Probabilistic reanalysis of storm surge extremes in Europe

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Practical motivation

- The impacts of sea-level rise will be largely felt through changes in extremes.
- Floods resulting from extreme sea levels are among the costliest and deadliest natural hazards.
- Numerical models project dramatic changes in sea-level extremes by the end of the 21st century.

How can the risks be managed?

Cost-effective risk mitigation strategies: balance expected damage with protection costs.

What is needed?

Knowledge of extreme event probabilities and their changes with time.

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How do we estimate event probabilities?

Event probabilities are unobservable quantities that need to be inferred indirectly from sea-level measurements.

Extreme value theory (EVT)

⇨ the distribution of extremes is always in the **same family**, regardless of the distribution of the overall data.

- EVT is analogous to the central limit theorem for means, but it does not guarantee convergence.

- Block maxima (e.g., annual maxima) can only converge to the GEV distribution.

- To estimate event probabilities we need to determine the specific distribution within the GEV family, which involves estimating the GEV parameters (location, scale, shape).

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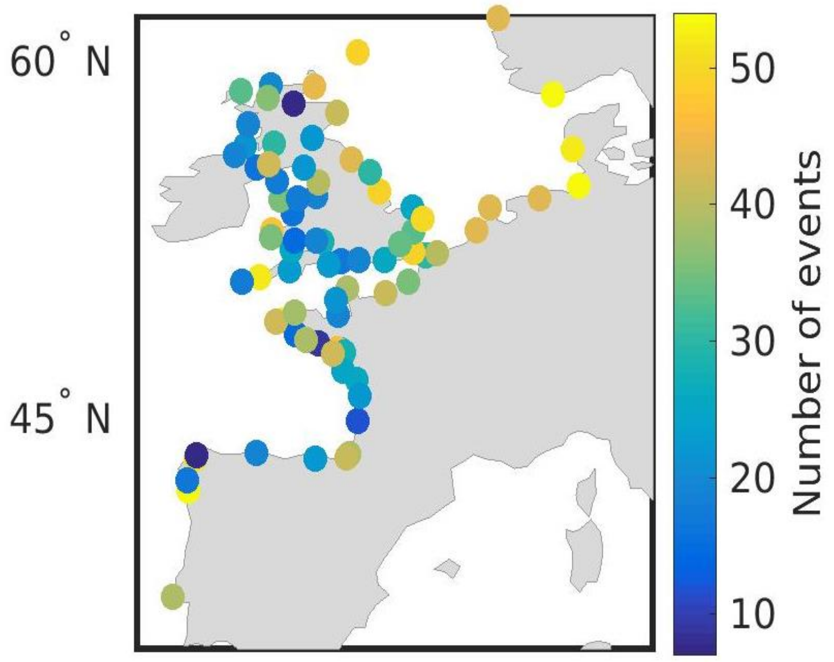
Challenges in applying classical EVT

In sea-level research, EVT has primarily been applied on a **site-by-site** basis, namely by fitting a GEV separately at each tide gauge site. The **challenges** with this approach are:

- Number of events in the tide gauge record is small
  ⇨ *large estimation uncertainty*
- Tide gauge record is sparse in space
  ⇨ *No estimates at many ungauged locations*

