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LUIS ANGEL Espinosa Villalpando

Changes in Hydrological Extremes

3rd February 2022

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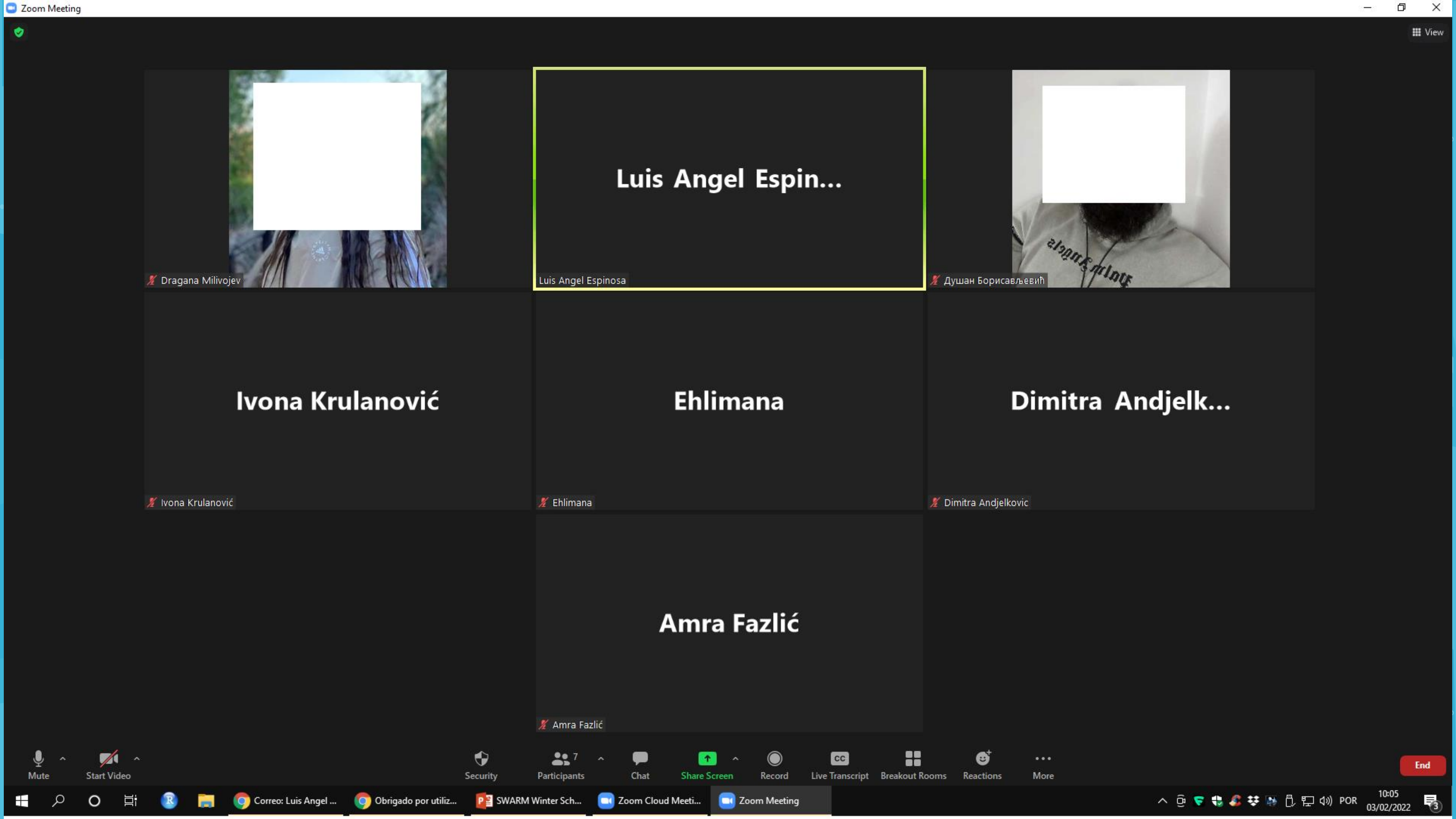
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Changes in Hydrological Extremes:

Advances in climate-induced extremes, focusing on a small North Atlantic island

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3rd February 2022

swarm

TÉCNICO LISBOA

Just to warm up…

‘Climate change has been called the crisis of our time,… and it is.’

