

# M6 Extreme Value Theory

General Insurance Modelling : Actuarial Modelling III <sup>1</sup>

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<sup>1</sup>References: Unit 4 of CS2

- 1 Introduction
- 2 Generalised Extreme Value distribution
- 3 Generalised Pareto distribution
- 4 Measures of tail weight

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# 1 Introduction

- Extreme events
- Framework
- Motivating example (Paul Embrechts, Resnick, and Samorodnitsky 1999)
- A limiting argument

# Extreme events

- financial (and claims) data has often leptokurtic severity (more peaked - heavy tailed - than normal)
- reasons include heteroscedasticity (stochastic volatility)
- almost by definition, extreme events happen with low frequency
- but extreme events are the ones leading to financial distress, possibly ruin
- accurate fitting is crucial for capital and risk management (risk based capital, reinsurance, ART such as securitisation via CAT bonds)
- fitting presents specific issues:
  - there is little data to work from
  - when fitting a whole distribution, the big bulk of the data (around the mode) overpowers observations in the tails in the optimisation routine (MLE), leading to poor fit in the tail
  - sometimes (in fact, almost always) a good distribution for the far tail is different from that for the more common outcomes.

# 1 Introduction

- Extreme events
- **Framework**
- Motivating example (Paul Embrechts, Resnick, and Samorodnitsky 1999)
- A limiting argument

# Framework

- Consider iid random variables  $X_i$ ,  $i = 1, \dots, n$ , with df  $F$
- We denote the order statistics

$$X_{n,n} \leq X_{n-1,n} \leq \dots \leq X_{1,n}$$

such that

$$X_{n,n} = \min(X_1, \dots, X_n) \text{ and } X_{1,n} = \max(X_1, \dots, X_n).$$

- Specifically, we may be interested in

$$\begin{aligned} \text{average of } k \text{ largest losses} &= \sum_{r=1}^k \frac{X_{r,n}}{k} \\ \text{empirical mean excess function above } u &= \sum_{r=1}^{n_u} \frac{(X_{r,n} - u)}{n_u}, \text{ where} \\ n_u &= \# \{1 \leq r \leq n : X_r > u\} \end{aligned}$$

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## Motivating example (Paul Embrechts, Resnick, and Samorodnitsky 1999)

Consider the following situation:

- Let  $X_i$  be exponential mean  $1/\lambda = 10$
- We have  $n = 100$  observations
- The maximum observed was 50. How likely is it if the model is correct?  
What if the maximum had been 100?

The probability that the maximum  $X_{1,n}$  is at least  $x$  is

$$\Pr[X_{1,n} > x] = 1 - (\Pr[X \leq x])^{100} = 1 - (1 - e^{-x/10})^{100},$$

and hence

$$\begin{aligned}\Pr[X_{1,n} > 50] &= 0.4919, \\ \Pr[X_{1,n} > 100] &= 0.00453.\end{aligned}$$

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## A limiting argument

We now perform the following calculations:

$$\Pr \left[ \frac{X_{1,n}}{10} - \log n \leq x \right] = \Pr[X_{1,n} \leq 10(x + \log n)] = \left( 1 - \frac{e^{-x}}{n} \right)^n,$$

where the elements in red were chosen based on an educated guess, so that

$$\lim_{n \rightarrow \infty} \Pr \left[ \frac{X_{1,n}}{10} - \log n \leq x \right] = \lim_{n \rightarrow \infty} \left( 1 - \frac{e^{-x}}{n} \right)^n = e^{-e^{-x}} \equiv \Lambda(x),$$

which is the df of a Gumbel (or double exponential) random variable.

## General result for $X$ exponential ( $\lambda$ )

We can easily generalise the previous result to any  $\lambda$  and  $n$ . Noting that 10 was actually  $1/\lambda$  before, we had in summary

$$\Pr[X_{1,n} \leq (x + \log n)/\lambda] \approx \Lambda(x).$$

If we set

$$y = (x + \log n)/\lambda$$

then we get

$$\Pr[X_{1,n} \leq y] \approx \Lambda(\lambda y - \log n).$$

In the limit ( $n \rightarrow \infty$ ), the approximation is exact.

This means that for large  $n$ , one can approximate the distribution of the maximum of a set of iid exponentially distributed  $X_i$ 's (with parameter  $\lambda$ ) with a Gumbel distribution.

Indeed, this works well for our example, especially in the tail:

$$\begin{aligned}\Pr[X_{1,n} > 50] &\approx 1 - e^{-e^{-(50/10 - \log 100)}} = 0.4902, \\ \Pr[X_{1,n} > 100] &\approx 0.00453.\end{aligned}$$

## Questions

- This is nice, but not all random variables are exponential.
- Can we generalise such a limiting approach to any df?

**Yes!**

- Can we find norming constants (such as  $\lambda$  and  $\log n$  in the exponential case) in general?

That is, how do we find  $a_n$  and  $b_n$  so that

$$\lim_{n \rightarrow \infty} \Pr \left[ \frac{X_{1,n} - b_n}{a_n} \leq x \right]$$

exists?

**We can!** (there are only three cases to consider), but we won't discuss that here (see, e.g., P. Embrechts, Klüppelberg, and Mikosch 1997 for the proofs)

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## 2 Generalised Extreme Value distribution

- The GEV distribution
  - Case study - data
  - Case study - fitting
  - Case study - choice of block size
  - Moments
  - PML and quantiles
  - Case study - quantiles

## Parallel with CLT

The theoretical results of the previous section lead to an extreme value complement or homologue, for the tails, of the CLT approximation (which works only around the middle of the distribution).

- In the exponential example, the “normalised” maximum

$$\frac{X_{1,n}}{\text{mean of } X} - \log n$$

for infinite sample  $n$  stabilised to a Gumbel distribution  $\Lambda$ .

- This generalises to any distribution for  $X$  - the distribution of the normalised maximum then becomes a “Generalised Extreme Value” distribution, a special case of which is the Gumbel distribution.

# Extreme Value Distributions

The Gumbel distribution  $\Lambda(x)$  derived earlier is a special case of a general distribution family

$$H_{\gamma;\mu,\sigma}(x) = \exp \left\{ - \left( 1 + \gamma \frac{x - \mu}{\sigma} \right)_+^{-\frac{1}{\gamma}} \right\}, \quad \gamma \in \mathbb{R}, \mu \in \mathbb{R}, \sigma > 0.$$

This Generalised Extreme Value distribution (GEV) encompasses **all** extreme value distributions, of which we distinguish three cases:

- $\gamma < 0$ : upper bounded Weibull (Sometimes referred to as the reverse or reflected Weibull) df with  $x < \mu - \sigma/\gamma$
- $\gamma = 0$ : Gumbel df with  $x \in \mathbb{R}$
- $\gamma > 0$ : Fréchet-type df with  $x > \mu - \sigma/\gamma$

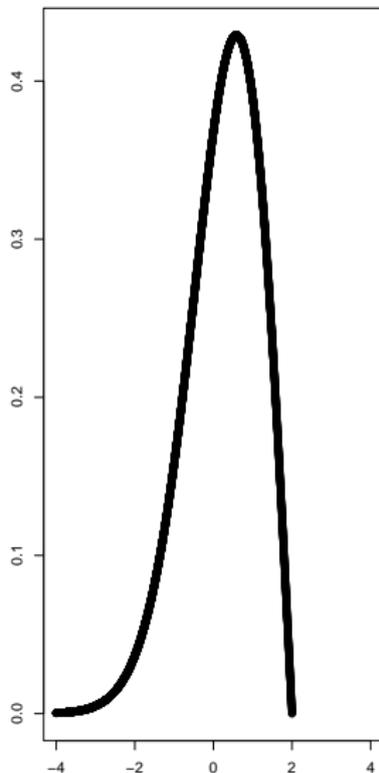
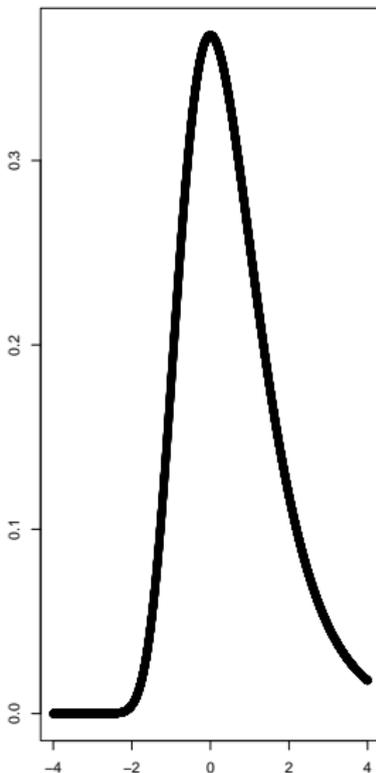
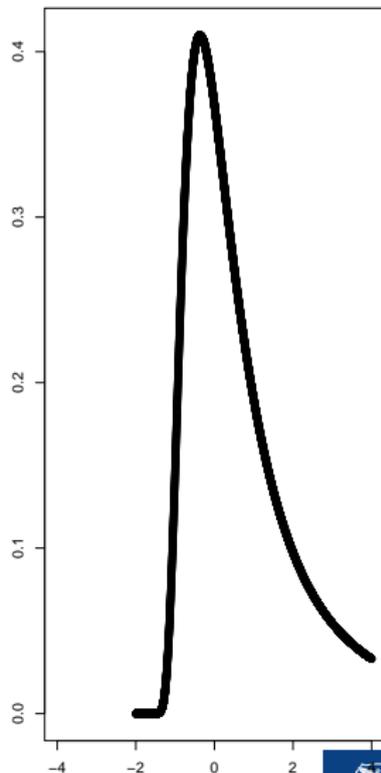
The last one relates to the heavy tailed distributions (typically with moments existing only up to a certain order, infinite afterwards), and is the most relevant to actuarial applications.

# Three cases

GEV distributions (for the maximum value) corresponding to common loss distributions			
Type	WEIBULL	GUMBEL	FRÉCHET
Shape parameter	$\gamma < 0$	$\gamma = 0$	$\gamma > 0$
Underlying Distribution	Beta Uniform Triangular	Chi-square Exponential Gamma Log-normal Normal Weibull	Burr $F$ Log-gamma Pareto $t$
Range of values permitted	$x < \alpha - \frac{\beta}{\gamma}$	$-\infty < x < \infty$	$x > \alpha - \frac{\beta}{\gamma}$

(Unit 4, Page 4, IoA 2020) Note  $\alpha \equiv \mu$  and  $\beta \equiv \sigma$

```
GenEV <- function(x, alpha, beta, gamma) {  
  1/beta * (1 + gamma * (x - alpha)/beta)^(-(1 + 1/gamma)) *  
  exp(-((1 + gamma * (x - alpha)/beta)^(-1/gamma)))  
}  
  
par(mfrow = c(1, 3), oma = c(0, 0, 3, 0))  
plot(-4000:2000/1000, GenEV(-4000:2000/1000, 0, 1, -0.5), main = "Density w  
  xlim = c(-4, 4), xlab = "", ylab = "", cex = 1)  
plot(-4000:4000/1000, GenEV(-4000:4000/1000, 0, 1, 1e-05), main = "Density  
  xlim = c(-4, 4), xlab = "", ylab = "", cex = 1)  
plot(-2000:4000/1000, GenEV(-2000:4000/1000, 0, 1, 0.5), main = "Density of  
  xlim = c(-4, 4), xlab = "", ylab = "", cex = 1)  
mtext("Density of GEV with mu=0, sigma=1, and various values of gamma",  
  outer = TRUE, cex = 1.5)
```

Density of GEV with  $\mu=0$ ,  $\sigma=1$ , and various values of  $\gamma$ Density with  $\gamma=-0.5$  (Weibull)Density of GEV with  $\gamma=0$  (Gumbel)Density of GEV with  $\gamma=0.5$  (Fréchet)

## Estimation: Block Maxima

- The EVD is a distribution of maxima
- To fit it we need a sample of maxima
- To achieve this, the data is transformed into block maxima
  - 1 assume we have  $n$  data points (*say, monthly data over 1000 years, so  $n = 12000$* )
  - 2 consider blocks of length  $m$  (*say, all observations in a given year such that  $m = 12$* )
  - 3 the block maxima are the equal to the maximum observation within a block (*the maximum value within each of the 1000 years*)
  - 4 we have then a sample size of  $n/m$  (*our sample size of maxima is of size  $12000/12=1000$* )
- The block maxima are then fitted to the EVD
- The larger the block size, the closer to the asymptotic distribution we get, but the less data we have: conflicting requirements
- In R, this can be done efficiently with the function `fevd` of the package `extRemes` (Gilleland and Katz 2016)

## 2 Generalised Extreme Value distribution

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- Case study - choice of block size
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## Data sets

We consider three simulated data sets with  $n = 12000$  (provided along with the lecture notes), expected value \$ 10,000 and variance \$ 9,000<sup>2</sup>:

month	beta	gamm	logg
⋮			
61	12862.84	33493.02	18773.47
62	408.64	6070.20	7564.21
63	2404.87	26093.36	5083.10
64	4753.73	3773.61	2070.88
65	594.57	3885.25	43601.62
66	16805.64	6881.97	6163.90
67	4335.52	5163.38	8158.35
68	5575.15	24401.76	19172.13
⋮			

```
claims <- as_tibble(read_excel("simulated-claims.xlsx"))
summary(claims$beta)
```

```
##      Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##         0   2102   7585   10078   16532   33287
```

```
summary(claims$gamm)
```

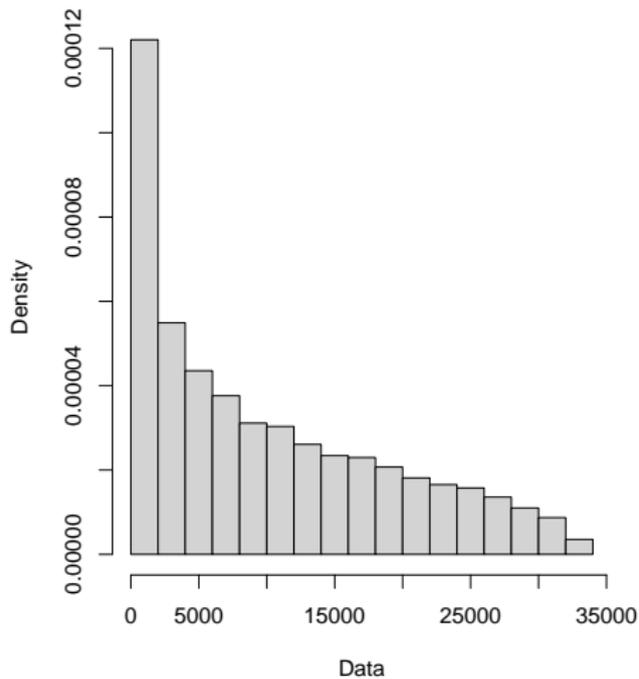
```
##      Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##      6.12 3566.46 7668.73 10107.70 14070.25 90712.14
```

```
summary(claims$logg)
```

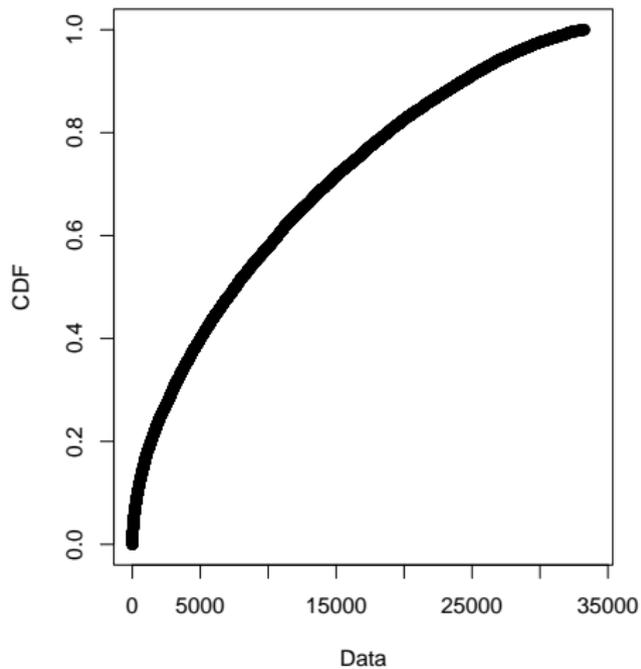
```
##      Min. 1st Qu.  Median    Mean 3rd Qu.    Max.
##     432.7  4611.7  7374.7  9931.9 12124.2 157377.1
```

```
plotdist(claims$beta)
```