Location of tide gauges and number of annual maxima for 1960-2013



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Extremes are spatial

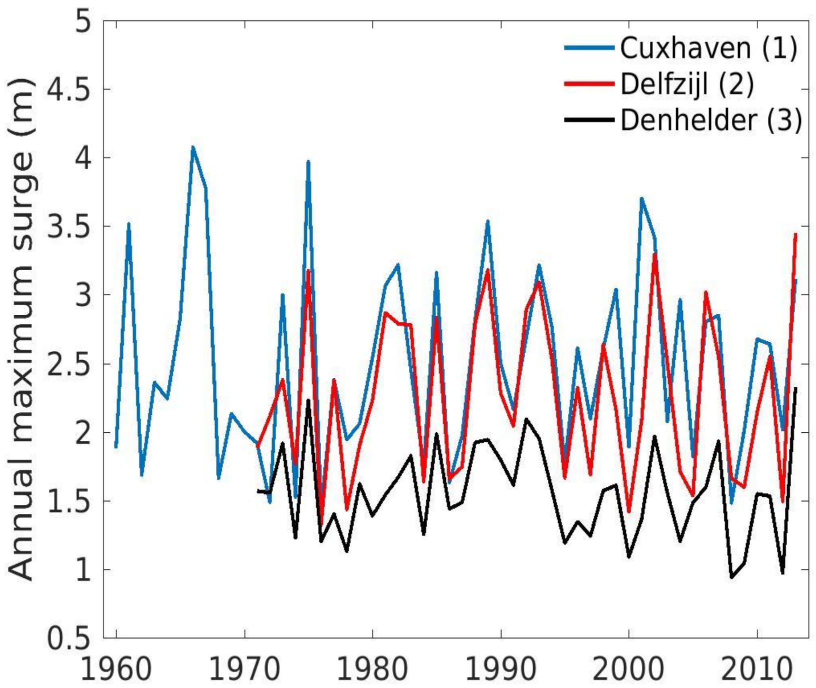
Extreme values and their probabilities tend to be similar among neighbouring locations and regions. There are two types of **spatial dependence**:

1. Locations with correlated annual maxima

   ⇨ *They are affected by the same events*

We capture this dependence using a **max-stable process** (the infinite-dimensional generalization of a GEV)

Annual maxima at 3 tide gauge sites



Tide gauge data from GESLA (Woodworth et al., 2017)

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Extremes are spatial

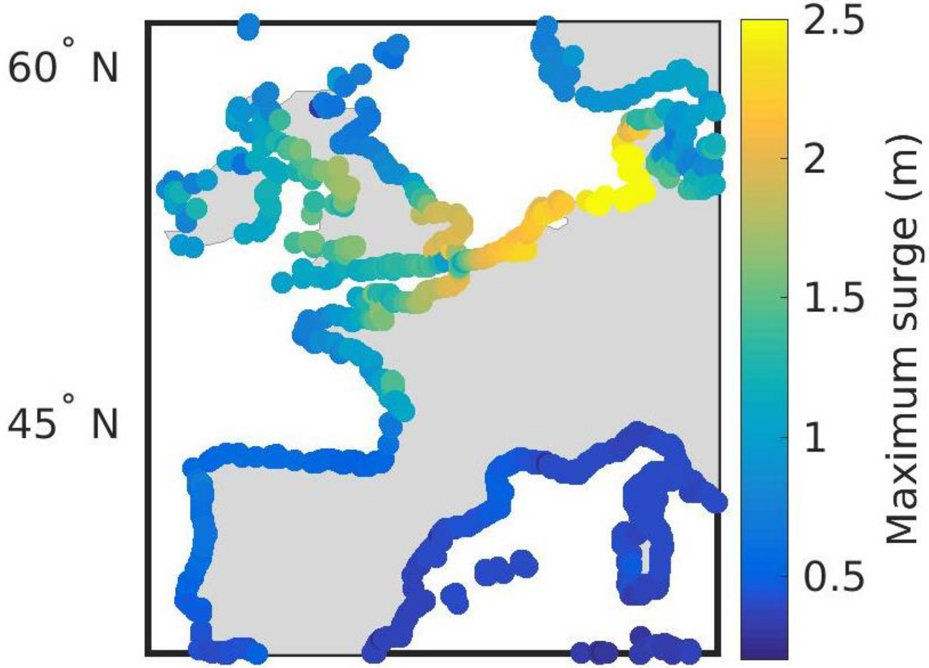
The second type of spatial dependence is called **climatological dependence** since it is related to event probabilities:

2. Locations with correlated GEV(μ,σ,ξ) parameters

   ⟹ *They have similar event probabilities*

We capture this type of dependence using **Gaussian processes**

Maximum surge over 1960-2013



Model data from Muis et al. (2016)