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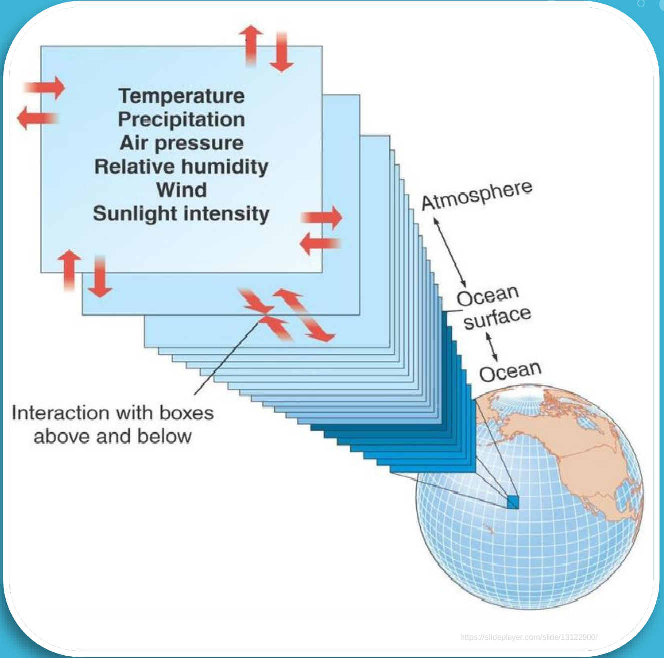
1
Overview & rationale of the research

Extreme rainfall and droughts in a changing climate

These extreme hydrological events have increased globally – but not at the same pace

Motivation of the research

Extreme hydrological events in small areas (e.g. small islands) are often poorly understood or not well reproduced by climate models (e.g. General Circulation Models, GCMs)



Selected case study

Madeira Island (741 km^2 ≈ 7.5 times Lisbon county area) located in the North Atlantic Ocean, in the European part of Macaronesia

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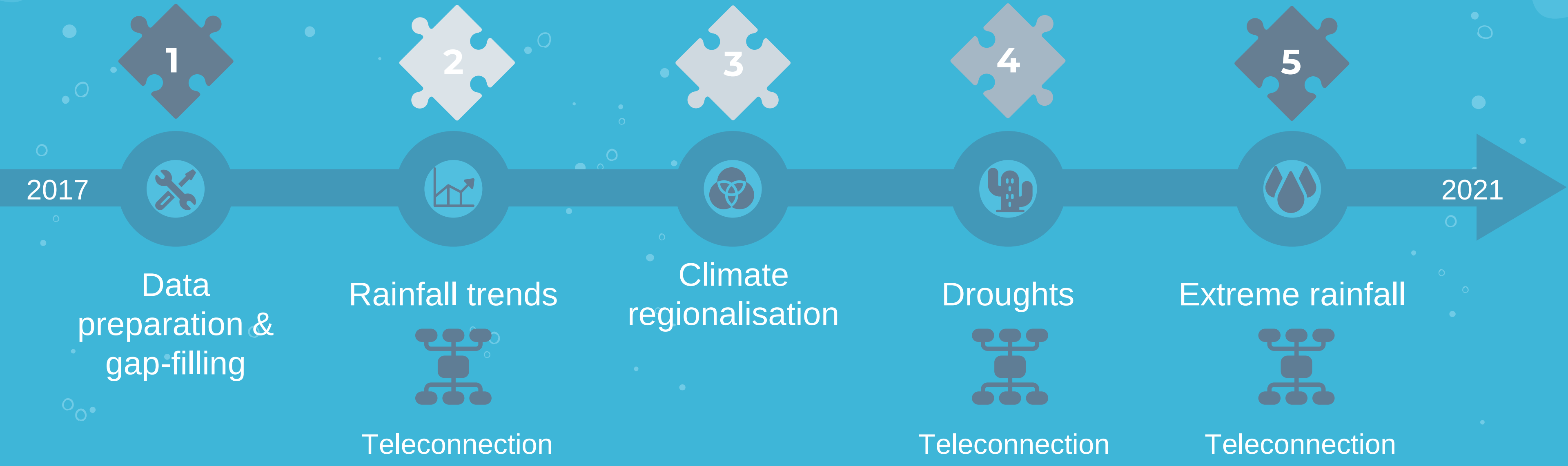
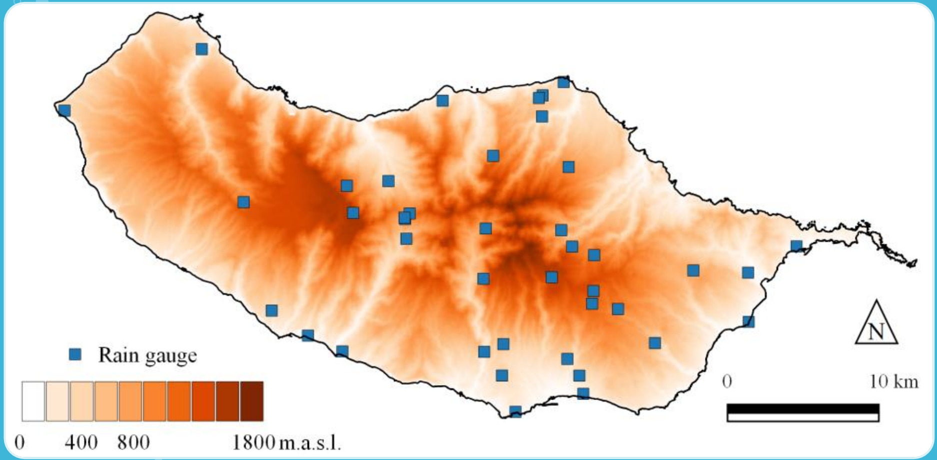
Keywords