Histogram

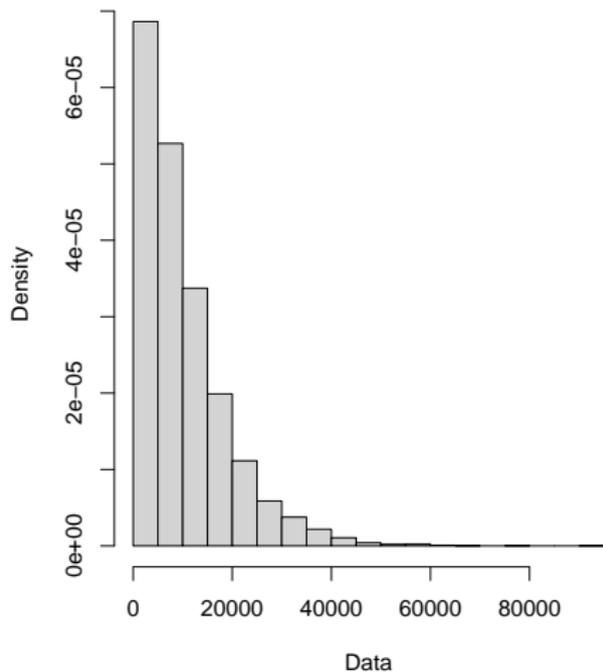


Cumulative distribution

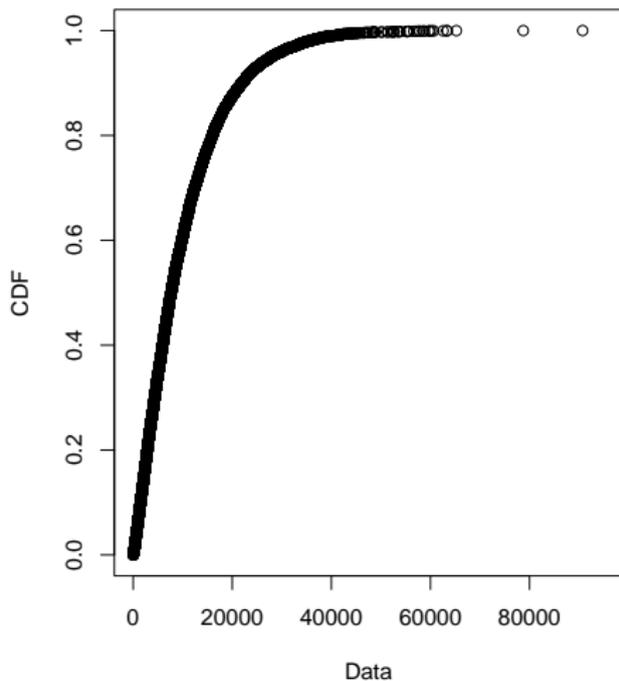


```
plotdist(claims$gamm)
```

Histogram

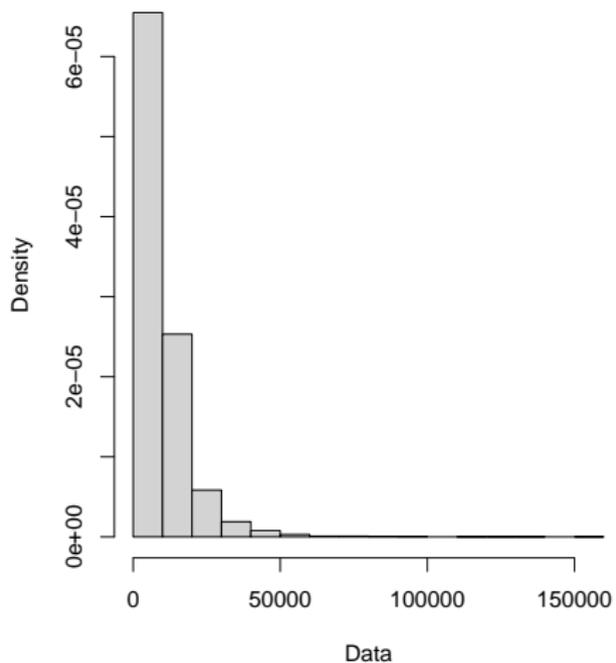


Cumulative distribution

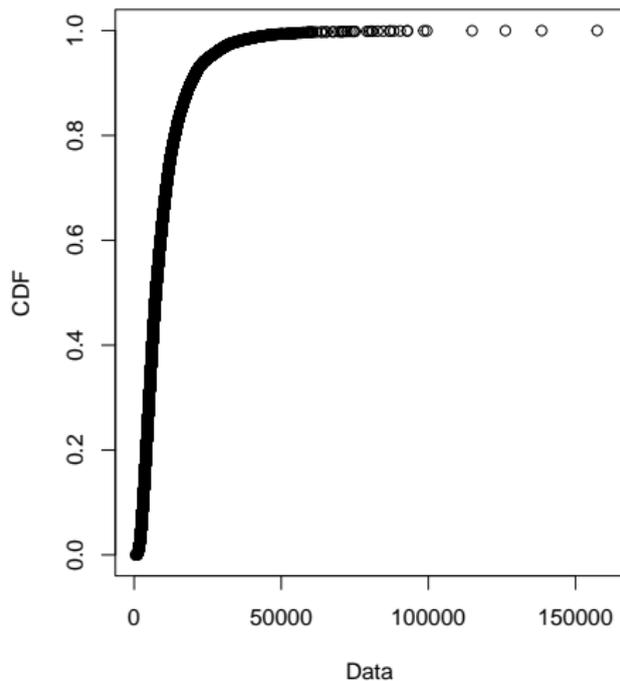


```
plotdist(claims$logg)
```

Histogram



Cumulative distribution



# Block maxima

## Creating block maxima

```
# block maxima index
claims$block <- (claims$month - 1)%/%12 + 1
# %/% gives the integer part of the result of the division
blockmax <- tibble(beta = aggregate(beta ~ block, claims,
  max)$beta, gamm = aggregate(gamm ~ block, claims, max)$gamm,
  logg = aggregate(logg ~ block, claims, max)$logg)
# have a look at what the aggregate function does
```

We now have a sample of  $12000/12 = 1000$  block maxima.

What do these look like in comparison with the original data?

```
claims <- as_tibble(read_excel("simulated-claims.xlsx"))
summary(blockmax$betablock)
```

```
##      Min. 1st Qu.  Median      Mean 3rd Qu.      Max.
##  11376  23803  27155  26606  30035  33287
```

```
summary(blockmax$gammblock)
```

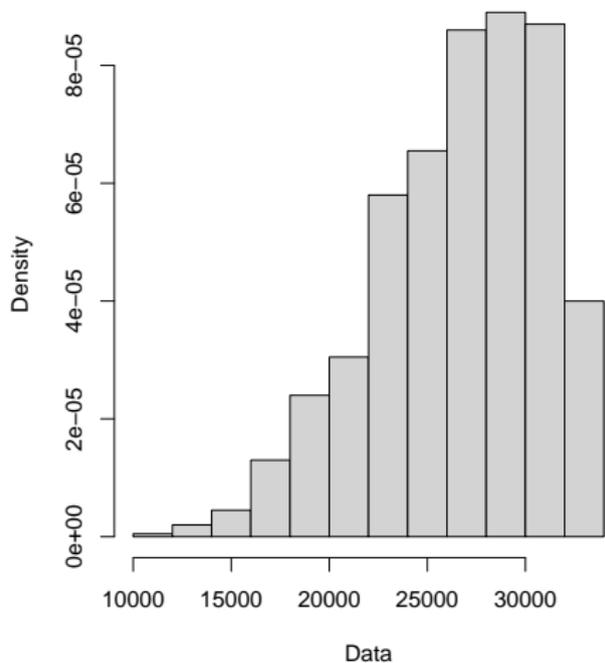
```
##      Min. 1st Qu.  Median      Mean 3rd Qu.      Max.
##   9521  21036  27278  28479  34299  90712
```

```
summary(blockmax$loggblock)
```

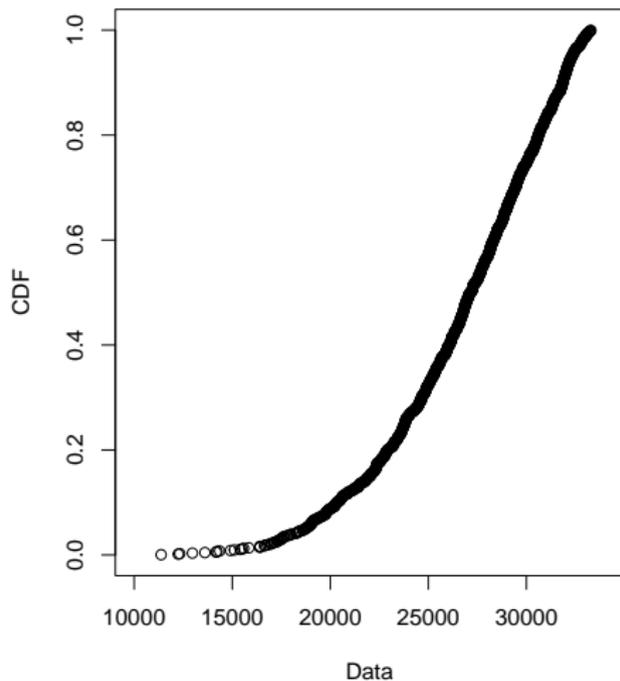
```
##      Min. 1st Qu.  Median      Mean 3rd Qu.      Max.
##   9326  18618  24590  28587  33259  157377
```

```
plotdist(blockmax$betablock)
```

Histogram

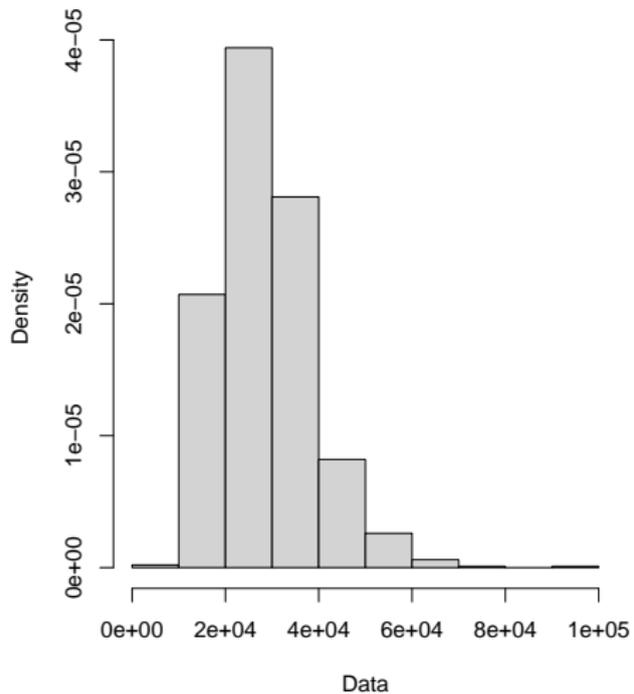


Cumulative distribution

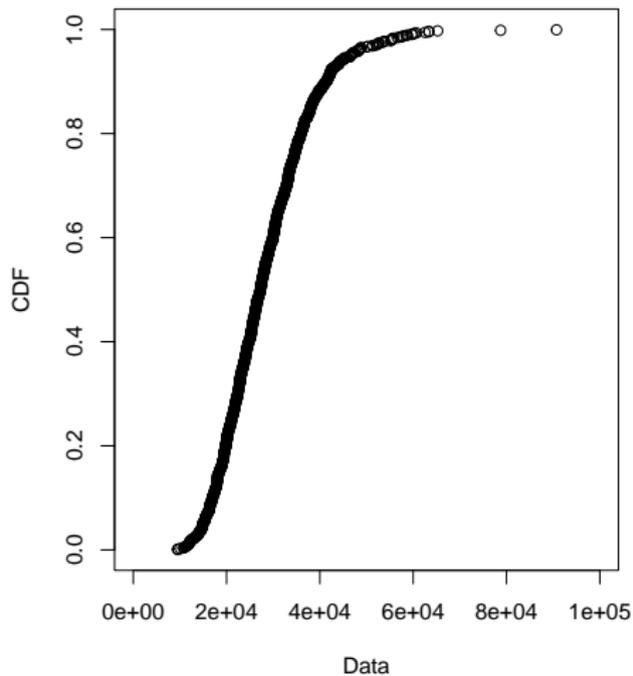


```
plotdist(blockmax$gammblock)
```

Histogram

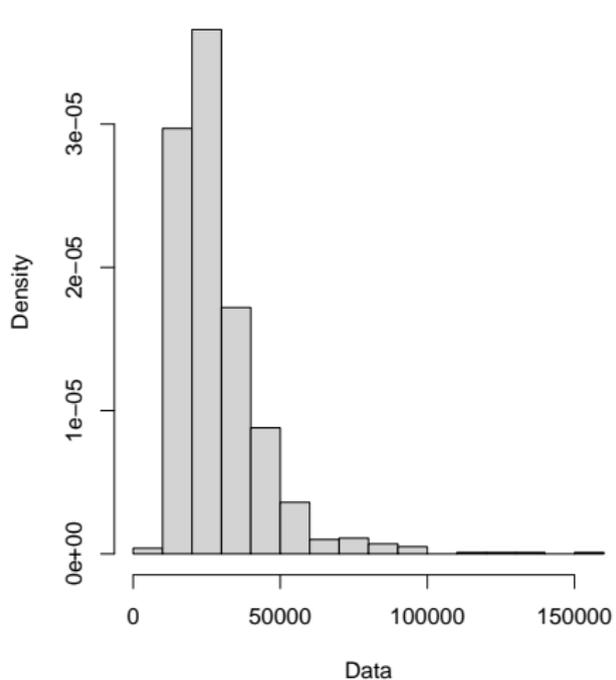


Cumulative distribution

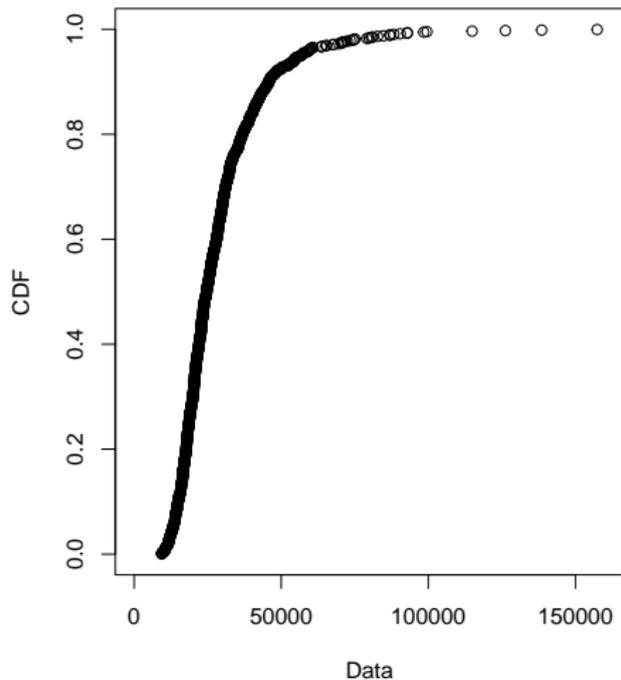


```
plotdist(blockmax$loggblock)
```

Histogram

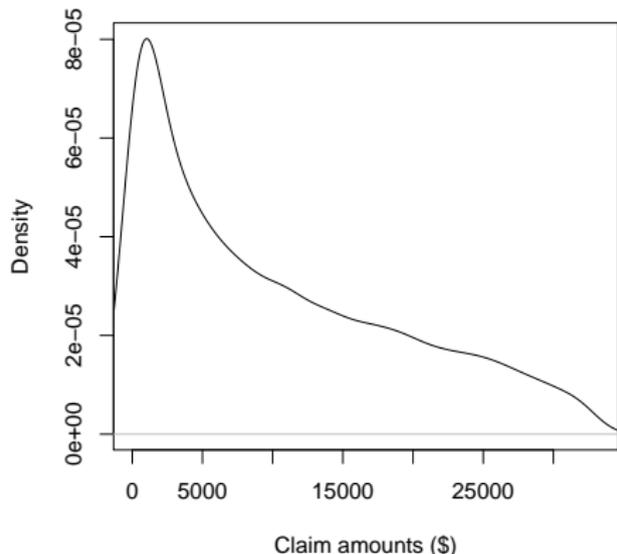


Cumulative distribution

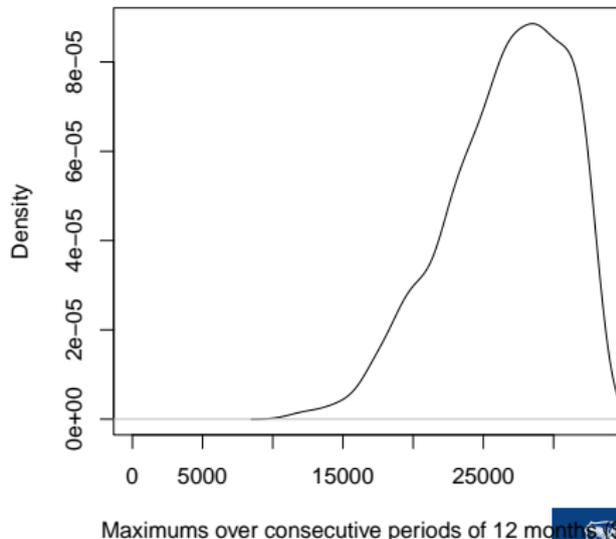


```
par(mfrow = c(1, 2))  
plot(density(claims$beta), main = "Density of the beta claims",  
     xlab = "Claim amounts ($)", xlim = c(0, max(claims$beta)))  
plot(density(blockmax$betablock), main = "Density of the beta block maxima",  
     xlab = "Maximums over consecutive periods of 12 months ($)",  
     xlim = c(0, max(claims$beta)))
```

