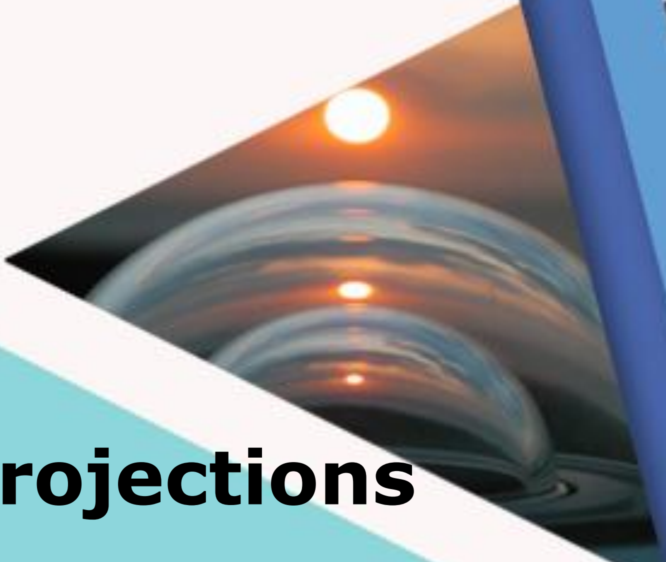
Making Ireland Weather and Climate Prepared



Rainfall Extremes and Projections

14th January 2026

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Climate Services Division

Met Éireann

IAH CPD - Groundwater, Hydrology and Climate Change

An Roinn Tithíochta, Rialtais Áitiúil agus Oidhreachta
Department of Housing, Local Government and Heritage

National Framework for Climate Services

OPW

agenda

- Introduction to extremes
- Extreme Value Theory
- Extreme rainfall example
  - Dublin Airport 24-hour rainfall
- Extremes in a changing climate
  - Extremes with projections

200-year anniversary of severe Dublin flooding

Although the newspaper account of widespread flooding in Dublin shown on the right could refer to the recent past in Dublin, it is actually a 200-year old report taken from ***Walker's Hibernian Magazine*** of December 1802. The 'heavy and unremitting rain' referred to was a fall of 75mm in a 30-hour period over the 2nd and 3rd of that month, which led to what F.E. Dixon described in his 1953 article ***Weather in Old Dublin*** as 'the most serious of all Dublin floods'. This amount represents what would normally be expected to fall in the entire month of December in Dublin. Most of what was then the central area of the city was cover by floodwater, with 3 metres of water reported in the lower Castle Yard and Patrick Street, where 'boats were plying to save the lives of poor people'.

STORM AND INUNDATION.

Dec. 4.] The tempeſtuous weather experienced from Wedneſday night till late on Thurſday, together with the heavy and unremitting rain during that period, have produced various diſaſtrous occurrences near the metropolis, and in the interior of the country. Some mills and other works a few miles from the capital, ſituated within the range of the flood, have been materially injured, and in ſome inſtances altogether deſtroyed.—We are concerned to ſtate, among the damage of this kind effected in the neighbourhood of the capital, that the backs, weirs, &c. at Old Bawn paper-mills, are entirely ſwept away.—Nearly an acre and an half of Mr. Wildridge's meadow, adjacent to the mills, has been ſevered from the reſt by the violence of the flood, and carried completely off!

The Belfaſt mail-coach was yeſterday morning, in coming to town, obliged to ſtop from five o'clock until nine, upon the road between Turvey

The heavy rainfall caused flooding in many parts of Dublin and the east coast, flooding roads and causing lengthy traffic delays. Several flights were delayed or cancelled at Dublin Airport.

Many homes and businesses were under water by Monday evening. Dublin City Council activated a major emergency plan to deal with the floods. Tragically two deaths were attributed to this rainfall event, with damage to Dublin homes, businesses and infrastructure estimated to be worth millions of Euro.

Flooding in Midleton Garda Station during Storm Babet

Putting these events in historical context:

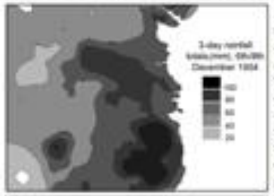
- Over 180mm was recorded on 11th June 1963 during a violent thunderstorm in the Mount Merrion area of South Dublin.
- 11th June 1993, exactly 30 years later, saw amounts of rain of around 100mm over hours in the Dublin area.
- 29th June 2005 saw 45mm fall in the Phoenix Park in less than an hour.
- 9th August 2008 saw heavy rainfall, particularly affecting the North Kildare and Dublin area with amounts in excess of 70mm measured in the Celbridge, Lucan, Leixlip area.
- Hurricane Charley on the 25th August 1986, almost 90mm was recorded in 24 hours at Casement Aerodrome.

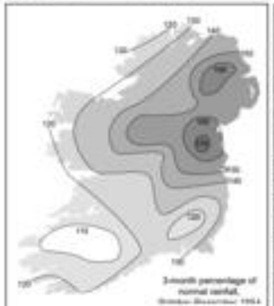
Widespread floods of December 1954

The last quarter of 1954 was exceptionally wet, with more than 50% of normal rainfall for the 3-month period recorded in parts of the east and northeast *(see map bottom left)*. Late November and early December brought a spell of particularly wet and windy weather; there were a number of ships sunk or run aground off the Irish coast in what were described in newspaper reports as "mountainous seas".

Flooding was already widespread in many parts of the country before a band of heavy rain moved eastwards late on December 6th, clearing for a while on the 7th before another band of persistent and heavy rain became established in all areas on the 8th. Rain was particularly heavy over eastern counties, with more than 80mm falling in the 3-day period between the 6th and 8th *(see map centre left)*. Dublin Airport recorded a daily total of 49mm on the 8th, a value that has not since been exceeded at the station during December.

Early on the 9th, the swollen river Tolka undermined the foundations of the railway bridge across the river at Fairview *(below)*. The collapsed bridge then formed a barrier across the river, causing water to flow out across a very wide area; approximately 1,500 houses accommodating 2,000 families were affected by the flood waters and several hundred people were forced to evacuate their homes. There was extensive flooding elsewhere across the city, particularly in the Kilmainham area along the river Camac, while the Shannon reached its highest level since 1925 and many thousands of acres of farmland were inundated. There were also reports of widespread power outages on the 8th, with further disruption caused by heavy falls of snow in parts of the midlands and northwest. (pictures Irish Times)

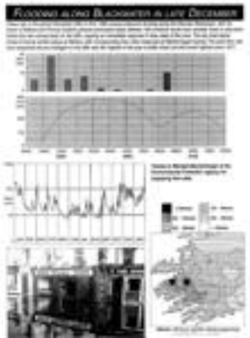




Storm of 11/12th January 1974 : Summary of newspaper reports of damage

Kerry: Two mile line of trees in Muckross National Park flattened. A Spanish trawler went ashore at Valentia and another trawler sank at Fenit. The railway line near Headford collapsed in a landslide. Widespread wreckage of caravans.

Cork: High tides and severe flooding in city area in advance of storm. Premises of William Transport Group at Cork Airport demolished and Joyce Aviation hangar with several light aircraft damaged. Roof blown off grainstore at Midleton. Roof of an incompleted factory at Charleville blown across a field some of it landing on top of a 30 ft. tree. Fermoy reported many trees down in the town and plate glass windows broken. Caravan blown over a 5 ft. wall at Blackrock. Holiday caravans wrecked in many places. Bandon and Kinsale areas reported extensive damage to dwellings and outhouses. Much glass breakage at nurseries at Upton and Ardkeena. Lightning killed several cattle near Nohoval.



Home / Weather

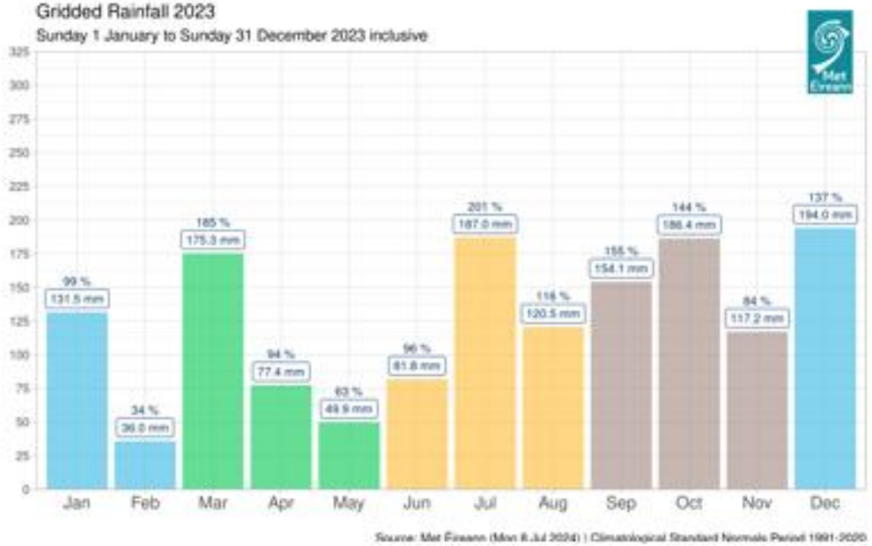
LATEST | Storm Babet: Millions of euro in damage as army deployed to parts of Cork and new rain warning issued for Dublin

Ralph Riegel
Wed 18 Oct 2023 at 21:30

Millions of euro worth of damage has been left in the wake of Storm Babet as parts of Ireland suffered its worst rainfall related flooding in over a decade.