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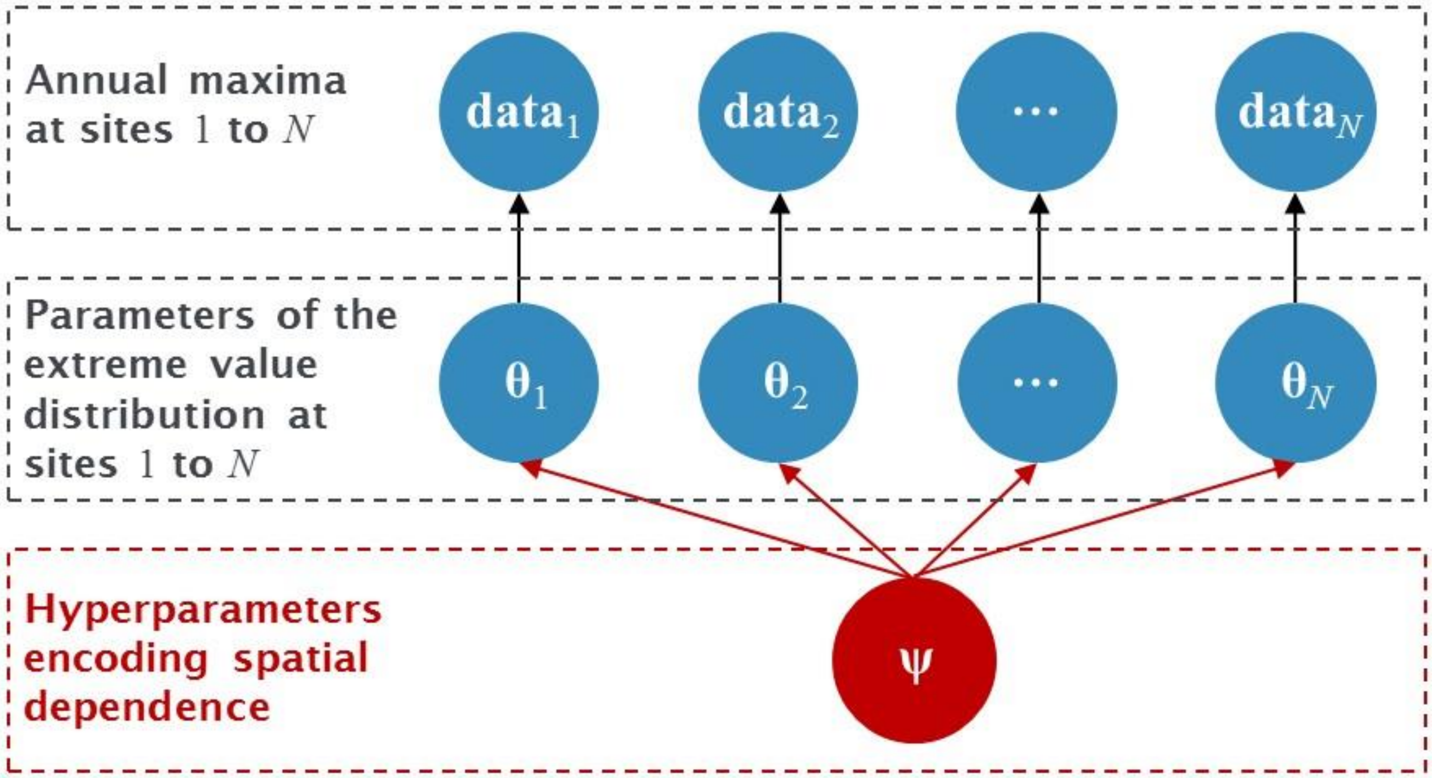
Approach: Bayesian hierarchical model

Aim: exploit spatial dependence to enable sharing of information across tide gauge sites



p(**data** | **θ**,**ψ**)
Max-stable process

p(**θ** | **ψ**)
Spatial Gaussian Processes

p(**ψ**)
Prior knowledge

In our model, $\boldsymbol{\theta}_i$ learns not only from data at the *i*-th site but from data at all other sites through the hyperparemeters **ψ**

