UNIVERSITY OF EXETER

Direct IFORM:

High-dimensional environmental contours from short datasets

Ed Mackay

TIGER TIDAL STREAM INDUSTRY ENERGISER

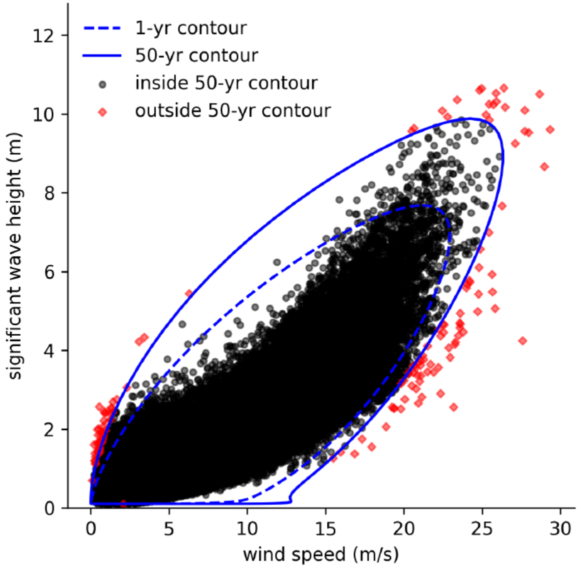
9th PRIMaRE Conference on Marine Renewable Energy
6th & 7th July 2022, University of Exeter Cornwall Campus

Interreg France (Channel Manche) England
EUROPEAN UNION
European Regional Development Fund

Designing for extreme loads

- Design of ORE structures requires estimates of joint extremes of environmental variables, e.g. winds, waves and tides
- Current design standards recommend use of environmental contours
- Recent benchmarking exercise demonstrated large uncertainties: $\pm 50\%$ on loads [1,2]
- Reduced uncertainty in environmental conditions leads to more efficient and reliable designs

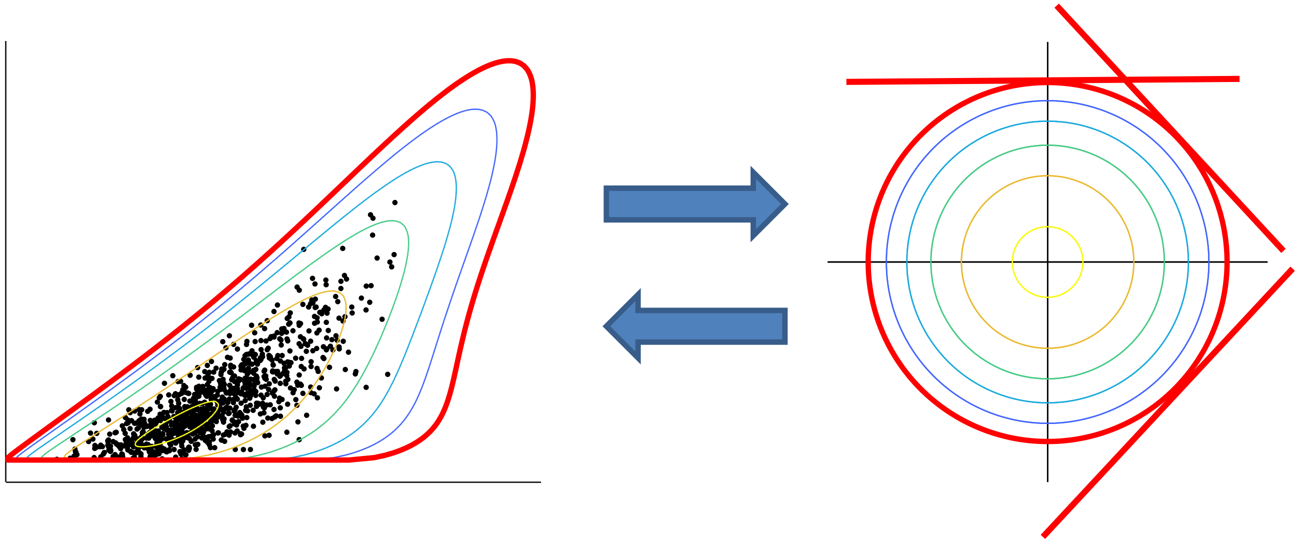
Source: Dennis Schroeder / NREL



Source: [3]

