ABC-based Forecasting in State Space Models

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State Space Models

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$$\text{(Markov) transition density:} \quad p(x_t | x_{t-1}, \theta)$$

- Plus

$$\text{Initial state density:} \quad p(x_1 | \theta)$$

- May depend on a set of unknown, **static** parameters θ

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p(y_{T+1}|y_{1:T}) \quad &= \int_{\mathsf{X}}\int_{\mathsf{X}}\int_{\Theta} p(y_{T+1}|x_{T+1},\theta)p(x_{T+1}|x_T,\theta) \\
&\times \underbrace{\left(p(x_{1:T}|y_{1:T},\theta)\right)}\, \underbrace{p\left(\theta|y_{1:T}\right)}\, d\theta dx_{1:T}dx_{T+1}
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- Often readily accessible via
  - Bayesian Markov chain Monte Carlo (MCMC) methods or
  - Particle MCMC variants

- But... challenges remain when the model is **intractable** in some sense

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- $\Rightarrow$ exact Bayesian prediction **may not be feasible**

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- SSMs with unavailable components are managed via **approximate Bayesian computation** (ABC) :
  - **[Dean et al., 2014], [Creel and Kristensen, 2015], [Frazier et al., 2019], [Martin et al., 2019]**
  - $\Rightarrow$ **Our focus**

We focus on ABC...

- The **aim of ABC**
  - is to produce draws from an **approximation** to $p(\theta|y_{1:T})$
  - in the case where DGP cannot be evaluated
  - But *can* be **simulated** from

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- $d\{.\}$ is a **distance criterion**
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4. Selected draws $\Rightarrow$ draws from $p_\varepsilon(\theta | \eta(y_{1:T}))$

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- Under **correct model specification,**
  - ABC posterior - Bayesian consistent for the true parameter, asymptotically normal
    [Frazier et al., 2018] - 'Asymptotic properties of approximate Bayesian computation'
  - also in an explicitly SSM setting
    [Martin et al., 2019] - 'Auxiliary likelihood-based approximate Bayesian computation in state space models'
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- Under **model misspecification**
  - **[Frazier et al., 2020] - 'Model misspecification in approximate Bayesian computation: consequences and diagnostics'**

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- the whole focus of the Bayesian forecasting exercise **needs to change**.
  - argument put forward in recent forecasting works by
    - **[Loaiza-Maya et al., 2021a] - 'Focused Bayesian prediction'**
    - **[Frazier et al., 2021] - 'Loss-based variational Bayes prediction'**

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    - **[Loaiza-Maya et al., 2021a] - 'Focused Bayesian prediction'**
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- *For the first time:* **ABC-based forecasting + Loss-based Bayesian prediction**

Loss-based Bayesian Prediction

- **Essence of the idea:**

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- In the spirit of the various generalized Bayesian *inferential* methods,
  - **[Bissiri et al., 2016]; [Giummolè et al., 2019]; [Knoblauch et al., 2019]; [Pacchiardi and Dutta, 2021]**
- replace the **likelihood function (log-score loss)** in the conventional Bayesian update
- by the *particular* **predictive loss** that matters for the *particular* forecasting problem being tackled

Loss-based Bayesian Prediction in SSMs

- Assume a class of plausible **predictive SSMs** for Y_{T+1}, conditioned on information $\mathcal{F}_T$:

$$\mathcal{P}^{(T)} := \{P_\theta^{(T)}, \theta \in \Theta\}$$

- **Key thing:** Do not assume $P_0 \in \mathcal{P}^{(T)}$
- Construct the **loss-based posterior/Gibbs posterior** $p_L(\theta|y_{1:T})$
  - via some (positively-oriented) **scoring rule**

$$S_T(\theta) := \sum_{t=1}^{T} s(P_\theta^{(t)}, y_{t+1})$$

Loss-based Bayesian Prediction in SSMs

- $\Rightarrow$ **Loss-based predictive**

$$
\begin{aligned}
& p_L(y_{T+1}|y_{1:T}) \\
= & \int_{\mathsf{X}}\int_{\mathsf{X}}\int_{\Theta} p(y_{T+1}|x_{T+1},\theta)p(x_{T+1}|x_T,\theta) \\
& \times p(x_T|y_{1:T},\theta)\color{red}{p_L(\theta|y_{1:T})}\color{black}{d\theta dx_{1:T}dx_{T+1}}
\end{aligned}
$$

Immediate Problems...

