SyntheSeas: A stochastic simulation model of benchmark sea state time series

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Outline

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- State of the art in generation of synthetic sea states
- Methodology: a tailored IAAFT approach
- Results
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Motivation and Aim

Long-term (multi-years, decadal) modelling of beach evolution requires the description of sea states over the time frame of the prediction.

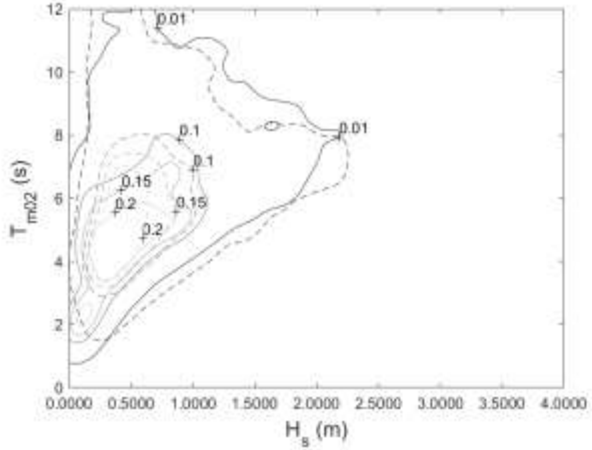
Methods to provide synthetic sea states are well developed, however:

-Excessive simplification in storms characteristics leads to inaccurate modelling of shoreline evolution (e.g. see Duo et al. 2020)

-Most of existing models rely on complex methods, sub-models, ad-hoc parametrisation.

-Wave direction variability is never modelled at high temporal resolution (hours)

Aim: to develop a methodology to generate synthetic multivariate sea state time series with as little assumptions/ad-hoc parametrisation as possible



Reference:

Duo, E., Sanuy, M., Jiménez, J. A., & Ciavola, P. (2020). How good are symmetric triangular synthetic storms to represent real events for coastal hazard modelling. Coastal Engineering, 159, 103728.

State of the art in generation of synthetic sea states

We consider multi-annual time series of the significant wave height (H_{m0}), the mean spectral period (T_{m02}), and mean wave direction of propagation (Θ_m)

We identified two broad classes of approaches:

-Event based modelling: time series are described as alternating storms and calm periods. Storms are identified using a threshold and the parameters relevant to erosion are computed using stochastic methods, their joint dependence is modelled using copulas (e.g. Callaghan et. al., 2008; Davies et al., 2017). Interarrival time is usually modelled assuming a Poisson distribution.

-Complete time series modelling: the multivariate time series of, typically, H_{m0}, Θ_m, and a spectral period are modelled, trying to preserve the autocorrelation of each variable, the cross-correlation among variables, and their marginal distributions (e.g. Jager et al., 2019).

While the former is a more practical approach and focuses on modelling the more energetic (erosive) events, the latter is more flexible and does not require threshold that are site-specific.

Reference:

Callaghan, D. P., Nielsen, P., Short, A., & Ranasinghe, R. W. M. R. J. B. (2008). Statistical simulation of wave climate and extreme beach erosion. Coastal Engineering, 55(5), 375-390.

Davies, G., Callaghan, D. P., Gravois, U., Jiang, W., Hanslow, D., Nichol, S., & Baldock, T. (2017). Improved treatment of non-stationary conditions and uncertainties in probabilistic models of storm wave climate. Coastal Engineering, 127, 1-19.

Jäger, W. S., Nagler, T., Czado, C., & McCall, R. T. (2019). A statistical simulation method for joint time series of non-stationary hourly wave parameters. Coastal Engineering, 146, 14-31.