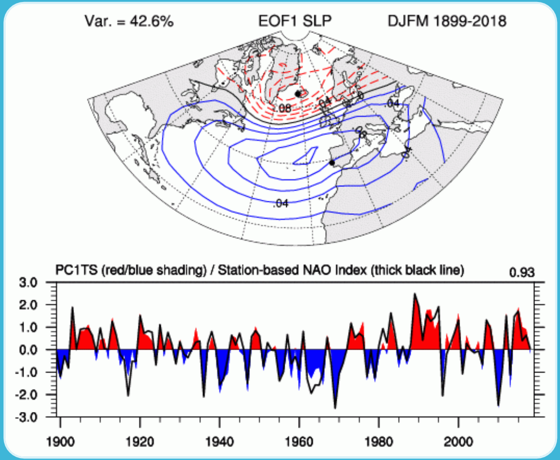
- Trend analysis
- North Atlantic Oscillation
- Drought
- Extreme rainfall
- Small island hydrology
- Teleconnection

The logic of the research



Primary data used for the analyses





Daily rainfall

Data from October 1936 to September 2017 (80 hydrological years) at 41 raingauges in Madeira Island

Modes of climate variability

Different definitions of the North Atlantic Oscillation (e.g. daily NAO index)

Main models used

1 Data preparation
- Multivariate imputation by chained equations (MICE) for gap-filling
- Synthetic missing data generation for validation

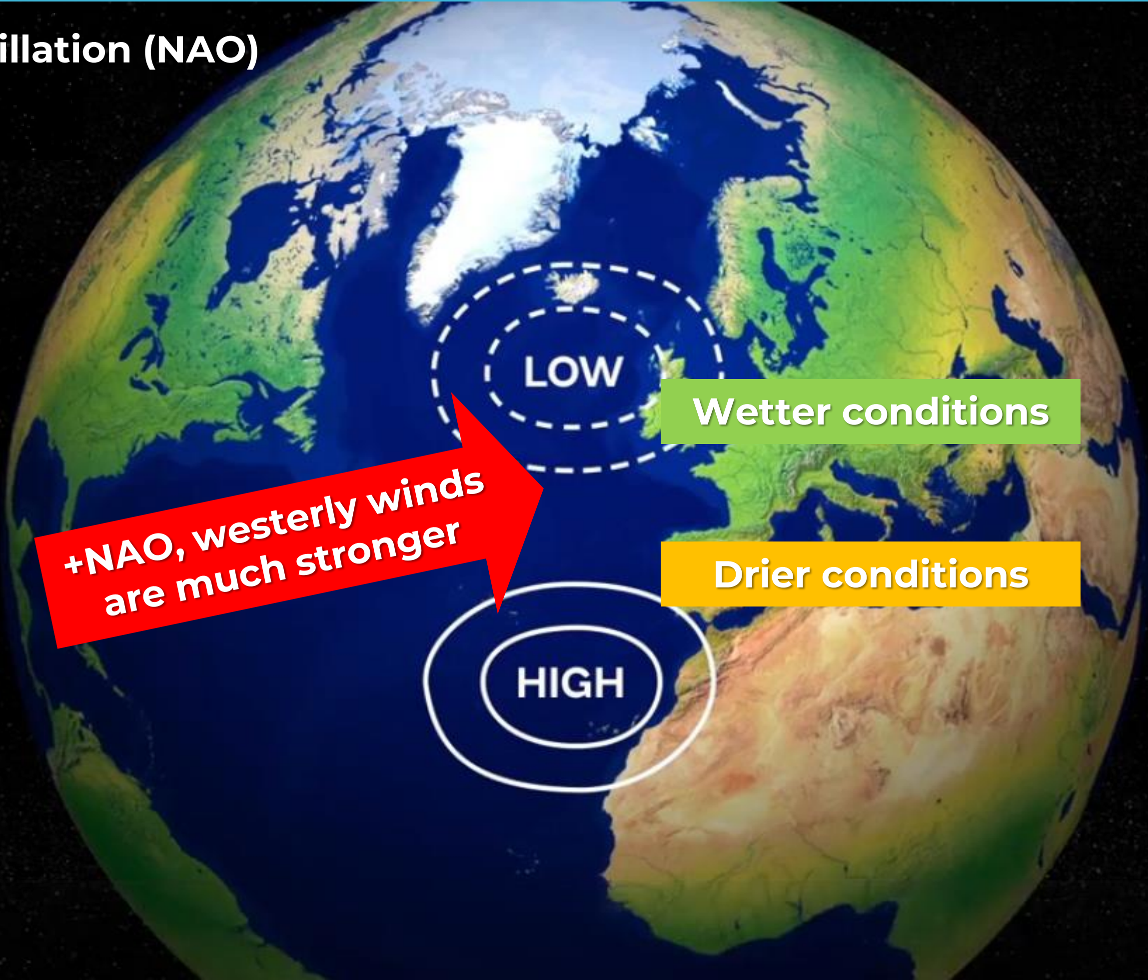
2 Rainfall trends
- Mann-Kendall (MK) test
- Sen's slope estimator
- Sequential Mann-Kendall (SQMK) test