Cork was worst-hit by the torrential downpours which dumped over a month's worth of rain in less than 24 hours - swamping drainage systems.

Parts of the south received over 100m of rainfall in less than 36 hours - with fields, streams and rivers already sodden from recent heavy rainfall unable to handle the deluge.

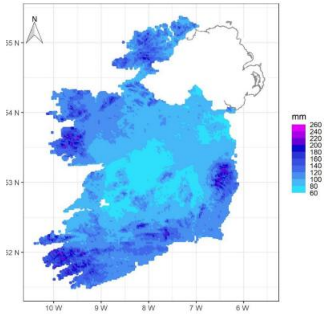


Source: Met Éireann (Mon 8 Jul 2024) | Climatological Standard Normals Period 1991-2020

Extremes analysis applications

Building standards

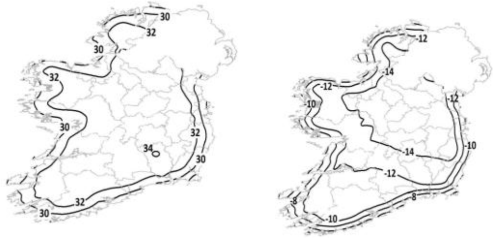
ESTIMATION OF POINT RAINFALL FREQUENCIES IN IRELAND



DURATION	Interval 6months	1year	Years 2	3	4	5	10	20	30	50	75	100	120
5 mins	3.0	4.0	4.5	5.3	5.8	6.1	7.3	8.7	9.5	10.7	11.7	12.5	13.0
10 mins	4.2	5.6	6.3	7.3	8.0	8.5	10.2	12.1	13.2	14.9	16.3	17.4	18.1
15 mins	4.9	6.6	7.4	8.6	9.4	10.0	12.0	14.2	15.6	17.5	19.2	20.4	21.3
30 mins	6.6	8.7	9.8	11.4	12.4	13.2	15.8	18.6	20.4	22.8	25.0	26.6	27.7
1 hours	8.8	11.6	13.0	15.1	16.4	17.5	20.8	24.4	26.7	29.8	32.6	34.6	36.0
2 hours	11.8	15.4	17.3	20.0	21.7	23.1	27.3	31.9	34.9	39.0	42.5	45.1	46.9
3 hours	13.9	18.2	20.4	23.5	25.6	27.1	32.1	37.4	40.9	45.6	49.6	52.7	54.7
4 hours	15.7	20.5	22.9	26.4	28.7	30.4	36.0	41.9	45.7	50.9	55.4	58.8	61.1
6 hours	18.6	24.2	27.0	31.1	33.8	35.8	42.2	49.1	53.5	59.5	64.7	68.7	71.3
9 hours	22.1	28.6	31.9	36.7	39.8	42.1	49.6	57.6	62.7	69.6	75.6	80.2	83.2
12 hours	24.9	32.2	35.9	41.2	44.7	47.3	55.6	64.5	70.1	77.8	84.5	89.5	92.9
18 hours	29.6	38.1	42.4	48.6	52.6	55.7	65.3	75.6	82.2	91.1	98.8	104.6	108.4
24 hours	33.4	42.9	47.7	54.6	59.1	62.5	73.2	84.7	91.9	101.8	110.3	116.8	121.0
2 days	43.0	53.9	59.3	66.9	71.8	75.5	87.1	99.2	106.8	117.1	125.8	132.4	136.7
3 days	51.8	63.9	69.8	78.2	83.5	87.5	99.9	112.8	120.9	131.7	140.9	147.7	152.2
4 days	60.0	73.2	79.6	88.7	94.4	98.7	111.9	125.7	134.2	145.5	155.1	162.3	167.0
6 days	75.5	90.8	98.1	108.4	114.9	119.7	134.4	149.6	159.0	171.4	181.8	189.5	194.6
8 days	90.3	107.5	115.7	127.0	134.2	139.5	155.6	172.1	182.2	195.6	206.8	215.0	220.5
10 days	104.8	123.7	132.6	145.0	152.8	158.5	175.9	193.6	204.5	218.7	230.6	239.4	245.1
12 days	119.1	139.5	149.2	162.5	170.9	177.0	195.6	214.5	226.0	241.1	253.6	262.9	268.9
16 days	147.2	170.7	181.7	196.8	206.1	213.1	233.9	254.9	267.6	284.2	298.0	308.1	314.7
20 days	175.1	201.4	213.6	230.3	240.7	248.3	271.2	294.1	307.9	325.9	340.8	351.8	358.9
25 days	210.0	239.5	253.2	271.8	283.3	291.7	316.9	342.0	357.1	376.8	393.0	404.8	412.5

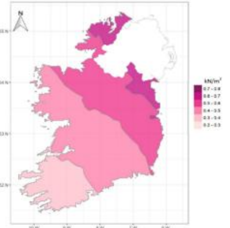
ISOTHERMAL MAPS OF MAXIMUM AND MINIMUM SHADE AIR TEMPERATURES IN IRELAND

NA EN 1991-1-5:2003



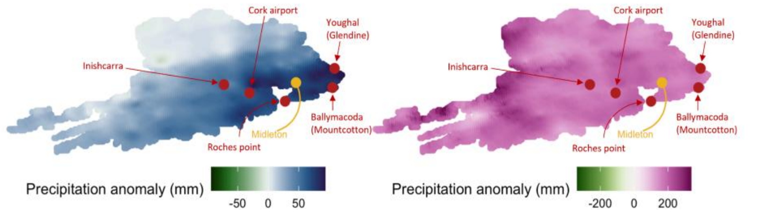
SNOW LOADINGS AT 100M ABOVE MEAN SEA LEVEL IN IRELAND

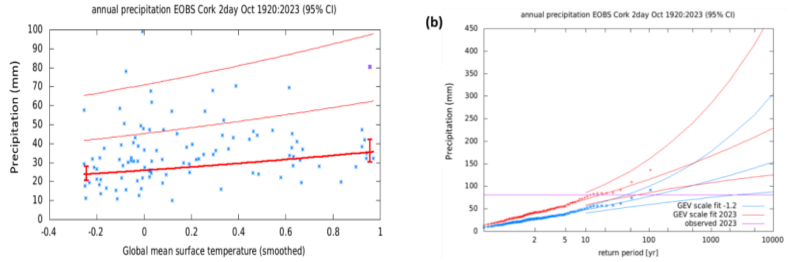
I.S. EN 1991-1-3:2003



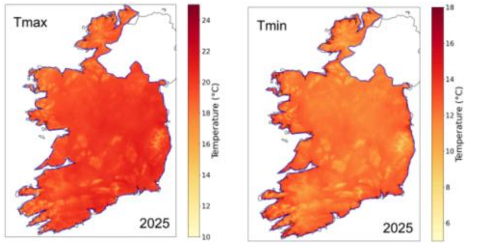
World Weather Attribution

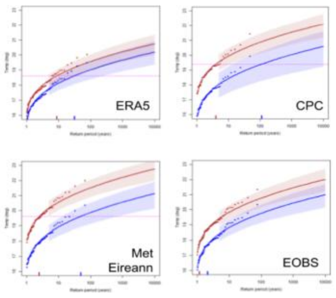
Climate change made the extreme 2-day rainfall event associated with flooding in Midleton, Ireland more likely and more intense



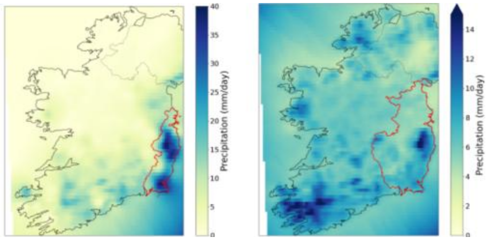


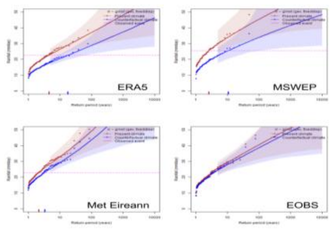
Increasing global temperatures transformed an otherwise average Irish summer into a record breaking warm summer





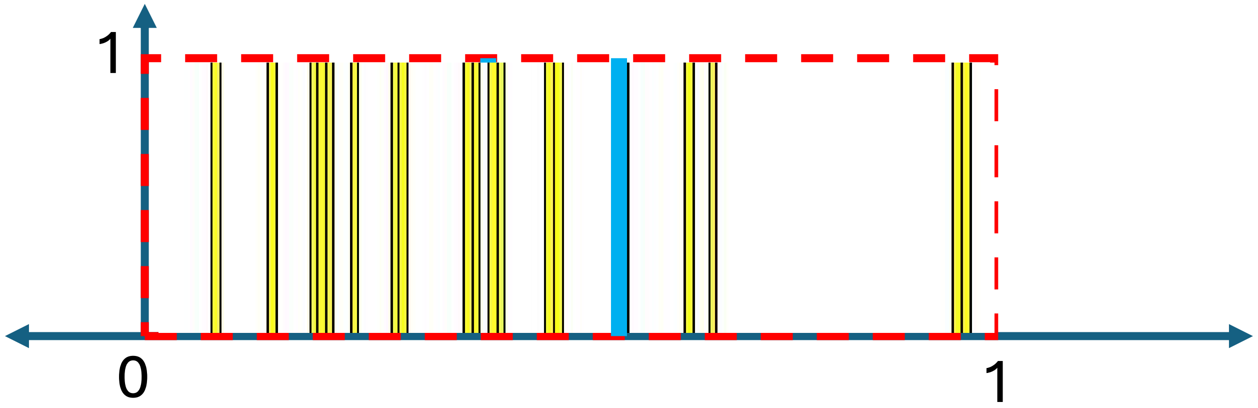
Human-caused climate change increases potential for flooding in south-eastern counties of Ireland as rainfall intensifies

