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# Estimating extreme sea levels combining systematic observed skew surges and historic record sea levels

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## INTRODUCTION

The estimation of the sea levels corresponding to a high return period is crucial for coastal planning. High tide levels can be seen as the combination of the predicted astronomical high tide and the skew surge (i.e. the difference between the predicted astronomical high tide and the observed maximum sea level during a tidal cycle). This presentation is a contribution to the integration of historical information (i.e. events observed before the beginning of systematic tide gauge recordings) to better estimate extreme sea levels. It is largely recommended by the literature to separately model astronomical high tides and skew surges. Historic records consist of record sea level values. Their corresponding skew surges may be estimated but the exhaustiveness of historic skew surge series, which is an essential criterion for an unbiased statistical inference<sup>1</sup>, cannot be guaranteed. Indeed, extreme skew surges can easily remain unnoticed if they occur with low or moderate high tides and do not generate extreme sea levels<sup>2</sup>. This study proposes to combine, in a single Bayesian inference procedure, information of two different nature: measured systematic skew surges and observed historic extreme sea levels to estimate the statistical distribution of skew surges. The proposed approach is compared to two previously published methods aiming at valuating historical reconstructed skew surges<sup>3,4</sup>.

## PROPOSED MODEL

- The global likelihood expression of systematic skew surges and historic sea levels is:

$$L(X_{sys}, Z_{hist} | \theta, \lambda) = L(X_{sys} | \theta, \lambda) L(Z_{hist} | \theta, \lambda)$$

Extreme skew surges above the threshold  $u$  are chosen to be modelled by a General Pareto (GP) distribution:

$$\forall x > u, F_{\theta}(x) = \begin{cases} 1 - \left[1 + \xi \frac{(x-u)}{\sigma}\right]^{-\frac{1}{\xi}}, & \xi \neq 0, \\ 1 - \exp\left(-\frac{x-u}{\sigma}\right), & \xi = 0. \end{cases}$$

where  $\theta = (\sigma, \xi)$  are the scale ( $\sigma > 0$ ) and shape ( $\xi \in \mathbb{R}$ ) parameters.

- The likelihood formulation of systematic skew surges ( $>u$ ) is:

$$L(X_{sys} | \theta, \lambda) = P_{\lambda}(N = n) \prod_{i=1}^n f_{\theta}(x_{sys,i})$$

with  $f_{\theta}$  the GP density function.

The number of systematic skew surges exceeding  $u$  during the systematic period  $w_S$  follows a Poisson process of intensity  $\lambda w_S$ .

- The likelihood formulation of historic sea levels accounts for:

- [A] the  $N - h$  ordinary historical sea levels that did not exceed  $\eta_H$  ...
- [B] the  $h$  extreme historic sea levels that exceeded the threshold  $\eta_H$  ... during the historical period

$$L(Z_{hist} | \theta, \lambda) = \underbrace{G_{\theta,\lambda}(\eta_H)^{N-h}}_{[A]} \underbrace{\left[1 - G_{\theta,\lambda}(\eta_H)\right]^h \prod_{i=1}^h \frac{g_{\theta,\lambda}(Z_{hist,i})}{1 - G_{\theta,\lambda}(\eta_H)}}_{[B]}$$

where  $g_{\theta,\lambda}$  and  $G_{\theta,\lambda}$  are respectively the density and the cumulative distribution functions of sea levels which can be numerically computed given the statistical distributions of the skew surges and of the maximum astronomical tidal levels.

## METHOD

- Data and Monte Carlo simulations

Time series of hourly sea level observations are recorded by tide gauges of the SHOM (Service Hydrographique et Oceanographique de la Marine) and are processed to retrieve series of astronomical high tides and skew surges. Record historic sea levels are contained in the database « Tempêtes et submersions marines » developed by IRSN. For a given site, a statistical distribution is adjusted to the observed series of skew surges, with parameters  $(\lambda, \sigma, \xi)$ . 1000 Random samples of skew surges and maximum sea levels (after a convolution with the empirical series of observed high tides), with the same characteristics than the observed systematic and historical series are then generated through Monte Carlo simulations, to test the proposed statistical estimation method.

