How extreme can storms get in space and time?

RACEWIN project

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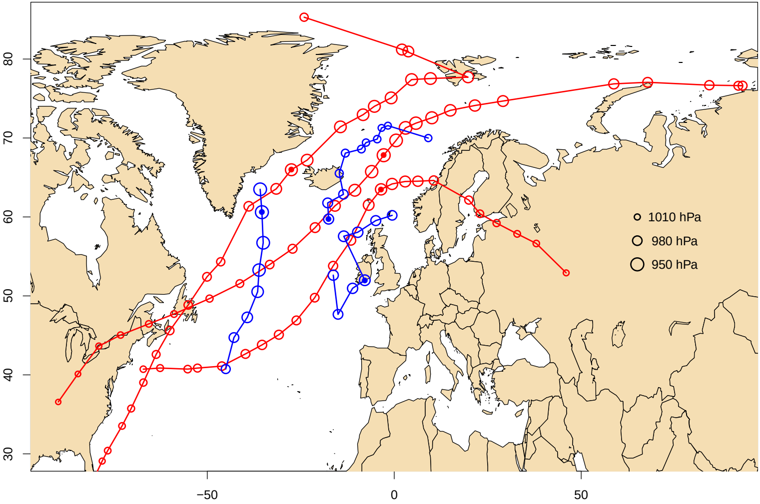
- In the absence of reliable physical arguments, we need to estimate bounds empirically using statistical approaches and extreme value theory.

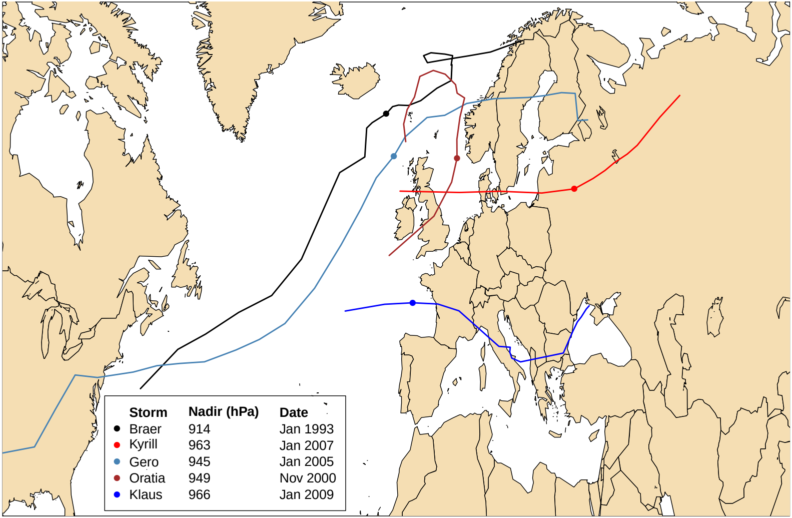
Data: Storm tracks from 30-year (1979-2009) reanalysis NCEP-CFS*

- Sea Level Pressure (SLP) used as measure of storm intensity along tracks.
- Storm tracks in Jan 1993 (+ve NAO phase) and in Jan 1985 (-ve NAO).
- The **nadir**, the minimum SLP value along each track, is marked with a solid circle.



* Thanks to Kevin Hodges for providing the tracks

Some “famous” storms in the reanalysis tracks.