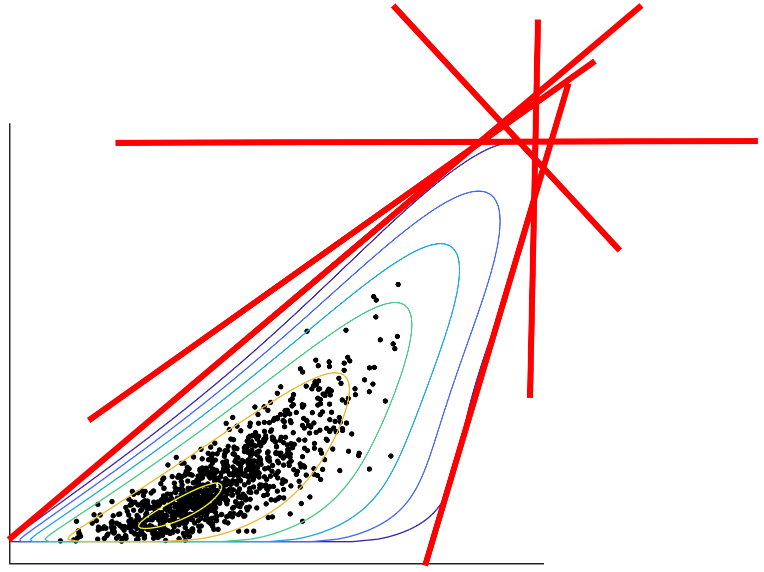
Original IFORM method: Winterstein et al. (1993)

- We don't know where the failure region is
- Aim: define a region which will exclude any convex failure region with a given return period
- Procedure:
    1. Fit joint model
    2. Transform to independent normal variables (Rosenblatt transformation)
    3. Intersection of regions containing probability α forms a circle
    4. Apply inverse transformation to obtain contour



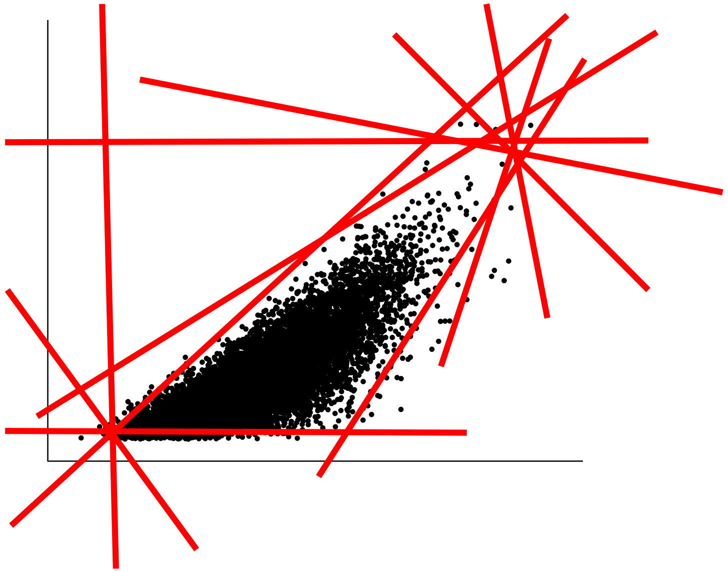
Monte Carlo Sampling Method: Huseby & Vanem (2013)

- Observation: This is silly
- No need to transform to normal space
- Just calculate exceedance regions in original space by simulating from joint model
- Contour is intersection of non-exceedance regions