- Properties of the estimated 100-year quantile and parameters with maximum likelihood (ML)

The estimated 100-year quantiles and model parameters corresponding to the ML  $(\hat{Q}_{100}^{ML}, \hat{\lambda}^{ML}, \hat{\sigma}^{ML}, \hat{\xi}^{ML})$  obtained for the 1000 random samples are compared to their real values  $(Q_{100}, \lambda, \sigma, \xi)$ : see Fig.1.

- Reliability of the posterior credibility intervals

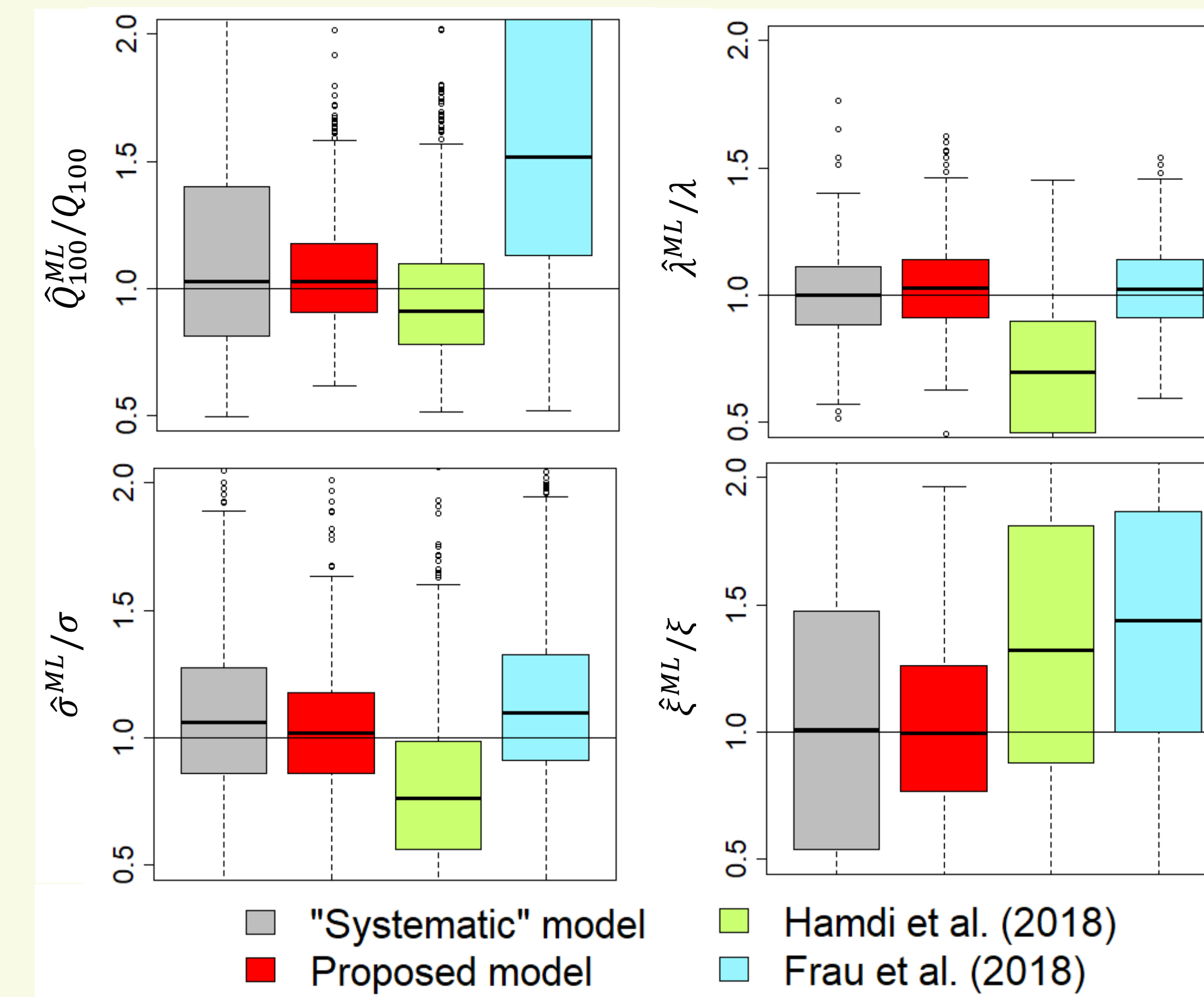
In the Bayesian framework, the result is the posterior density of parameters conditionally to the data which allow to compute credibility intervals for the estimated quantiles. The reliability of the posterior credibility intervals is evaluated with a diagnosis method named the rank histogram<sup>5</sup> (Fig. 2). It consists in estimating the non exceedance probability of the real quantile  $P(\hat{Q}_{100} < Q_{100})$ , according to the computed credibility intervals for each random sample.  $P(\hat{Q}_{100} < Q_{100})$  should be uniformly distributed if the credibility intervals are reliable.

