}, K, A; \eta) = 0.$$

Since the policy function $C = C(K, A; \eta)$ is unknown, we approximate it by means of a k -th order perturbation around the deterministic steady state. Substituting into the functional \mathcal{H} yield the new functional

$$F(K, A; \eta) = \mathcal{H}(C(K, A; \eta), C_K(K, A; \eta), C_A(K, A; \eta), C_{AA}(K, A; \eta), K, A; \eta) = 0.$$

Consider the case of $k = 1$. Hence, optimal consumption is approximated as

$$C(K, A; \eta) \approx \bar{C} + \bar{C}_K (K - \bar{K}) + \bar{C}_A (A - \bar{A}) + \bar{C}_\eta \eta,$$

where \bar{C} is the deterministic steady-state value of consumption.

Let \mathcal{H}_j denote the partial derivative of $\mathcal{H}(\cdot)$ with respect to its j -th element. Then, in order to find the yet unknown coefficients \bar{C}_K , \bar{C}_A and \bar{C}_η we compute

$$\begin{aligned} F_K(K_t, A_t; \eta) &= \mathcal{H}_1 C_K + \mathcal{H}_2 C_{KK} + \mathcal{H}_3 C_{AK} + \mathcal{H}_4 C_{AAK} + \mathcal{H}_5 = 0 \\ F_A(K_t, A_t; \eta) &= \mathcal{H}_1 C_A + \mathcal{H}_2 C_{KA} + \mathcal{H}_3 C_{AA} + \mathcal{H}_4 C_{AAA} + \mathcal{H}_6 = 0 \\ F_\eta(K_t, A_t; \eta) &= \mathcal{H}_1 C_\eta + \mathcal{H}_2 C_{K\eta} + \mathcal{H}_3 C_{A\eta} + \mathcal{H}_4 C_{AA\eta} + \mathcal{H}_7 = 0, \end{aligned}$$

which evaluated at the deterministic steady state reduces to a system of three non-linear equations in the three unknowns, \bar{C}_K , \bar{C}_A , \bar{C}_η , that can be solved recursively

$$\begin{aligned} F_K(\bar{K}, \bar{A}; 0) &= \mathcal{H}_1 \bar{C}_K + \mathcal{H}_5 = 0 \\ F_A(\bar{K}, \bar{A}; 0) &= \mathcal{H}_1 \bar{C}_A + \mathcal{H}_6 = 0 \\ F_\eta(\bar{K}, \bar{A}; 0) &= \mathcal{H}_1 \bar{C}_\eta + \mathcal{H}_7 = 0, \end{aligned}$$

where \mathcal{H}_1 , \mathcal{H}_5 , \mathcal{H}_6 and \mathcal{H}_7 are also functions of the unknowns. In particular,

$$F_K(\bar{K}, \bar{A}; 0) = \left(\alpha \exp(\bar{A}) \bar{K}^{\alpha-1} - \delta - \bar{C}_K \right) \frac{\bar{C}_K}{\bar{C}} - \frac{1}{\gamma} \alpha (\alpha - 1) \exp(\bar{A}) \bar{K}^{\alpha-2}.$$

Since this derivative must be zero, we arrive to the quadratic equation

$$\bar{C}_K^2 - \left(\alpha \exp(\bar{A}) \bar{K}^{\alpha-1} - \delta \right) \bar{C}_K + \frac{1}{\gamma} \alpha (\alpha - 1) \exp(\bar{A}) \bar{K}^{\alpha-2} \bar{C} = 0$$

with roots

$$\bar{C}_K = \frac{\left(\alpha \exp(\bar{A}) \bar{K}^{\alpha-1} - \delta \right)}{2} \pm \sqrt{\frac{\left(\alpha \exp(\bar{A}) \bar{K}^{\alpha-1} - \delta \right)^2 - 4 \frac{1}{\gamma} \alpha (\alpha - 1) \exp(\bar{A}) \bar{K}^{\alpha-2} \bar{C}}{4}}.$$

We pick the positive root since it is the only one that is consistent with a concave value function $V(K, A)$ in the capital stock. To see why, recall that the first-order condition

$$u'(C(K, A)) = V_K(K, A),$$

together with the assumptions on the utility function $u(C)$ imposes a necessary condition for concavity of the value function. A sufficient condition for concavity is given by the

derivative of the first order condition

$$u''(C(K, A)) C_K(K, A) = V_{KK}(K, A)$$

which suggests that $V_{KK}(K, A) < 0$ if and only if $C_K(K, A) > 0$ given that $u''(C) < 0$.