3 Climate regionalisation
- Principal components analysis (PCA)
- Principal factor analysis (PFA)

4 Droughts
- Standardized Precipitation index (SPI)
- Kernel occurrence rate estimator (KORE)
- Bivariate copulas

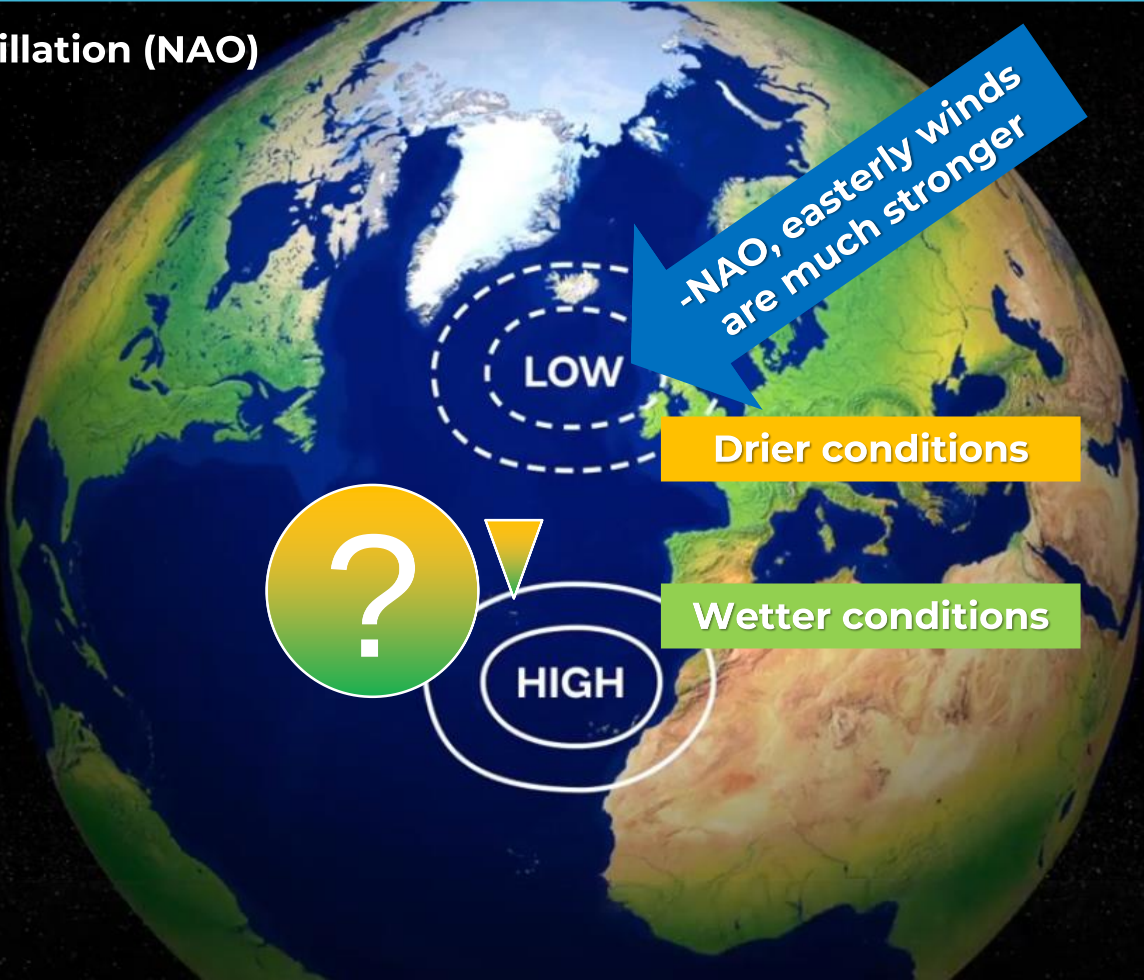
5 Extreme rainfall
- Extremogram
- Cross-extremogram
- Bivariate copulas