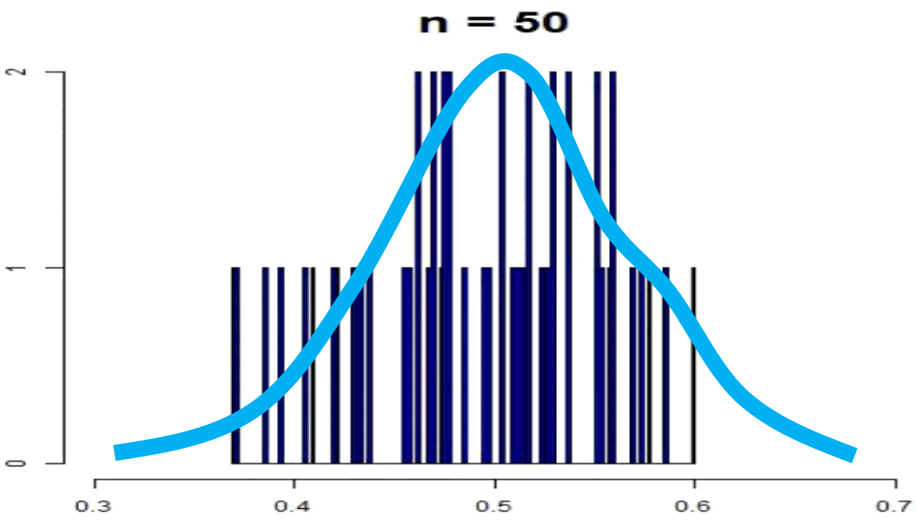




Extreme Value Theory

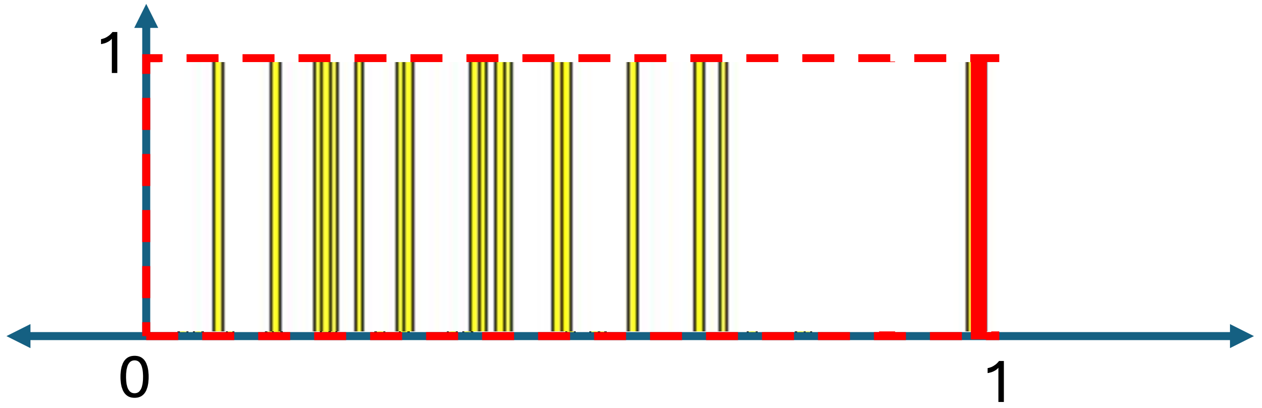
- Example: Sampling from a distribution – uniform (0,1)
- Mean of a Sample
  - Central Limit Theorem
  - Distribution of sample means approaches normal distribution

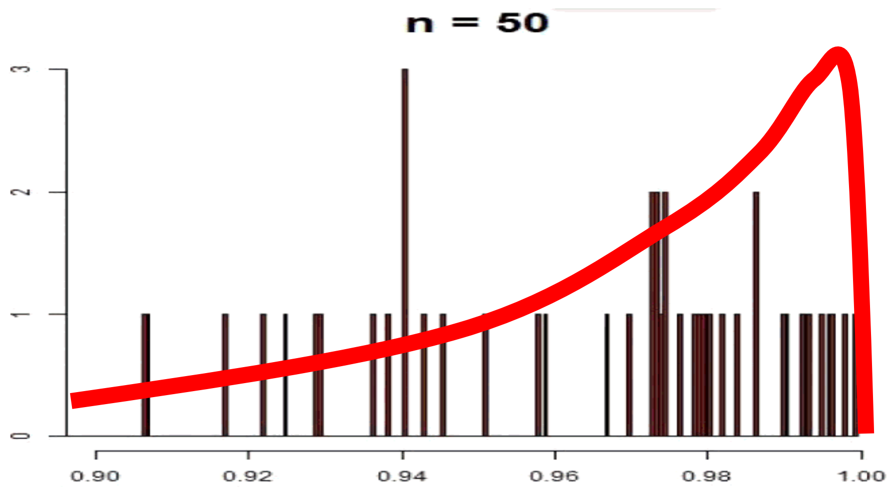




Extreme Value Theory

- Example: Sampling from a distribution – uniform (0,1)
- Maximum of a sample
  - Distribution of sample means approaches Extreme Value Distribution
  - Uniform Distribution => reversed Weibull Distribution
    - Upper bound, distribution tail towards $-\infty$





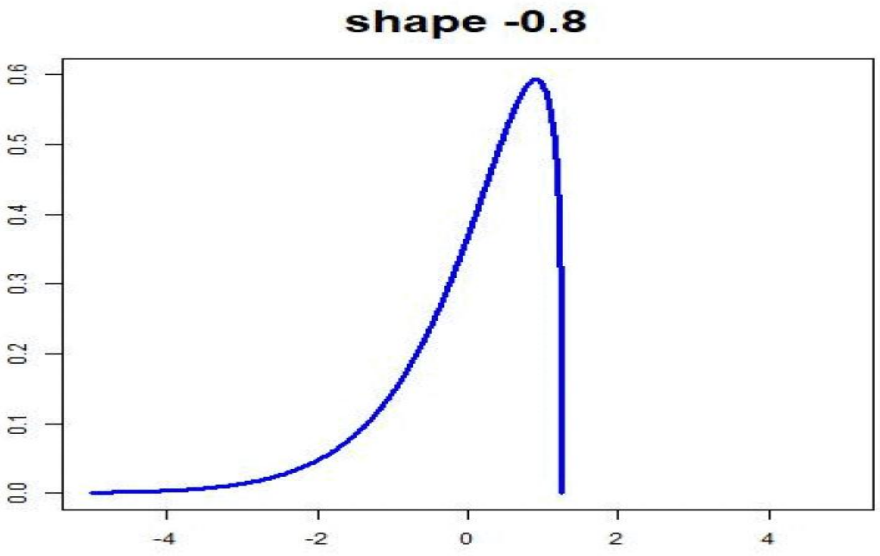
Extreme Value Theory

- Generalised Extreme Value distribution - pdf

$$f(x|\xi,\sigma,\mu) = \left(1 + \xi\left(\frac{x-\mu}{\sigma}\right)\right)^{-\left(1+\frac{1}{\xi}\right)} \exp\left(-\left(1+\xi\left(\frac{x-\mu}{\sigma}\right)\right)^{-\frac{1}{\xi}}\right)$$

$\xi = shape$
$\sigma = scale$
$\mu = location$

Parent distribution	Shape	EVD	Type	Bound
Uniform	< 0	reversed Weibull	Type III	upper
Weibull (wind)	0	Gumbel	Type I	none
Gamma (rainfall)	> 0	Fréchet	Type II	lower

