Vertical profiles of wind gust statistics

from a regional reanalysis using multivariate extreme value theory

Julian Steinheuer and Petra Friederichs

May 8, 2020

Institute for Geophysics and Meteorology, University of Cologne
&
Institute of Geosciences, Bonn University

Julian.Steinheuer@uni-koeln.de

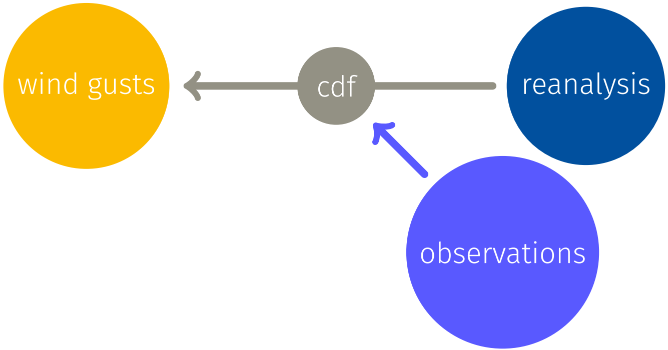
Motivation

(from `www.sun-stadtwerke.de/projekte/windpark-wolfhagen`)

Create a stochastic model for wind gusts in different heights as a function of weather model predictions!

Method

Overview



Article:

J. Steinheuer and P. Friederichs (2020). "Vertical profiles of wind gust statistics from a regional reanalysis using multivariate extreme value theory". In: *Nonlinear Processes in Geophysics* 27.2, pp. 239–252. DOI: *10.5194/npg-27-239-2020*

Data

Wind gusts from the **Hamburg Weather Mast** (Brümmer et al. 2012)

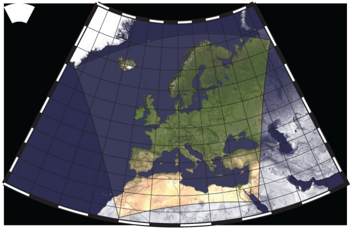
- in 5 levels (10m, 50m, 110m, 175m, 250m)
- for every 5 min from 2004 to 2014 $\Rightarrow$ hourly gust maxima of 3 s duration

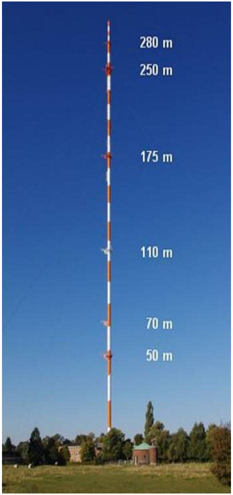
Hourly **COSMO-REA6** regional reanalysis data (Bollmeyer et al. 2014)

- in 40 levels and mast surrounding 25 columns

right: Hamburg Weather Mast (from *wettermast.uni-hamburg.de*)

left: Domain COSMO-REA6 (CORDEX EUR-11) (from Bollmeyer et al. 2014).





Model: layer-wise EVT

Members of generalized extreme value (GEV) family have cdf

$$G(y;\mu,\sigma,\xi) = \begin{cases} \exp\Big(-\big[1+\xi(\frac{y-\mu}{\sigma})\big]_+^{-1/\xi}\Big) & \xi \neq 0 \\ \exp(-\big[-\exp(\frac{y-\mu}{\sigma})\big]_+) & \xi = 0, \end{cases}$$

with location $\mu \in (-\infty, \infty)$, scale $\sigma \in [0, \infty\}$, shape $\xi \in (-\infty, \infty)$.

- We assume $P(\text{gust}_z \leq y) \approx G(y;\mu,\sigma,\xi)$ with

$$\mu = \mu_0 + \mu_1 C_1 + \mu_2 C_2 + \mu_3 C_3 + \dots$$
$$\sigma = \exp(\sigma_0 + \sigma_1 C_1 + \sigma_2 C_2 + \sigma_3 C_3 + \dots)$$
$$\xi = \xi_0$$

- Covariates $C_i(t)$ from COSMO-REA6 and identical in every height.
- Censored Maximum Likelihood Estimation (with LASSO) in a cross-validation method on the years $\mapsto$ 11 sets of estimates

Model: vertical Legendre model

- Use Legendre polynomials for vertical parameter modeling:

$$P_0(z) = 1, \quad P_1(z) = z, \quad P_2(z) = \frac{1}{2}(3z^2 - 1) \quad \text{for } z \in [0, 1].$$