Density of the beta claims

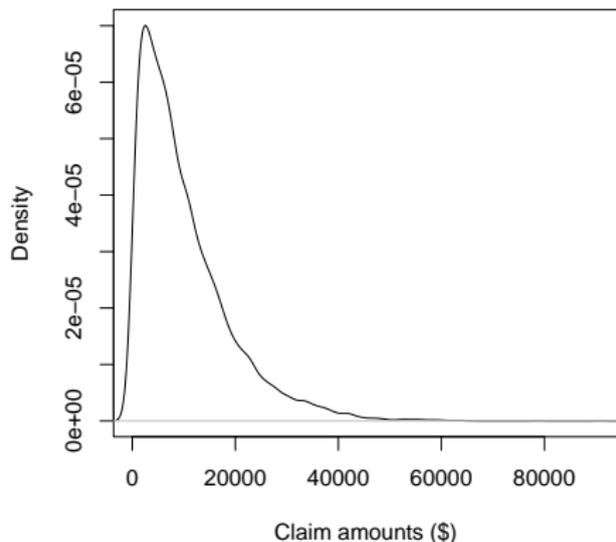


Density of the beta block maxima

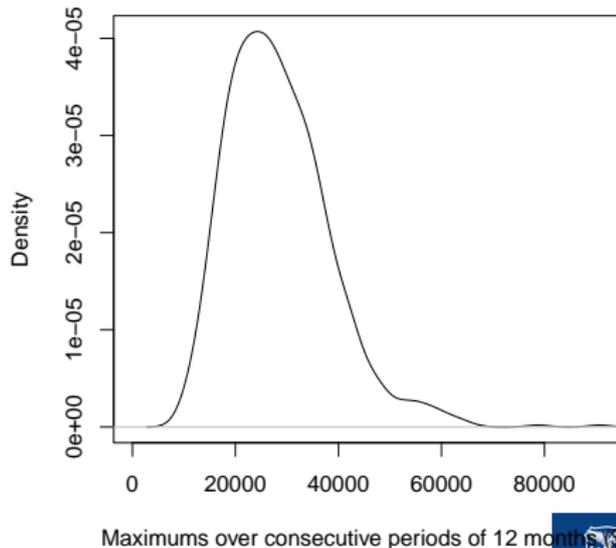


```
par(mfrow = c(1, 2))  
plot(density(claims$gamm), main = "Density of the gammormal claims",  
     xlab = "Claim amounts ($)", xlim = c(0, max(claims$gamm)))  
plot(density(blockmax$gammblock), main = "Density of the gammormal block maxima",  
     xlab = "Maximums over consecutive periods of 12 months ($)",  
     xlim = c(0, max(claims$gamm)))
```

Density of the gammormal claims

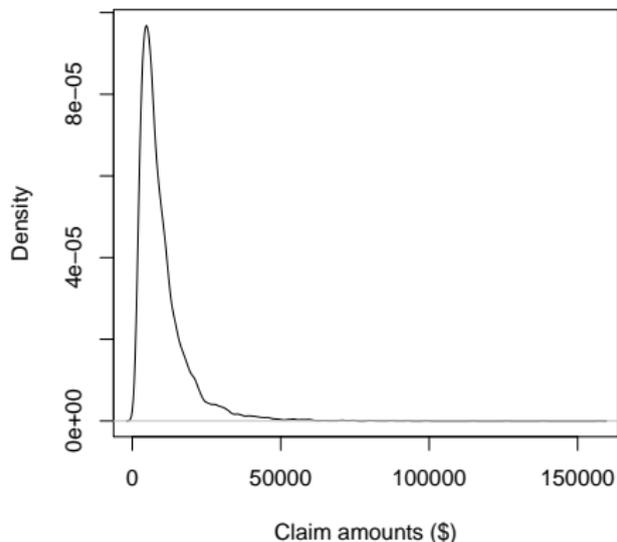


Density of the gammormal block maxima

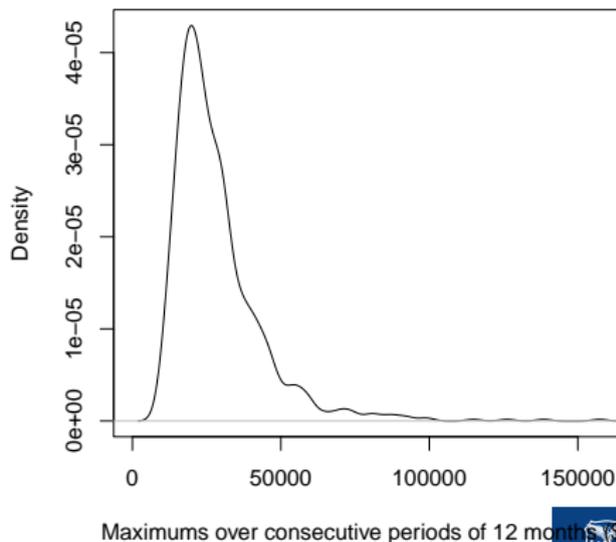


```
par(mfrow = c(1, 2))  
plot(density(claims$logg), main = "Density of the log-gamma claims",  
     xlab = "Claim amounts ($)", xlim = c(0, max(claims$logg)))  
plot(density(blockmax$loggblock), main = "Density of the log-gamma block maxima",  
     xlab = "Maximums over consecutive periods of 12 months ($)",  
     xlim = c(0, max(claims$logg)))
```

Density of the log-gamma claims



Density of the log-gamma block maxima

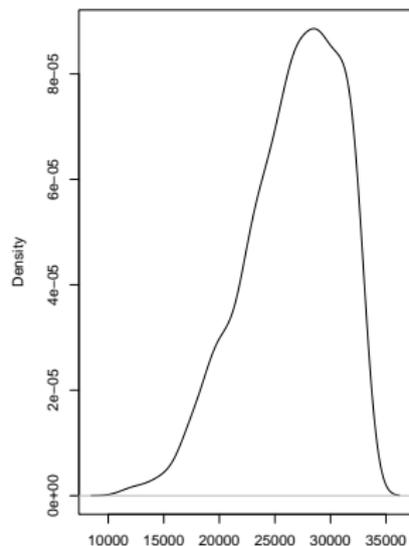


```

par(mfrow = c(1, 3))
plot(density(blockmax$betablock), main = "Density of the beta block maxima"
     xlab = "Maximums over consecutive periods of 12 months ($)")
plot(density(blockmax$gammablock), main = "Density of the gammormal block maxima"
     xlab = "Maximums over consecutive periods of 12 months ($)")
plot(density(blockmax$loggblock), main = "Density of the loggamma block maxima"
     xlab = "Maximums over consecutive periods of 12 months ($)")

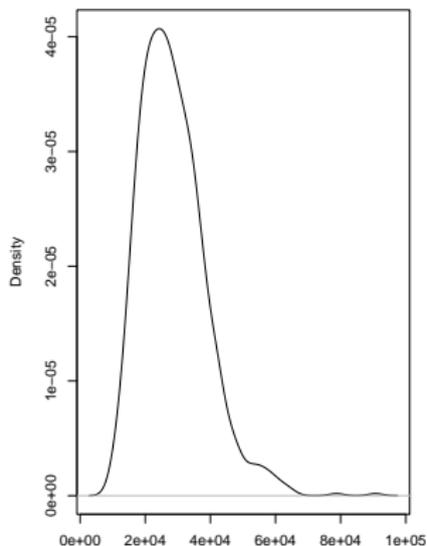
```

Density of the beta block maxima



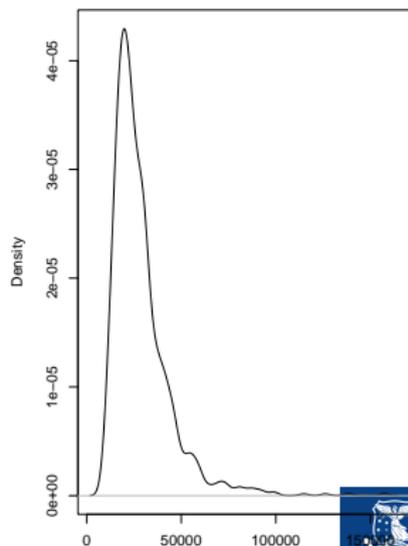
Maximums over consecutive periods of 12 months (\$)

Density of the gammormal block maxima



Maximums over consecutive periods of 12 months (\$)

Density of the loggamma block maxima



Maximums over consecutive periods of 12 months (\$)

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- **Case study - fitting**
- Case study - choice of block size
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## Fitting results

For example for the logg BM we use the following code:

- `fit.logg <- fevd(blockmax$loggblock)` will perform the fit
- `fit.logg` will display the results of the fitting
- `plot(fit.logg)` will plot goodness of fit graphical analysis
- `plot(fit.logg,"trace")` will plot the likelihood function around the chosen parameters

More details can be found in Gilleland and Katz (2016).

Results (MLE with standard errors in parentheses) are

	location $\mu$	scale $\sigma$	shape $\gamma$
beta	25644.93 (163.26)	4695.76 (130.07)	-0.6012 (0.0212)
gamma	24069.68 (288.51)	8225.98 (215.80)	-0.0243 (0.0222)
loggamma	21466.22 (305.26)	8496.86 (251.97)	0.2299 (0.0278)

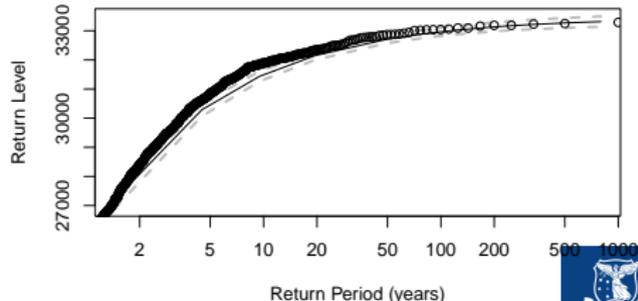
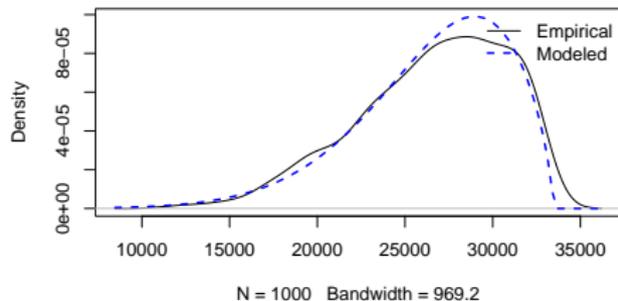
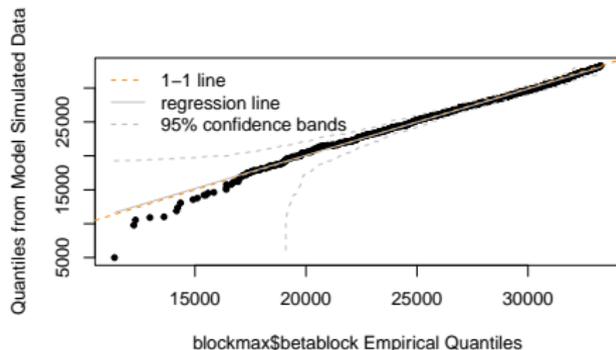
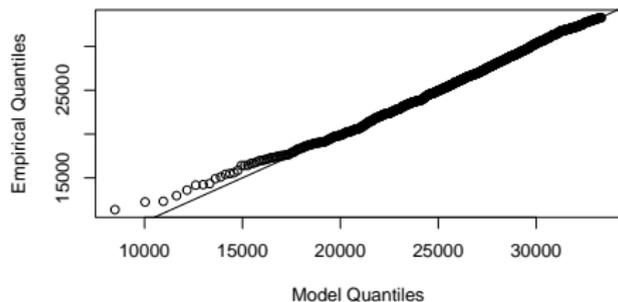
Note:

- These correspond to the three distinct cases introduced before as expected (look at the sign of  $\gamma$ )
- Whether  $\gamma \neq 0$  for gamma can be formally tested in different ways (see Gilleland and Katz 2016), but the standard error for  $\gamma^{\text{gamm}}$  suggests a null hypothesis of  $\gamma^{\text{gamm}} = 0$  would not be rejected.

```
fit.beta <- fevd(blockmax$betablock)
fit.beta
...
## Estimated parameters:
##      location      scale      shape
## 25644.9318770  4695.7556362  -0.6011579
##
## Standard Error Estimates:
##      location      scale      shape
## 163.26448220 130.06954138  0.02120487
##
## Estimated parameter covariance matrix.
##      location      scale      shape
## location 26655.291148 -8463.804677 -1.2827274300
## scale    -8463.804677 16918.085595 -1.7746706658
## shape     -1.282727   -1.774671  0.0004496465
##
## AIC = 19385.23
##
## BIC = 19399.96
...
```

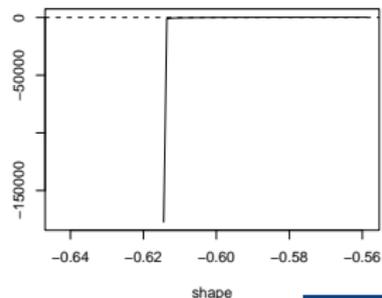
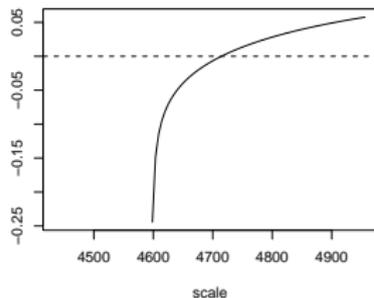
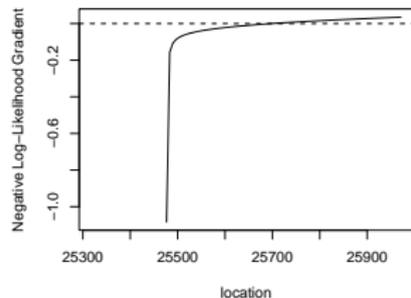
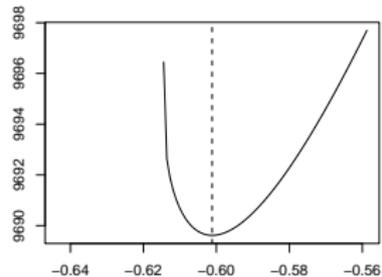
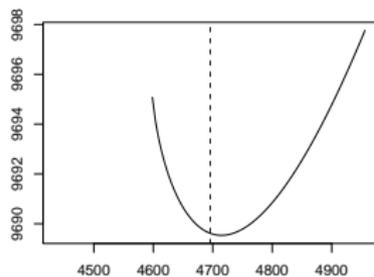
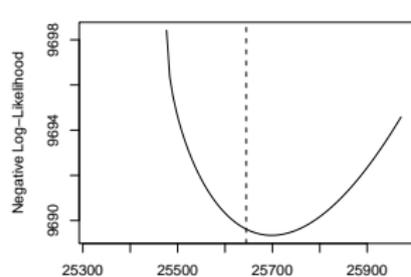
```
plot(fit.beta)
```

```
fevd(x = blockmax$betablock)
```



```
plot(fit.beta, "trace")
```

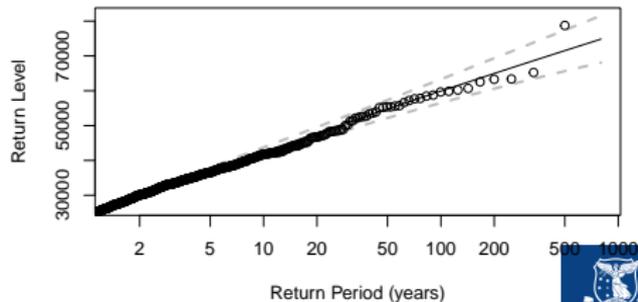
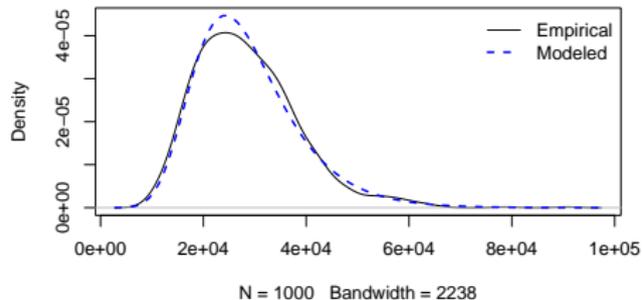
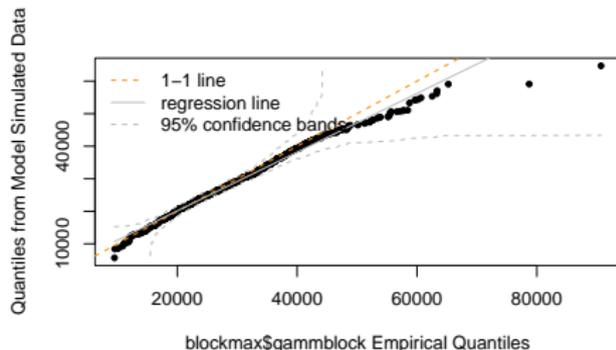
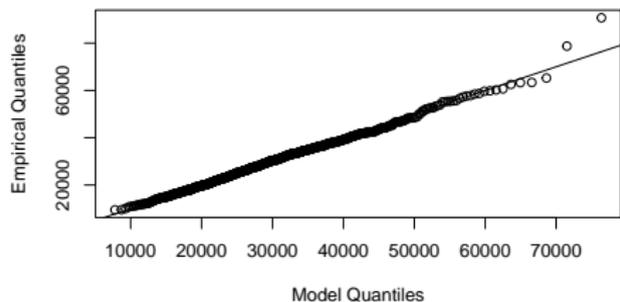
fevd(x = blockmax\$betablock)



```
fit.gamm <- fevd(blockmax$gammblock)
fit.gamm
...
## Estimated parameters:
##      location      scale      shape
## 2.406968e+04  8.225984e+03 -2.428561e-02
##
## Standard Error Estimates:
##      location      scale      shape
## 288.51126151  215.80131542  0.02220903
##
## Estimated parameter covariance matrix.
##      location      scale      shape
## location 83238.748021 21650.963339 -2.0732933864
## scale    21650.963339 46570.207736 -1.4944271291
## shape    -2.073293   -1.494427  0.0004932409
##
## AIC = 21127.17
##
## BIC = 21141.89
...
```