State of the art in generation of synthetic sea states

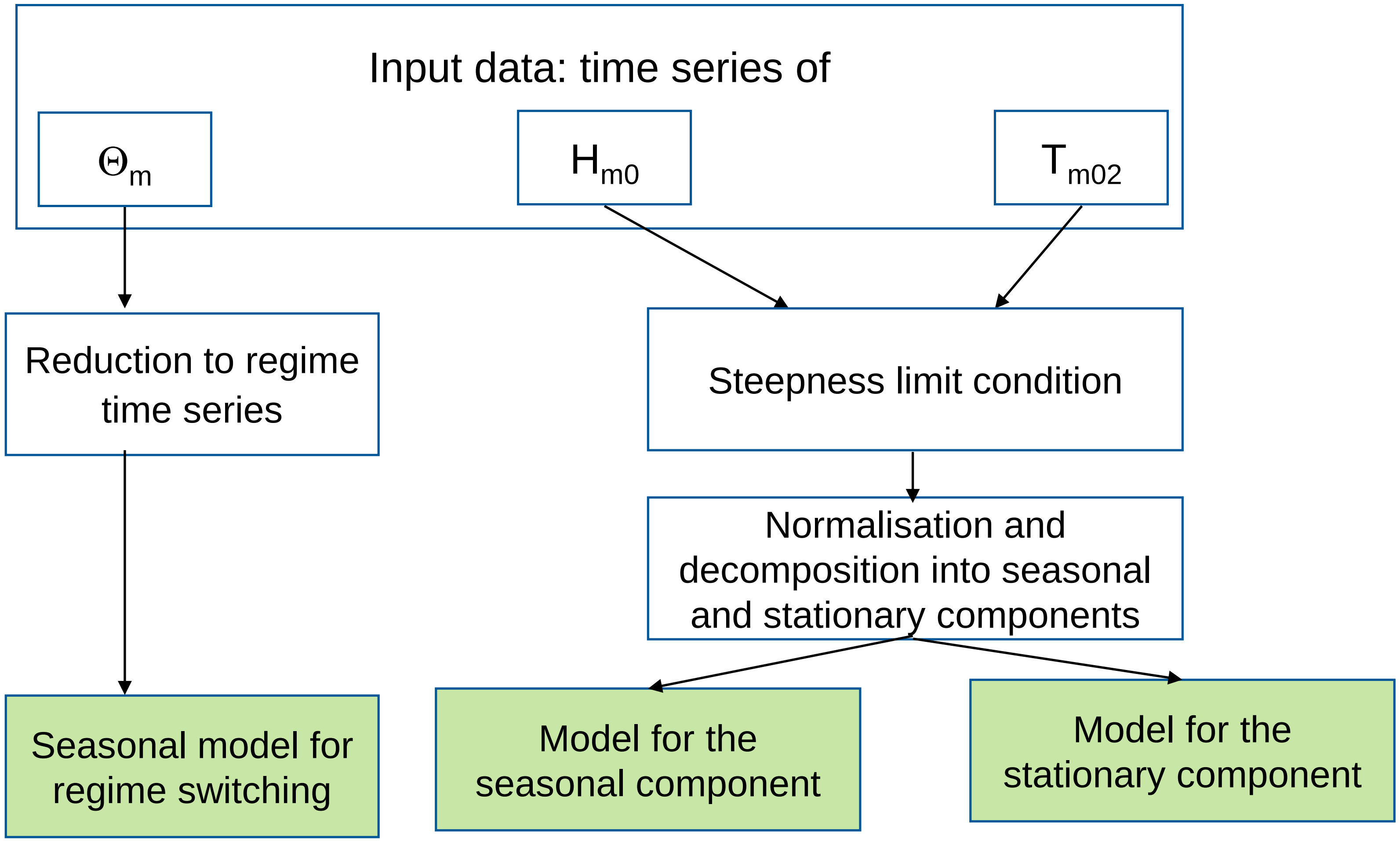
We focus on **complete sea state time series simulation**
Example methodology of complete time series modelling (adapted from Jager et al. 2019).

Existing models are generally accurate but:

-increased complexity due to sub-models

-need for limiting conditions.

-wave direction modelling over-simplified.