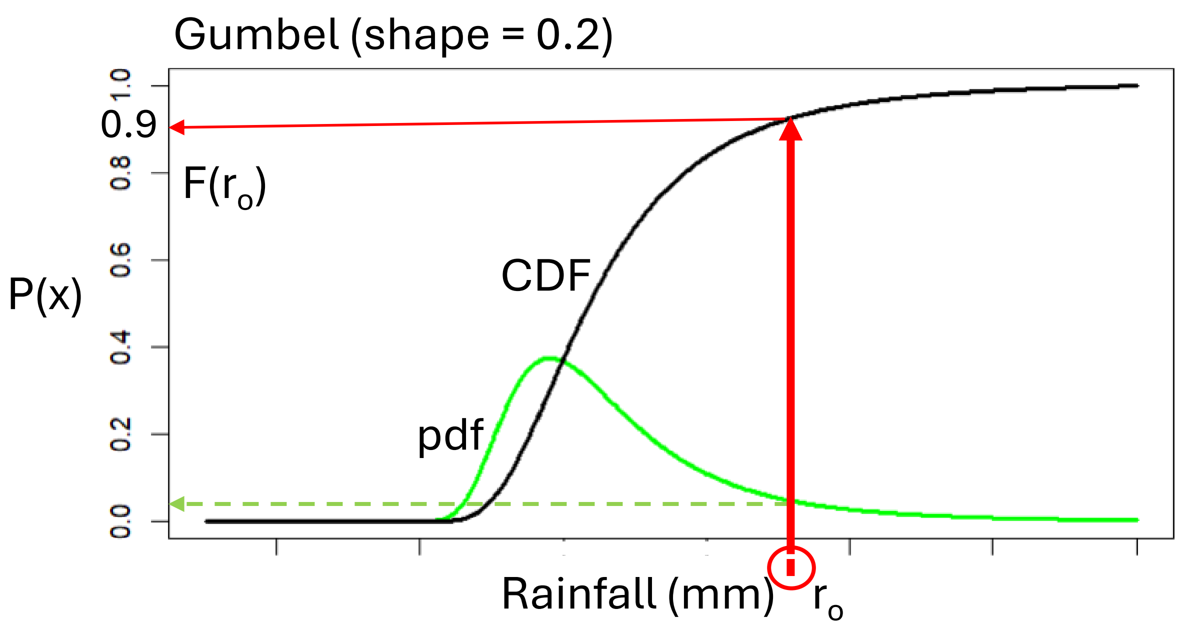


Extreme Value Theory

- Cumulative Distribution Function - calculation of exceedances

$$F(x|\xi,\sigma,\mu) = \exp\left(-\left(1+\xi\left(\frac{x-\mu}{\sigma}\right)\right)^{-\frac{1}{\xi}}\right)$$

$\xi = shape$
$\sigma = scale$
$\mu = location$



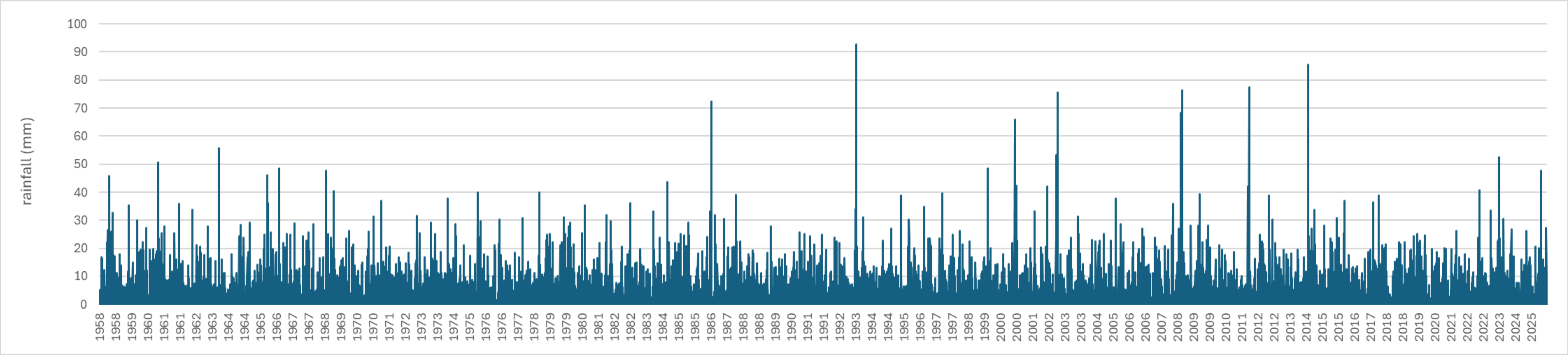
Probability of non-exceedance = $F(r_o) = 0.9$

Probability of exceedance = $1 - F(r_o) = 0.1$

Return years = $1 / (1 - F(r_o))$ = 10 years

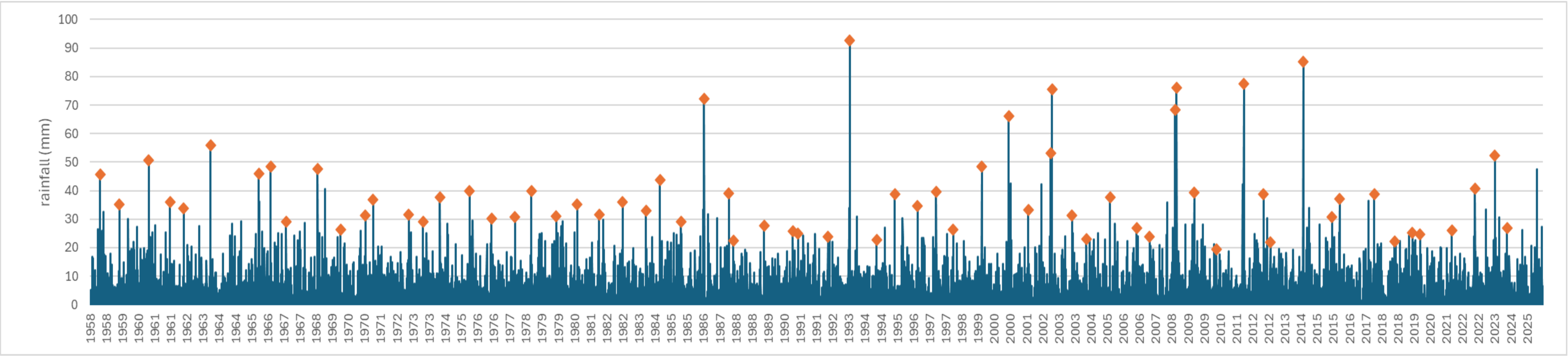
Example – Dublin Airport 24 hour rainfall

- Raw daily rainfall data over 68 years



Example – Dublin Airport 24 hour rainfall

- Annual maxima (block maxima – GEV distribution)



Annual Maxima dataset

- Dublin Airport
  - 68 years of rainfall data (1958 – 2025)
  - 24 hour duration rainfall amounts
  - Analyse the annual maxima

year	month	day	24 hour rainfall (mm)
1958	6	25	45.8
1959	11	13	35.2
1960	10	2	50.6
1961	9	28	35.9
1962	9	26	33.7
1963	8	16	55.8
1964	8	16	28.3
1965	11	16	46.0
…	…	…	…
2025	*7*	*21*	*47.6*

Data ordering

- Ordered annual maxima

year	month	day	24 hour rainfall (mm)
1958	6	25	45.8
1959	11	13	35.2
1960	10	2	50.6
1961	9	28	35.9
1962	9	26	33.7
1963	8	16	55.8
1964	8	16	28.3
1965	11	16	46.0
…	…	…	…
2025	*7*	*21*	*47.6*

year	month	day	24 hour rainfall (mm)	rank
1993	6	11	92.6	1
2014	8	2	85.3	2
2011	10	24	77.4	3
2008	8	9	76.2	4
2002	11	14	75.4	5
1986	8	25	72.4	6
2000	11	5	66	7
1963	8	16	55.8	8
…	…	…	…	…
2010	*9*	*6*	*21.1*	*68*

Plotting

- Plot extreme values versus exceedance rate

year	month	day	24 hour rainfall (mm)	rank
1993	6	11	92.6	1
2014	8	2	85.3	2
2011	10	24	77.4	3
2008	8	9	76.2	4
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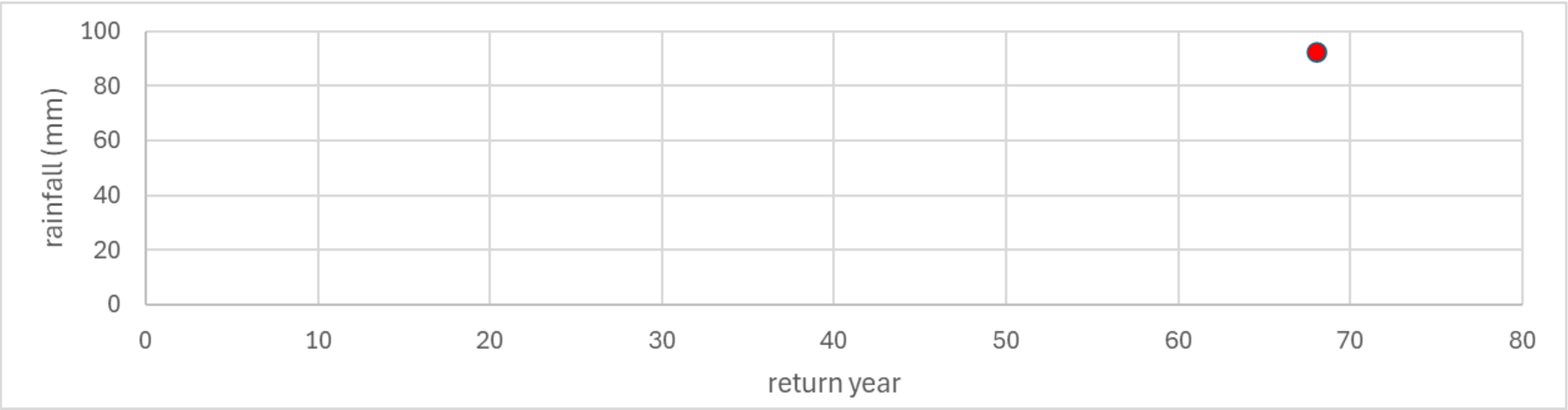
…	…	…	…	…
2010	*9*	*6*	*21.1*	*68*