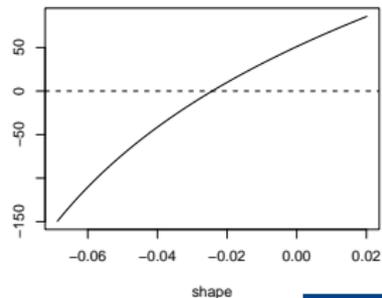
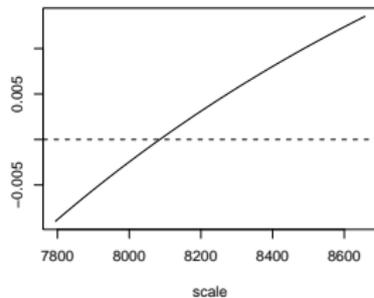
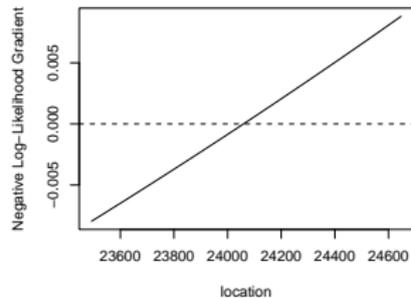
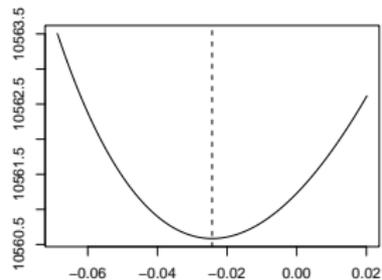
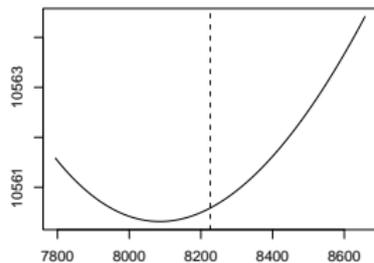
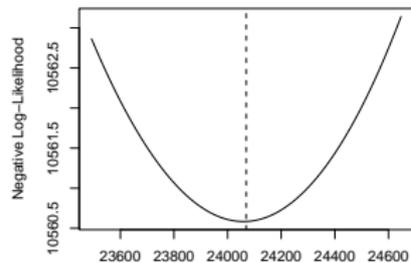
```
plot(fit.gamm)
```

```
fevd(x = blockmax$gammblock)
```



```
plot(fit.gamm, "trace")
```

```
fevd(x = blockmax$gammblock)
```

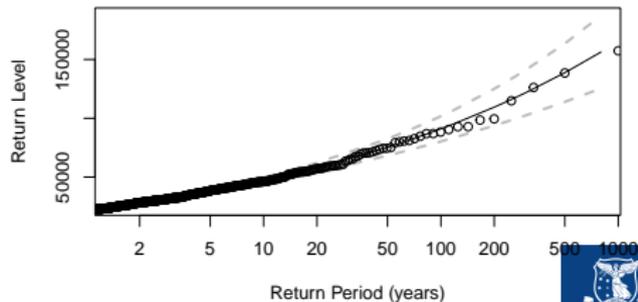
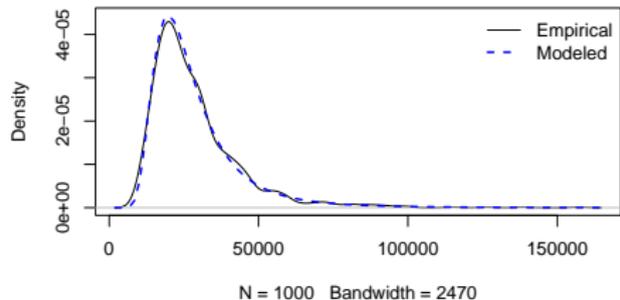
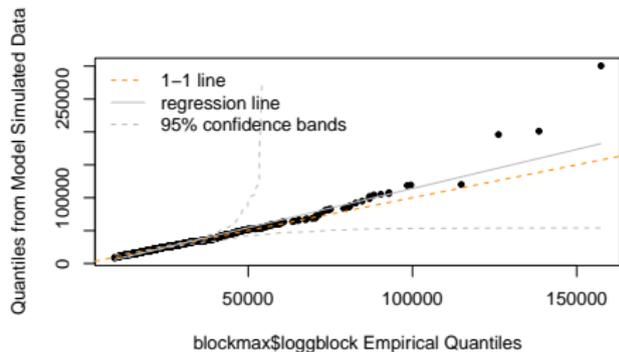
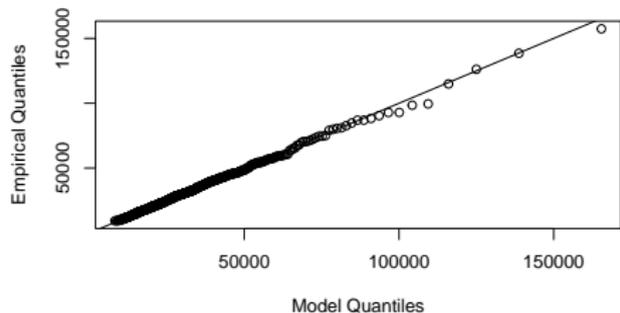


```
fit.logg <- fevd(blockmax$loggblock)
fit.logg
...
## Estimated parameters:
##      location      scale      shape
## 21466.224267  8496.863050    0.229869
##
## Standard Error Estimates:
##      location      scale      shape
## 305.26319633 251.96813464    0.02779193
##
## Estimated parameter covariance matrix.
##      location      scale      shape
## location 93185.619034 45516.589907 -2.5704729225
## scale    45516.589907 63487.940873 -0.5065090364
## shape    -2.570473   -0.506509   0.0007723913
##
## AIC = 21491.68
##
## BIC = 21506.4
...

```

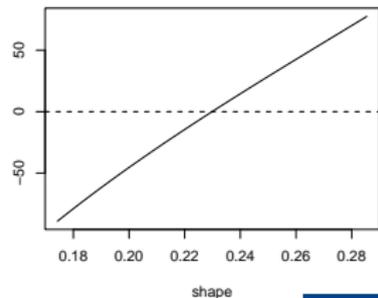
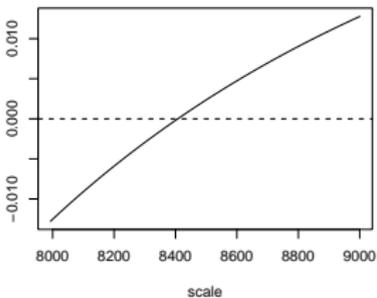
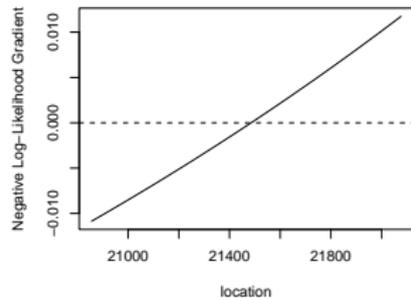
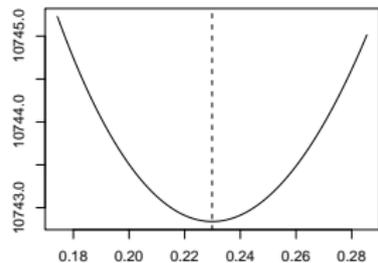
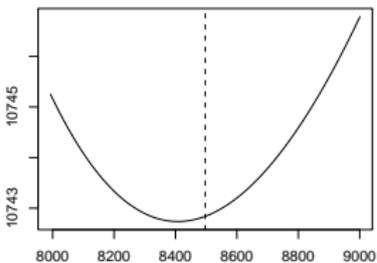
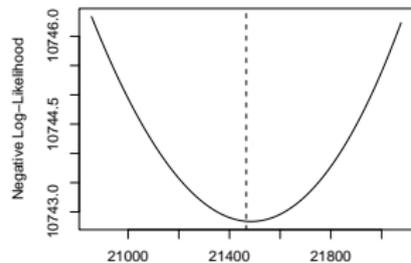
```
plot(fit.logg)
```

```
fevd(x = blockmax$loggblock)
```



```
plot(fit.logg, "trace")
```

fevd(x = blockmax\$loggblock)



## 2 Generalised Extreme Value distribution

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- **Case study - choice of block size**
- Moments
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## Case study - choice of block size

Remember that

- the larger the block, the closer we are to the limiting distribution (this is good)

However

- the larger the block, the least data we have (this is bad)

Here we aim to illustrate the impact on the parameter estimates of increasing block sizes.

# Convergence with increasing block sizes

```

# block sizes
blocksizes <- c(1, 2, 3, 4, 6, 12, 18, 24, 30, 60, c(1:20 * 120))
results <- c()
for (i in blocksizes) {
  # number of full blocks to work with
  numbers <- floor(length(claims$beta)/max(blocksizes))
  # trimming claims vector
  claims_trimmed <- claims[1:(numbers * i), ]
  # block maxima
  claims_trimmed$block <- (claims_trimmed$month - 1)%/%i +
    1
  blockmax2 <- tibble(betablock2 = aggregate(beta ~ block,
    claims_trimmed, max)$beta, gammblock2 = aggregate(gamm ~
    block, claims_trimmed, max)$gamm, loggblock2 = aggregate(logg ~
    block, claims_trimmed, max)$logg)
  # fitting
  fit.beta2 <- fevd(blockmax2$betablock2)
  fit.gamm2 <- fevd(blockmax2$gammblock2)
  fit.logg2 <- fevd(blockmax2$loggblock2)
  results <- rbind(results, c(i, as.double(fit.beta2$results$par[1:3]),
    as.double(fit.gamm2$results$par[1:3]), as.double(fit.logg2$results$par[1:3])))
}

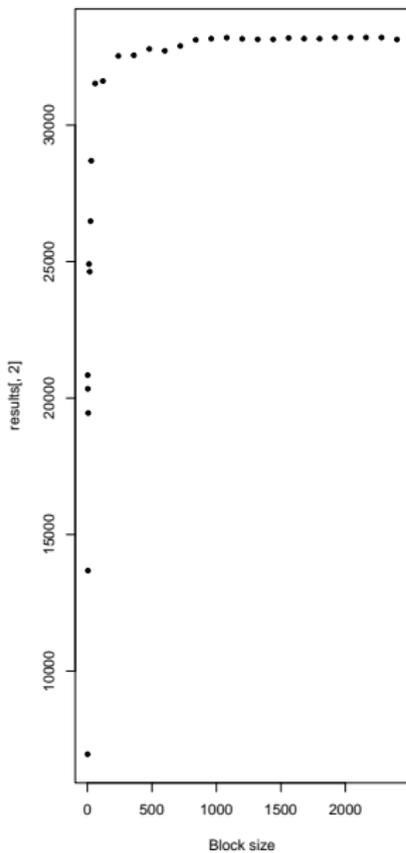
```

```
par(mfrow = c(1, 3))
plot(results[, 1], results[, 2], pch = 20, main = "Convergence of mu (betab)
      xlab = "Block size")
plot(results[, 1], results[, 3], pch = 20, main = "Convergence of sigma (be
      xlab = "Block size")
plot(results[, 1], results[, 4], pch = 20, main = "Convergence of gamma (be
      xlab = "Block size")
```

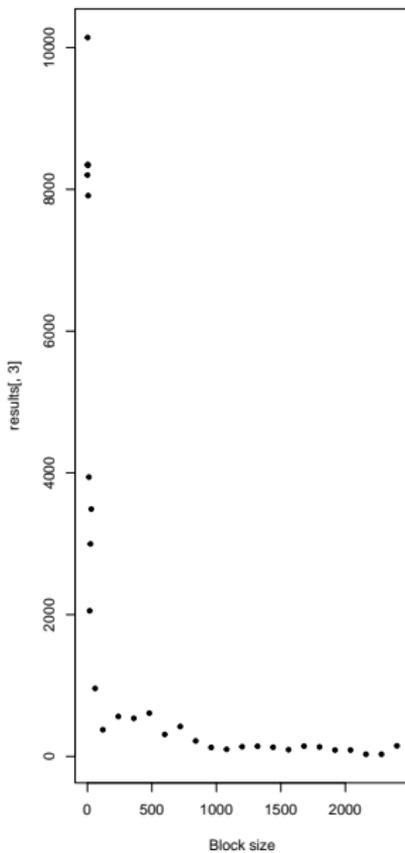
```
par(mfrow = c(1, 3))
plot(results[, 1], results[, 5], pch = 20, main = "Convergence of mu (gambb)
      xlab = "Block size")
plot(results[, 1], results[, 6], pch = 20, main = "Convergence of sigma (ga
      xlab = "Block size")
plot(results[, 1], results[, 7], pch = 20, main = "Convergence of gamma (ga
      xlab = "Block size")
```

```
par(mfrow = c(1, 3))
plot(results[, 1], results[, 8], pch = 20, main = "Convergence of mu (loggb)
      xlab = "Block size")
plot(results[, 1], results[, 9], pch = 20, main = "Convergence of sigma (lo
      xlab = "Block size")
plot(results[, 1], results[, 10], pch = 20, main = "Convergence of gamma (l
      xlab = "Block size")
```

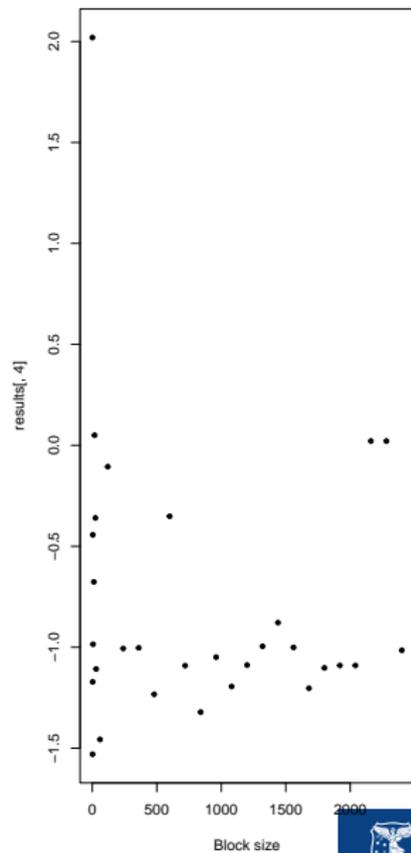
Convergence of mu (betablock)



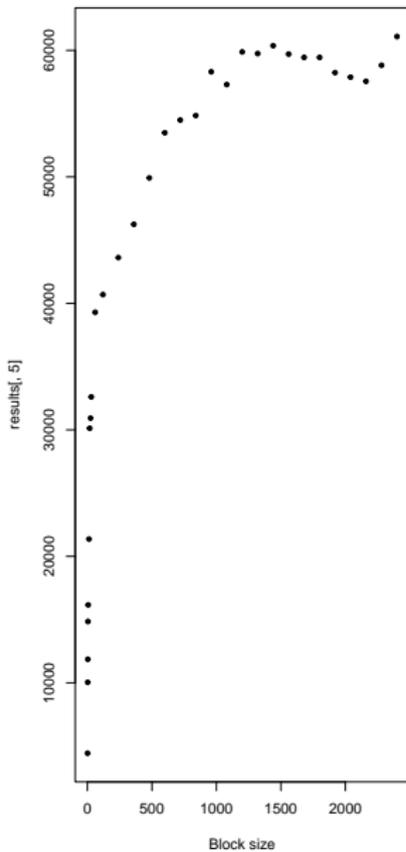
Convergence of sigma (betablock)