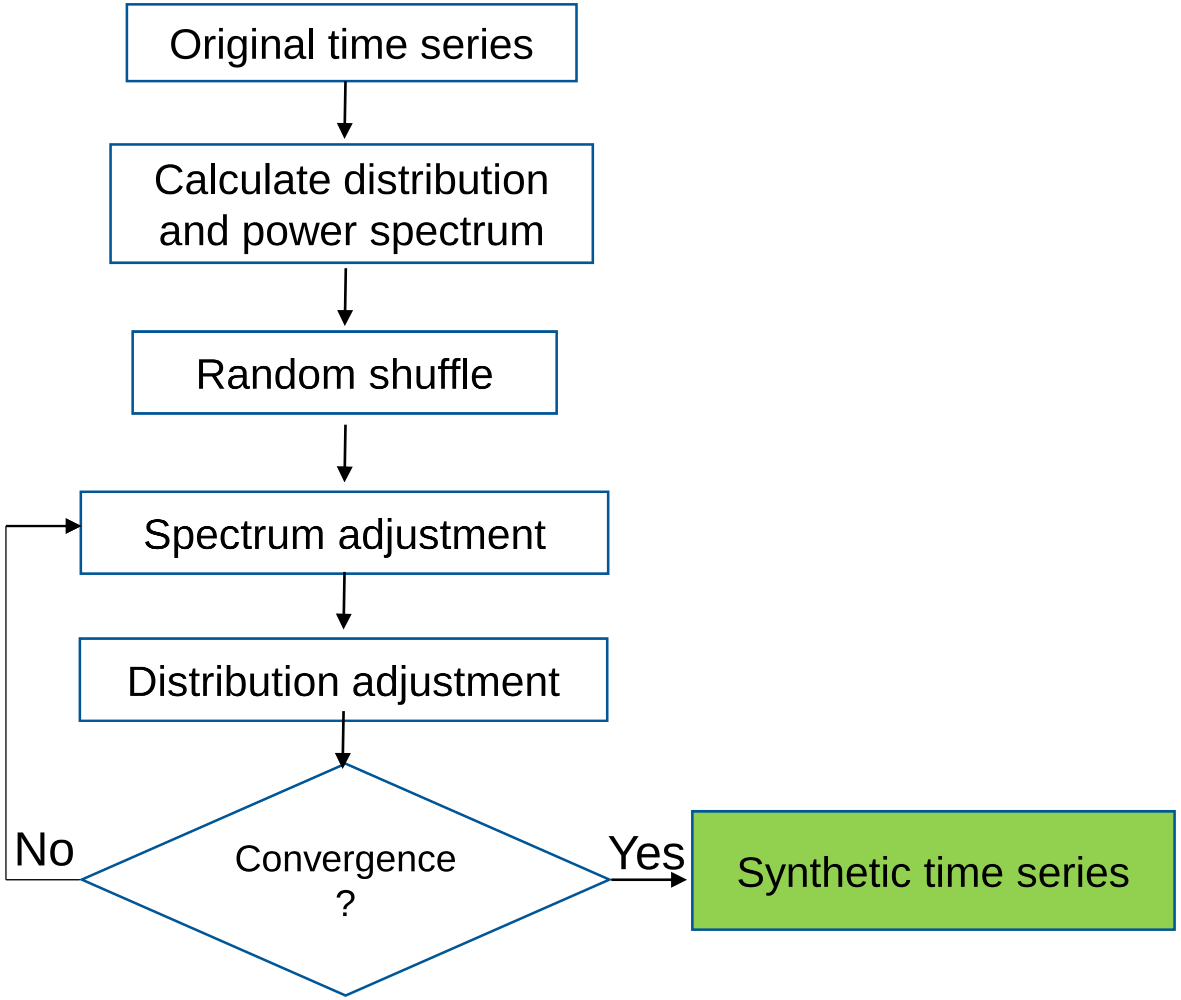


Methodology: a tailored IAAFT approach

Iterative Amplitude Adjusted Fourier Transform (IAAFT) allows the simulation of synthetic sequences preserving the empirical marginal distribution and approximate the empirical power spectrum of the original data

T. Schreiber; A. Schmitz (1996). "Improved Surrogate Data for Nonlinearity Tests". Phys. Rev. Lett. 77 (4): 635–638..

A basic IAAFT algorithm is shown



For sea state time series:

-We followed Serinaldi and Lombardo (2017), who used IAAFT to simulate time series with a prescribed marginal distribution and correlation structure, allowing to simulate values beyond the observed range. This is done by applying the quantile function proposed by Hutson (2002) to obtain auxiliary sequences of unobserved quantiles for the initial time series (not a simple random shuffle)

-The steepness *s* is expressed as a function of H_{m0} and T_{m02} (linear theory $s = \frac{2\pi H_{m0}}{g T_{m02}^2}$) and used to find T_{m02} once H_{m0} is known.

-Instead of Θ_m we use the variable $Z_m = \sin(\Theta_m - \mu)$, where μ is the Θ_m conditional mean.

Methodology: a tailored IAAFT approach

SyntheSeas algorithm

Input data: time series of n values of

Θ_m | H_{m0} | T_{m02}

Compute *s and Z_m*

Compute FT of original time series of H_{m0}, T_{m02}, and Z_m

Generation of a starting series of H_{m0} and T_{m02} using Hutson quantiles. Shuffle Z_m Compute FT.

Iteration b (b=0,1,2,..)

Use the bth FT phases and the original amplitudes to generate (b+1)th series of H_{m0}, T_{m02}, and Z_m

Adjust the distribution of H_{m0} and T_{m02} by rank matching the prime series with (b+1)th series,

Compute s for the ranked pairs and adjust T_{m02} so that *s* distribution matches the original series.

Adjust the distribution of Z_{m0} by rank matching the prime series with (b+1)th series. New series of Θ_m selecting the original values of Θ_m corresponding to each element of the adjusted Z_m series

MAE^{b+1}-MAE^{b}<10^{-4}

No

Yes

Synthetic time series

We call these series the prime (‘) series. H_{m0} and $T_{m0.}$ have marginal distributions very close to those of the observed time series with potential values beyond the observed range

Each iteration generates the (b+1)th series

These intermediate sequences have the desired marginal power spectra and cross-spectra, but their marginal distributions have been modified.

These steps generate more intermediate series

This step assures that the steepness limiting condition is satisfied.

This step yields the sequences of wave directions corresponding to series of Θ_m preserving circular autocorrelation .

Adjusting marginal distributions modifies the spectrum. We check convergence

Results

We simulated time series of sea states at four locations around the U.K.

CEFAS Wavenet data are used, spanning the intervals below
(some locations used in Bricheno and Wolf, 2018).

Buoy	Latitude	Longitude	Start date	End date
Dowsing	53°31′.88N	1°03′.20E	30 December 2003	Present
Poole Bay	50°38′.02N	1°43′.13W	17 December 2003	Present
Liverpool Bay	53°32′.01N	3°21′.30W	13 November 2002	Present
West of Hebrides	57°17′.53N	7°54′.85W	23 February 2009	Present

Reference:
Bricheno, L. M., & Wolf, J. (2018). Future wave conditions of Europe, in response to high-end climate change scenarios. Journal of Geophysical Research: Oceans, 123(12), 8762-8791.