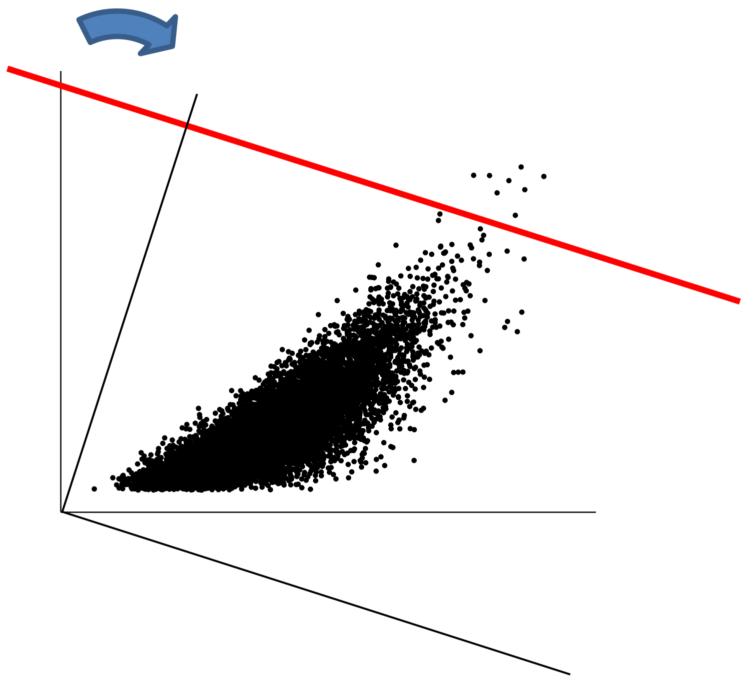
Direct IFORM:
Derbanne & de Hauteclocque (2019)

- Observation: This is still silly
- Exceedance regions are univariate regions under rotations of the axes
- No need to fit joint model
- Apply standard univariate peaks-over-threshold analysis at a range of angles
- Accounts for serial correlation – reduces bias [7]



Further observations

- D-IFORM method reduces problem to a series of univariate problems at various angles
- All data points used at each angle
- No loss of data with additional angles/dimensions
- Method can be applied in arbitrary dimensions
- Limitation becomes computational:
  - Number of angles
  - Corresponding number of load cases



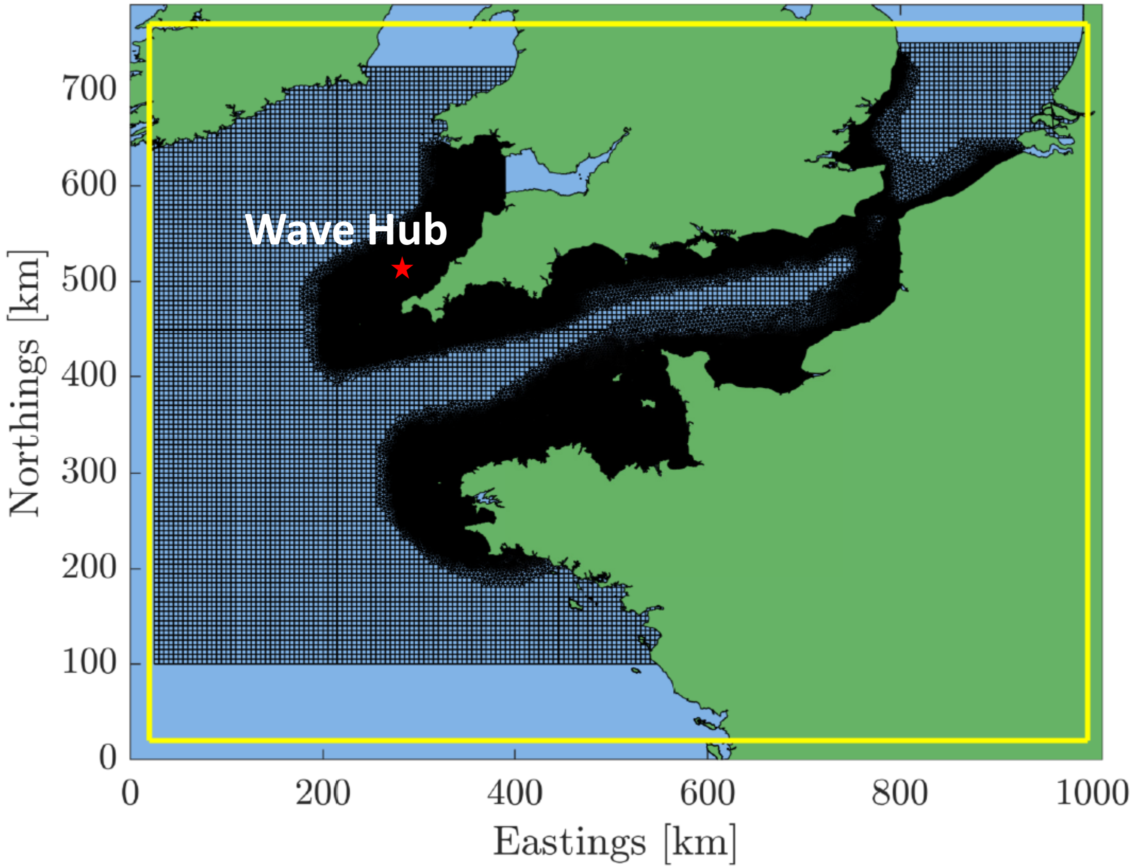
Example: joint extremes of winds and waves