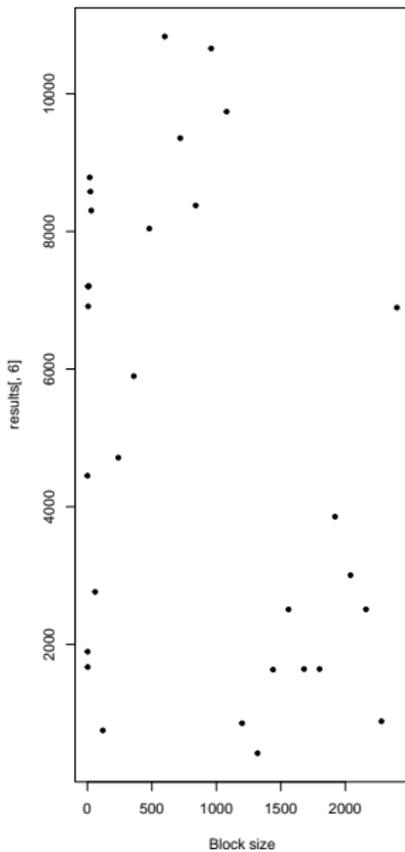
Convergence of gamma (betablock)



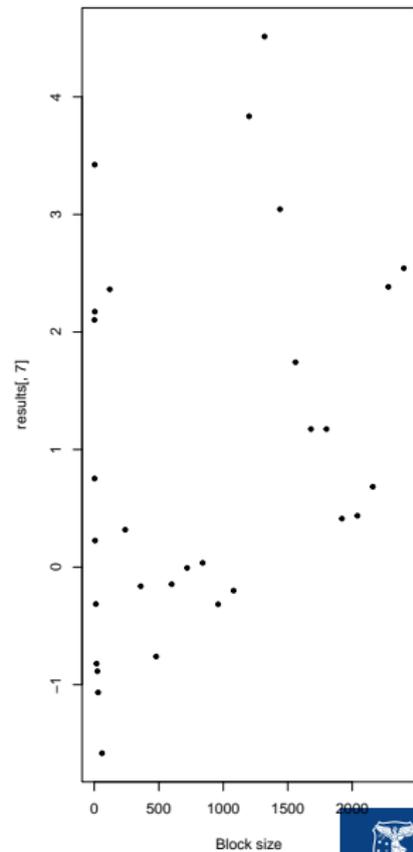
Convergence of mu (gammblock)

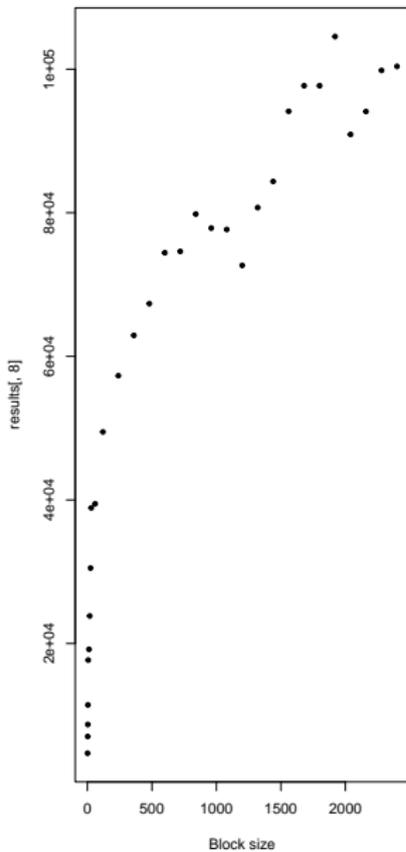
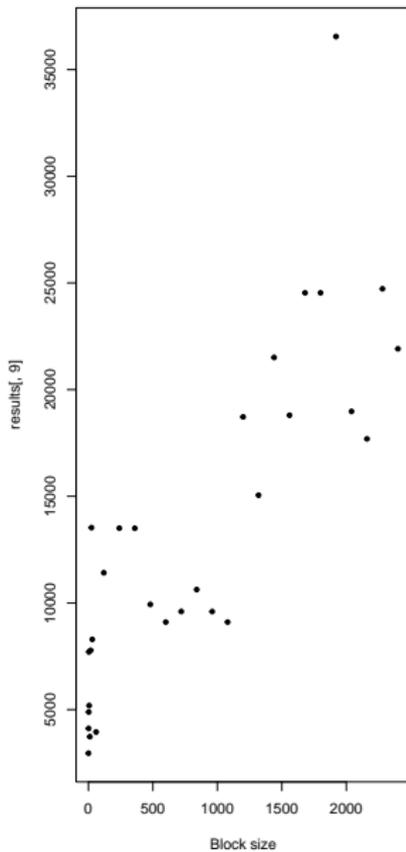
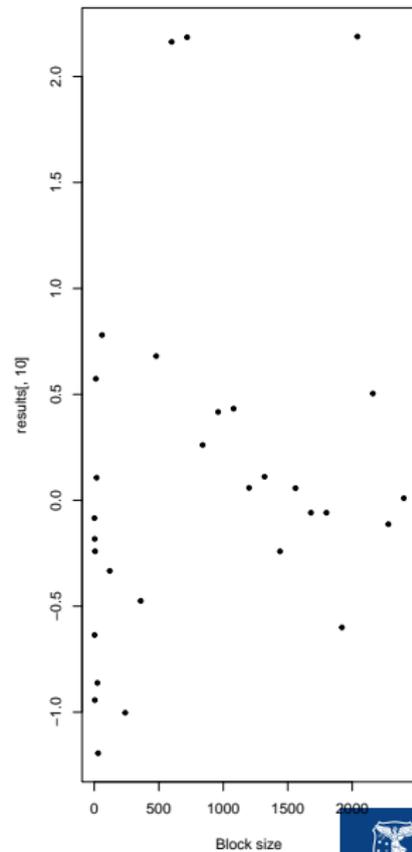


Convergence of sigma (gammblock)



Convergence of gamma (gammblock)



Convergence of  $\mu$  (logblock)Convergence of  $\sigma$  (logblock)Convergence of  $\gamma$  (logblock)

## 2 Generalised Extreme Value distribution

- The GEV distribution
- Case study - data
- Case study - fitting
- Case study - choice of block size
- **Moments**
- PML and quantiles
- Case study - quantiles

# Moments

Let  $Z$  follow a  $GEV(\mu, \sigma, \gamma)$ . We have then

$$E[Z] = \begin{cases} \mu + \sigma (\Gamma(1 - \gamma) - 1) / \gamma, & \gamma \neq 0, \gamma < 1, \\ \mu + \sigma \cdot e, & \gamma = 0, \\ \infty, & \gamma \geq 1. \end{cases}$$

$$Var(Z) = \begin{cases} \sigma^2 [\Gamma(1 - 2\gamma) - \Gamma(1 - \gamma)^2] / \gamma^2, & \gamma \neq 0, \gamma < 1/2, \\ \sigma^2 \cdot \pi/6, & \gamma = 0, \\ \infty, & \gamma \geq 1/2. \end{cases}$$

	Emp Mean	Emp Variance	Theo Mean	Theo Variance
beta	26606.41	18381480	26475.58	18584454
gamm	28141.08	222758930	28242.00	249582072
logg	28586.58	239426765	28842.05	280329757

(Empirical moments are calculated from the data,  
Theoretical are calculated with parameters estimates as per above)

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# PML

- Since actual maxima can become infinite in insurance (in practical terms), we need to find a “reasonable” maximum to work with for capital and (mitigation) investment purposes (cost-benefit analysis)
- The question of “how bad” the losses can get cannot be disentangled from frequency, as the longer the timeframe, the bigger the losses can be
- The answer is called a “probable maximum loss” (PML). It has a probability (or frequency) attached to it.

# Example

Table 3 – Estimated cost of flooding in the Brisbane River floodplain for different size floods

AEP	Tangible (\$million)	Intangible (\$million)	Total (\$million)
10% (1 in 10)	\$39	\$0	\$39
2% (1 in 50)	\$1,560	\$190	\$1,750
1% (1 in 100)	\$5,150	\$1,610	\$6,760
0.2% (1 in 500)	\$14,360	\$11,050	\$25,410
0.05% (1 in 2,000)	\$22,960	\$24,500	\$47,460
0.001% (100,000)	\$73,650	\$127,100	\$200,750

“Brisbane River Strategic Floodplain Management Plan” (Queensland Reconstruction Authority (2019))

“AEP” = “Annual Exceedance Probability”

## $t$ -year events and PML

- Imagine you are focused on yearly outcomes, and that you want to estimate the outcome that you would expect will happen on average no more often than every 200 years (such as in solvency requirements in Australia)
- This is a “one-in-200-years” event, and is referred to as “ $t$ -year event” (where  $t = 200$  above), or outcome with a  $t$ -year “return period”
- This is what we will use to calculate a PML of corresponding probability  $1/t$
- This is obviously impossible to estimate from data for large  $t$ , as it is simply not available - there is not enough information about the tail
- And this is even ignoring non stationarity (e.g., climate change)

- Note that that a  $t$ -year event can happen more often than every  $t$  years! For instance:
  - The probability that a 200-year event will happen within the next 10 years is as high as  $1 - \text{pbinom}(0, 10, 1/200) = 0.0488899$
  - The probability that it will happen more than twice in the next 50 years is  $1 - \text{pbinom}(1, 20, 1/200) = 0.0261315$
  - These calculations become even more dramatic with slightly lower frequency events (1-in-100 or 1-in-50 year events)

# Example

Table 1 – Likelihood for a range of flood AEPs occurring in an 80-year lifetime in the Brisbane River floodplain derived from the Flood Study

AEP	At least once in 80 years	At least twice in 80 years	Brisbane City gauge (m, AHD)	Ipswich CBD (m, AHD)
10% (1 in 10)	100%	100%	1.8	14.8
5% (1 in 20)	98%	91%	2.2	16.1
2% (1 in 50)	80%	48%	3.2	18.7
1% (1 in 100)	55%	19%	4.5	20.1
0.2% (1 in 500)	15%	1%	7.3	23.4
0.05% (1 in 2000)	4%	0.1%	9.9	25.7
0.001% (1 in 100,000)	0.1%	< 0.1%	23.7	36.1

“Brisbane River Strategic Floodplain Management Plan” (Queensland Reconstruction Authority (2019))

## Caution: what are you modelling?

- Although it is possible to get  $t$ -year quantiles from the GEV, it is not always obvious how to relate those to the above actuarial problem unless you are fitting portfolio level loss data
- It is not clear how to aggregate the maximum of a single loss to the maximum of a whole portfolio
- Because of this, the above results are generally used to model outcomes of the peril (e.g. flood level), not losses. Damages are subsequently mapped into aggregate losses
- The interpretation and fitting is easier in that context
  - for instance climate data, where you have daily maximum temperatures, and you may want to get a maximum with 200 day return period
  - furthermore, the R package allows for seasonality

# Quantiles

For  $t$ -year events we seek  $u_t$  such that  $H_{\gamma;\mu,\sigma}(u_t) = 1 - 1/t$ , that is,

$$u_t = H_{\gamma;\mu,\sigma}^{-1}(1 - 1/t).$$

We have

$$u_t = \begin{cases} \mu + \frac{\sigma}{\gamma} \left[ \left( -\frac{1}{\log(1-1/t)} \right)^\gamma - 1 \right] & \text{for } \gamma \neq 0. \\ \mu + \sigma \log \left( -\frac{1}{\log(1-1/t)} \right) & \text{for } \gamma = 0. \end{cases}$$

Close examination of those formulas tells us that the curvature of  $u_t$  as a function of  $\log(-1/\log(1 - 1/t)) \equiv y$  depends on the distribution:

- $\gamma < 0$  (Weibull): concave with asymptotic upper limit as  $t \rightarrow \infty$  at its upper bound  $\mu - \sigma/\gamma$ :

$$\mu + \frac{\sigma}{\gamma} (e^{\gamma y} - 1) \xrightarrow{y \rightarrow \infty} \mu - \sigma/\gamma$$

since  $\gamma < 0$ .

- $\gamma = 0$  (Gumbel): linear
- $\gamma > 0$  (Fr'chet) convex with no finite upper bound

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## Case study - quantiles

First, note that empirical  $(1 - 1/t)$ -th quantiles in the data  $(X_{n(1/t),n})$  are

```
ret.per <- c(10, 50, 100, 200, 500)
Xnn <- cbind(beta = sort(claims$beta, decreasing = TRUE), gamm = sort(claims$gamm, decreasing = TRUE), logg = sort(claims$logg, decreasing = TRUE))
empquant <- data.frame(Xnn[length(claims$beta) * 1/ret.per, ])
rownames(empquant) <- ret.per
empquant
```

	beta	gamm	logg
10	24308.60	21986.51	19253.06
50	30526.74	35395.89	35621.35
100	31753.68	40474.56	44351.62
200	32235.67	45118.02	54439.08
500	32790.91	53731.02	71437.34

These are **not** to be compared with the quantiles of the GEV.

The GEV models the distribution of **maxima**.

## Empirical quantiles in the blocks:

```
Xnn2 <- cbind(betablock = sort(blockmax$betablock, decreasing = TRUE),
  gammblock = sort(blockmax$gammblock, decreasing = TRUE),
  loggblock = sort(blockmax$loggblock, decreasing = TRUE))
empquantblock <- data.frame(Xnn2[length(blockmax$betablock) *
  1/ret.per, ])
rownames(empquantblock) <- ret.per
empquantblock
```

	betablock	gammblock	loggblock
10	31845.47	41496.29	45836.54
50	32869.52	55387.21	74562.03
100	33042.45	59653.57	88275.45
200	33186.66	63289.25	99494.12
500	33249.33	78734.31	138514.02

## Theoretical quantiles in the blocks (maxima):

```

parm <- cbind(as.double(fit.beta$results$par[1:3]), as.double(fit.gamm$resu
  as.double(fit.logg$results$par[1:3]))
ut.theo <- data.frame(cbind(beta = parm[1, 1] + parm[2, 1]/parm[3,
  1] * ((-1/(log(1 - 1/ret.per)))^parm[3, 1] - 1), gamm = parm[1,
  2] + parm[2, 2]/parm[3, 2] * ((-1/(log(1 - 1/ret.per)))^parm[3,
  2] - 1), logg = parm[1, 3] + parm[2, 3]/parm[3, 3] * ((-1/(log(1 -
  1/ret.per)))^parm[3, 3] - 1)))
rownames(ut.theo) <- ret.per
ut.theo

```

	beta	gamm	logg
10	31436.86	42084.41	46508.37
50	32707.95	54693.10	75140.65
100	32964.40	59873.26	90920.27
200	33132.46	64947.90	109373.87
500	33269.71	71513.08	138703.54

Now this can be done with `extRemes` (with confidence intervals!)

```
return.level(fit.beta, return.period = ret.per, do.ci = TRUE)
```

```
...
##                95% lower CI Estimate 95% upper CI
## 10-year return level      31263.52 31436.86      31610.19
## 50-year return level      32573.09 32707.95      32842.81
## 100-year return level     32821.90 32964.40      33106.90
## 200-year return level     32978.01 33132.46      33286.90
## 500-year return level     33099.84 33269.71      33439.57
...
```

```
return.level(fit.gamm, return.period = ret.per, do.ci = TRUE)
```

```
...
##                95% lower CI Estimate 95% upper CI
## 10-year return level     40867.26 42084.41      43301.56
## 50-year return level     52139.71 54693.10      57246.48
## 100-year return level    56484.68 59873.26      63261.84
## 200-year return level    60578.48 64947.90      69317.31
## 500-year return level    65635.36 71513.08      77390.81
...
```

```
return.level(fit.logg, return.period = ret.per, do.ci = TRUE)
```

```
...  
##                95% lower CI  Estimate  95% upper CI  
## 10-year return level    44199.82  46508.37    48816.91  
## 50-year return level    68082.59  75140.65    82198.71  
## 100-year return level   80241.17  90920.27   101599.36  
## 200-year return level   93750.30 109373.87   124997.45  
## 500-year return level  113913.35 138703.54   163493.72  
...
```

Theoretical figures are close to the empirical ones (as they should!), but obviously the theoretical versions are smoothed and will be less likely to underestimate extreme events, especially in high return level figures (which are more prone to sampling issues in the empirical data).