## CASE STUDY AND RESULTS

Case study: La Rochelle (tide gauge located on the French Atlantic Coast)

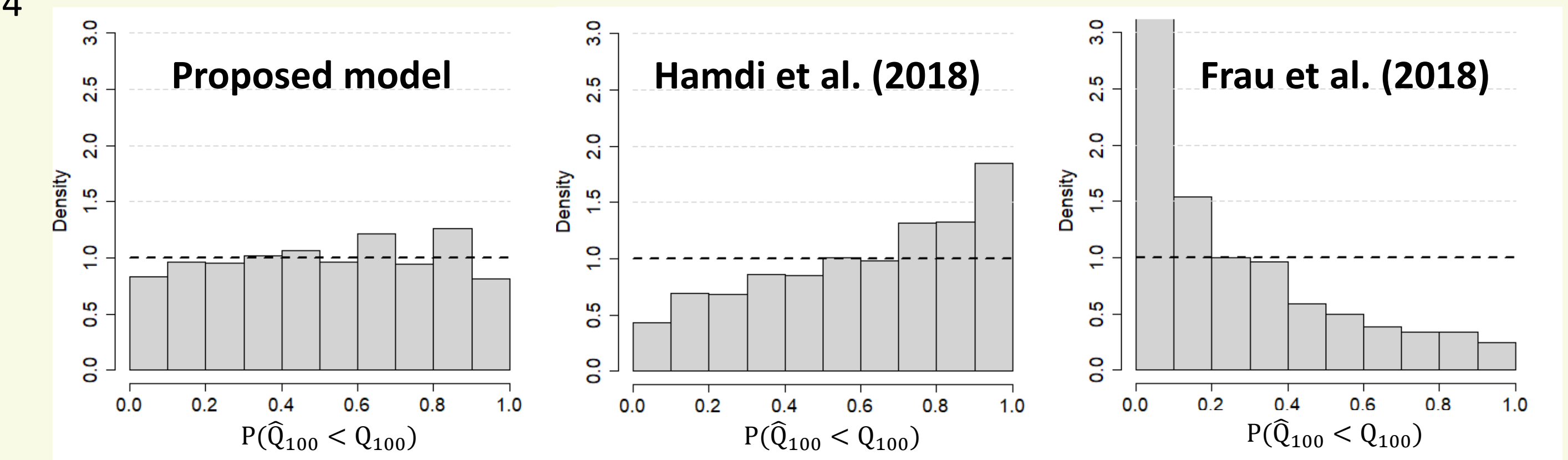
- Systematic period (1941 – 2017):  $w_S = 32.58$  years,  $\mu = 0.62$  m,  $n = 34$
- Historical period (1866 – 1940):  $w_H = 80$  years,  $\eta_H = 7.15$  m,  $h = 4$  (7.15m - 7.15m - 7.30m - 7.40m)

Fig 1. Accuracy of the 100-year quantile and the parameters estimated based on the maximum likelihood