- 4-dimensional problem:
  - Wind speed, U_{10}
  - Significant wave height, H_s
  - Mean wave period, T_m
  - Wind-wave misalignment direction, θ_{rel}
- Directions are periodic and defining “extreme directions” does not make sense
- Work with components of wave height in line and transverse to wind direction instead:

$$H_{long} = H_s \cos(\theta_{rel}), \qquad H_{trans} = H_s \sin(\theta_{rel})$$

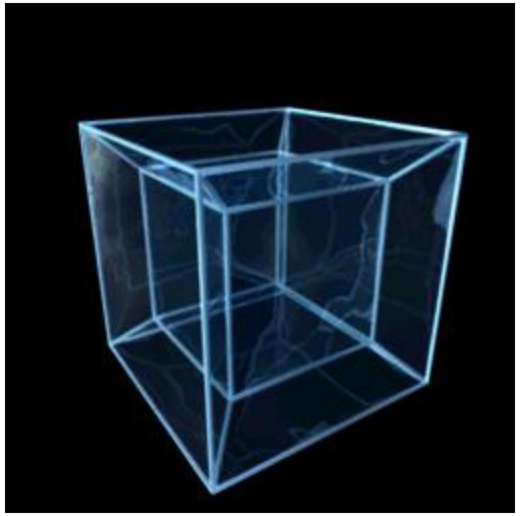
Application

- 31-year wind-wave-current hindcast
- Analysis for floating wind test site off Cornish coast
- Contours derived using angular spacing of ~10° in each dimension
- 2720 direction vectors
- Approx. 30 s computational time