Results

Results for H_{m0}.

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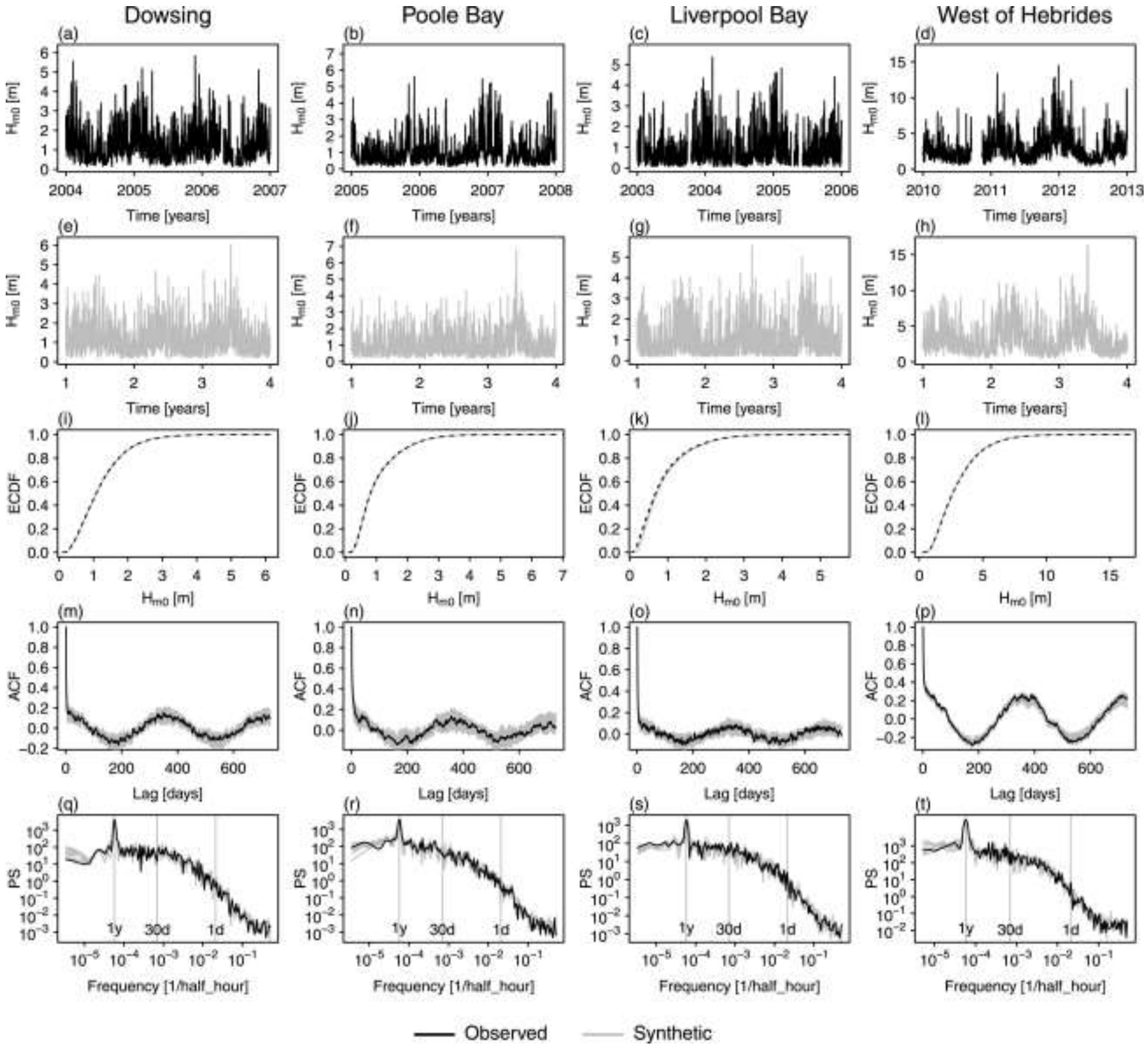

Results

Results for T_{m02}.