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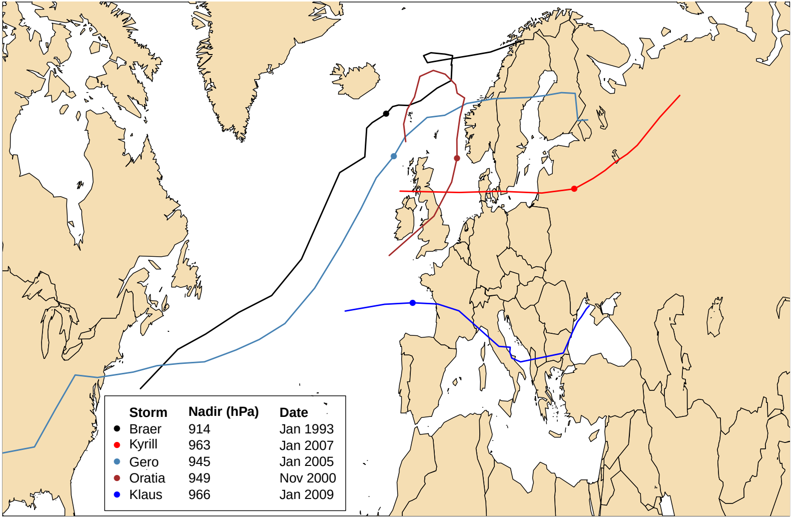
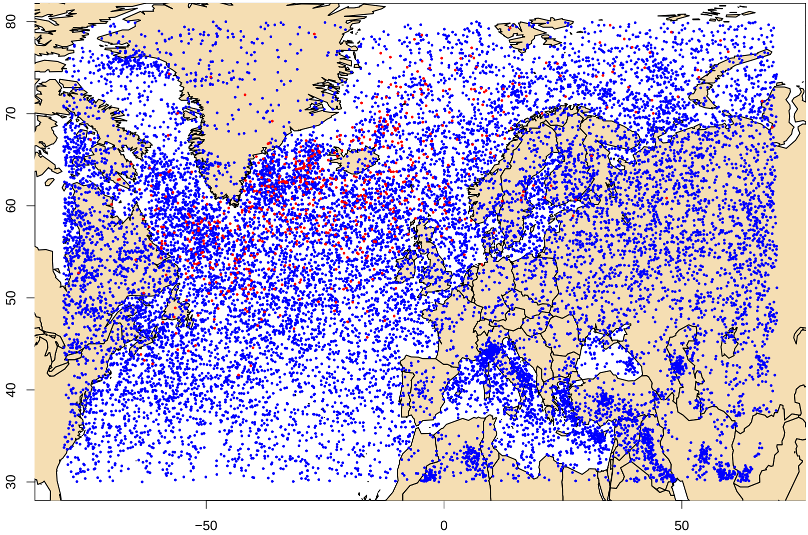


- Interested in how low storm pressure can get, so investigate nadirs.

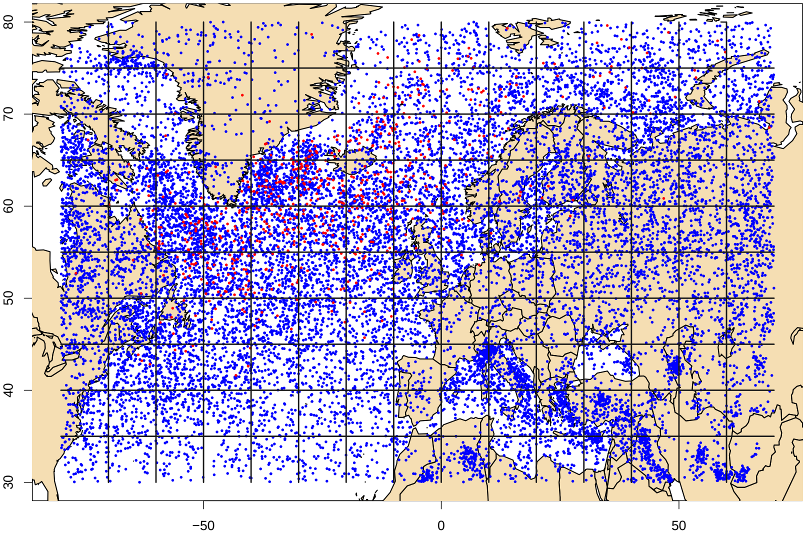
How low can nadirs get?

- Want to investigate extreme nadirs e.g SLP $<$ 960hPa.
- How low storms get varies with space.