- for $z(10\,m) = 0$ and $z(250\,m) = 1$:

$$\mu(z,t) = \mu_{00}P_0(z) + \mu_{01}P_1(z) + \mu_{02}P_2(z) + [\mu_{10}P_0(z) + \mu_{11}P_1(z) + \mu_{12}P_2(z)]C_1(t) + \dots,$$

$$\sigma(z,t) = \exp(\,\sigma_{00}P_0(z) + \sigma_{01}P_1(z) + \sigma_{02}P_2(z) + [\sigma_{10}P_0(z) + \sigma_{11}P_1(z) + \sigma_{12}P_2(z)]C_1(t) + \dots).$$

$\rightarrow$ enables prediction between layers
(leave-layer-out model to test ability)

- and fix $\xi(z,t) = 0$ (Gumbel distribution).

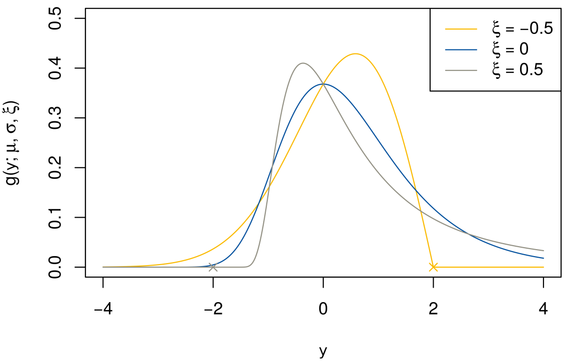
Restriction on Gumbel distribution

Example GEV pdf's for the three sub-classes

Weibull

Gumbel

Frechét



Advantage: no restriction in domain of definition

→ no upper endpoint (e.g. no highest gust)

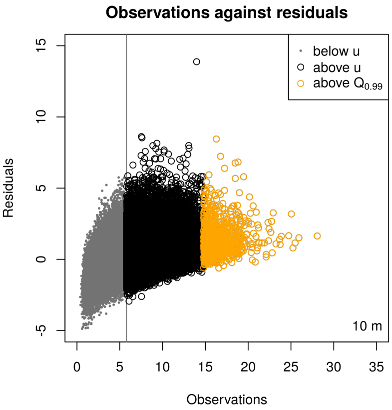
→ stable optimization routines

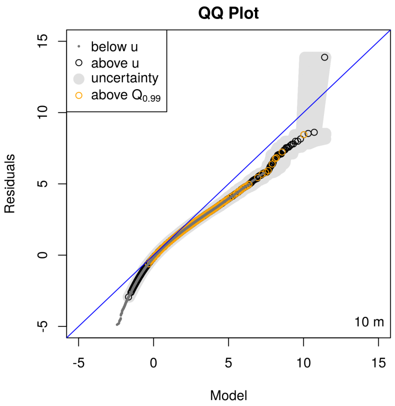
Results

LASSO selection

LASSO selection (×) in Model covariates (light blue) for	LP1 ∼ const.		LP2 ∼ lin.		LP3 ∼ quad.	
	μ	σ	μ	σ	μ	σ
Wind gust diagnostic in 10 m (VMAX_10M)	×	×				
Temporal variance (±2 h) of VMAX_10M		×		×		
Barotropic mode of horizontal wind in mast layers	×		×			
Baroclinic mode of horizontal wind in mast layers		×	×			
Mean horizontal wind in 700 hPa	×	×	×			
SD of horizontal wind in 700 hPa						
Mean vertical wind in 700 hPa						
SD of vertical wind in 700 hPa		×				
Pressure tendency	×	×				
Lifted index		×				
Water content grid column	×					
SD of CAPE						
Diff abs. horizontal wind in 6 km and 1 km						
Temperature in 2 m						
Annual cycle		×				

Residuals in 10 m

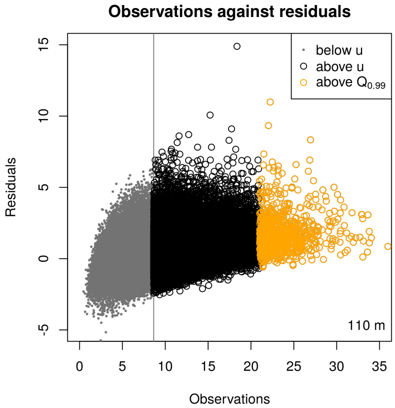


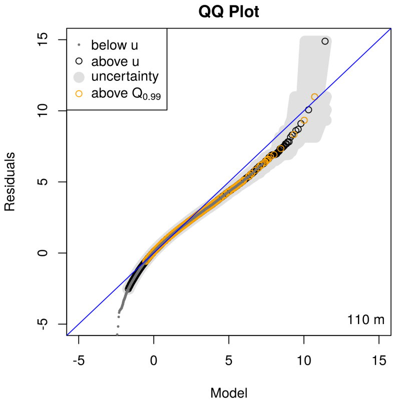


Legendre model diagnostics: censoring threshold $u = 5.79\,\mathrm{m\,s^{-1}}$ for MLE at 50 % quantile