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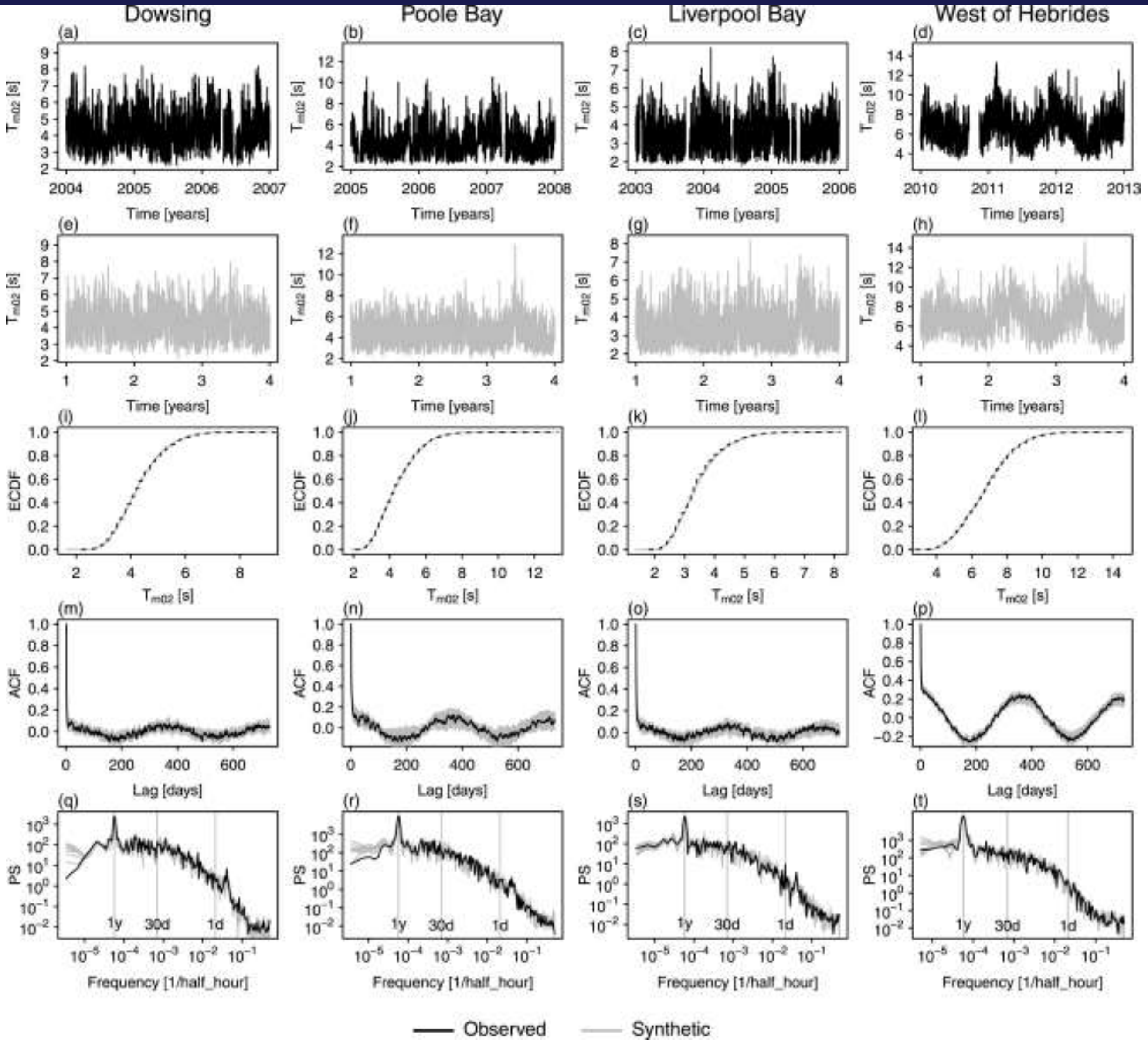

Results

Results for Θ_m.

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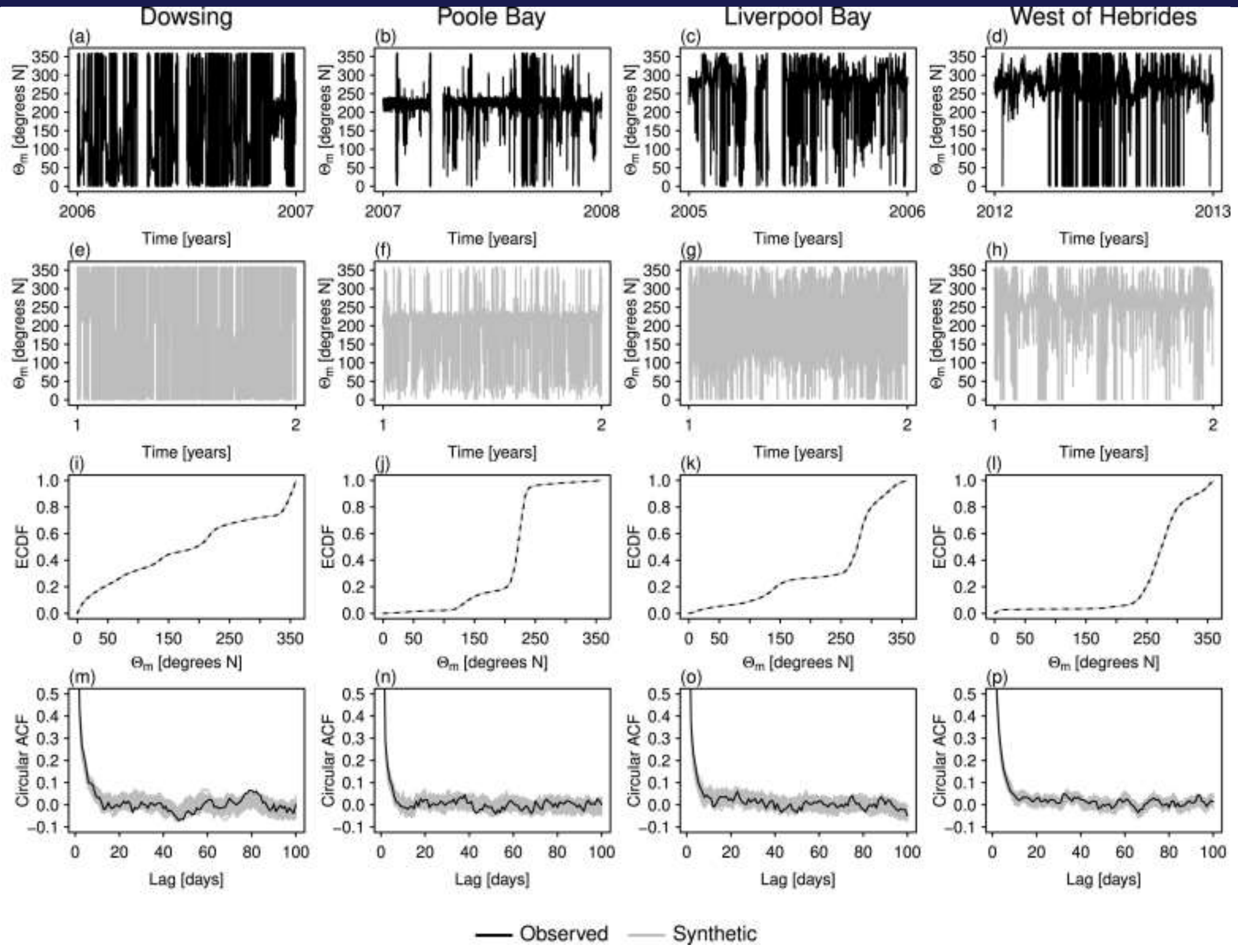