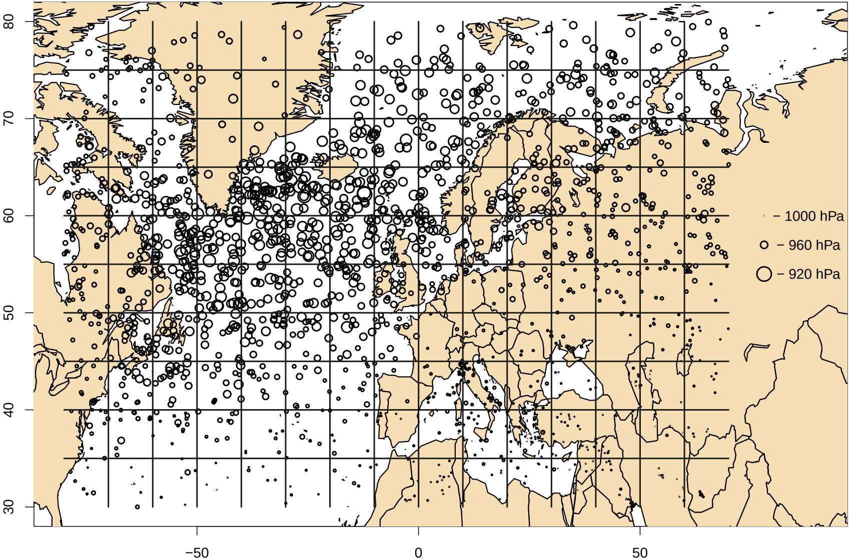


Spatially varying threshold to define extreme nadirs

- Discretise space by imposing a grid.
- Extremeness defined with respect to grid cells (nadirs below the 10% empirical quantile).

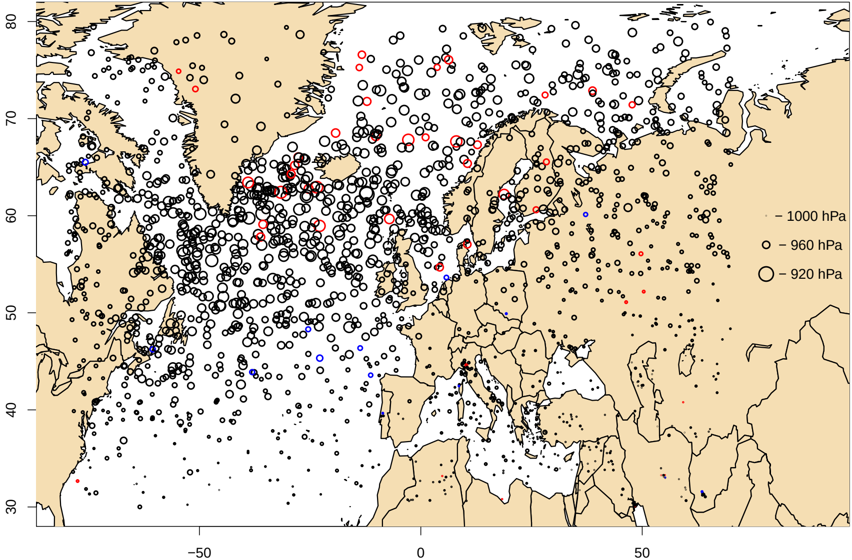


Extreme nadirs



- Not many data points in some cells so need to pool information across cells

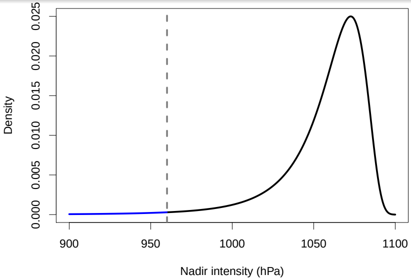
Extreme nadirs



- Red colour implies NAO > 1.6, Blue colour implies NAO < -1.6

Extreme value modelling

- Interested in capturing the tails of the nadir intensity distribution



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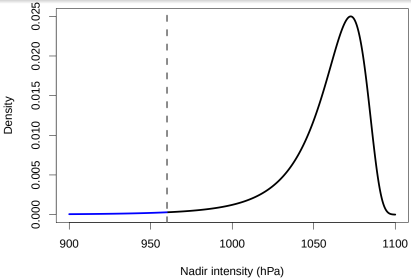

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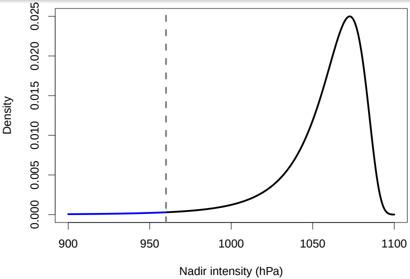