- the one residual outlier correspond to no reanalysis signal and is an outlier in observation data
- high gusts are slightly overestimated, but overall they fit well

Residuals in 110 m





Legendre model diagnostics: censoring threshold $u = 8.65\,\mathrm{ms}^{-1}$ for MLE at 50 % quantile

- similar pattern as for 10 m
  → good vertical agreement

Verification

- use proper scoring rules to validate a prediction against observation y
- CRPS, Brier Score, or Quantile Score (QS) for probabilistic prediction G
- QS can verify the prediction quality in high quantiles

$$QS_\tau = \rho_\tau(y - G^{-1}(\tau)). \tag{1}$$

for $\tau \in [0, 1]$ and Check Loss Function:

$$\rho_\tau(x) = \begin{cases} x\tau & \text{if } x \geq 0, \\ x(\tau - 1) & \text{if } x < 0. \end{cases} \tag{2}$$

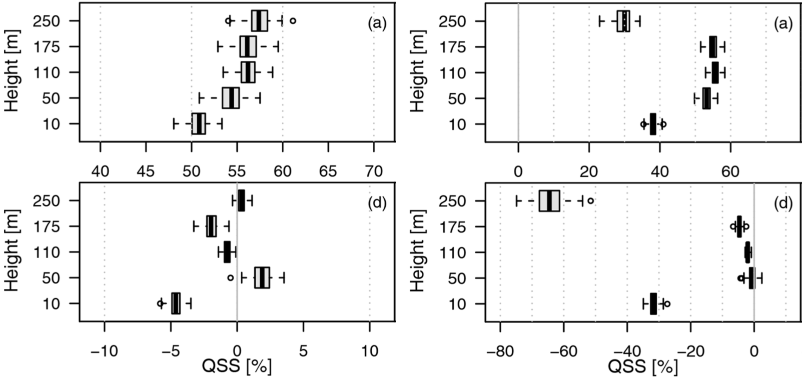
$$\text{Skill Score} = 1 - \frac{\text{Score}}{\text{Score}_{\text{Ref}}} \tag{3}$$

Verification: Quantile skill score

$\tau = 99\,\%$ quantile (from Steinheuer and Friederichs 2020)

Legendre model vs. climatology

leave-layer-out vs. climatology



Legendre model vs. layer-wise

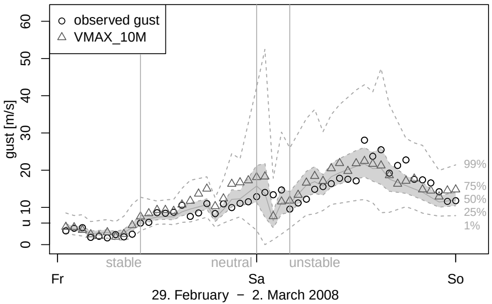
leave-layer-out vs. layer-wise

→ improvements up to 60 %

→ Legendre model similar to layer-wise model

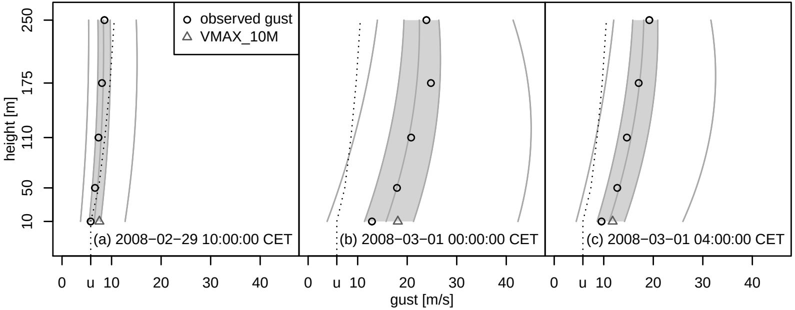
→ prediction of intermediate gust layers reasonable

Example: Storm Emma



Post-processing of vertical model over time (left) and height (below; from Steinheuer and Friederichs 2020).