Rainfall ≥ **92.6mm** once in 68 years



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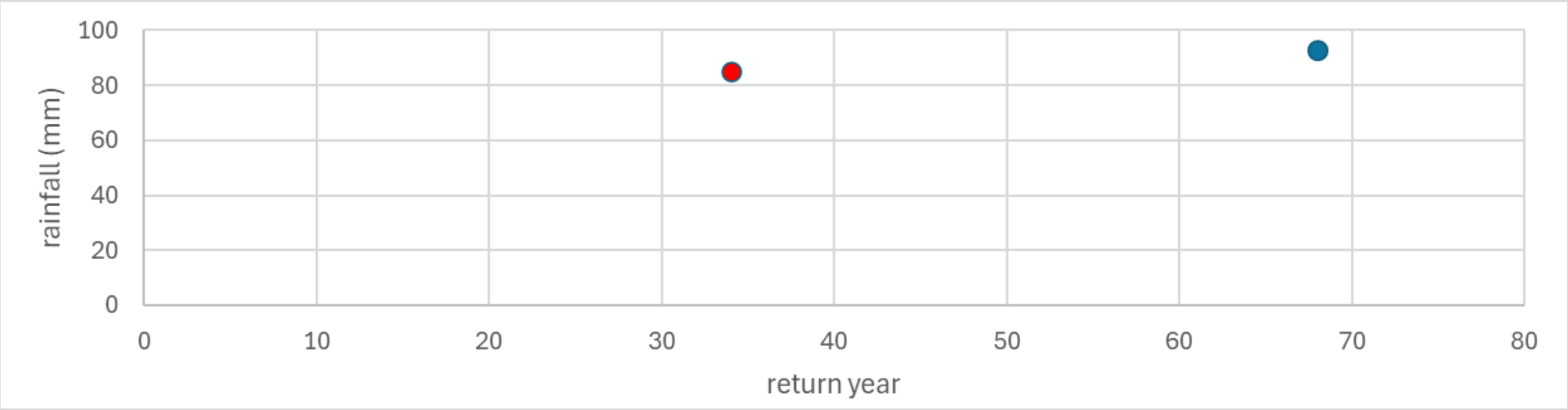
…	…	…	…	…
2010	*9*	*6*	*21.1*	*68*

Rainfall ≥ **85.3mm twice** in 68 years -> return year 68 / 2 = **34 years**



Plotting

- Plot extreme values versus exceedance rate

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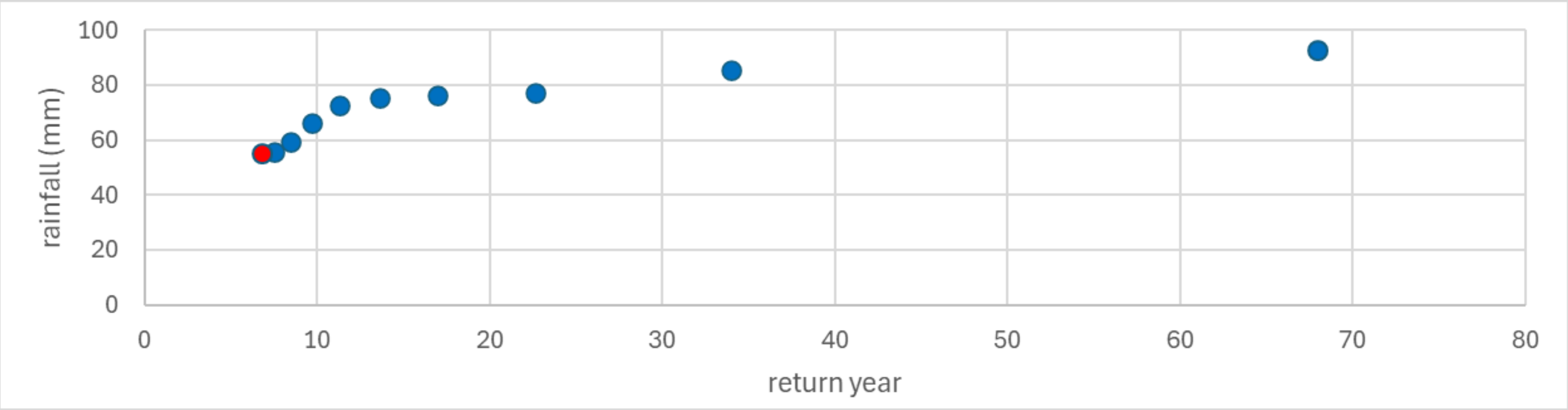
2000	11	5	66	7
1963	8	16	55.8	8
…	…	…	…	…
2010	*9*	*6*	*21.1*	*68*

Rainfall ≥ y **mm, 'rank' times** in 68 years -> return year 68 / rank = x **years**



Fitting model to observation data

- Exceedances can be fitted using a GEV CDF

year	month	day	24 hour rainfall (mm)	rank
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2011	10	24	77.4	3
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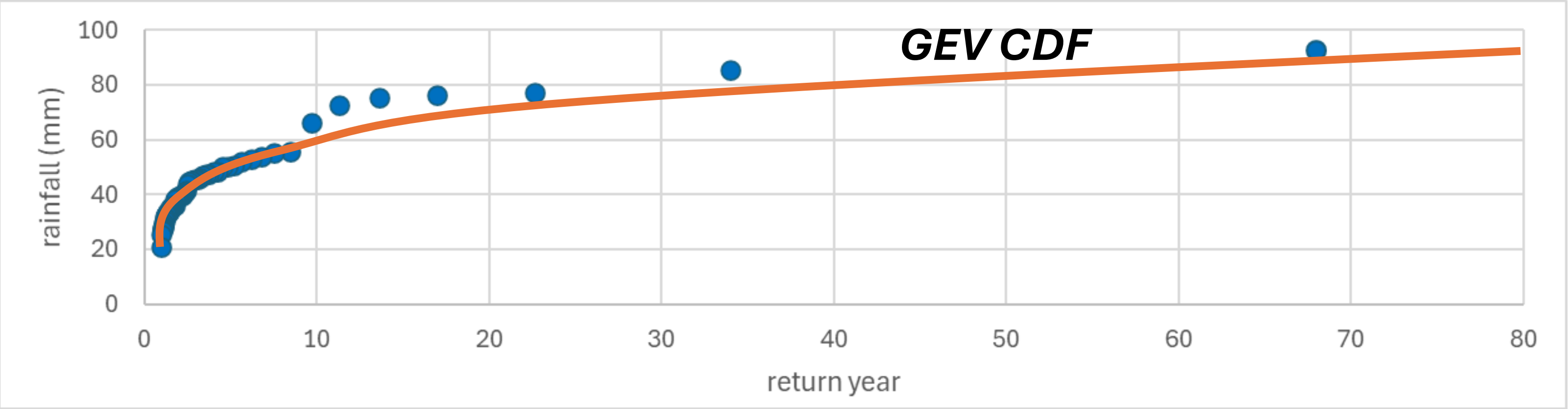
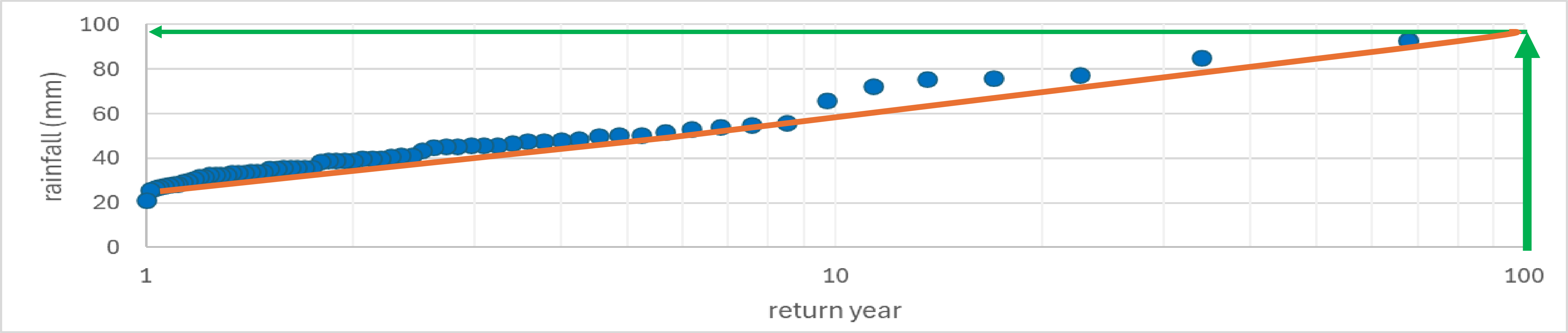


Determine the return period

- Example: designing for a 1 in 100 year event



- use R – ***extRemes*** package

```
gev_dublin_airport <- fevd(dub_airport$annual_maxima, type = "GEV",
                          na.action = na.exclude)
```

location	Named num 35.8
scale	Named num 9.22
shape	Named num 0.154

Fréchet distribution

	95% lower CI	Estimate	95% upper CI
10-year return level	52.63323	60.53255	68.43186
50-year return level	63.90395	85.01970	106.13545
100-year return level	66.93663	97.39287	127.84911