Results

Scatter plots and density contours: H_{m0} and T_{m02}.

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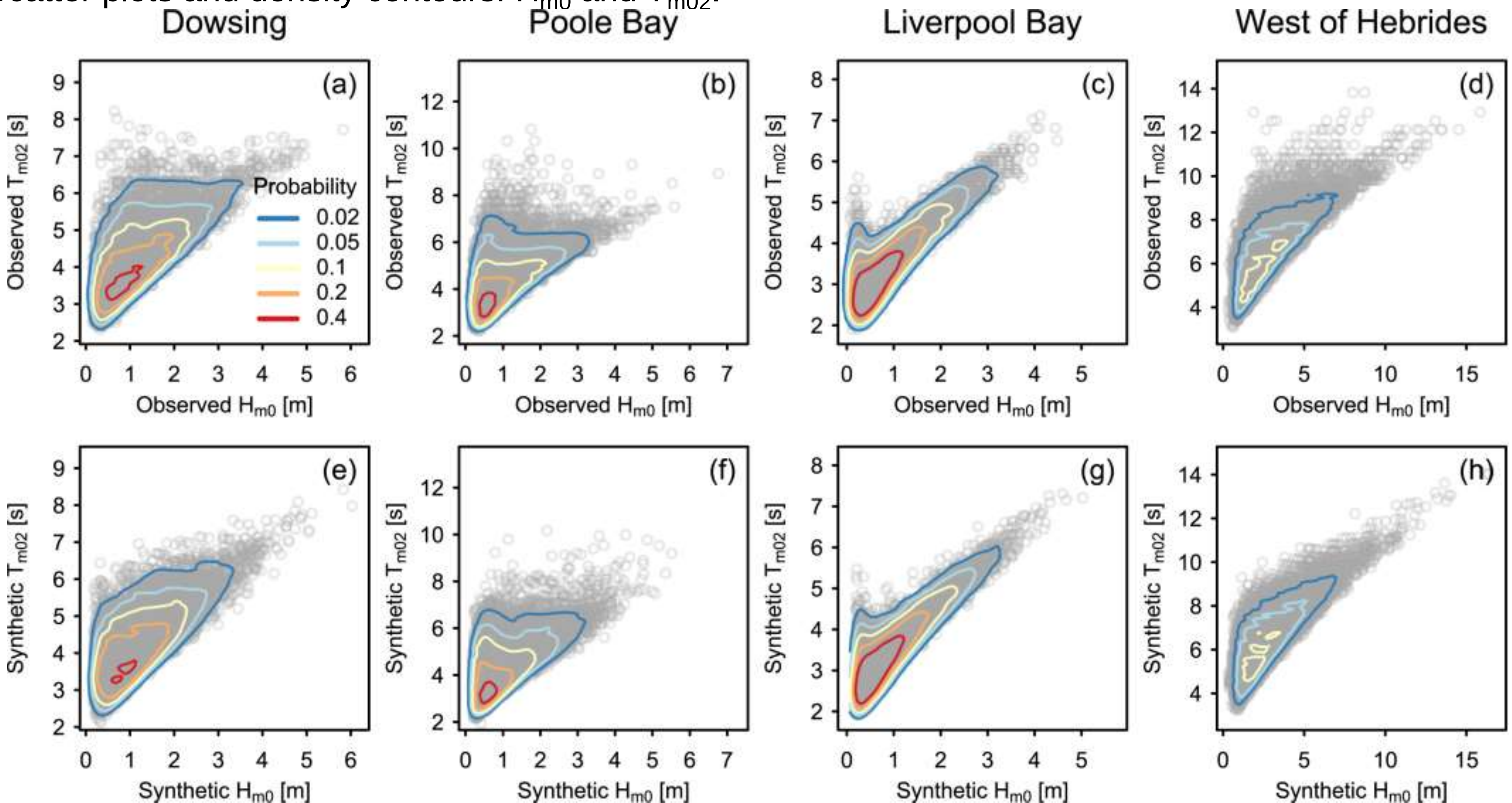