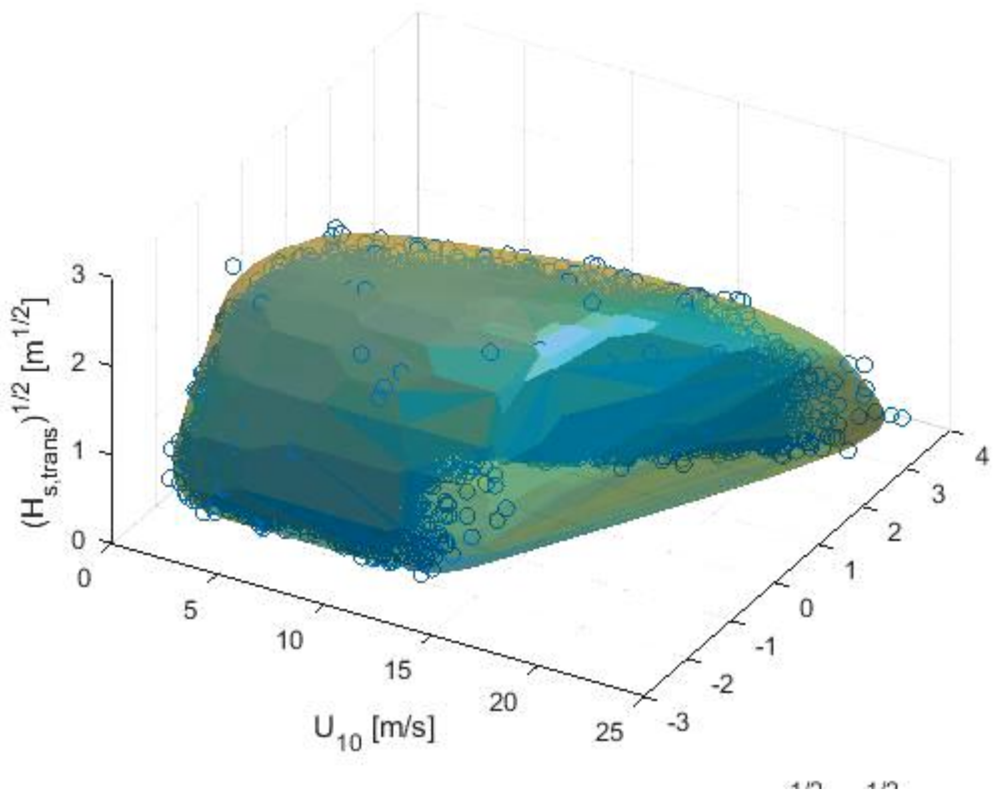
Visualisation

- Tricky for 4-dimensions
- Options include
  - Projections into 3D or 2D
  - Slices through variable space
  - Using colour as a variable
- There are many ways to slice a 4-dimensional pie



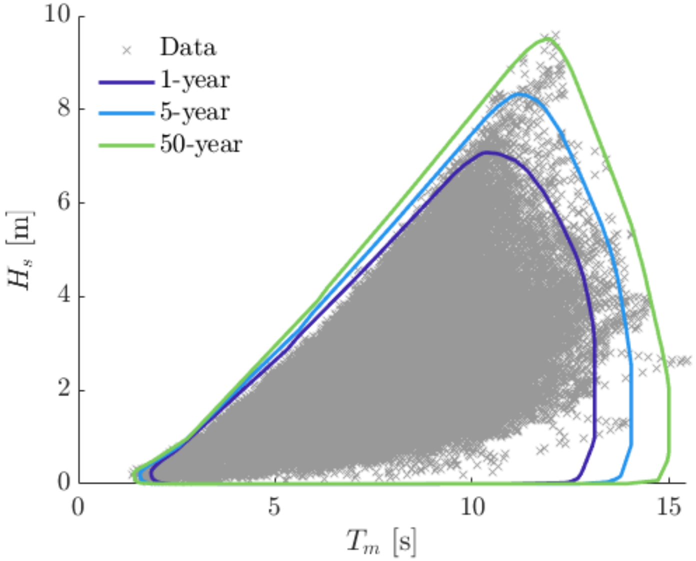
"I'll take your brain to another dimension"
The Prodigy