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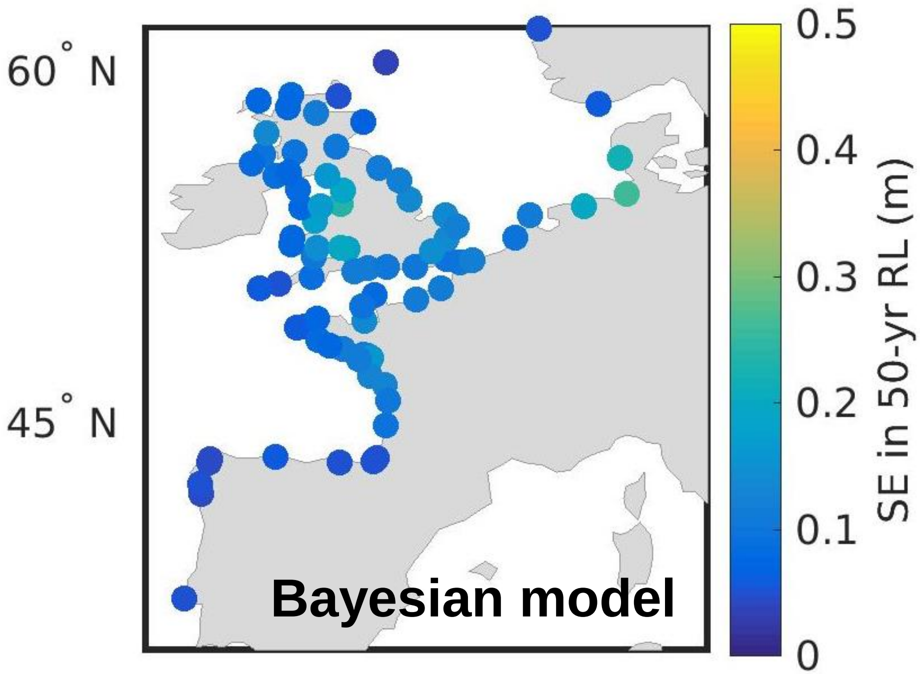
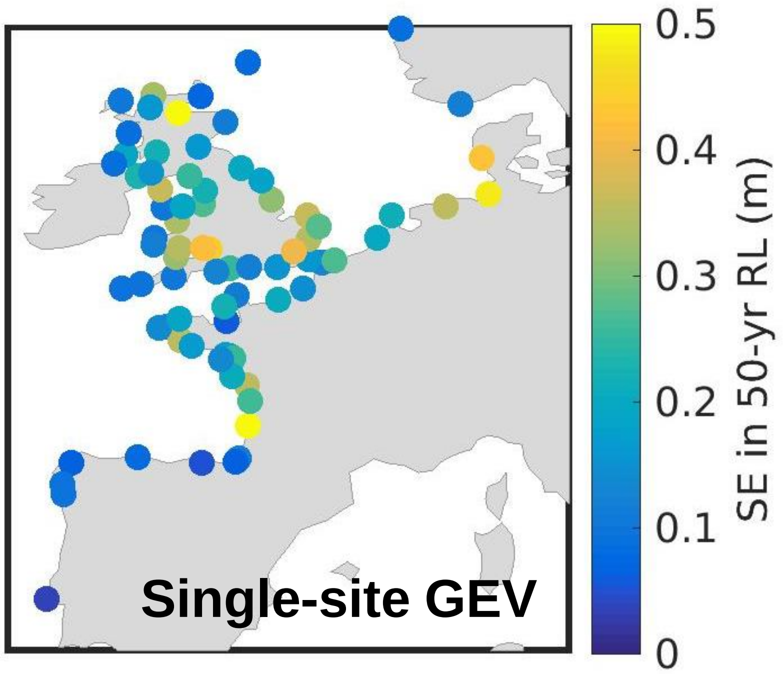
Advantages of spatiotemporal modeling