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  - σ, the scale parameter;

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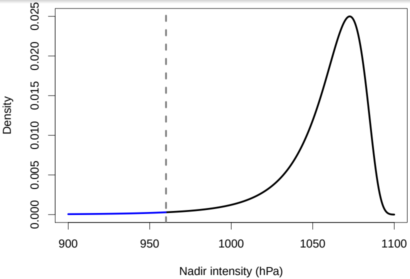

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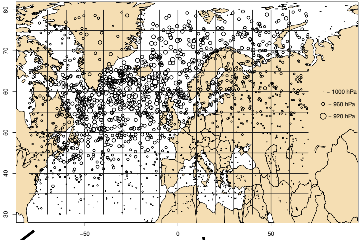
  - μ, the location parameter;
  - σ, the scale parameter;
  - and ξ, the shape parameter which controls the "tails". In particular, if $\xi < 0$ then the distribution has an upper bound or a lower limit of nadir pressure.

Bayesian hierarchical model for extreme nadirs



~ GEV distribution

μ

- **Varies spatially across grid cells**
- **Pooling information across neighbouring grid cells**
- **Varies with latitude**
- **Varies with NAO**
- **Different NAO effect in each grid cell**

σ

- **Varies spatially across grid cells**
- **Pooling information across neighbouring grid cells**
- **Varies with latitude**

ξ

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Mathematical formulation

- Let $X(s,t)$ denote the nadir pressure in grid cell s at occurrence time t.

- Point process (PP) model formulation (extended from Cooley and Sain*):

$$
\begin{aligned}
X(s,t)|X(s,t) < u(s) &\sim \mathrm{PP}\big(\mu(s,t), \sigma(s,t), \xi(s)\big) \\
\mu(s,t) &= \beta_0^{\mu} + \beta_1^{\mu}\mathrm{Lat}(t) + \beta_2(s)\mathrm{NAO}(t) + \theta^{\mu}(s) \\
\log(\sigma(s,t)) &= \beta_0^{\sigma} + \beta_1^{\sigma}\mathrm{Lat}(t) + \theta^{\sigma}(s) \\
\xi(s) &= \beta_0^{\xi} + \theta^{\xi}(s)
\end{aligned}
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* Cooley, D. and Sain, S.R. (2010). Journal of Agricultural, Biological, and Environmental Statistics, **15**, 381–402.

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- Each $\theta^\psi(s)$ for $\psi = \mu, \sigma, \xi$ accounts for
  - spatial variability;
  - spatial dependence (correlation) in neighbouring cells.

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- Each $\theta^\psi(s)$ for $\psi = \mu, \sigma, \xi$ accounts for
  - spatial variability;
  - spatial dependence (correlation) in neighbouring cells.
- "Random slope" $\beta_2(s) \sim \mathrm{N}(\nu, \phi^2)$ is spatially varying but unstructured where ν is the overall NAO effect on extreme storms.

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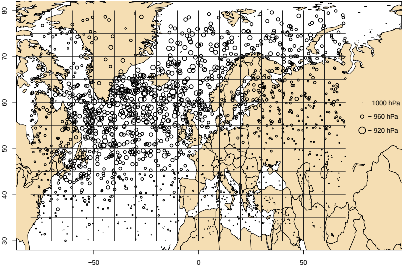
Spatial pooling

A 100-year estimated return level is the nadir pressure expected to occur once in 100 years.



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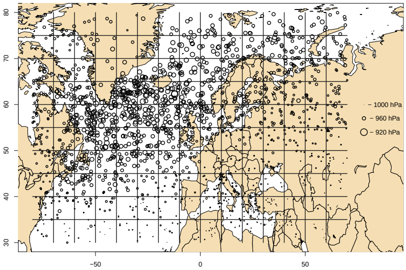