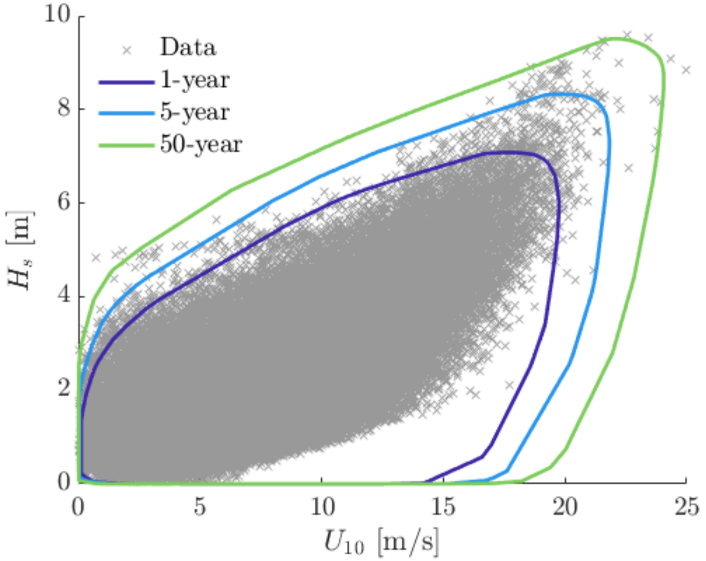
3D projection of 50-year surface

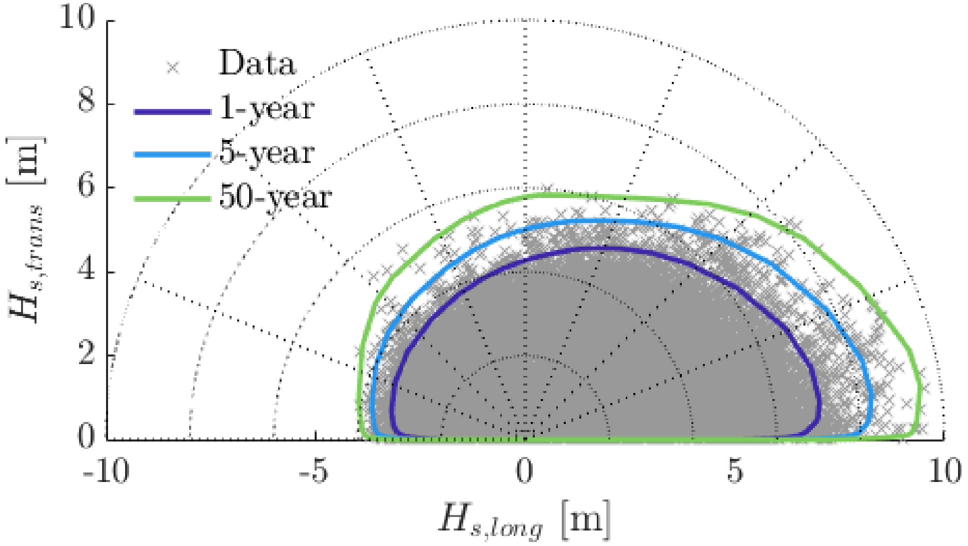


- Circles: observations
- Surface: 50-year contour
- Hollow centre not important for extremes
- Want to know return value of largest H_s at given U_{10} and θ_{rel}