Advantage 1: reduction in estimation uncertainty

Standard errors in estimates of 50-yr return levels at tide gauge locations





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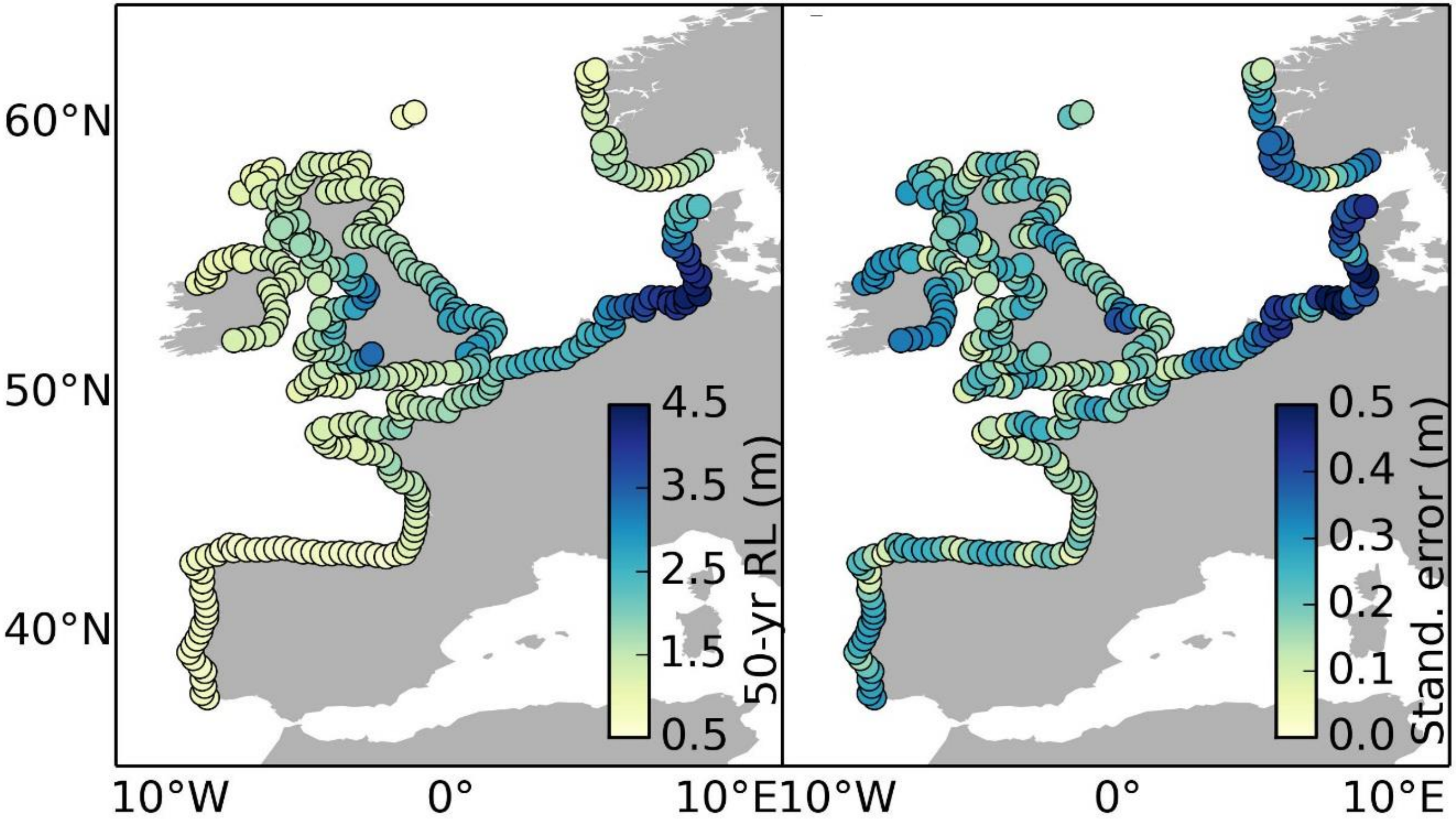
Advantages of spatiotemporal modeling