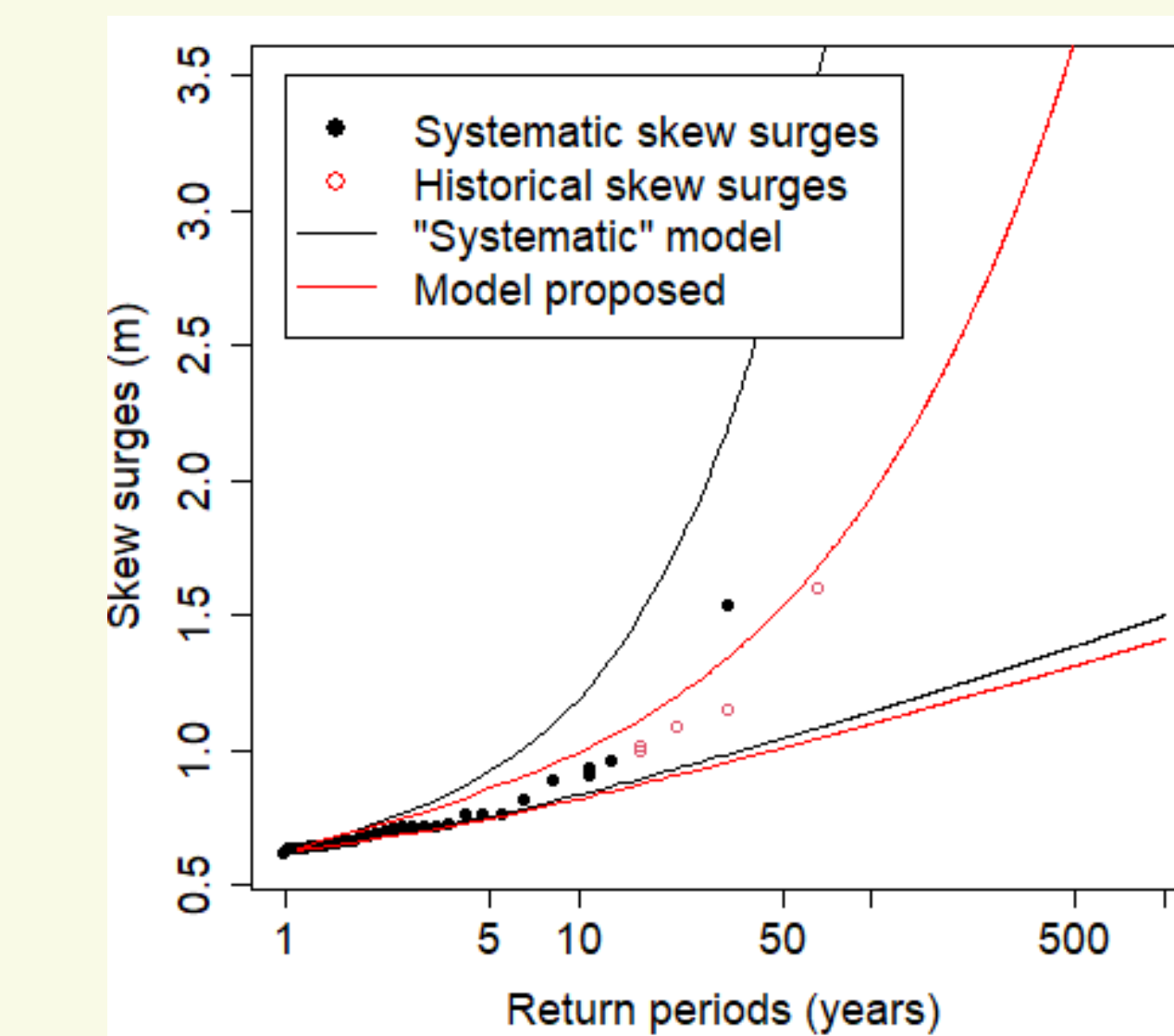
- The proposed model provides unbiased estimates with the ML (compared to the previously published methods) and reduces the uncertainties especially of the 100-year quantile  $Q_{100}$  and the shape parameter  $\xi$  of the skew surge distribution.

Fig 2. Rank histograms



- $P(\hat{Q}_{100} < Q_{100})$  is uniformly distributed. The posterior credibility intervals for the 100-year quantile seem accurate with the proposed model but not with the previously published methods.

Fig 3. Adjusted statistical models for the observed series at La Rochelle



- The credibility intervals obtained with the proposed approach well fit the data.
- Integrating historic sea levels with the proposed model allows to decrease the width of the credibility intervals.

## CONCLUSION

- The proposed approach combines, in a single Bayesian inference, skew surges for the recent period and record sea levels for the historical period.
- It has been successfully tested and applied to four different sites located on the French Channel and Atlantic coast (La Rochelle illustrated here). Unlike some other previously published methods, it provides unbiased quantile estimates and accurate credibility intervals.
- For more details, an article will come soon...

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