- 1 Introduction
- 2 Generalised Extreme Value distribution
- 3 Generalised Pareto distribution**
- 4 Measures of tail weight

- 3 Generalised Pareto distribution
  - Asymptotic properties of the tails
  - The GP distribution
  - Estimation
  - Case study

## Main result: Asymptotic properties of the tails

- Let us now consider a distribution  $F$  of losses  $Y$ . We are interested in the asymptotic behaviour of the tail so that we can approximate it due to lack of data [see also Chapter 4 of Wuthrich (2023);  $S_{sc}$  vs  $S_{lc}$ ]
- If we were pricing an excess of loss (or stop loss on a portfolio), the *attachment point* or *retention level* or *limit* could be expressed as a  $t$ -year event or quantile

$$u_t = F^{-1} \left( 1 - \frac{1}{t} \right).$$

- The tail is the distribution beyond this point. We characterise the tail with the help of the distribution function of the excess over threshold  $u$

$$F_u(x) = \Pr[Y - u \leq x | Y > u].$$

- The **main result is that, for high  $u$ ,  $F_u(x)$  can be approximated by a Generalised Pareto**. (technically, as  $u$  increases to the maximum possible value of  $x$  then the absolute difference between both distributions is asymptotically zero)

### 3 Generalised Pareto distribution

- Asymptotic properties of the tails
- The GP distribution
- Estimation
- Case study

# Generalised Pareto distribution

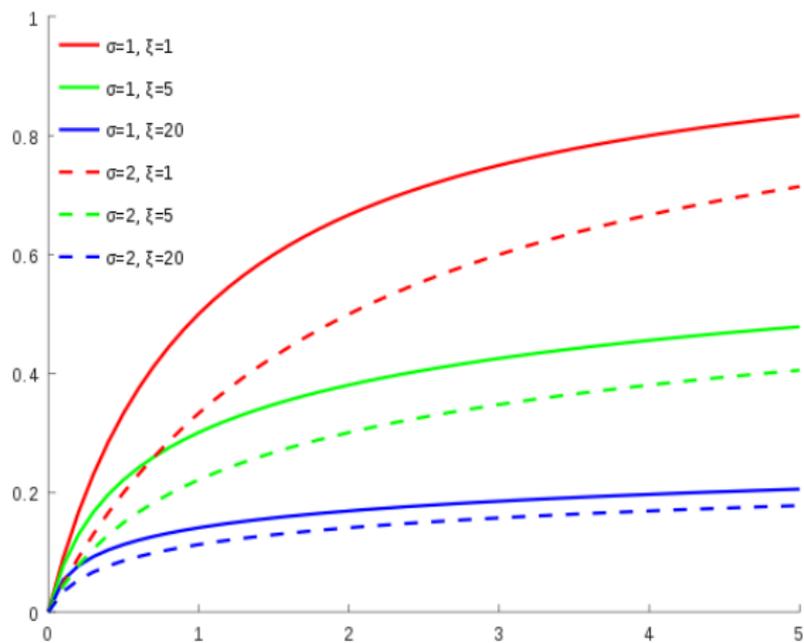
- The Generalised Pareto distribution function is given by

$$G_{\gamma,\sigma}(x) = \begin{cases} 1 - \left(1 + \gamma \frac{x}{\sigma}\right)_+^{-\frac{1}{\gamma}} & \gamma \neq 0 \\ 1 - \exp\left(-\frac{x}{\sigma}\right) & \gamma = 0 \end{cases}$$

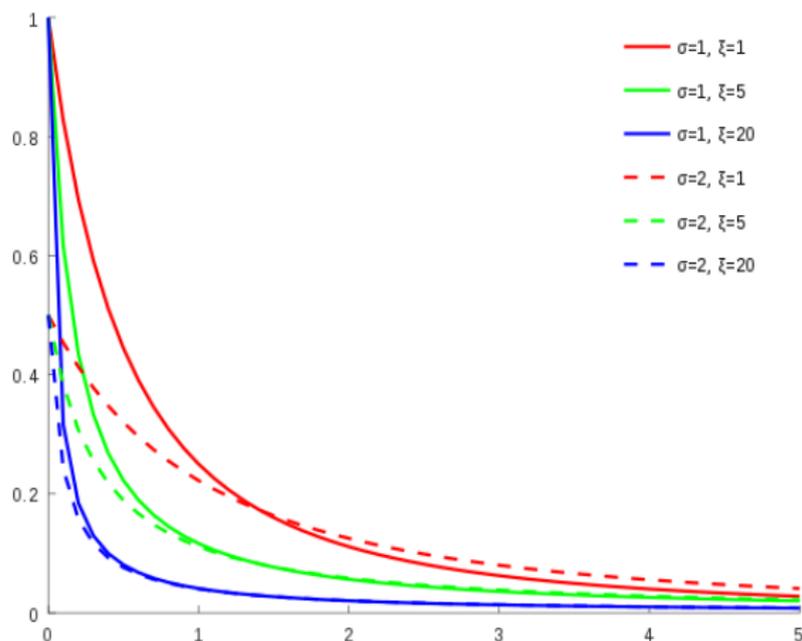
for a scale parameter  $\sigma > 0$ .

- We distinguish again three cases:
  - $\gamma < 0$  (upper bound, also referred to as “Pareto Type II”): light tail,  $X \in (0, \sigma/|\gamma|)$
  - $\gamma = 0$  (exponential): base case  $X \in \mathbb{R}$
  - $\gamma > 0$  (Pareto): heavy tail,  $X \in \mathbb{R}^+$

## GP df



## GP pdf



- note  $\xi \equiv \gamma$  (both graphs are from Wikipedia)

# Moments

The first central moments of  $X$ , the excess of  $u$ , are

$$\begin{aligned} E[X] &= \frac{\sigma}{1-\gamma}, \quad \gamma < 1, \\ \text{Var}(X) &= \frac{\sigma^2}{(1-\gamma)^2(1-2\gamma)}, \quad \gamma < 1/2. \end{aligned}$$

Note:

- The first four  $k$  moments exist only for  $\gamma < 1/k$ .
- $E[X]$  is the stop loss premium (since  $X$  is the excess over threshold  $u$ )

### 3 Generalised Pareto distribution

- Asymptotic properties of the tails
- The GP distribution
- Estimation
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## Estimation: choice of threshold $u$

We seek to estimate the tail (remember Tutorial Exercise NLI11)

$$\bar{F}(u+x) = \bar{F}(u)\bar{F}_u(x)$$

for a fixed large value  $u$  and all  $x \geq 0$ . To do so, we need to estimate:

- Probability of exceeding  $u$

$$\widehat{\bar{F}(u)} = \frac{n_u}{n}$$

which will be more accurate for  $u$  not too large.

- Then for given value of  $u$

$$\widehat{\bar{F}_u(x)} = G_{\hat{\gamma}, \hat{\sigma}}(x)$$

where  $\hat{\gamma}(u)$  and  $\hat{\sigma}(u)$  are estimated from the data in the tail above  $u$  (via MLE). This approximation will work well only for large  $u$  (as the result is an asymptotic result for  $u \rightarrow \infty$ ).

## Estimation: choice of threshold $u$

The choice of  $u$  presents conflicting requirements for  $u$ :

- larger  $u$  will lead to a better approximation from a distributional perspective
- but larger  $u$  reduces the amount of data to estimate  $\bar{F}(u)$ ,  $\gamma$  and  $\sigma$

The choice is often also based on the following further considerations:

- mean-excess plot: Pareto should be linear (slope same sign as  $\gamma$ )
- empirical df on a doubly logarithmic scale: Pareto should be linear
- Hill plot (Wuthrich (2023), p. 76): stability of Pareto parameter
- stability of  $\hat{\gamma}$  for different choices of  $u$  (note this requires a full fit for each value of  $u$  but the `extRemes` package does that automatically)
- goodness of fit for different choices of  $u$

Unfortunately there is no “optimal” (or “automatic”) procedure for choosing  $u$ .

### 3 Generalised Pareto distribution

- Asymptotic properties of the tails
- The GP distribution
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## Case study: workers compensation medical costs

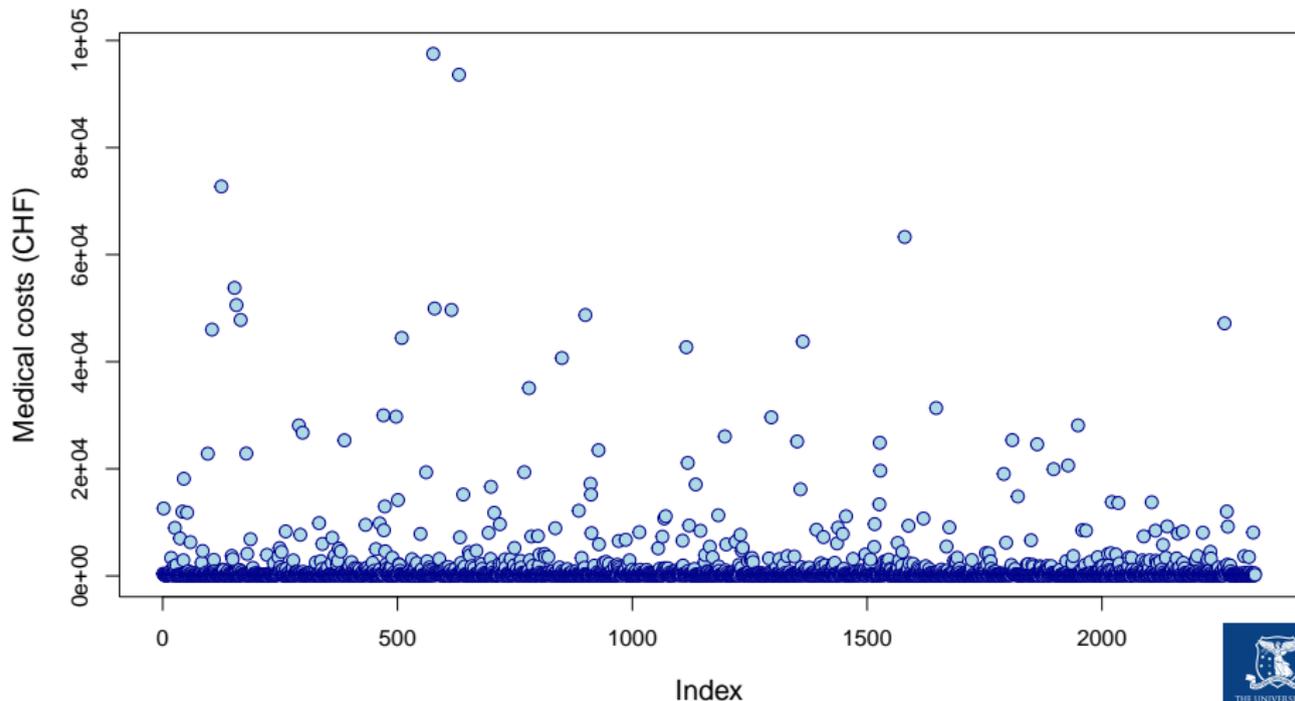
- Example of real actuarial data from Avanzi, Cassar, and Wong (2011)
- Data were provided by the SUVA (Swiss workers compensation insurer)
- Random sample of 5% of accident claims in construction sector with accident year 1999 (developped as of 2003)
- Claims are medical costs
- In Avanzi, Cassar, and Wong (2011) we model those claims with a Gumbel distribution, which suggests heavy tails, which is confirmed by the following graphs. This, however, wasn't the main objective of the paper, but was good enough for our purposes.

```
SUVA <- read_excel("SUVA.xls")
as_tibble(SUVA)
```

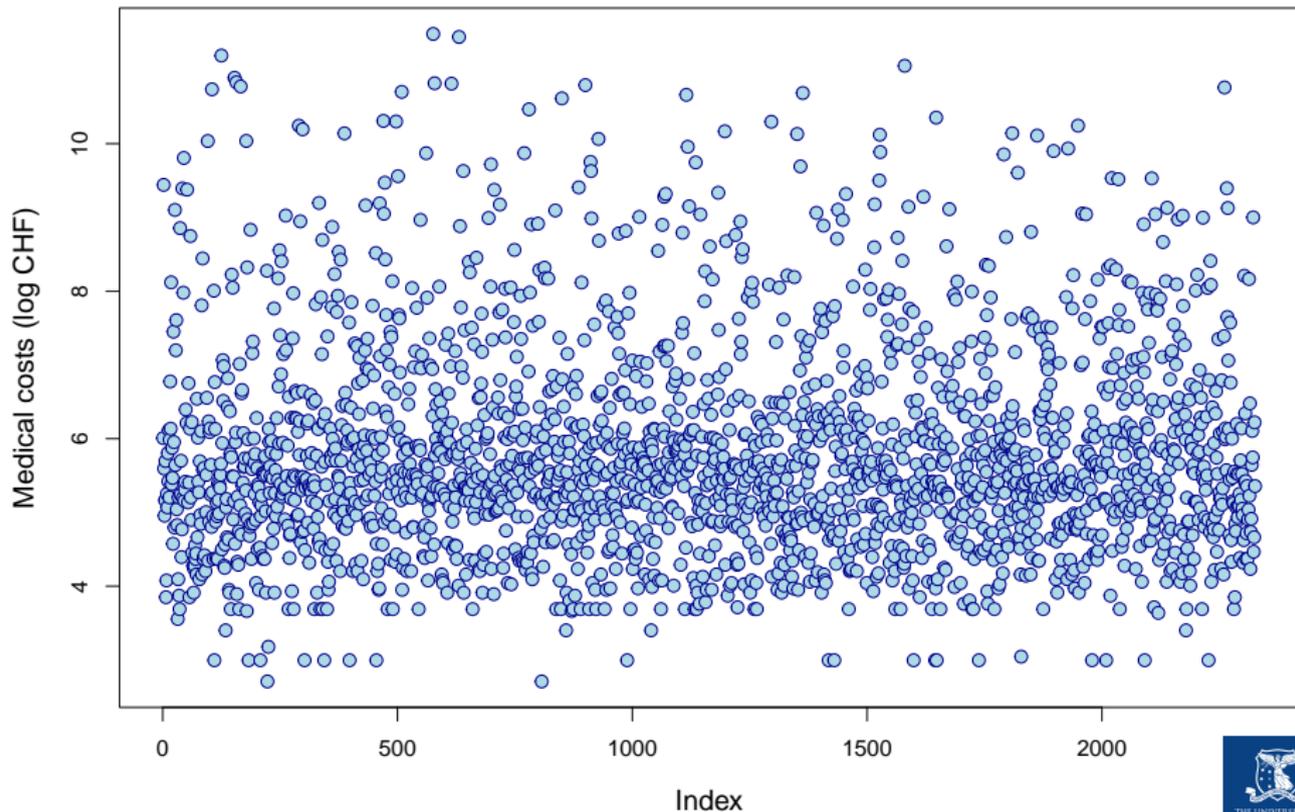
medcosts	dailyallow
407	0
12591	13742
269	0
142	0

# Data exploration

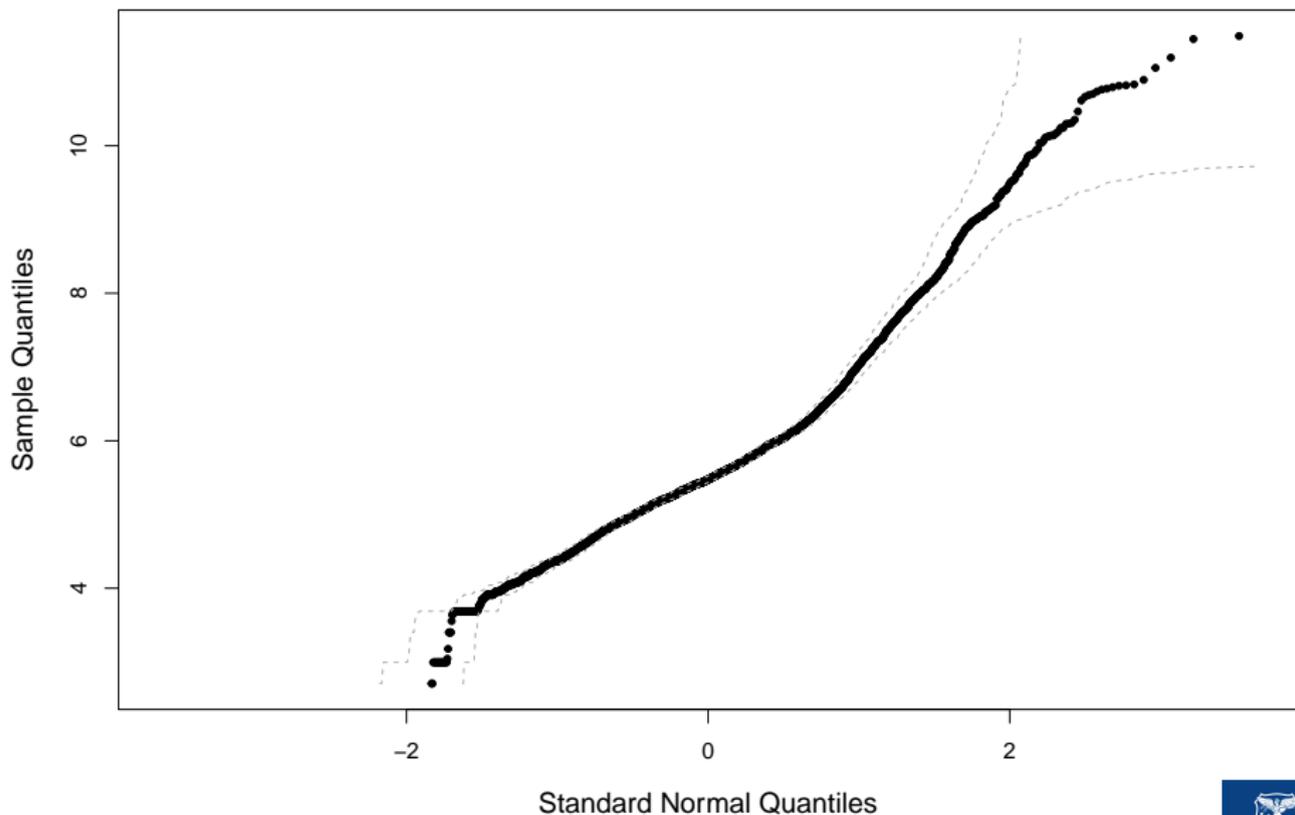
```
plot(SUVA$medcosts, ylab = "Medical costs (CHF)", cex = 1.25,  
     cex.lab = 1.25, col = "darkblue", bg = "lightblue", pch = 21)
```



```
plot(log(SUVA$medcosts), ylab = "Medical costs (log CHF)", cex = 1.25,  
     cex.lab = 1.25, col = "darkblue", bg = "lightblue", pch = 21)
```