- Consider the **loss-based predictive** $p_L(y_{T+1}|y_{1:T})$ which is constructed based on $p_L(\theta|y_{1:T})$ via

$$S_T(\theta) := \sum_{t=1}^{T} s(\underbrace{p(y_{t+1}|y_{1:T},\theta)}_{\text{with marginal of } x_{1:T}}, y_{t+1})$$

- Intractable SSM model $\Rightarrow$ $p_L(\theta|y_{1:T})$ out of reach

Our solution..

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    - **[Drovandi et al., 2011], [Drovandi et al., 2015] and [Martin et al., 2019]**
  - We choose an **auxiliary** model
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  - We choose an **auxiliary** model
    - that is a 'reasonable' approximation to the assumed **SSM** &
    - admit a **closed-form predictive** (with parameter vector β)
  - Define the score-based criterion as:

$$S_T(\beta) := \sum_{t=0}^{T-1} s(P_\beta^{(t)}, y_{t+1})$$

  - **NOTE:** this is useful ***even when the DGP itself is tractable***

How Do We Choose the Summary Statistics?

- *Summary statistics* : average of the first-derivative of $S_T(\beta)$ using a scoring rule s_j
  - evaluated at $\hat{\beta}_j(y_{1:T})$: optimizer of $S_T(\beta)$ using s_j

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- That is,

$$\eta_j(y^s_{1:T}) = T^{-1} \frac{\partial \sum_{t=1}^{T} s_j(P^{(t)}_{\beta}, y^s_{t+1}(\theta^i))}{\partial \beta}\Bigg|_{\beta=\hat{\beta}_j(y_{1:T})}$$

and:

$$\eta_j(y_{1:T}) = T^{-1} \frac{\partial \sum_{t=1}^{T} s_j(P^{(t)}_{\beta}, y_{t+1})}{\partial \beta}\Bigg|_{\beta=\hat{\beta}_j(y_{1:T})} = 0$$

Distance Criterion

- *ABC distance* : Mahalanobis distance

$$d\{\eta\left(y^s_{1:T}\right),\eta\left(y_{1:T}\right)\} = \sqrt{\left[\bar{S}_j\left\{y^s_{1:T}(\theta^i);\hat{\beta}_j(y_{1:T})\right\}\right]'\hat{\Sigma}\left[\bar{S}_j\left\{y^s_{1:T}(\theta^i);\hat{\beta}_j(y_{1:T})\right\}\right]},$$

  - where $\hat{\Sigma}$ is the inverse of the (estimated) covariance matrix of $\eta_j(y^s_{1:T})$ across draws and
  - $\bar{S}_j\left\{y^s_{1:T}(\theta^i);\hat{\beta}_j(y_{1:T})\right\} = T^{-1}\frac{\partial\sum_{t=1}^{T}s_j(P^{(t)}_{\beta},y^s_{t+1}(\theta^i))}{\partial\beta}\Big|_{\beta=\hat{\beta}_j(y_{1:T})}$

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\times \quad & p_{L,\varepsilon}(\theta|\eta(y_{1:T}))d\theta dx_T dx_{T+1}
\end{aligned}
$$

- $\Rightarrow$ loss-based ABC forecasting (**loss-based ABF**)