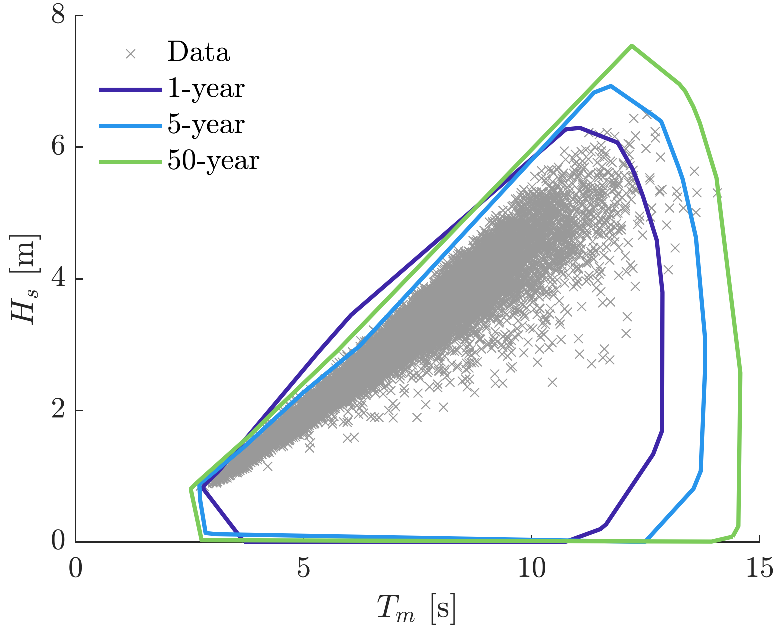
2D projections

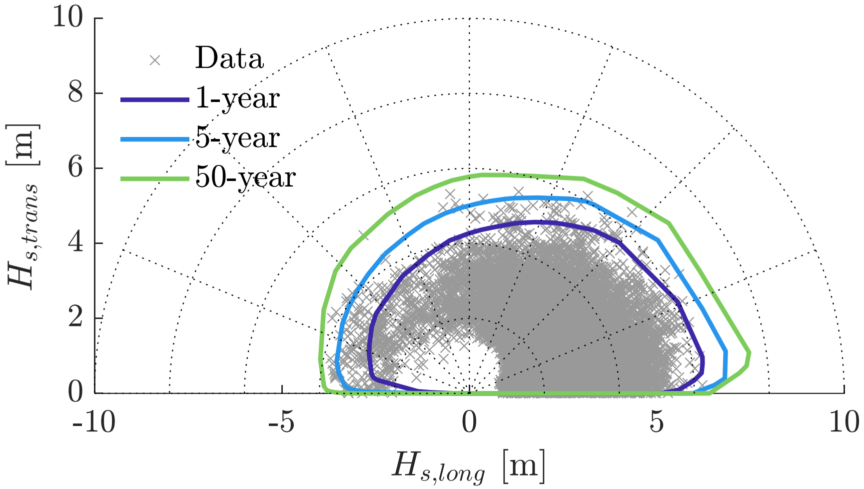






Slices: $10 \leq U_{10} \leq 12$ m/s





- This is around rated wind speed for an offshore wind turbine, where largest loads may occur
- We are interested in extreme H_s at given period or direction – lower values are not important

Conclusions & further work

- Direct IFORM provides rational approach for selecting extreme combinations of environmental variables for design of ORE structures
- No assumptions required about dependence structure
- Method can be applied in higher dimensions with no degradation in performance
- Previous work showed that short-term variability in the response is large source of uncertainty for offshore wind [8]
- Future work will investigate how contours can be used to determine conditions to characterise short-term response function and combine with data to obtain long-term extreme response

References

1. A.F. Haselsteiner, R.G. Coe, L. Manuel, W. Chai, B. Leira, G. Clarindo, C. Guedes Soares, Á. Hannesdóttir, N. Dimitrov, A. Sander, J.H. Ohlendorf, K.D. Thoben, G. de Hauteclocque, E. Mackay, P. Jonathan, C. Qiao, A. Myers, A. Rode, A. Hildebrandt, B. Schmidt, E. Vanem, A.B. Huseby, (2021). "A benchmarking exercise for environmental contours", Ocean Eng. 236, 109504. https://doi.org/10.1016/J.OCEANENG.2021.109504
2. G. de Hauteclocque, E. Mackay, E. Vanem, (2022). "Quantitative assessment of environmental contour approaches". Ocean Eng. 245, 110374. https://doi.org/10.1016/j.oceaneng.2021.110374
3. A.F. Haselsteiner, R.G. Coe, L. Manuel, P.T.T. Nguyen, N. Martin, A. Eckert-Gallup, (2019). "A benchmarking exercise on estimating extreme environmental conditions: Methodology & baseline results" 38th Int. Conf. Ocean. Offshore Arct. Eng., OMAE2019. https://doi.org/10.1115/OMAE2019-96523
4. Winterstein SR, Ude TC, Cornell CA, Bjerager P, Haver S (1993). Environmental parameters for extreme response: inverse FORM with omission factors. In: Proc. 6th Int. Conf. on Structural Safety & Reliability (ICOSSAR 93).
5. Huseby AB, Vanem E, Natvig B (2013). A new approach to environmental contours for ocean engineering applications based on direct Monte Carlo simulations. Ocean Eng. 60, 125–35. https://doi.org/10.1016/j.oceaneng.2012.12.034
6. Derbanne Q, de Hauteclocque G (2019). A new approach for environmental contour and multivariate de-clustering. In: 38th Int. Conf. on Ocean, Offshore & Arctic Eng. https://doi.org/10.1115/OMAE2019-95993
7. E. Mackay, G. de Hauteclocque, E. Vanem, P. Jonathan, (2021). "The effect of serial correlation in environmental conditions on estimates of extreme events". Ocean Eng. 242, 110092. https://doi.org/10.1016/j.oceaneng.2021.110092
8. A.F. Haselsteiner, M. Frieling, E. Mackay, A. Sander, K.D. Thoben, (2022). "Long-term extreme response of an offshore turbine: How accurate are contour-based estimates?". Renew. Energy. 181, 945–965. https://doi.org/10.1016/j.renene.2021.09.077

Thanks for your attention!

e.mackay@exeter.ac.uk