We now solve for \bar{C}_A from

$$F_A(\bar{K}, \bar{A}; 0) = \frac{\alpha \exp(\bar{A}) \bar{K}^{\alpha-1}}{\gamma} \bar{C} - \bar{C}_K (\exp(\bar{A}) \bar{K}^\alpha - \bar{C}_A) + \bar{C}_A \rho_A.$$

Since this derivative must be zero, we arrive at the following linear equation

$$\bar{C}_A = \frac{1}{(\bar{C}_K + \rho_A)} \left[\bar{C}_K \exp(\bar{A}) \bar{K}^\alpha - \frac{\alpha \exp(\bar{A}) \bar{K}^{\alpha-1}}{\gamma} \bar{C} \right]$$

which can be readily evaluated once $C_K(\bar{K}, \bar{A}; 0)$ is computed from the first step.

Finally, we obtain \bar{C}_η from

$$F_\eta(\bar{K}, \bar{A}; 0) = \bar{C}_\eta \bar{C}_K + \frac{1}{2} (1 + \gamma) \bar{C} \left(\frac{\bar{C}_A}{\bar{C}} \right)^2 \sigma_A^2,$$

and since $F_\eta(\bar{K}, \bar{A}; 0) = 0$, we arrive at the linear equation

$$\bar{C}_\eta = -(\bar{C}_K)^{-1} \left[\frac{1}{2} (1 + \gamma) \bar{C} \left(\frac{\bar{C}_A}{\bar{C}} \right)^2 \sigma_A^2 \right],$$

which completes the computation of the first-order perturbation to the unknown policy function for consumption.

Research Papers

2020



- 2019-10: Martin Møller Andreasen, Kasper Jørgensen and Andrew Meldrum: Bond Risk Premiums at the Zero Lower Bound
- 2019-11: Martin Møller Andrasen: Explaining Bond Return Predictability in an Estimated New Keynesian Model
- 2019-12: Vanessa Berenguer-Rico, Søren Johansen and Bent Nielsen: Uniform Consistency of Marked and Weighted Empirical Distributions of Residuals
- 2019-13: Daniel Borup and Erik Christian Montes Schütte: In search of a job: Forecasting employment growth using Google Trends
- 2019-14: Kim Christensen, Charlotte Christiansen and Anders M. Posselt: The Economic Value of VIX ETPs
- 2019-15: Vanessa Berenguer-Rico, Søren Johansen and Bent Nielsen: Models where the Least Trimmed Squares and Least Median of Squares estimators are maximum likelihood
- 2019-16: Kristoffer Pons Bertelsen: Comparing Tests for Identification of Bubbles
- 2019-17: Dakyung Seong, Jin Seo Cho and Timo Teräsvirta: Comprehensive Testing of Linearity against the Smooth Transition Autoregressive Model
- 2019-18: Changli He, Jian Kang, Timo Teräsvirta and Shuhua Zhang: Long monthly temperature series and the Vector Seasonal Shifting Mean and Covariance Autoregressive model
- 2019-19: Changli He, Jian Kang, Timo Teräsvirta and Shuhua Zhang: Comparing long monthly Chinese and selected European temperature series using the Vector Seasonal Shifting Mean and Covariance Autoregressive model
- 2019-20: Malene Kallestrup-Lamb, Søren Kjærgaard and Carsten P. T. Rosenskjold: Insight into Stagnating Life Expectancy: Analysing Cause of Death Patterns across Socio-economic Groups
- 2019-21: Mikkel Bennedsen, Eric Hillebrand and Siem Jan Koopman: Modeling, Forecasting, and Nowcasting U.S. CO2 Emissions Using Many Macroeconomic Predictors
- 2019-22: Anne G. Balter, Malene Kallestrup-Lamb and Jesper Rangvid: The move towards riskier pensions: The importance of mortality
- 2019-23: Duván Humberto Cataño, Carlos Vladimir Rodríguez-Caballero and Daniel Peña: Wavelet Estimation for Dynamic Factor Models with Time-Varying Loadings
- 2020-01: Mikkel Bennedsen: Designing a sequential testing procedure for verifying global CO2 emissions
- 2020-02: Juan Carlos Parra-Alvarez, Hamza Polattimur and Olaf Posch: Risk Matters: Breaking Certainty Equivalence