Cases correspond to lifted indices of stable (8.7 K), neutral (2.4), and unstable (-3.1) atmosphere.



Dependency

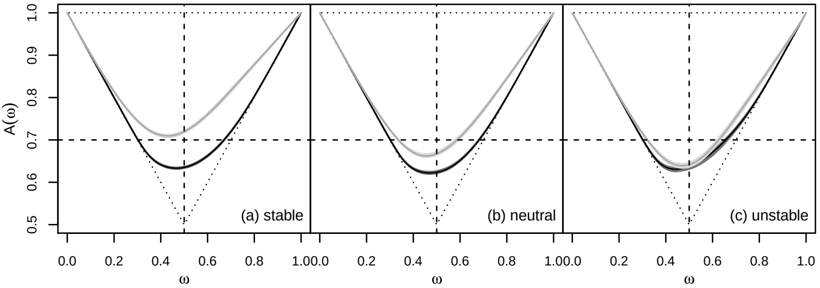
Dependency function

- Non-parametric Pickands dependency function in the bivariate case (Pickands 1981)

  $$A(\omega) = n \left[\sum_{i=1}^{n} \min(\frac{x_i}{\omega}, \frac{y_i}{1-\omega})\right]^{-1} \text{ for } \omega = \frac{y}{x+y} \text{ with } X, Y \sim F \text{ Frechét}$$

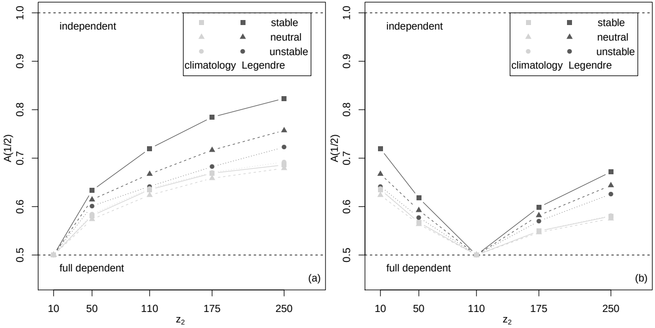
- Distinguish between stable, neutral, and unstable situations

  Legendre vertical model (light grey) and climatology (dark grey) with cases (a) 53 % LI ≥ 6, (b) 36 % $6 > \text{LI} \geq -2$, and (c) 11 % $-2 >$LI for $\omega = \frac{F_{110\ m}}{F_{10\ m}+F_{110\ m}}$ (from Steinheuer and Friederichs 2020).



Dependency function

Dependency at $\omega = 1/2$ between gusts (grey) and model residuals (black) at all layers and (a) $z_1 = 10\,m$, and (b) $z_1 = 110\,m$ (from Steinheuer and Friederichs 2020).



→ new model reduces vertical dependencies between the layers
→ dependency structure between gust layers does not follow a simple distance relation

Conclusion

→ Post-processing for the prediction of wind gusts in the vertical based on regional reanalysis COSMO-REA6

→ some outlier in the residuals exists, but the high gusts are captured well by the model

→ gusts in an interior layer can be predicted without observations from that layer

→ gust dependencies between the layers can be reduced

Vertical profiles of wind gust statistics

from a regional reanalysis using multivariate extreme value theory

Julian Steinheuer and Petra Friederichs

May 8, 2020

Institute for Geophysics and Meteorology, University of Cologne
&
Institute of Geosciences, Bonn University

Julian.Steinheuer@uni-koeln.de

References

Bollmeyer, C. et al. (Dec. 2014). "Towards a high-resolution regional reanalysis for the European CORDEX domain". In: *Q. J. R. Meteorol. Soc.* 141.686, pp. 1–15. DOI: *10.1002/qj.2486*.

Brümmer, Burghard, Ingo Lange, and Heike Konow (Aug. 2012). "Atmospheric boundary layer measurements at the 280 m high Hamburg weather mast 1995-2011: mean annual and diurnal cycles". In: *Meteorol. Z.* 21.4, pp. 319–335. DOI: *10.1127/0941-2948/2012/0338*.

Pickands, James, III (1981). "Multivariate extreme value distributions". In: *Bull. Inst. Internat. Statist* 49, pp. 859–878, 894–902.

Steinheuer, J. and P. Friederichs (2020). "Vertical profiles of wind gust statistics from a regional reanalysis using multivariate extreme value theory". In: *Nonlinear Processes in Geophysics* 27.2, pp. 239–252. DOI: *10.5194/npg-27-239-2020*.