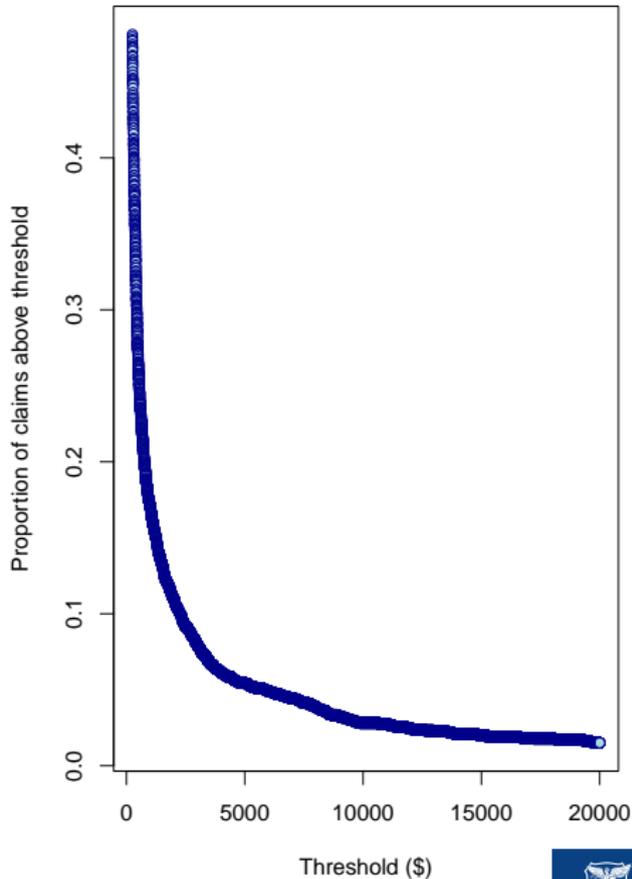
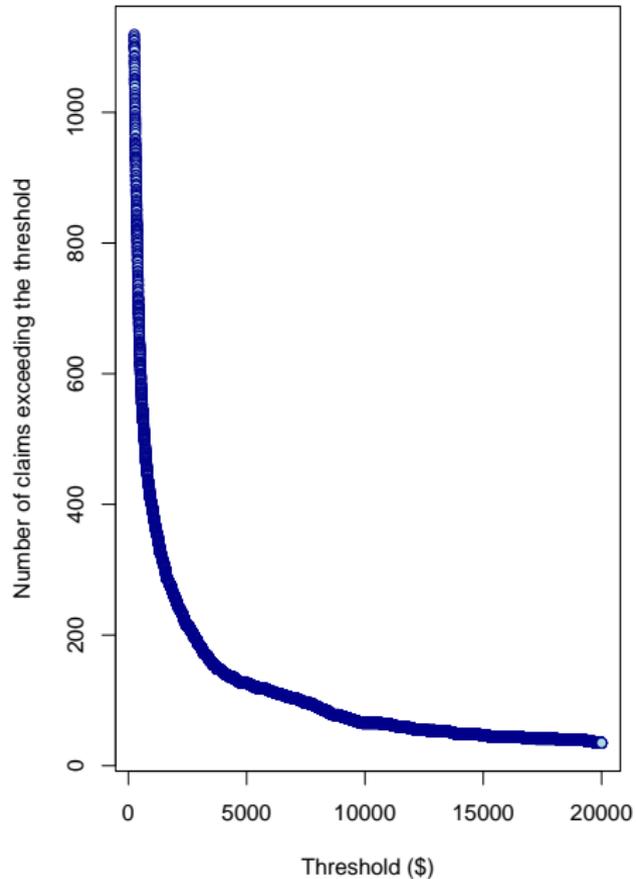


```
extRemes::qqnorm(log(SUVA$medcosts), cex.lab = 1.25)
```



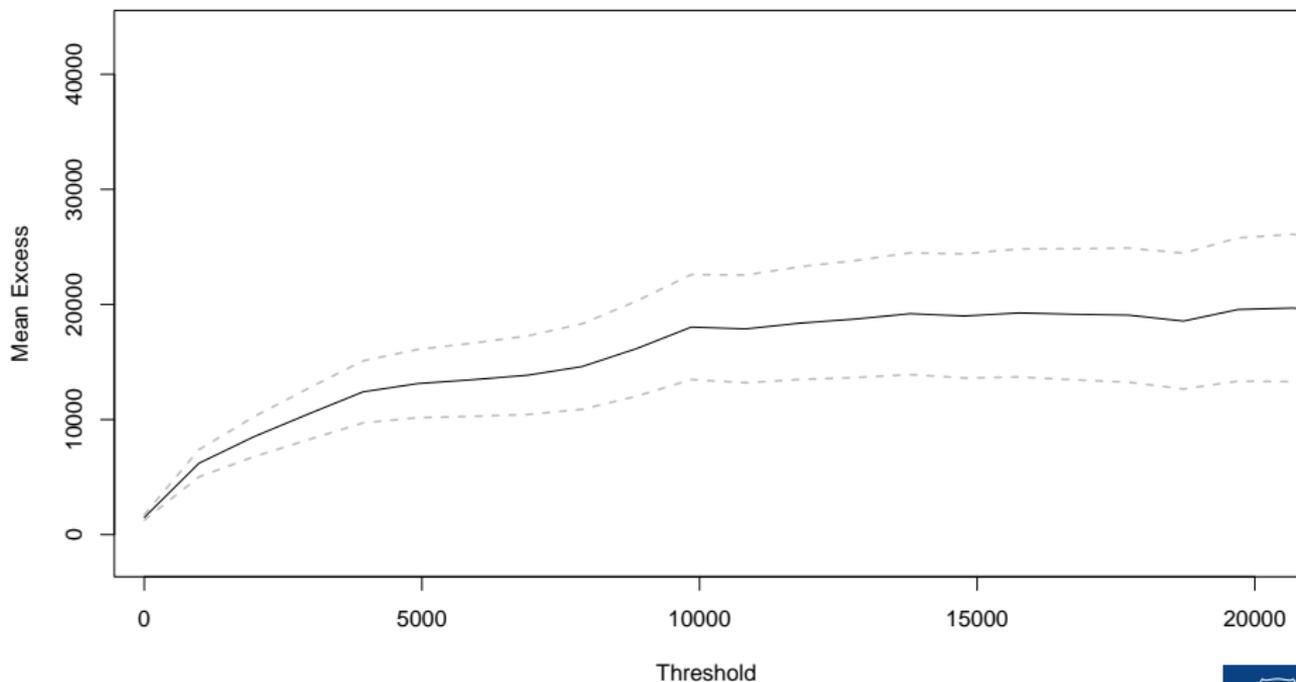
# Size of tail

```
numbexc <- c()
for (i in 250:20000) {
  numbexc <- c(numbexc, length(SUVA$medcosts[SUVA$medcosts >
    i]))
}
par(mfrow = c(1, 2))
plot(250:20000, numbexc, xlab = "Threshold ($)", ylab = "Number of claims e
  col = "darkblue", bg = "lightblue", pch = 21)
plot(250:20000, numbexc/length(SUVA$medcosts), xlab = "Threshold ($)",
  ylab = "Proportion of claims above threshold", col = "darkblue",
  bg = "lightblue", pch = 21)
```



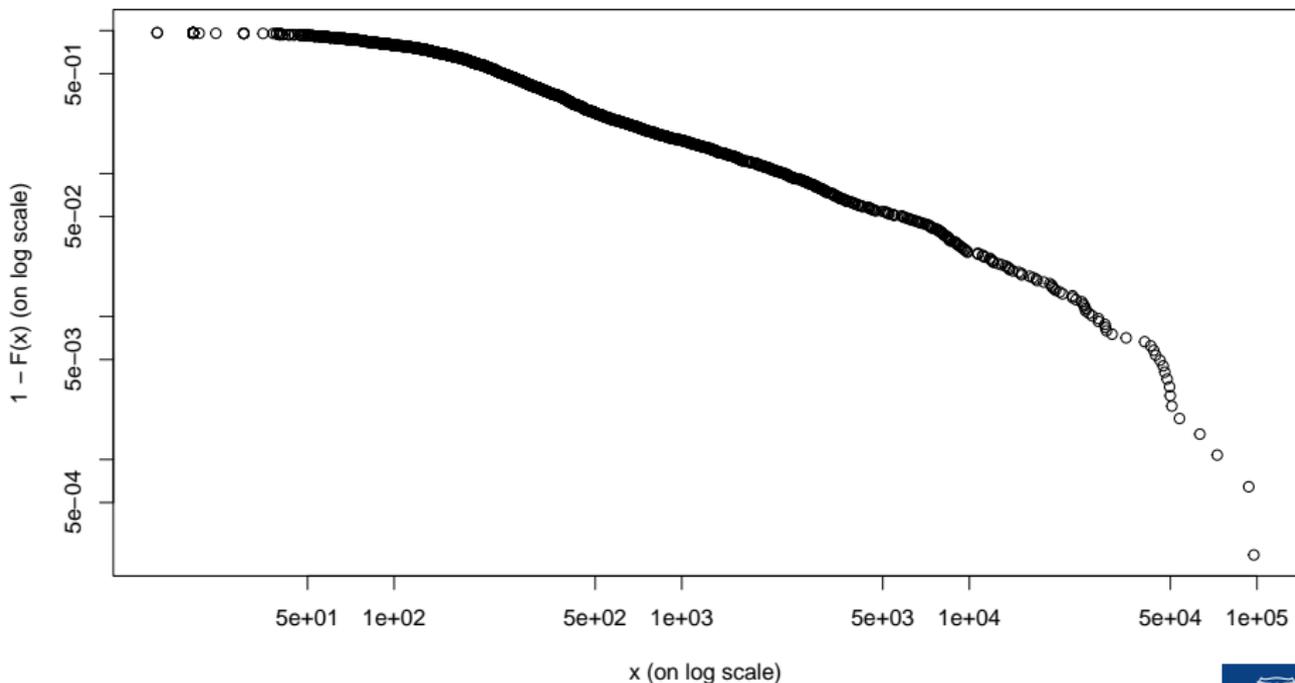
# Mean-excess plot

```
extRemes::mrlplot(SUVA$medcosts, xlim = c(250, 20000))
```



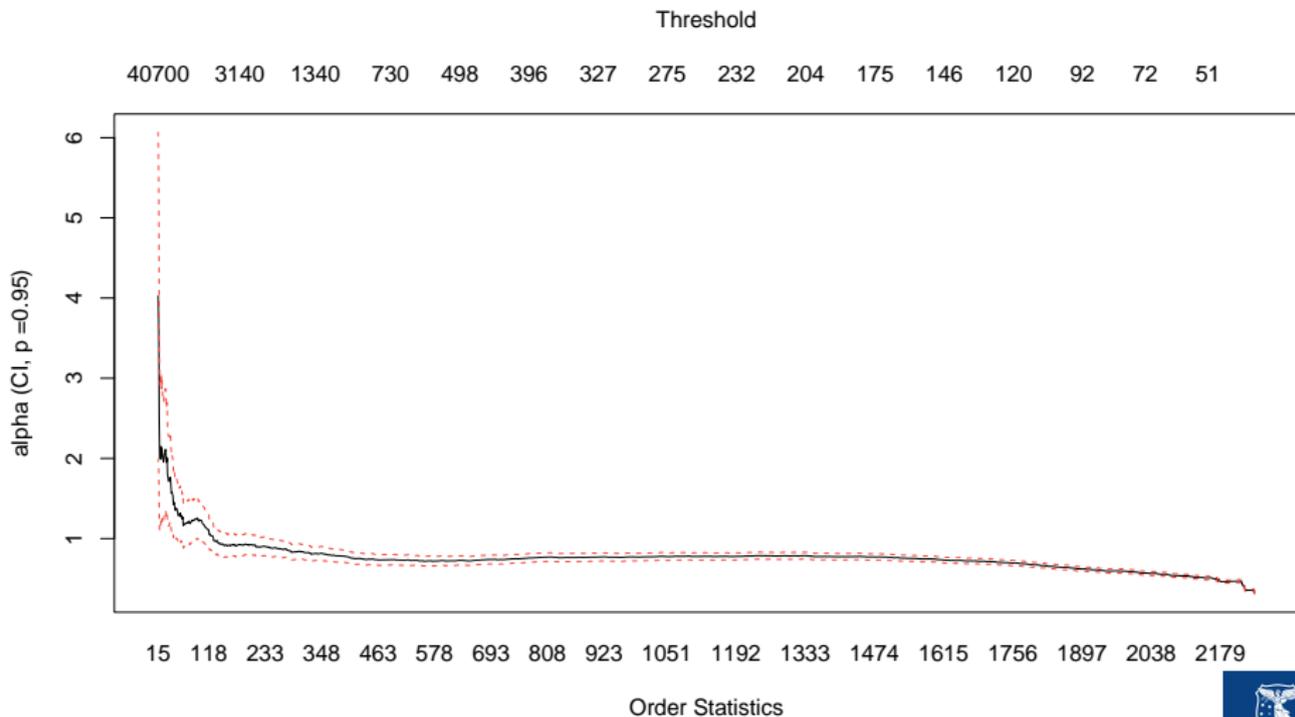
# Empirical $\bar{F}$ on log log scale

```
evir::emplot(SUVA$medcosts, alog = "xy", labels = TRUE)
```



# Hill plot

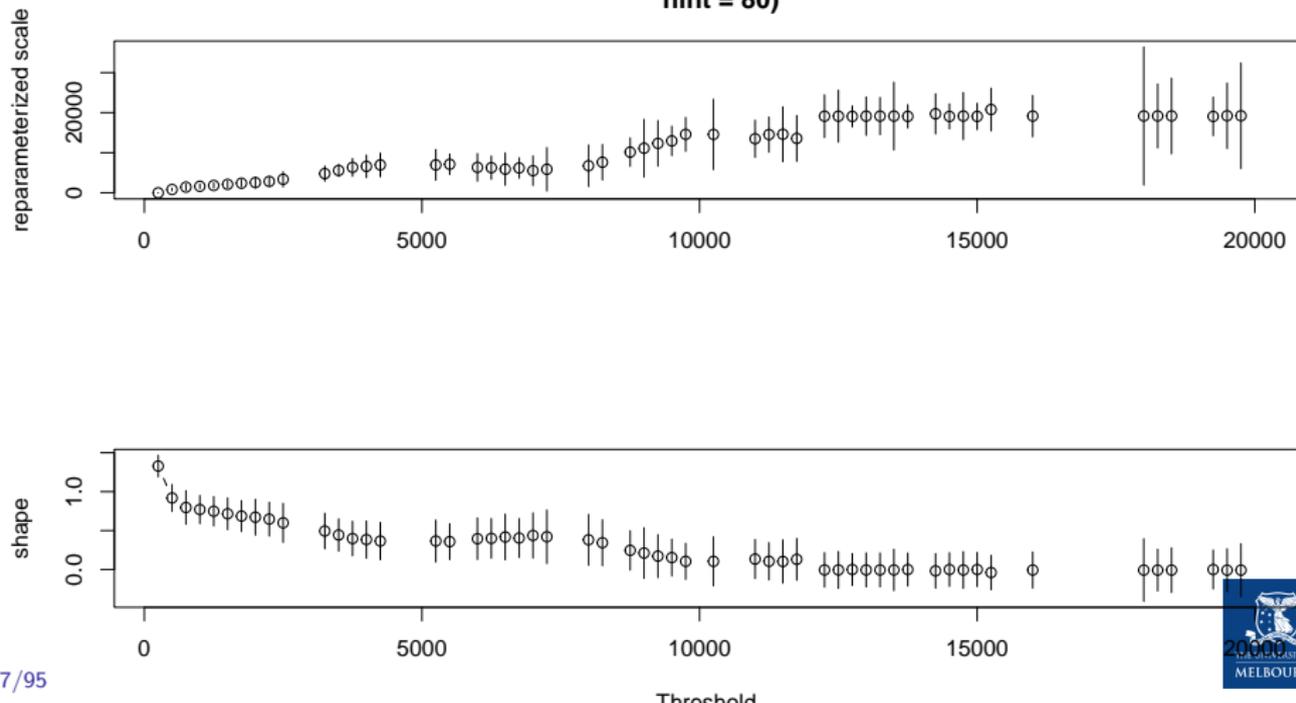
```
evir:::hill(SUVA$medcosts)
```



# Stability of $\hat{\gamma}$

```
extRemes::threshrange.plot(SUVA$medcosts, r = c(250, 20000),  
  nint = 80)
```

**extRemes::threshrange.plot(x = SUVA\$medcosts, r = c(250, 20000),  
 nint = 80)**



# Estimation results for $u = 500$

```
fit.SUVA.500 <- fevd(SUVA$medcosts, threshold = 500, type = "GP",
  time.units = "1/year")
fit.SUVA.500
...
## Estimated parameters:
##      scale      shape
## 1272.3550452  0.9193739
##
## Standard Error Estimates:
##      scale      shape
## 141.86425852  0.08861845
##
## Estimated parameter covariance matrix.
##      scale      shape
## scale 20125.467846 -7.931047764
## shape  -7.931048  0.007853229
##
## AIC = 11006.09
##
## BIC = 11014.93
```

```
numbexc[501 - 250] # n_u noting numbexc[1] = n_250
```