Comparator to Loss-based ABF

- Using the **auxiliary model predictive** ***directly*** in a generalized Bayesian update
  - Avoids the use of a SSM representation
  - But, use of a *simpler model* in a focused up-date well be adequate
  - $\Rightarrow$ **[Loaiza-Maya et al., 2021a] - 'Focused Bayesian prediction' (FBP)**

Numerical Illustration: Simulation design

- **Predictive class**, $P_\theta^{(t)}$ is a SSM:
  - **SV model** for a continuous financial return, y_t,

$$y_t = \mu + e^{\alpha_t/2} e_t \quad ; \quad e_t \sim N(0,1)$$

$$\alpha_t = \bar{h}_\alpha + \phi(\alpha_{t-1} - \bar{h}_\alpha) + w_t \quad ; \quad w_t \sim N(0, \sigma_\alpha^2)$$

$$\alpha_0 \sim N\left(\bar{h}_\alpha, \frac{\sigma_\alpha^2}{1-\phi^2}\right),$$

- $\theta = (\phi, \sigma_\alpha^2, \mu, \bar{h}_\alpha)'$

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  2. SV model that better replicates the stylized features of financial returns data, as used by **[Loaiza-Maya et al., 2021a]** :

$$z_t = e^{h_t/2}\epsilon_t$$
$$h_t = \bar{h} + a(h_{t-1} - \bar{h}) + \sigma_h \eta_t$$
$$y_t = G^{-1}(F_z(z_t))$$

     - $\Rightarrow$ Implied copula of a **stochastic volatility** model combined with a **skewed normal marginal,** $g(y_t)$ (imposed via G^{-1})
     - $\Rightarrow$ **Model misspecification**
- Predicting **extreme returns** accurately is important
- Will **focus** on that goal $\Rightarrow$ use an appropriate s_j in the update

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  1. a Gaussian ARCH(1) model
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- Results for three types of **scores** reproduced here:
  1. Log score (LS)
  2. **Censored** log score (CLS) (rewards **predictive accuracy in a tail**)
  3. Continuously ranked probability score (CRPS) (rewards the assignment of high predictive mass near to the realized value)
  - [Gneiting and Raftery, 2007]

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- Will discuss the results based on **Gaussian GARCH(1,1)** model under **model misspecification**

Simulation Results: Model misspecification

Loss-based ABF
Average out-of-sample score

ABC Score	LS	$CLS_{<10\%}$	$CLS_{>80\%}$	$CLS_{>90\%}$	CRPS
LS	-1.3427	-0.3586	-0.4900	-0.2975	-0.5331
$CLS_{<10\%}$	-1.4117	-0.3572	-0.5122	-0.3037	-0.5616
$CLS_{>80\%}$	-2.0917	-0.8118	-0.4675	-0.2822	-0.6082
$CLS_{>90\%}$	-2.4259	-0.8961	-0.4715	-0.2777	-0.6509
CRPS	-1.3371	-0.3629	-0.4881	-0.2998	-0.5309
Exact Bayes	-1.3343	0.3618	-0.4882	-0.3003	-0.5304

- **Rows** ⇒ Scoring rules used in underlying loss-based ABF results
- **Last Row** ⇒ Exact (but misspecified) Bayesian predictive
- **Columns** ⇒ Measure of out-of-sample accuracy

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- Positively-oriented scores $\Rightarrow$ large (**in bold**) is good
- Looking for **bold** values on the diagonal
  - The predictive constructed via the use of a particular scoring rule predicts best according to that rule
  - **'Coherent predictions'** are in evidence

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- **Loss-based ABF** > **misspecified exact Bayes**

Simulation Results: Model misspecification

Comparison of loss-based ABF and FBP

Panel A: Loss-based ABF

Average out-of-sample score

Scoring rule	LS	$CLS_{<10\%}$	$CLS_{>80\%}$	$CLS_{>90\%}$	CRPS
ABC-LS	*-1.3427*	-0.3586	-0.4900	-0.2975	*-0.5331*
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Panel B: FBP