Advantage 2: interpolation of event probabilities

50-yr return levels and SE's as estimated by the Bayesian model



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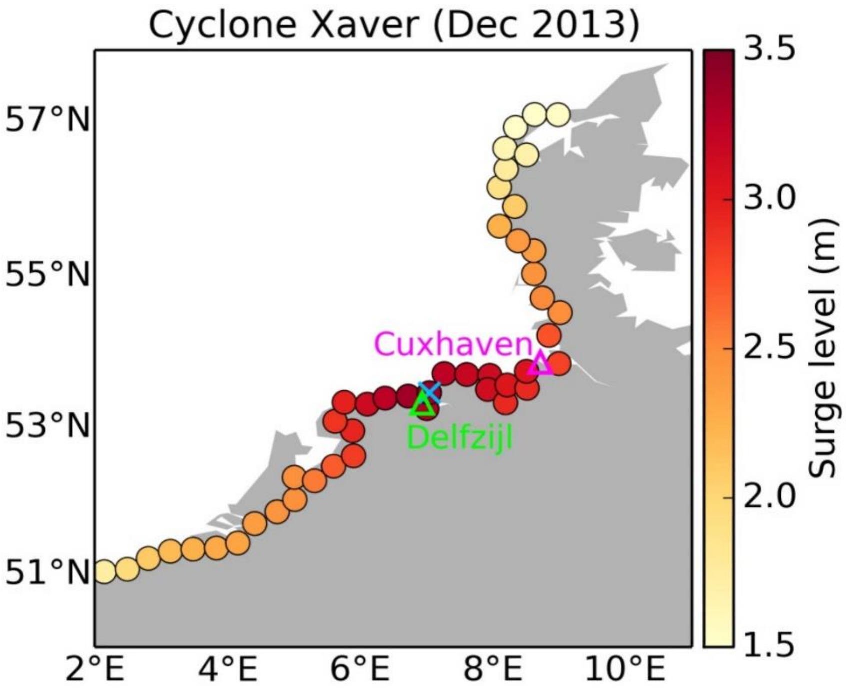
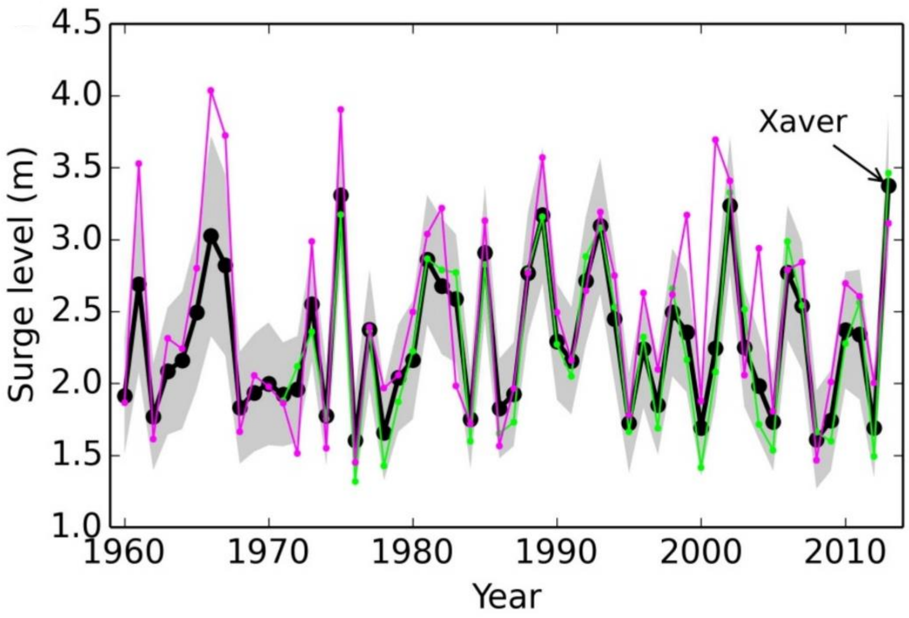
Advantages of spatiotemporal modeling

Advantage 3: interpolation of annual maxima



Estimated surge levels induced by cyclone Xaver in December 2013



Estimated annual maxima (black) compared with observed values at Delfzijl and Cuxhaven (green and magenta)

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References

Published article: Calafat, F. M., M. Marcos (2020). Probabilistic reanalysis of storm surge extremes in Europe, *Proc. Natl. Acad. Sci. U. S. A.*, 117 (4), 1877-1883.

The probabilistic reanalysis of storm surge extremes has been deposited in Zenodo: https://doi.org/10.5281/zenodo.3471600

The code for the Bayesian hierarchical model is also available from Zenodo: https://doi.org/10.5281/zenodo.3442167

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