Results

Scatter plots and density contours: Θ_m.

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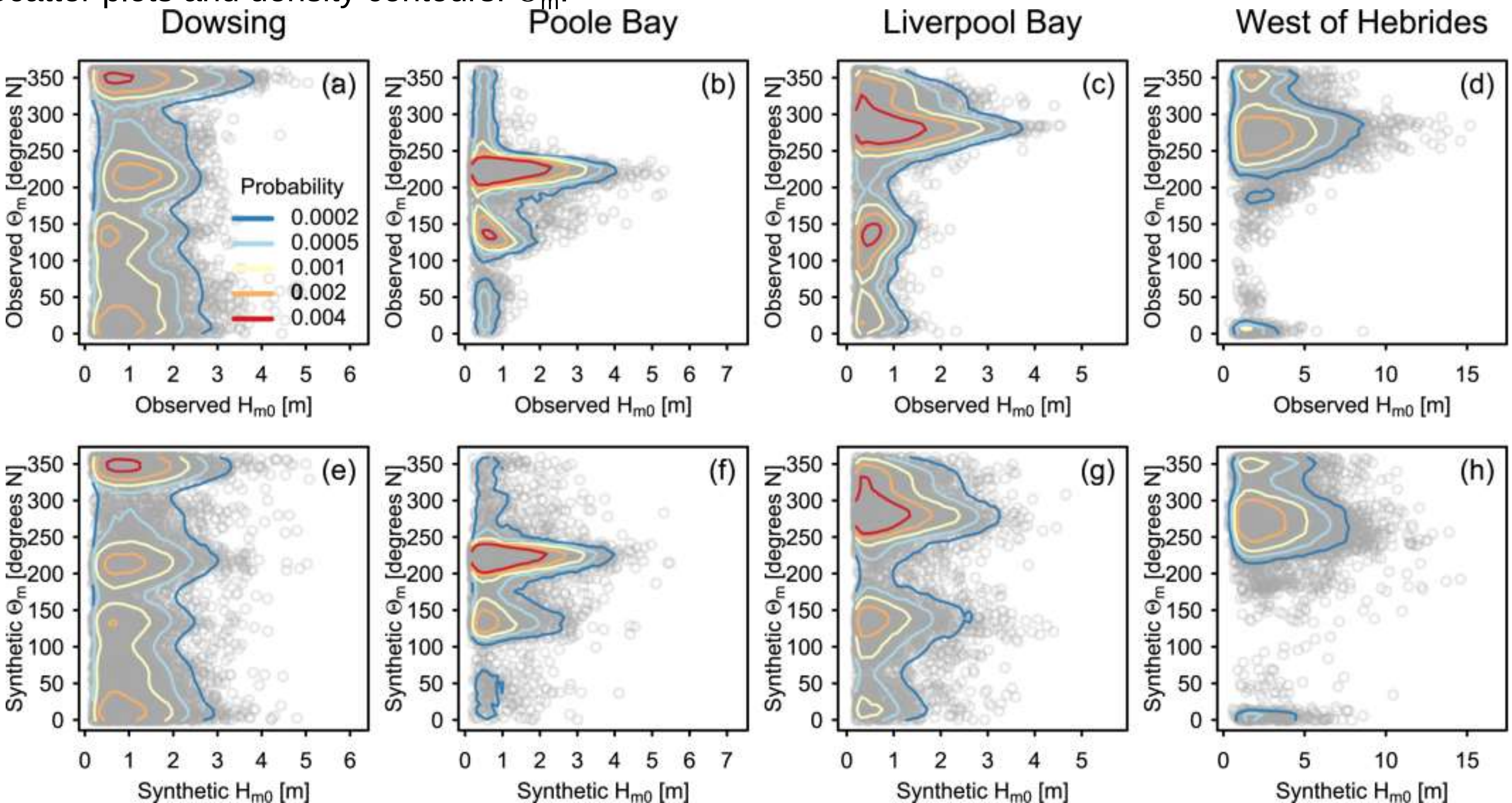
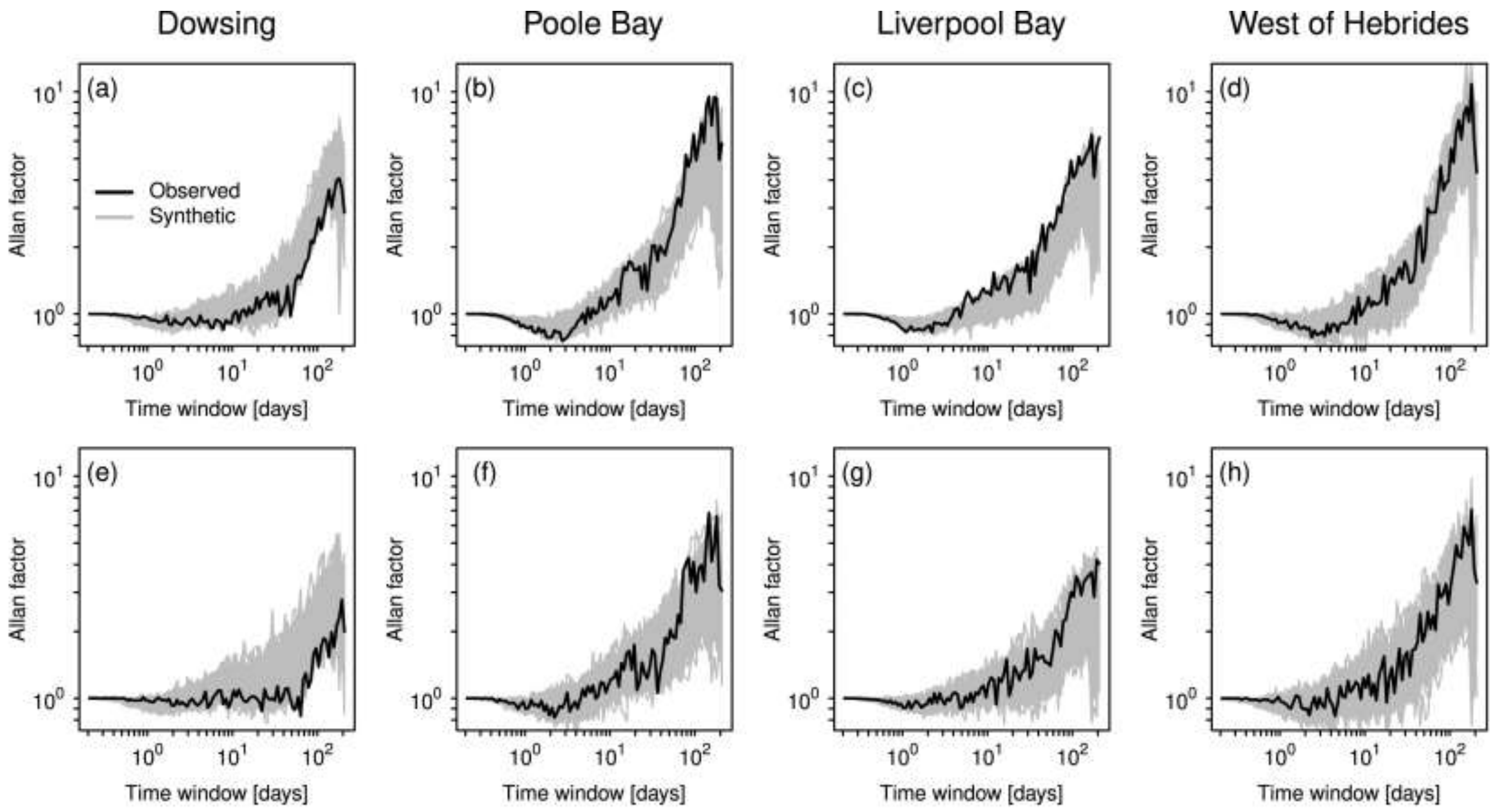


Results

Allan Factor (AF): statistic widely used to assess if the rate of occurrence of a certain event follows a homogeneous Poisson distribution (AF constant). If the AF is not constant for certain time scales, events tend to show clusters.



Events characterized by H_{m0} exceeding two percentile thresholds: 98% (a–d), and 99.5% (e–h).

Conclusions

- We attempted to define the conceptually simplest technique to draw synthetic samples mimicking as much as possible the observed behaviour of H_{m0}, T_{m02}, and. Θ_m.

- SyntheSeas accurately estimates key characteristics of the observed sea state time.

- Our results show that the statistical properties of both duration and inter-arrival times of sea states over high thresholds are captured as well as wave steepness limits.

- SyntheSeas can be used in various applications, such as a quick sensitivity analysis or preliminary design without requiring advanced statistical background, which instead is needed to fit highly parametrised models.

- Inclusion of climatic trends and replacement of empirical spectra with parametrised ones can be achieved to give the method more flexibility.

Reference:

Serinaldi, F., Briganti, R., Kilsby, C. G., & Dodd, N. (2022). Sailing synthetic seas: Stochastic simulation of benchmark sea state time series. Coastal Engineering, 176, 104164.