Average out-of-sample score

Scoring rule	LS	$CLS_{<10\%}$	$CLS_{>80\%}$	$CLS_{>90\%}$	CRPS
FBP-LS	**-1.3471**	-0.3694	-0.4840	-0.2954	*-0.5340*
FBP-$CLS_{<10\%}$	-1.3669	**-0.3593**	-0.5094	-0.3212	-0.5380
FBP-$CLS_{>80\%}$	-2.0718	-0.9227	**-0.4491**	*-0.2657*	-0.5888
FBP-$CLS_{>90\%}$	-2.5938	-1.1223	*-0.4579*	**-0.2644**	-0.6357
FBP-CRPS	*-1.3485*	-0.3786	-0.4839	-0.2973	**-0.5319**
Exact	-1.3343	-0.3618	-0.4882	-0.3003	-0.5304

Simulation Results: Model misspecification

Comparison of loss-based ABF and FBP

- Both methods produce ***coherent*** predictions
- Dominance of loss-based ABF over FBP is ***not uniform***
  - Likely to depend on the extent to which assumed SSM is misspecified

Empirical Illustration

- Applying **loss-based ABF** to daily returns data on the S & P500 index
- **Assumed predictive class**:
  - **SV model with α-Stable errors** for a continuous financial return, y_t,

$$y_t = e^{h_t/2}\varepsilon_t \quad ; \quad \varepsilon_t \overset{iid}{\sim} N(0,1)$$

$$h_t = \omega + \rho h_{t-1} + \sigma_h \eta_t \quad ; \quad \eta_t \overset{iid}{\sim} S(\alpha, -1, 0, dt = 1)$$

  - **Transition density is unavailable**
  - $\Rightarrow$ **Truly intractable SSM**
- $\theta = (\omega, \rho, \sigma_h^2, \alpha)'$

Empirical Illustration: Results

Panel A: Loss-based ABF
Average out-of-sample score

Scoring rule	LS	$CLS_{<10\%}$	$CLS_{<20\%}$	$CLS_{>80\%}$	$CLS_{>90\%}$
ABC-LS	3.3967	0.0268	0.2923	0.5170	0.1523
ABC-$CLS_{<10\%}$	**3.4058**	**0.0391**	**0.3048**	0.5122	0.1500
ABC-$CLS_{<20\%}$	*3.4053*	*0.0383*	*0.3041*	0.5126	0.1502
ABC-$CLS_{>80\%}$	3.3772	0.0052	0.2713	**0.5192**	**0.1547**
ABC-$CLS_{>90\%}$	3.3849	0.0134	0.2790	*0.5191*	*0.1540*

Panel B: FBP
Average out-of-sample score

Scoring rule	LS	$CLS_{<10\%}$	$CLS_{<20\%}$	$CLS_{>80\%}$	$CLS_{>90\%}$
FBP-LS	**3.3467**	-0.0262	0.2406	0.4801	0.1473
FBP-$CLS_{<10\%}$	3.1051	**0.0463**	**0.3096**	0.1903	-0.1119
FBP-$CLS_{<20\%}$	3.1788	*0.0417*	*0.3085*	0.2645	-0.0430
FBP-$CLS_{>80\%}$	*3.3293*	-0.0515	0.2155	**0.4860**	*0.1531*
FBP-$CLS_{>90\%}$	3.1941	-0.1204	0.1042	*0.4820*	**0.1543**

- Conclusions are a bit mixed
- But overall, loss-based ABF > FBP

Concluding remarks

- A new approach for conducting Bayesian prediction in **intractable** and *misspecified* SSMs
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- Simulation and Empirical results:
  - Coherent predictions are in evidence
  - More accurate forecasts than the exact (misspecified) predictive
  - Often more accurate than the FBP results

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  - Often more accurate than the FBP results
- Little to lose from adopting the ABC-based approach, and much to gain!

Thank you!

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