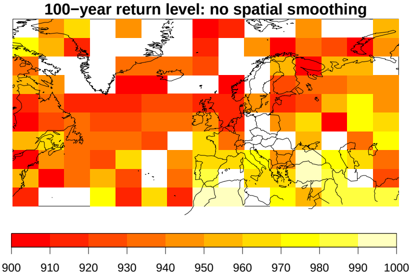

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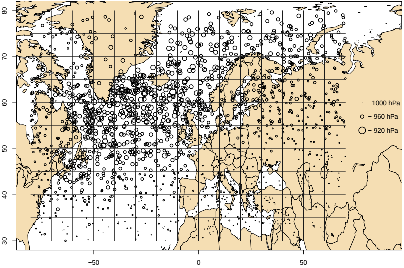

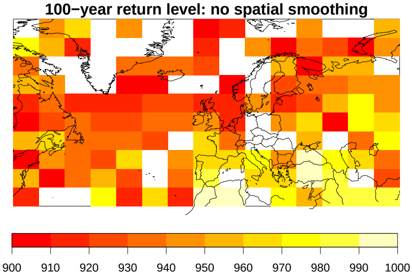

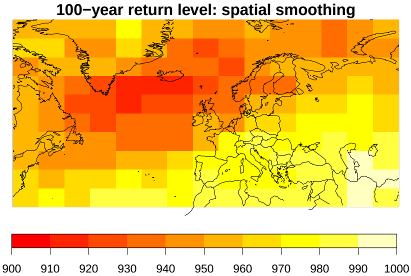

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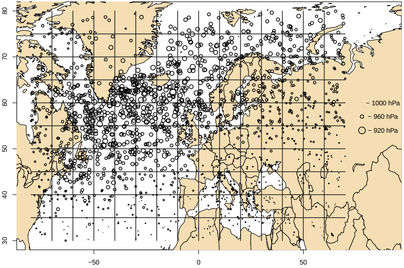
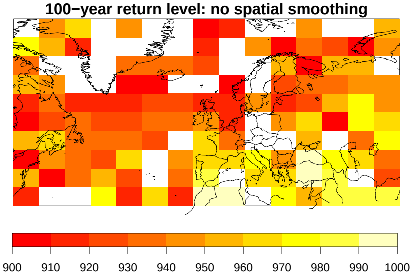
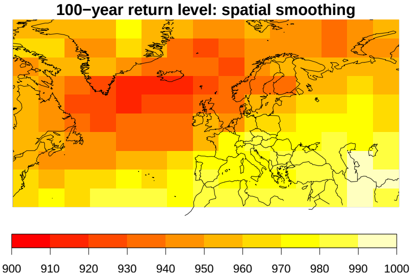
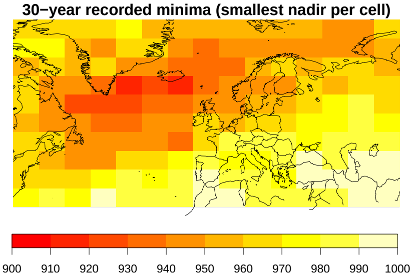


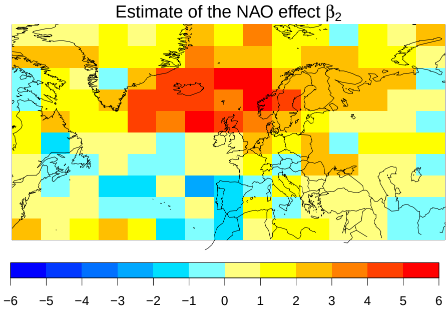


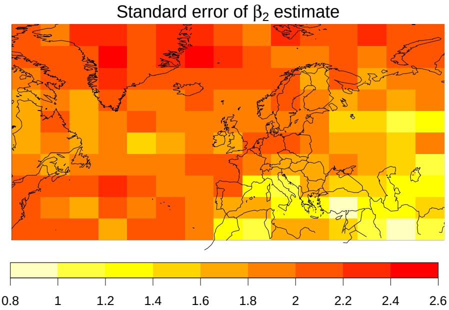




NAO effect

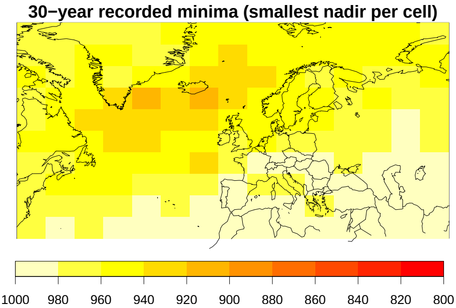
- Positive effect over North Europe and negative over Southern Europe.
- Effect is more notable (significant) over Iceland and Northern Europe.