North Atlantic Oscillation (NAO)



https://www.metoffice.gov.uk/

North Atlantic Oscillation (NAO)



https://www.metoffice.gov.uk/

2

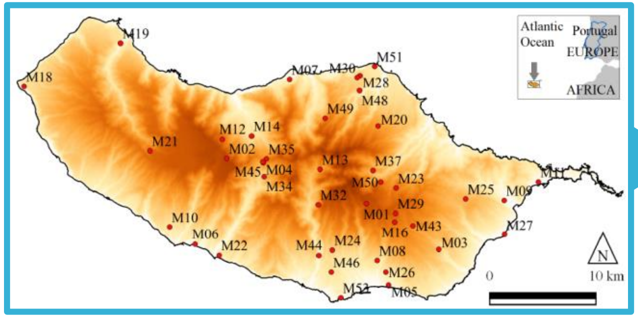
Major findings of the research

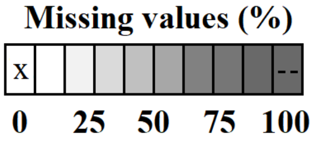
2.1
Filling of the missing rainfall data

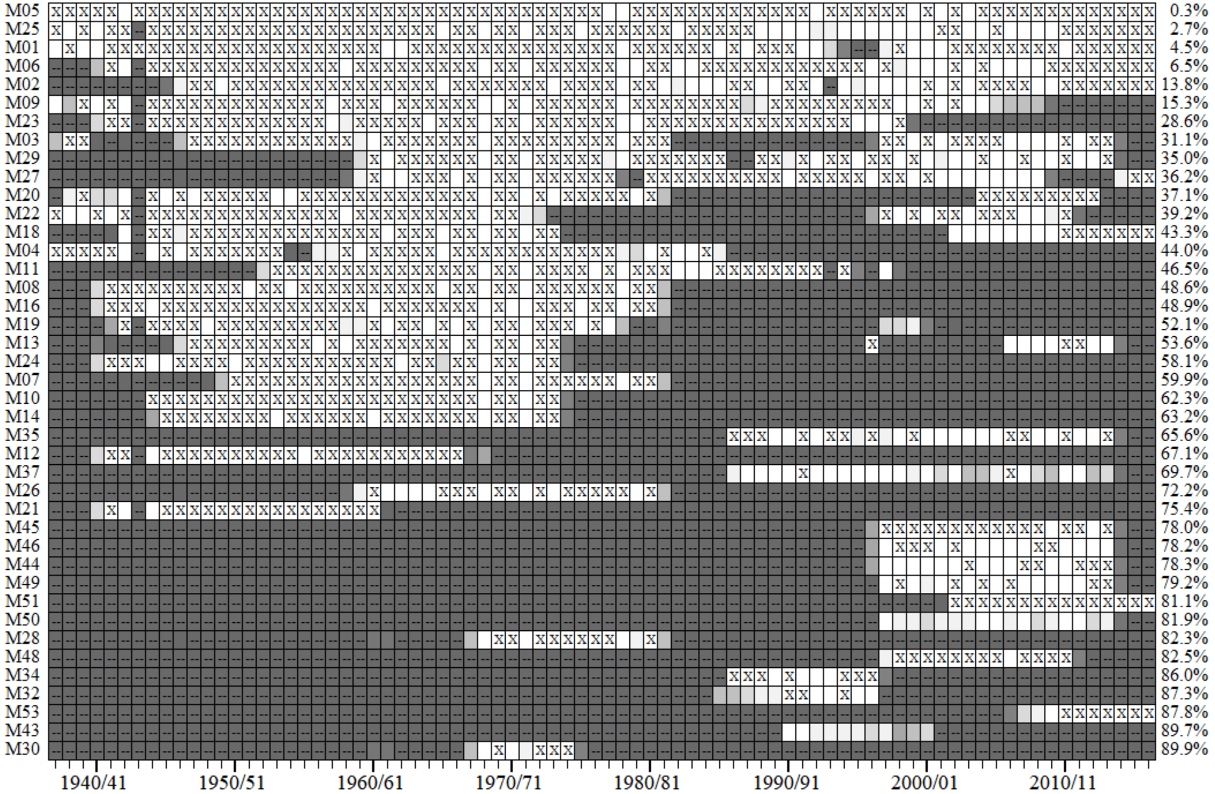
"The problem of missing values, as those of rainfall, is relatively common in almost all research related to hydrology."