Extreme analysis rules-of-thumb

- 1 in 10 year event expected on average 6.8 times in 68 years, a 1 in 100 year event may not happen at all (or could happen once maybe)
  - 1 in 10 year event (10 year return period) = 60.5 mm
  - This is exceeded 7 times in the 68 years ~ ok
  - 1 in 100 year event (100 year return period) = 97.4 mm
  - No 100 year return period events ~ ok (max observed = 92.6 mm)
- The maximum extreme at a station has by definition only happened once in the station record: this rainfall amount has a return period ~ equal to the station record in years
  - 68 year station record, max at station has 77 year return period ~ ok

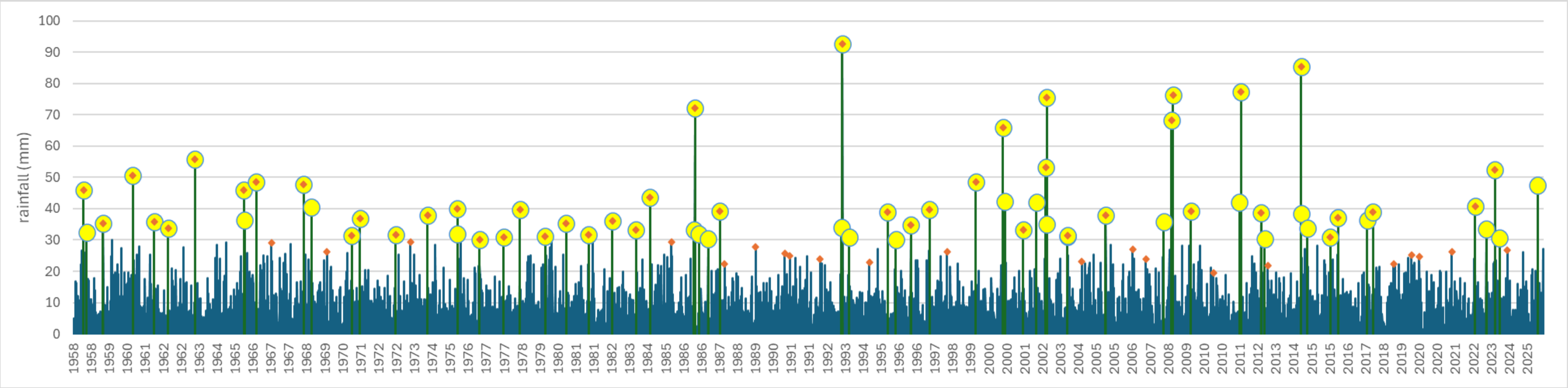
```
"77-year return level: 92.578"
```

Extreme Value Analysis methods

- GEV using block maxima – maximum annual values
- **Generalised Pareto Distribution** (GPD) using maxima above a threshold (θ)

$$\mathrm{F}(x > \theta | \xi, \sigma, \theta) = \exp\left(- \left(1 + \xi \left(\frac{x - \theta}{\sigma} \right) \right)^{-\frac{1}{\xi}} \right)$$

$\xi = shape$
$\sigma = scale$
$\theta = threshold$



	100-year RP	shape	
GEV	97.4 mm	0.154	μ = 35.8 mm
GPD	97.1 mm	0.118	θ = 35 mm

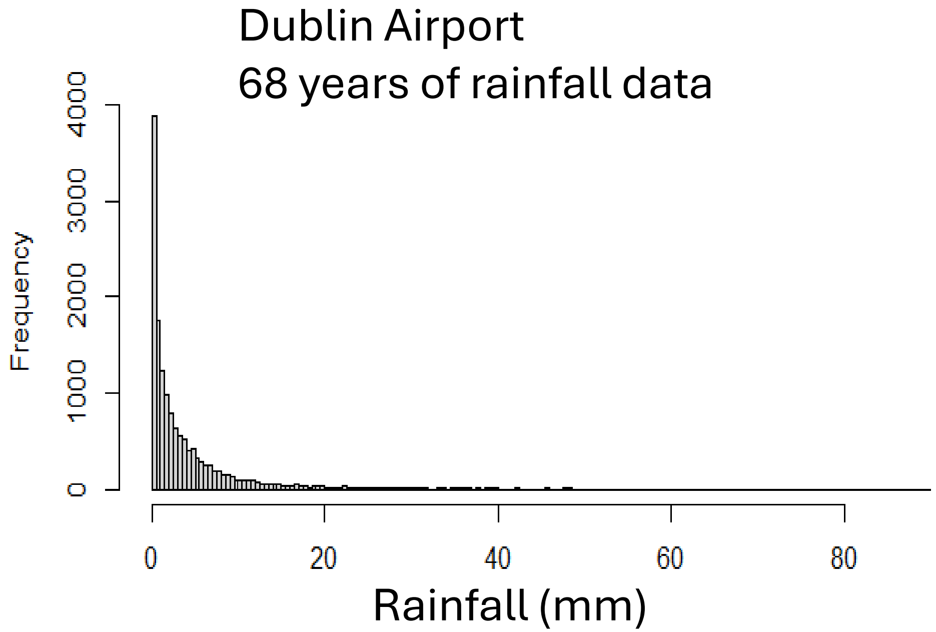
- **Depth Duration Frequency** model (DDF) ~(log-logistic distribution)

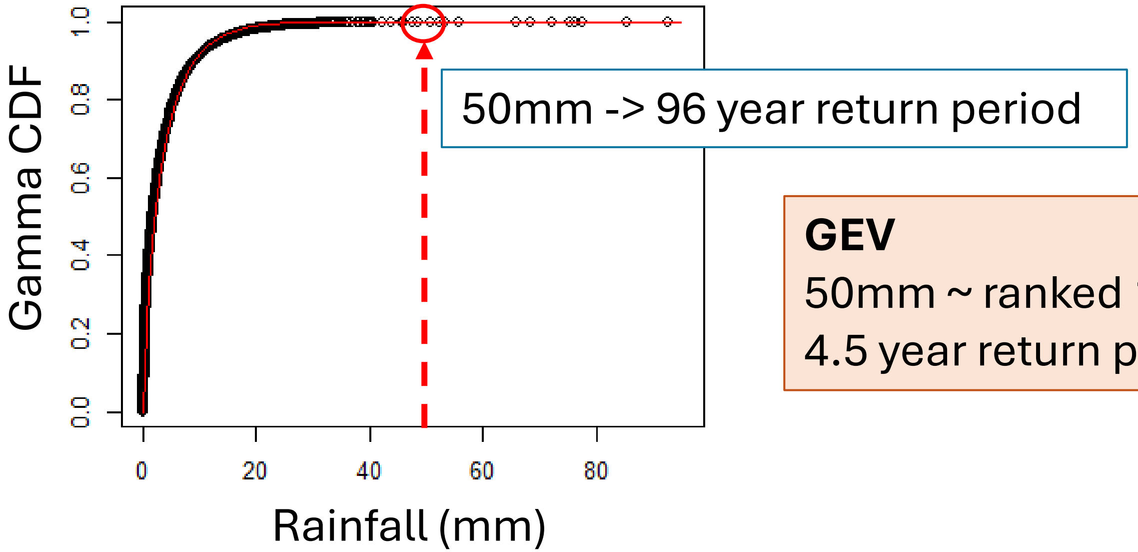
$$\mathrm{R(T, D)} = \mathit{24hr\_max\_median} \times \boldsymbol{D^{scale}} \times \boldsymbol{(T - 1)^{shape}}$$

Why use extreme value analysis?

- Distribution of bulk poorly models extreme values
- Rainfall Gamma distribution

$$f(x|\theta,\alpha) = \frac{x^{\alpha-1} e^{(\frac{-x}{\theta})}}{\Gamma(\alpha)\,\theta^{\alpha}} \qquad \begin{matrix} \alpha > 0 & shape \\ \theta > 0 & scale \end{matrix}$$