Estimated lower limits for storm nadir pressure

- Short historical records unlikely to contain deepest possible nadirs.



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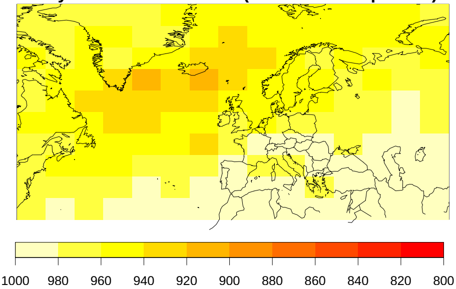
- Short historical records unlikely to contain deepest possible nadirs.
- Statistical modelling implies a lower limit on nadir pressure. Are we prepared for a storm with a 945hPa low over S. England?

30−year recorded minima (smallest nadir per cell)



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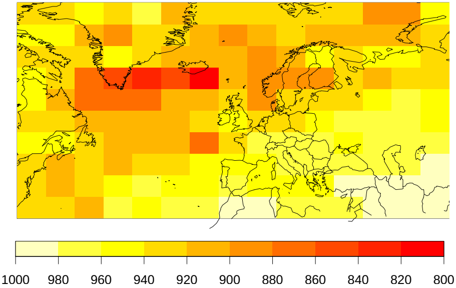

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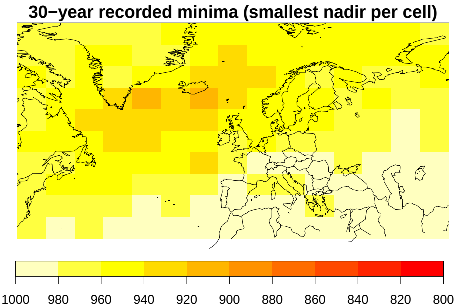
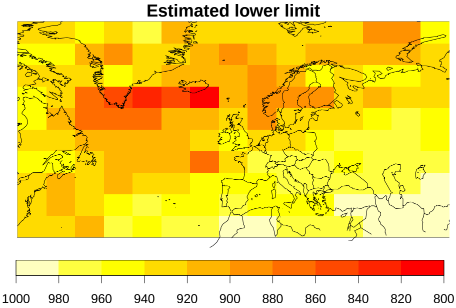
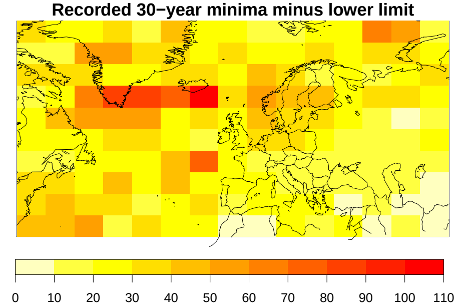
- Statistical modelling implies a lower limit on nadir pressure. Are we prepared for a storm with a 945hPa low over S. England?
- Lows could occur in the future that are typically 10-50hPa deeper than the most extreme storms we have observed.