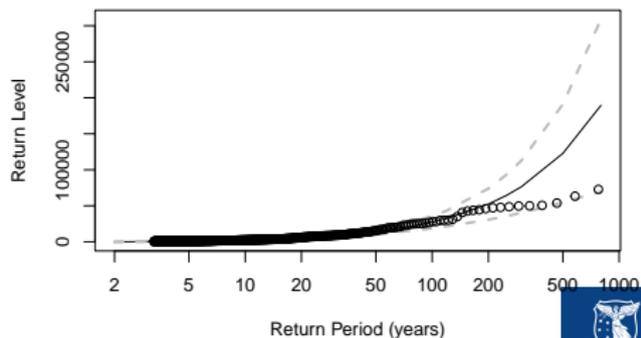
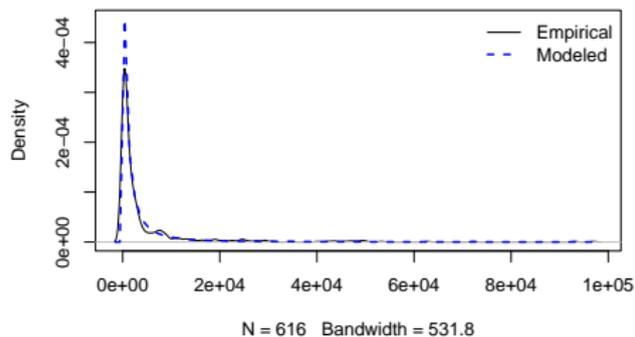
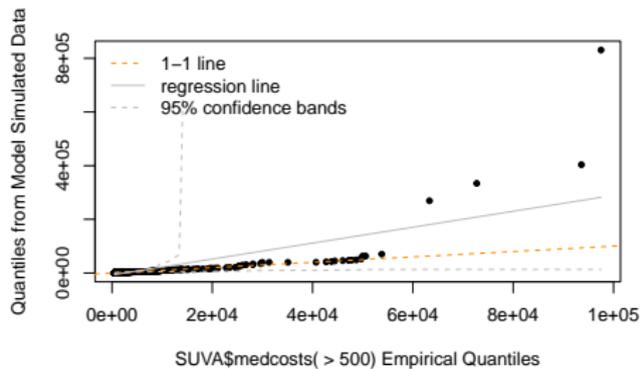
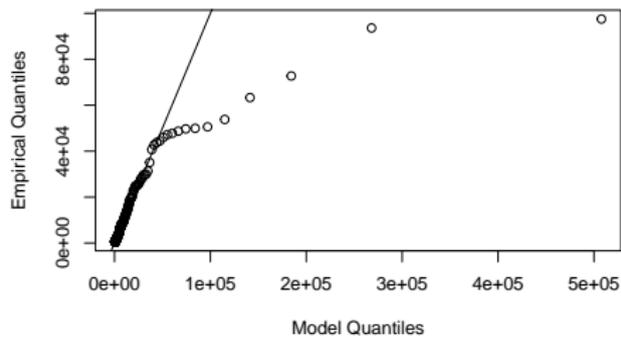
```
## [1] 616
```

```
numbexc[501 - 250]/length(SUVA$medcosts)
```

```
## [1] 0.2648323
```

```
plot(fit.SUVA.500)
```

fevd(x = SUVA\$medcosts, threshold = 500, type = "GP", time.units = "1/year")



# Estimation results for $u = 5500$

```
fit.SUVA.5500 <- fevd(SUVA$medcosts, threshold = 5500, type = "GP",
  time.units = "1/year")
fit.SUVA.5500
...
## Estimated parameters:
##      scale      shape
## 9080.1415439  0.3582073
##
## Standard Error Estimates:
##      scale      shape
## 867.9692478  0.1180018
##
## Estimated parameter covariance matrix.
##      scale      shape
## scale 753370.61513 -48.21705582
## shape -48.21706   0.01392443
##
## AIC = 2474.628
##
## BIC = 2480.169
```

```
numbexc[5501 - 250] # n_u
```

```
## [1] 118
```

```
numbexc[5501 - 250]/length(SUVA$medcosts)
```

```
## [1] 0.05073087
```

```
plot(fit.SUVA.5500)
```



# Estimation results for $u = 9500$

```
fit.SUVA.9500 <- fevd(SUVA$medcosts, threshold = 9500, type = "GP",
  time.units = "1/year")
fit.SUVA.9500
...
## Estimated parameters:
##      scale      shape
## 1.439198e+04 1.531774e-01
##
## Standard Error Estimates:
##      scale      shape
## 1105.107349    0.120504
##
## Estimated parameter covariance matrix.
##      scale      shape
## scale 1221262.25328 -52.03034314
## shape  -52.03034    0.01452121
##
## AIC = 1510.063
##
## BIC = 1514.56
```

```
numbexc[9501 - 250] # n_u
```

```
## [1] 70
```

```
numbexc[9501 - 250]/length(SUVA$medcosts)
```

```
## [1] 0.03009458
```

```
plot(fit.SUVA.9500)
```



# Estimation results for $u = 12500$

```
fit.SUVA.12500 <- fevd(SUVA$medcosts, threshold = 12500, type = "GP",
  time.units = "1/year")
fit.SUVA.12500
...
## Estimated parameters:
##           scale           shape
## 1.905240e+04 -5.131924e-03
##
## Standard Error Estimates:
##           scale           shape
## 2240.8326877    0.1206834
##
## Estimated parameter covariance matrix.
##           scale           shape
## scale 5021331.1344 -147.94884187
## shape -147.9488    0.01456447
##
## AIC = 1195.941
##
## BIC = 1199.956
```

```
numbexc[12501 - 250] #  $n_u$ 
```

```
## [1] 55
```

```
numbexc[12501 - 250]/length(SUVA$medcosts)
```

```
## [1] 0.02364574
```

```
plot(fit.SUVA.12500)
```



- 1 Introduction
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# Measures of tail weight

- Existence of moments (e.g. gamma vs Pareto)
- Limiting density ratios: relative value of density functions at the far end of the upper tail of two distributions
- Hazard rates  $\lambda(x) = f(x)/(1 - F(x))$ : constant for exponential, decreasing for heavy tails
- Log-log plot: linear decrease for heavy tails
- Mean excess function: linear increase for heavy tails

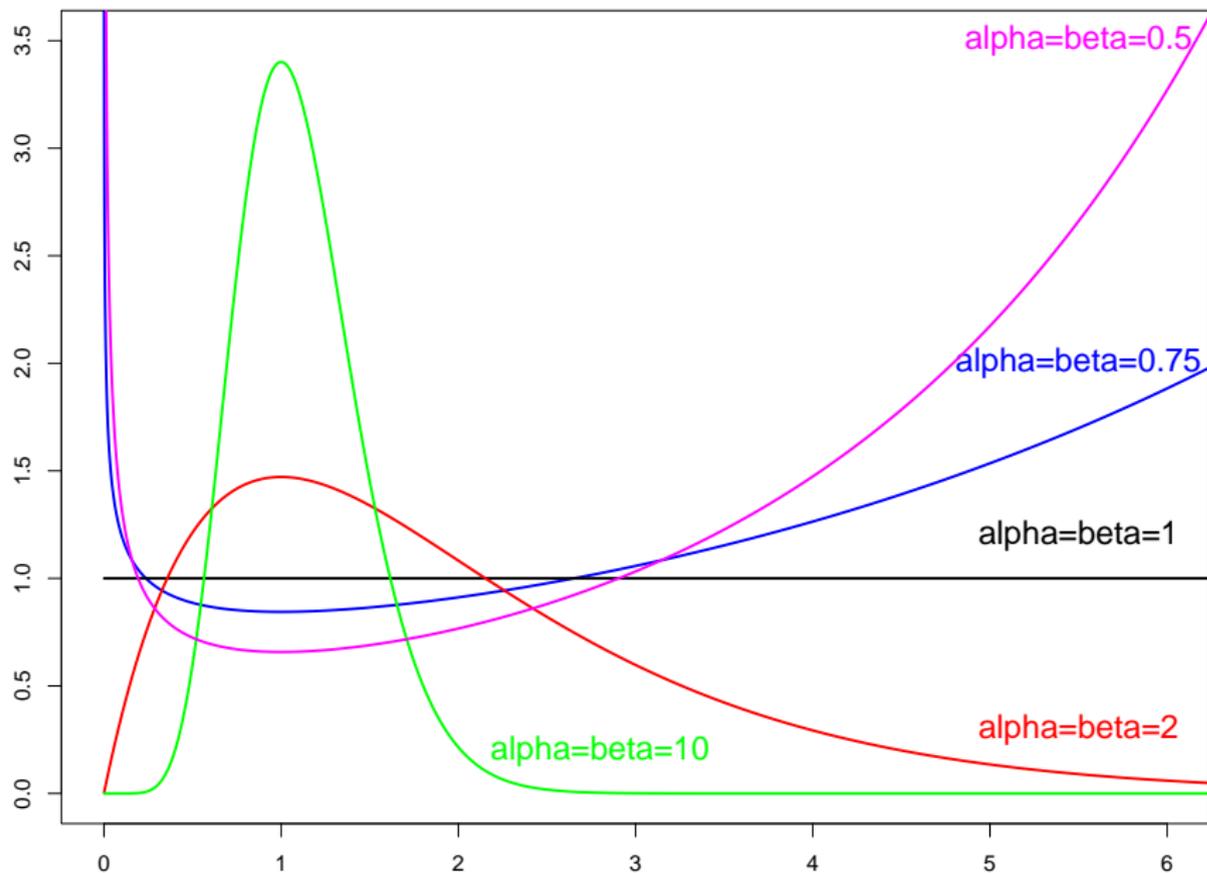
## Limiting density ratios: gamma example

```

plot(1:10000/1000, dgamma(1:10000/1000, shape = 0.75, rate = 0.75)/dexp(1:10000/1000),
     xlab = "x", main = "ratio of densities gamma(alpha,beta) to exponential",
     ylab = "", type = "l", col = "blue", ylim = c(0, 3.5), xlim = c(0, 6),
     lwd = 2, cex = 1.5)
text(5.5, 2, "alpha=beta=0.75", col = "blue", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 1, rate = 1)/dexp(1:10000/1000),
      type = "l", col = "black", lwd = 2)
text(5.5, 1.2, "alpha=beta=1", col = "black", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 2, rate = 2)/dexp(1:10000/1000),
      type = "l", col = "red", lwd = 2)
text(5.5, 0.3, "alpha=beta=2", col = "red", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 10, rate = 10)/dexp(1:10000/1000),
      type = "l", col = "green", lwd = 2)
text(2.8, 0.2, "alpha=beta=10", col = "green", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 0.5, rate = 0.5)/dexp(1:10000/1000),
      type = "l", col = "magenta", lwd = 2)
text(5.5, 3.5, "alpha=beta=0.5", col = "magenta", cex = 1.5)

```

## ratio of densities gamma(alpha,beta) to exponential(1)



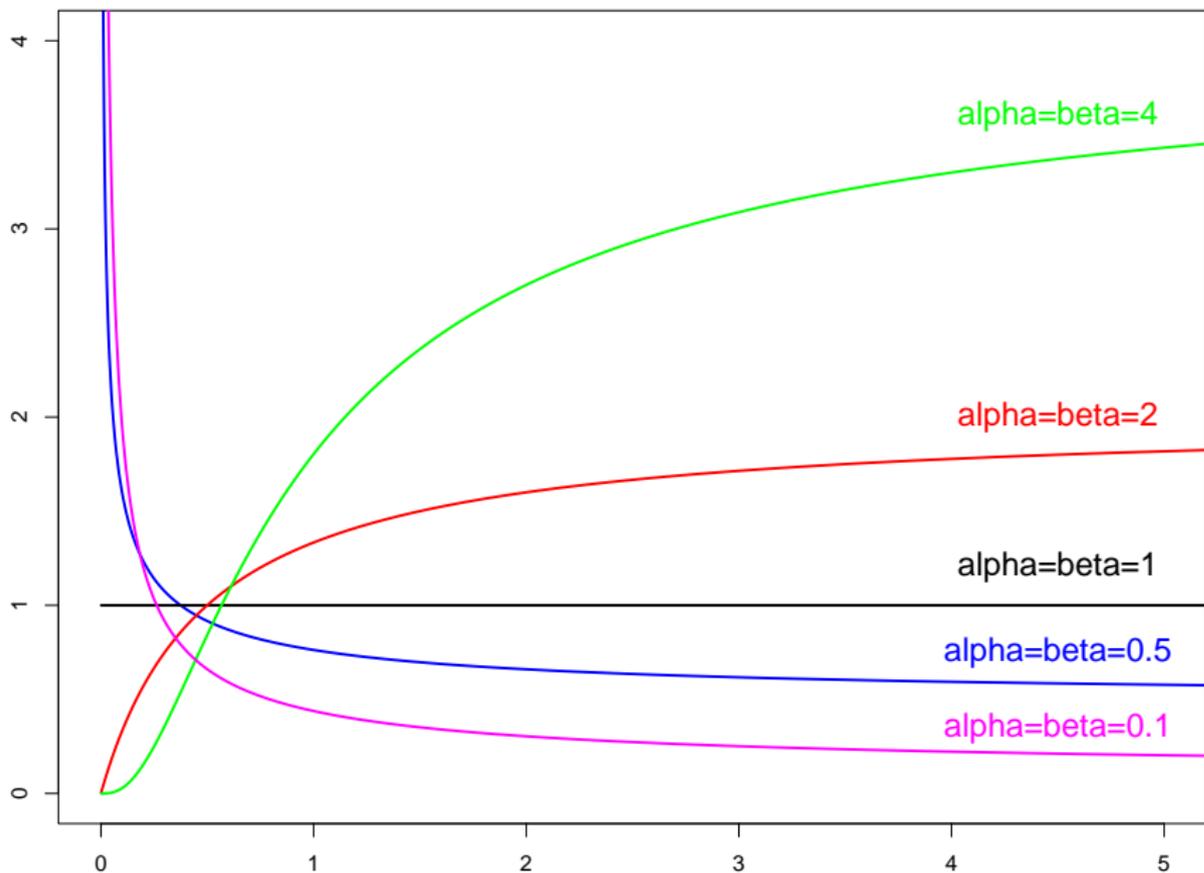
## Hazard rates: gamma example with fixed mean

```

plot(1:10000/1000, dgamma(1:10000/1000, shape = 0.5, rate = 0.5)/(1 -
  pgamma(1:10000/1000, shape = 0.5, rate = 0.5)), xlab = "x",
  main = "hazard rates for gamma(alpha,beta)", ylab = "", type = "l",
  col = "blue", ylim = c(0, 4), xlim = c(0, 5), lwd = 2, cex = 1.5)
text(4.5, 0.75, "alpha=beta=0.5", col = "blue", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 1, rate = 1)/(1 -
  pgamma(1:10000/1000, shape = 1, rate = 1)), type = "l", col = "black",
  lwd = 2)
text(4.5, 1.2, "alpha=beta=1", col = "black", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 2, rate = 2)/(1 -
  pgamma(1:10000/1000, shape = 2, rate = 2)), type = "l", col = "red",
  lwd = 2)
text(4.5, 2, "alpha=beta=2", col = "red", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 4, rate = 4)/(1 -
  pgamma(1:10000/1000, shape = 4, rate = 4)), type = "l", col = "green",
  lwd = 2)
text(4.5, 3.6, "alpha=beta=4", col = "green", cex = 1.5)
lines(1:10000/1000, dgamma(1:10000/1000, shape = 0.1, rate = 0.1)/(1 -
  pgamma(1:10000/1000, shape = 0.1, rate = 0.1)), type = "l",
  col = "magenta", lwd = 2)
text(4.5, 0.35, "alpha=beta=0.1", col = "magenta", cex = 1.5)

```

## hazard rates for gamma(alpha,beta)



# References

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