Espinosa, L.A., Portela, M. M., & Rodrigues, R. (2021). Rainfall trends over a North Atlantic small island in the period 1937/1938–2016/2017 and an early climate teleconnection. Theoretical and Applied Climatology, 144(1), 469-491; https://doi.org/10.1007/s00704-021-03547-7

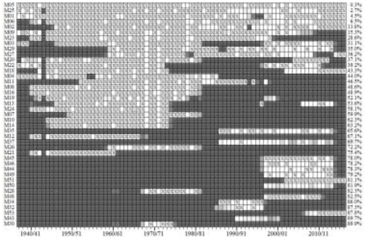
Characterisation of the missing daily rainfalls

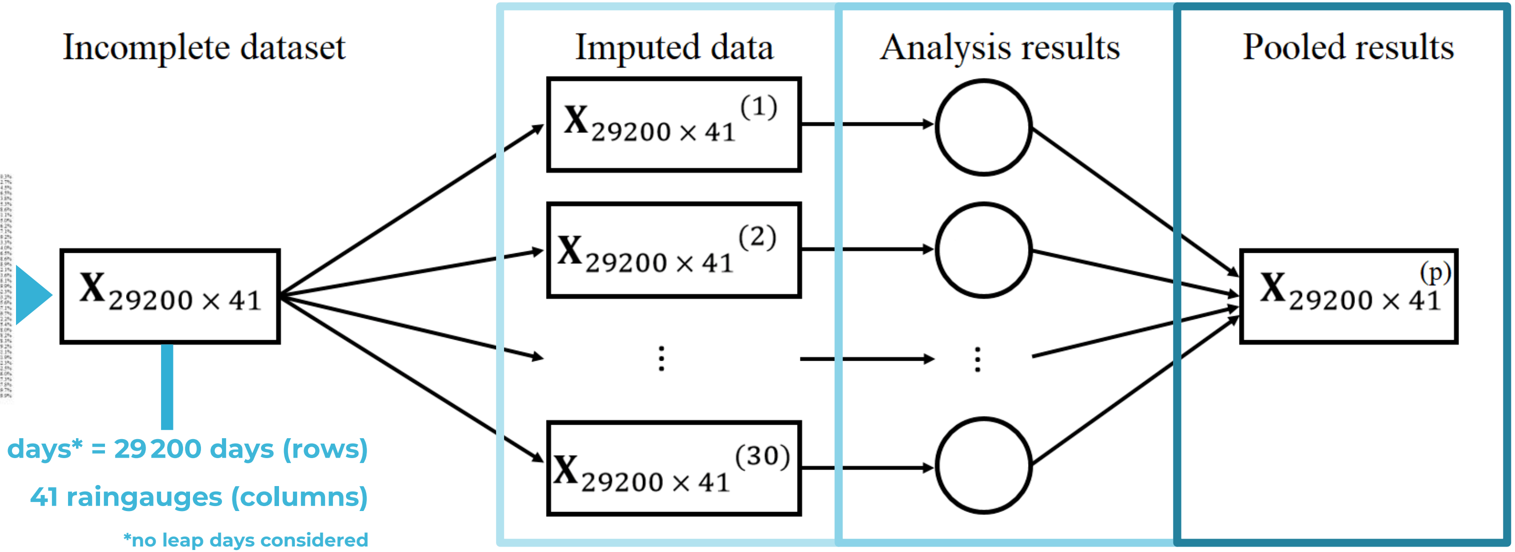






Multivariate imputation MICE main steps



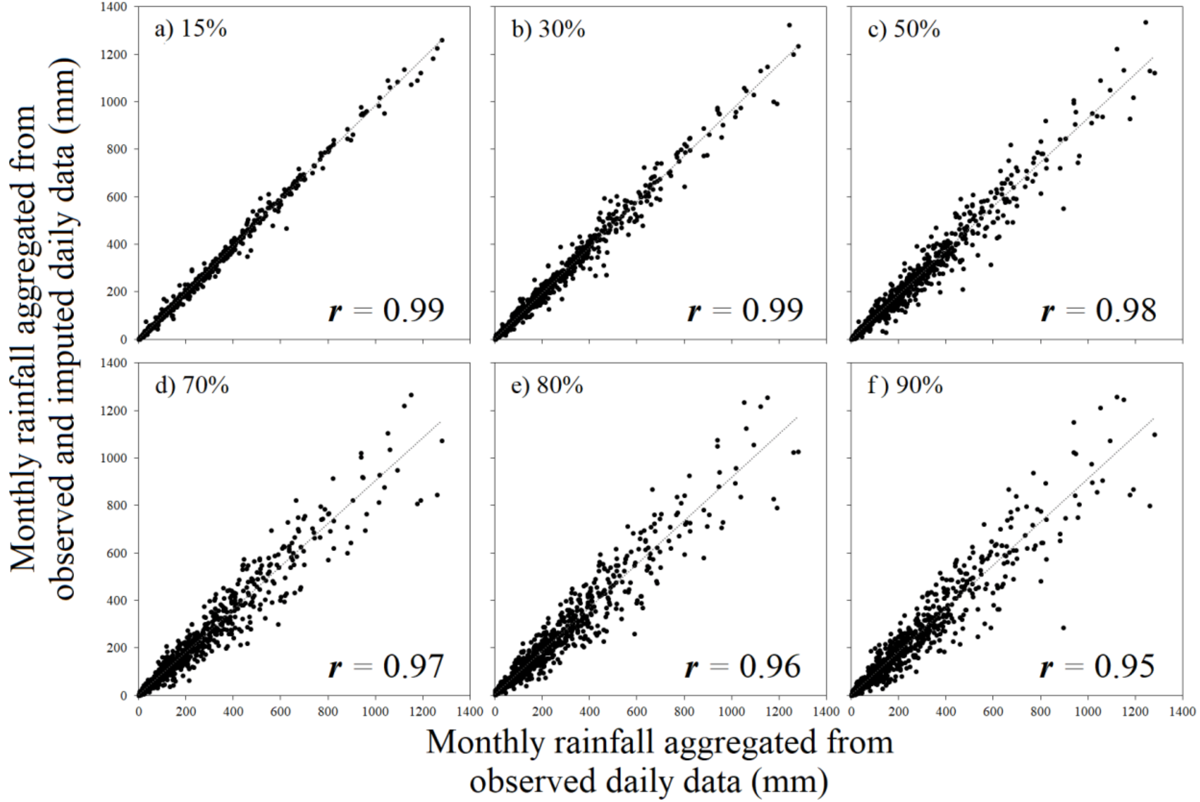


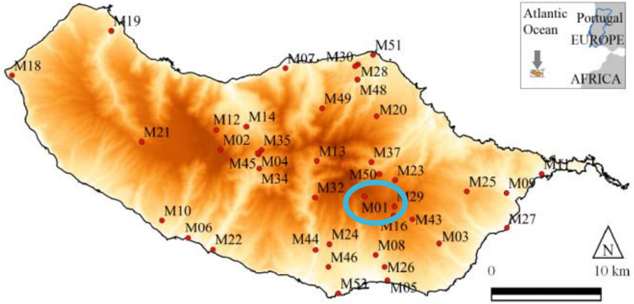
80 years x 365 days* = 29 200 days (rows)

41 raingauges (columns)

*no leap days considered

Validation of MICE (synthetic % missing data)





M01-Areeiro rain gauge

From top left to bottom right increasing % of synthetic daily missing date

2.1 Filling of the missing rainfall data

29,200×41

of complete daily rainfalls was achieved and validated from October 1936 to September 2017

2.2
Rainfall trends

"There is considerably and statistically significant decreases, exacerbated in recent years, at the central region of the island which is one of the most important locations in terms of fresh water security."

Espinosa, L.A., & Portela, M.M. (2020a). Rainfall Trends over a Small Island Teleconnected to the North Atlantic Oscillation - the Case of Madeira Island, Portugal. Water Resources Management 34, 4449–4467; https://doi.org/10.1007/s11269-020-02668-4