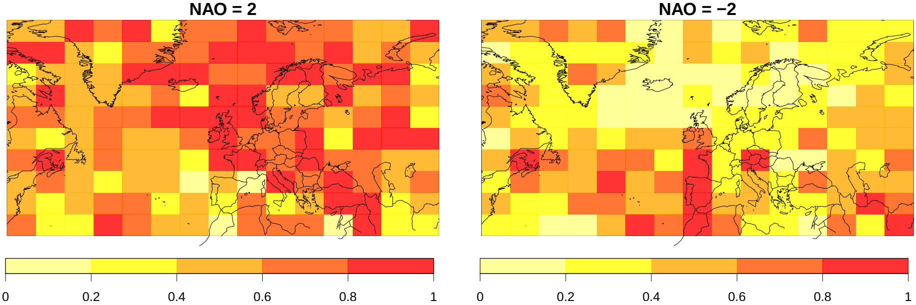




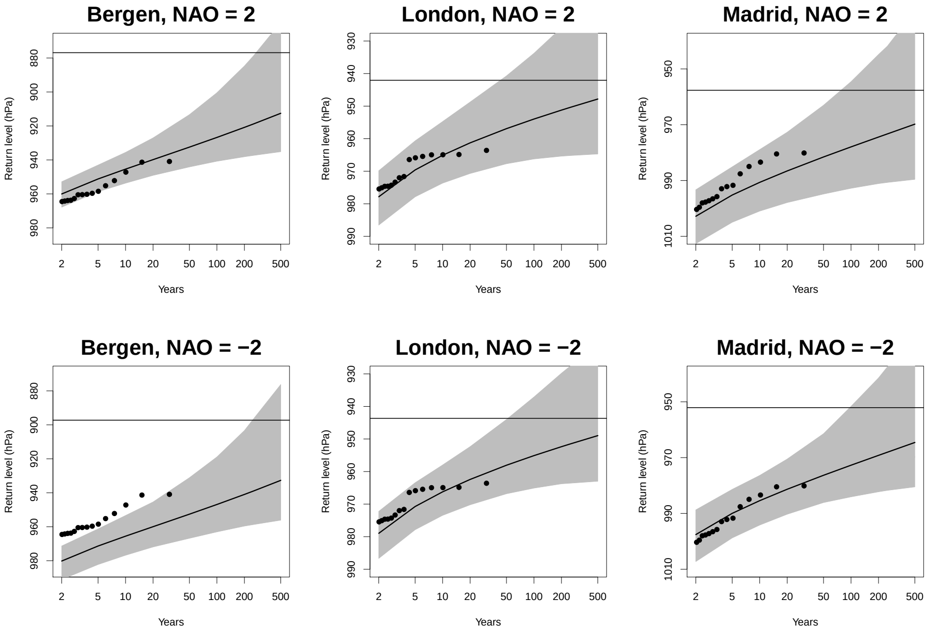


Probability of lower than observed nadirs

- Probability of observing a 30-year nadir minimum, that is smaller than the recorded 30-year minimum in each cell:



Individual area return level plots



Summary

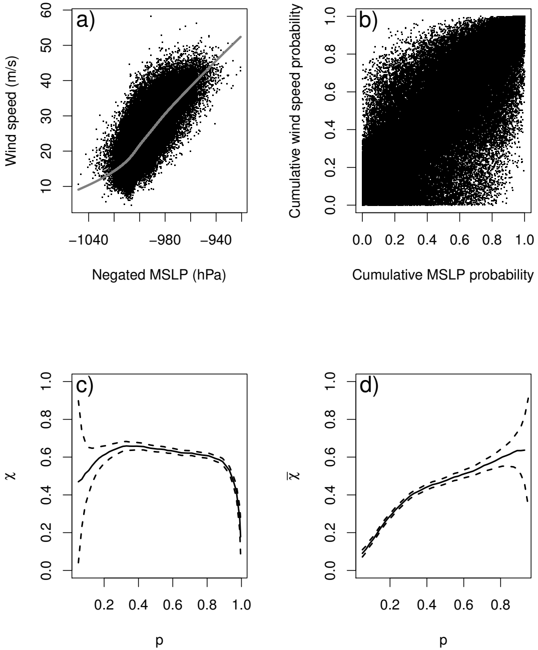
1. How low can rare extra-tropical storms get in space and time?
   For a positive NAO phase, storm nadirs can get as deep as 880hPa near Iceland and 935hPa over the UK.

2. What is the probability of experiencing even more extreme storms than recorded?
   For positive NAO, North Europe has high (> 0.7) probability of experiencing deeper nadirs than the ones recorded, whereas for negative NAO, it is South Europe that has high probability.

3. What is the effect from modes of variability such as the North Atlantic Oscillation (NAO)?
   NAO effect on extreme storm nadirs varies spatially: positive effect over Iceland and North Europe and negative in Southern Europe.

Economou et al. (2014), *Spatio-temporal modelling of extreme storms*, Annals of Applied Statistics, **8**, 2223–2246.

Extremal dependence of wind and SLP



Model checking: observed vs predicted values