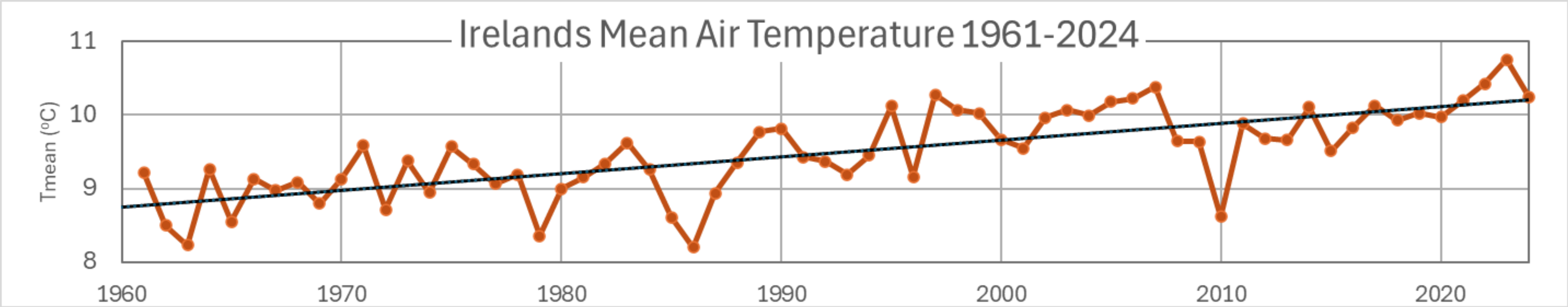


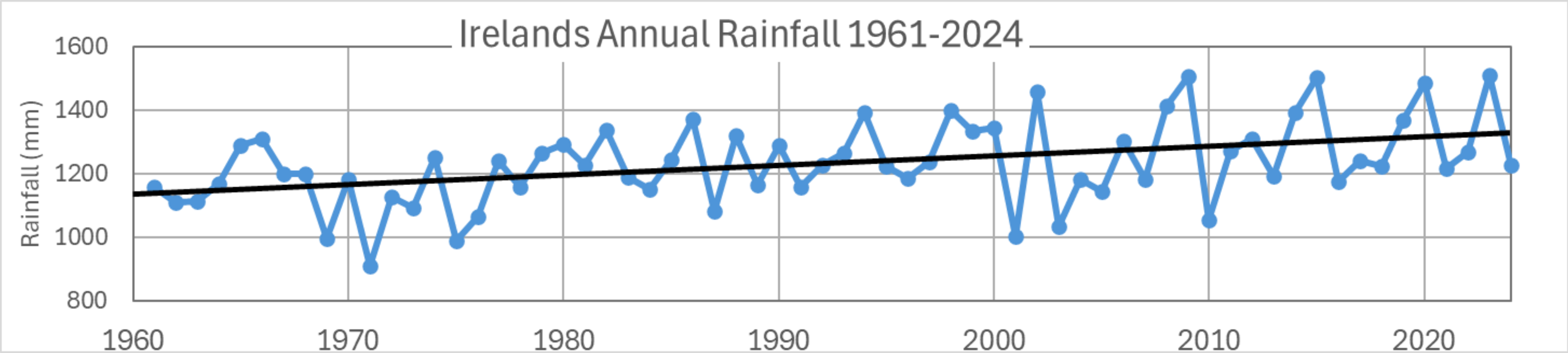
GEV
50mm ~ ranked 10^{th}
4.5 year return period

Extremes in a changing Climate

- Changing temperature in observational record
- Clausius-Clapeyron +1°C ≈ 7% (obs data +1°C ≈ 7%...)
- Observation based distribution is ***non-stationary***

```
gev_dub_temp <- fevd(dub_airport$annual_max, type = "GEV",
                     location.fun = ~ dub_sirport$temp,
                     scale.fun = ~ dub_airport$temp)
```

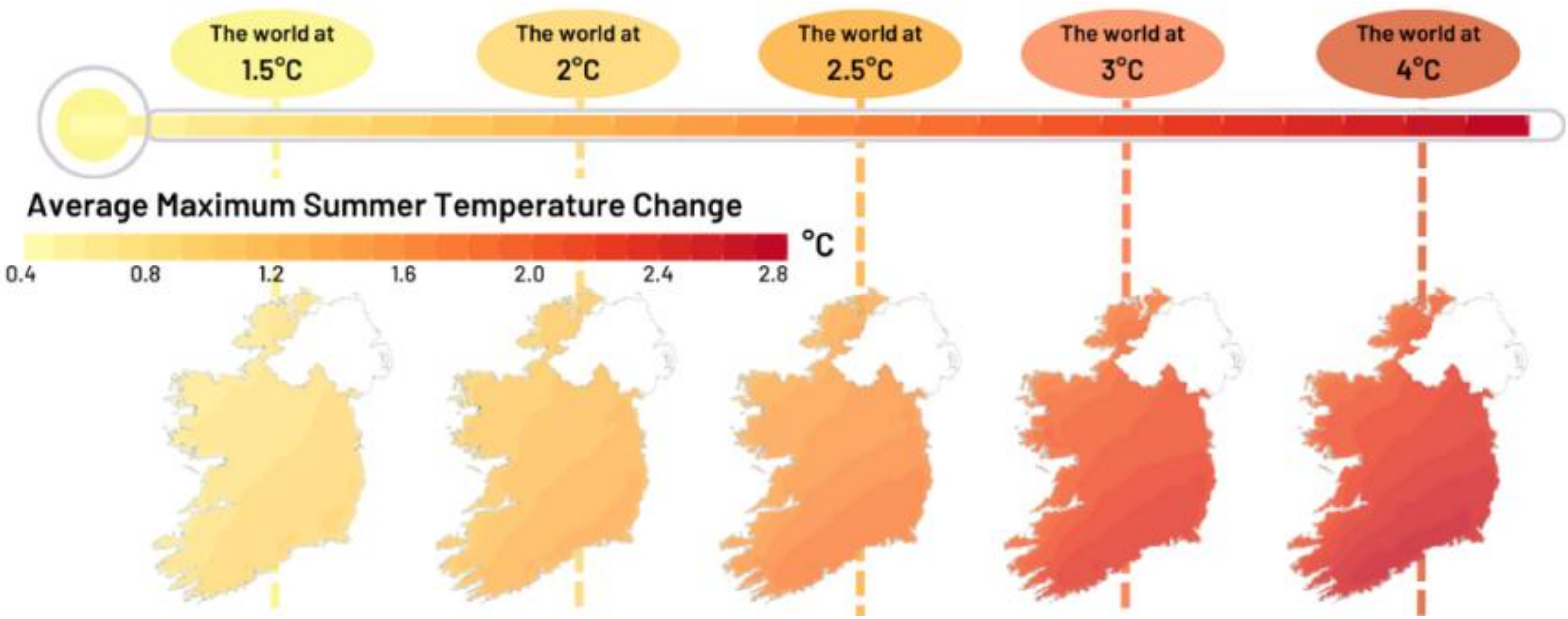




Irelands future Climate – TRANSLATE projections

- Single, reliable source for future climate information for Ireland
- Bias corrected, downscaled (1km x 1km) gridded projections
- Temperature, Rainfall, (Solar, RH, mean wind...)

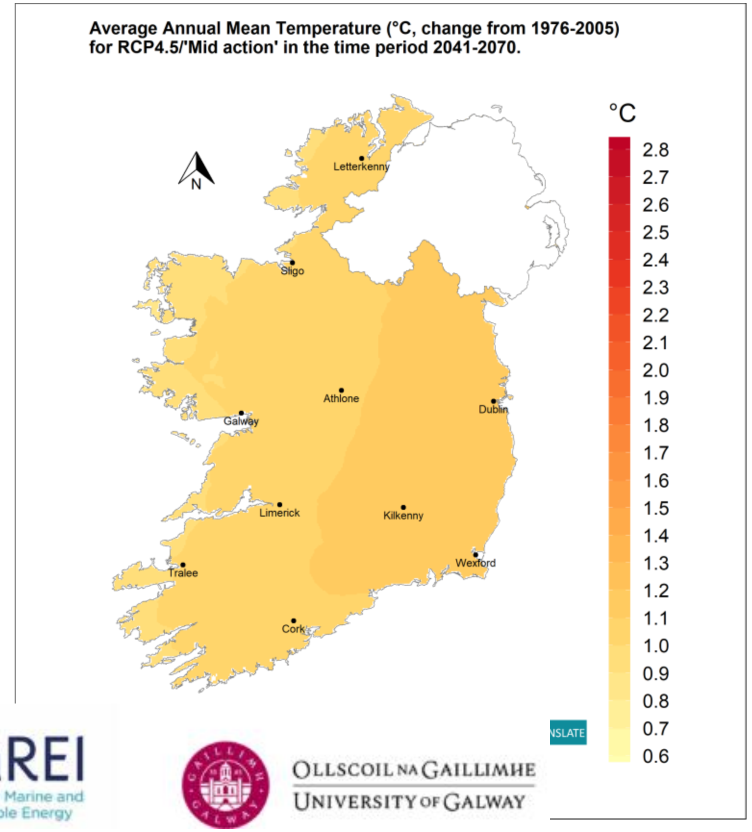
Relative to a 1976-2005 baseline

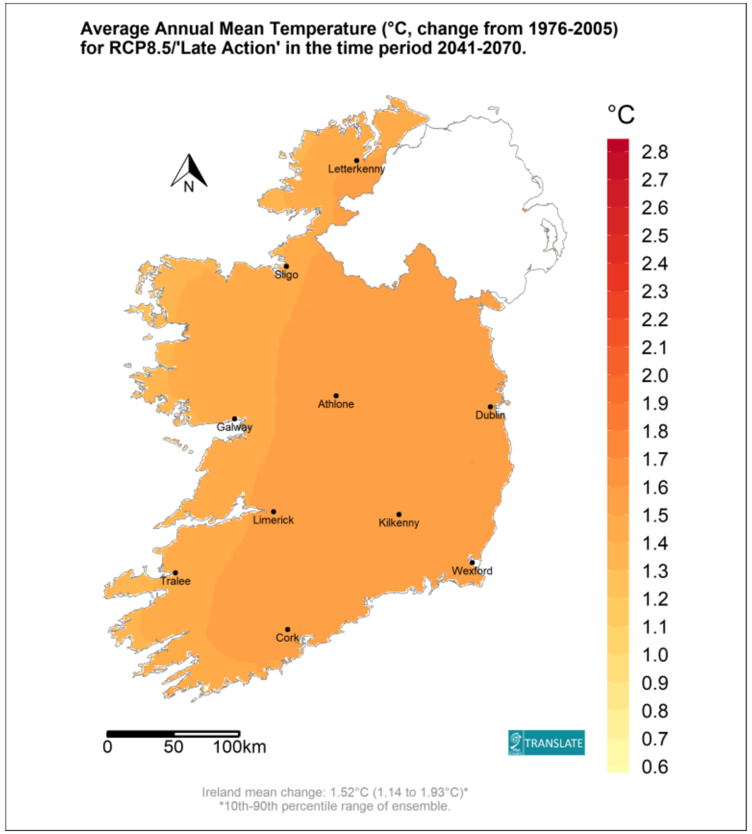


Temperature Projections - TRANSLATE

- RCP – Representative Concentration Pathway
- 2.5 low, 4.5 medium and 8.5 high emission projections

Dublin Airport	RCP	2041-2070
	2.5	+1.17 degC
	4.5	+1.37 degC
	8.5	+1.8 degC





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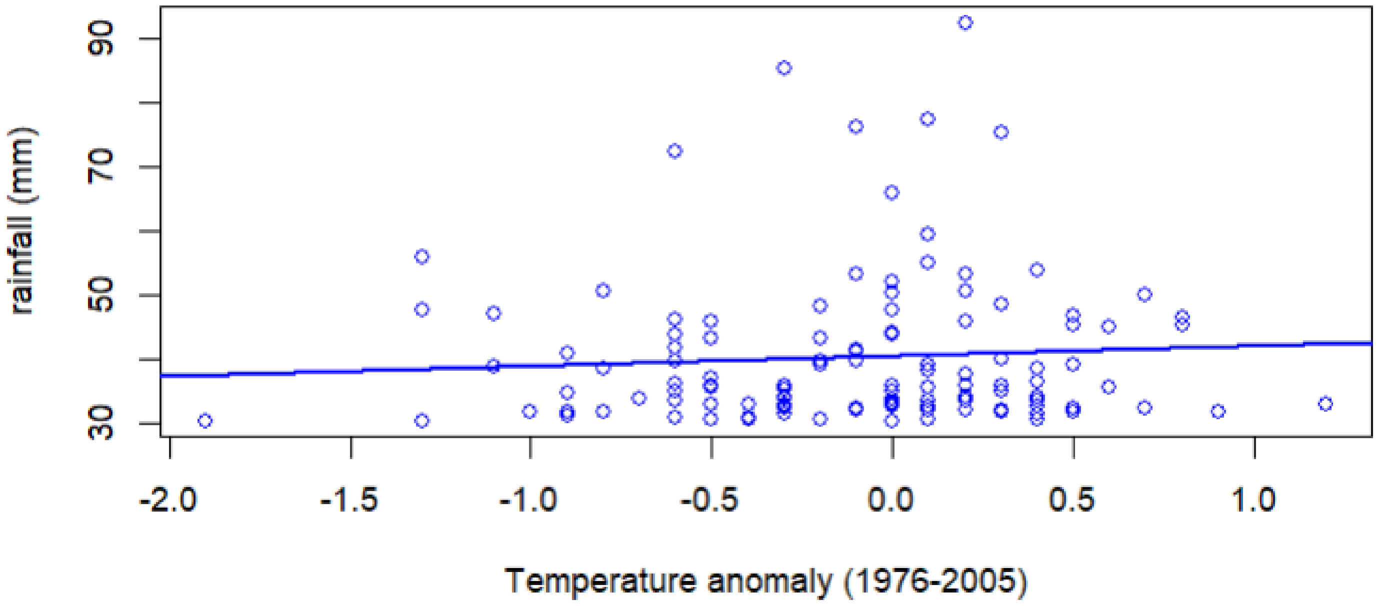
Extremes with Projections

- Determine relationship between extreme rainfall and temperature ($\boldsymbol{\alpha}$)
- Smoothed temperature (remove effects of NAO, ENSO etc)

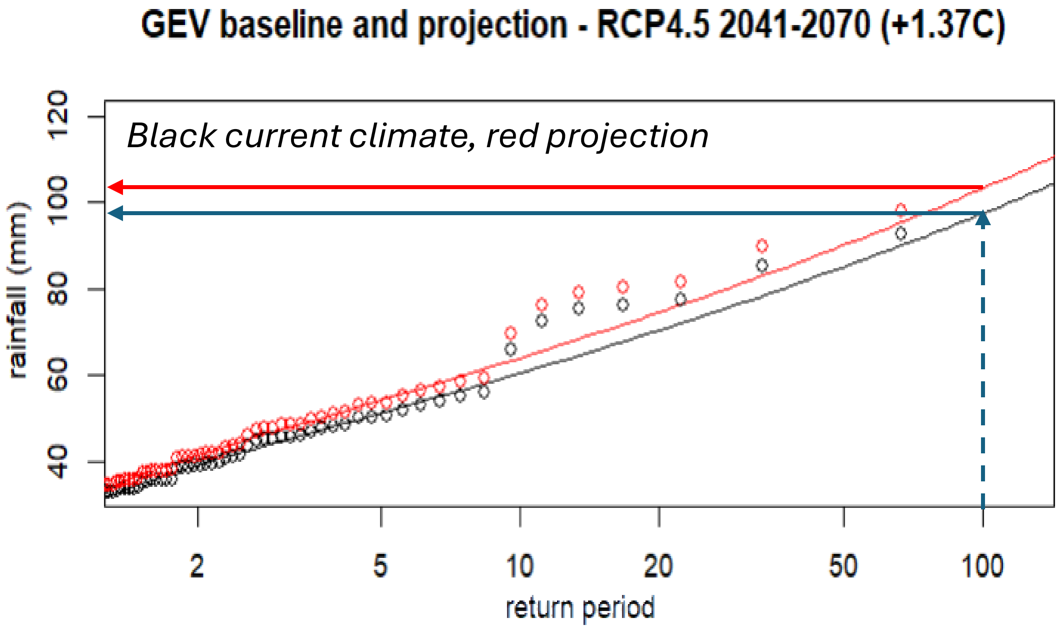


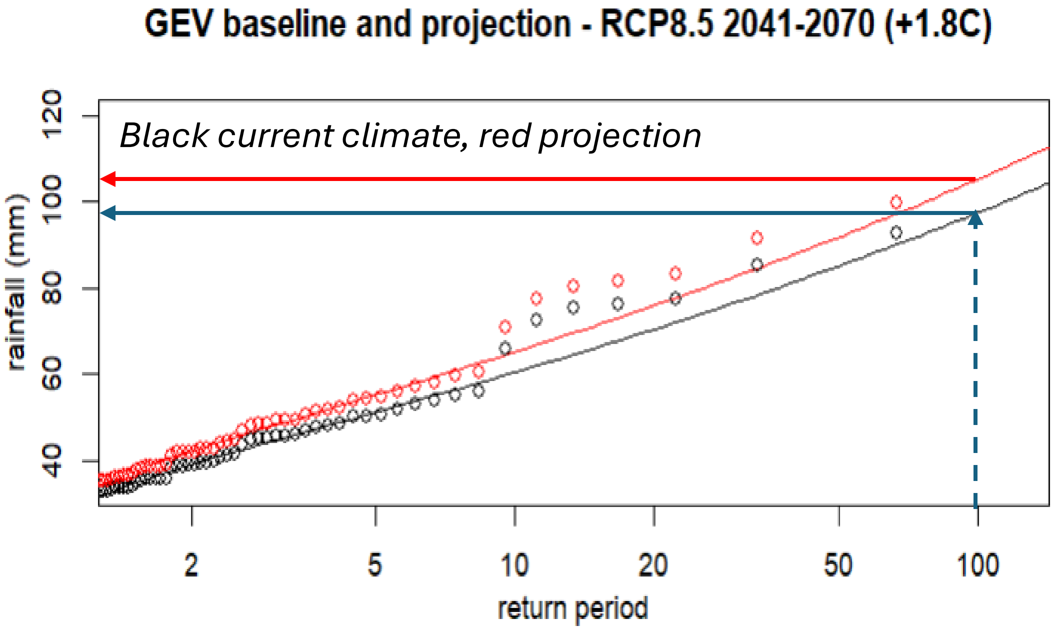
Extremes with Projections

- Adjust GEV CDF location and scale with temperature (shape fixed)

$$\mu = \mu_o exp^{(\frac{\alpha T'}{\mu_o})} \qquad \sigma = \sigma_o exp^{(\frac{\alpha T'}{\mu_o})}$$

- Recalculate projected CDF





Summary

- Analysis of **weather data** to determine probability of extreme events
- **Extreme Value Theory**
- **Cumulative Distribution Function (CDF)**
  - **Return period** = one in x-year event = 1 / probability
- Observational data – **independent events**
  - **Sampling** - annual maxima (block maxima), thresholded extremes
- Single parameters – rainfall, temperature, event days
- **Compound extremes** – extreme dryness and temperature...
- **Climate models** – how extremes change as climate changes

DDF log-logistic model

$$R(T, D) = \textit{24hr\_median} \times D^{e+f\ln(D)} \times (T-1)^{a+b\ln(D)}$$

- Scale **e + f ln(D),** rainfall as a function of duration
- Shape **a + b ln(D),** rainfall as a function of return period