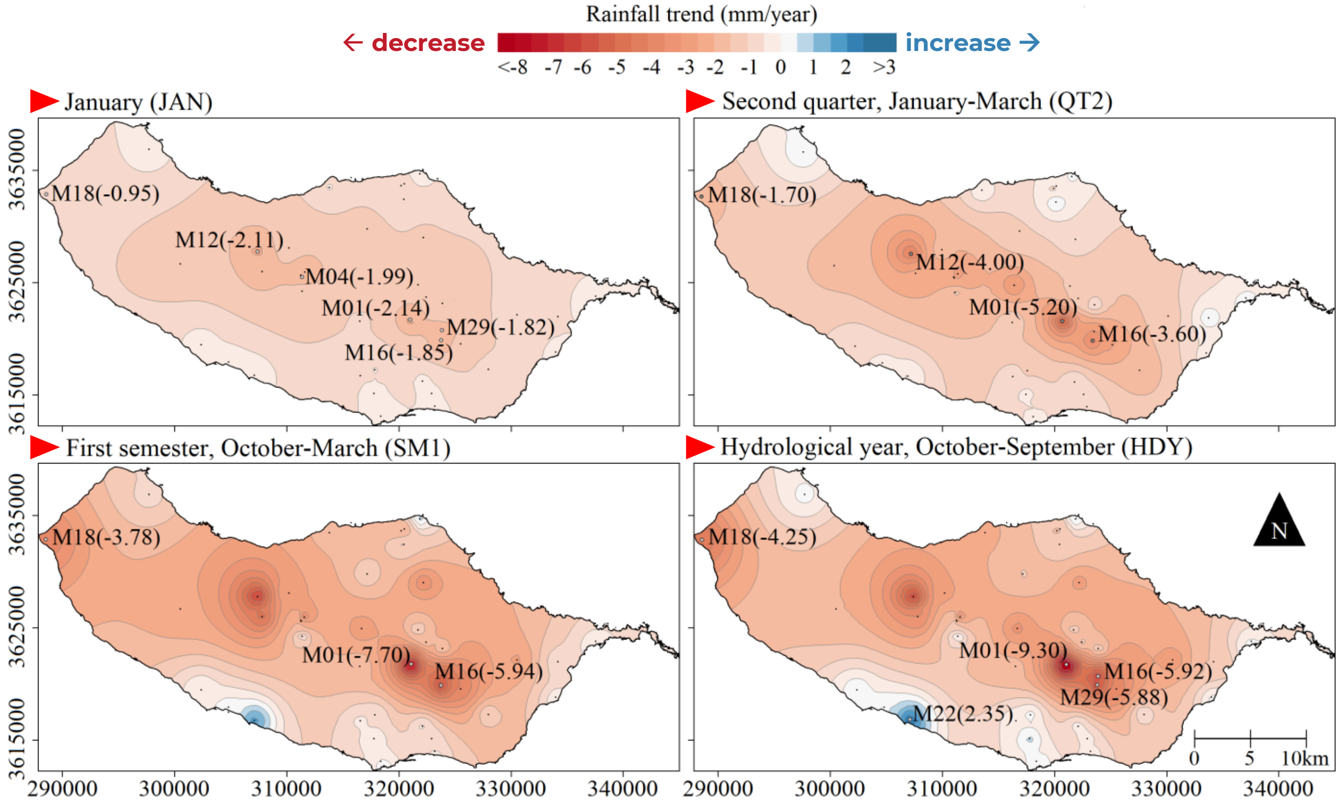
Espinosa, L.A., Portela, M. M., & Rodrigues, R. (2021). Rainfall trends over a North Atlantic small island in the period 1937/1938–2016/2017 and an early climate teleconnection. Theoretical and Applied Climatology, 144(1), 469-491; https://doi.org/10.1007/s00704-021-03547-7

Spatial distribution of trends (1937-2017)

IDW applied to the Sen's slope estimates, Q

$$Q_i = \frac{x_j - x_k}{j - k}, i = 1, 2, ..., N, j > k$$

$$Q = \begin{cases} Q_{\frac{N+1}{2}} & \text{, if } N \text{ is odd} \\ \frac{1}{2}\left(Q_{\frac{N}{2}} + Q_{\frac{N+2}{2}}\right) & \text{, if } N \text{ is even} \end{cases}$$



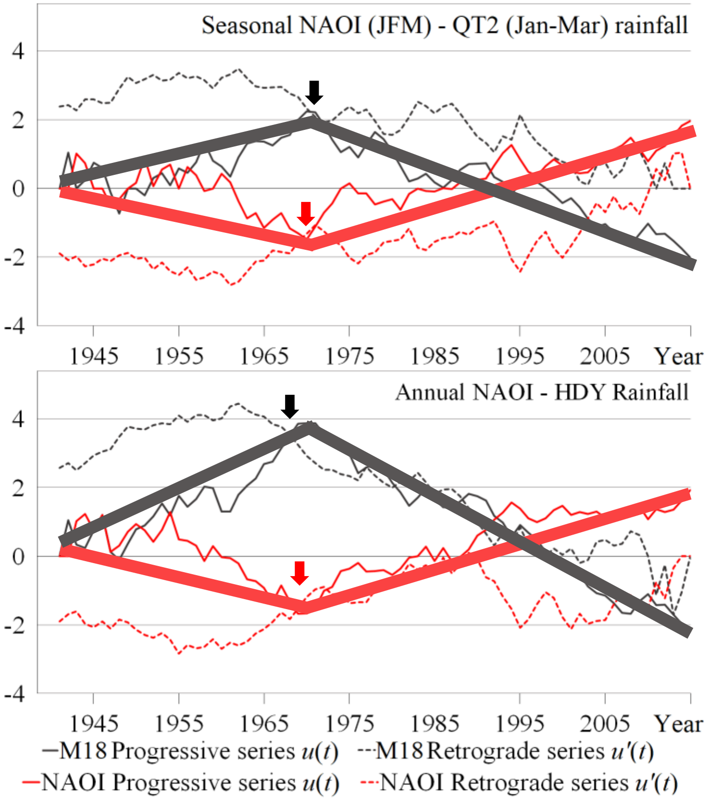
NAOI and rainfall trends (1937-2017)

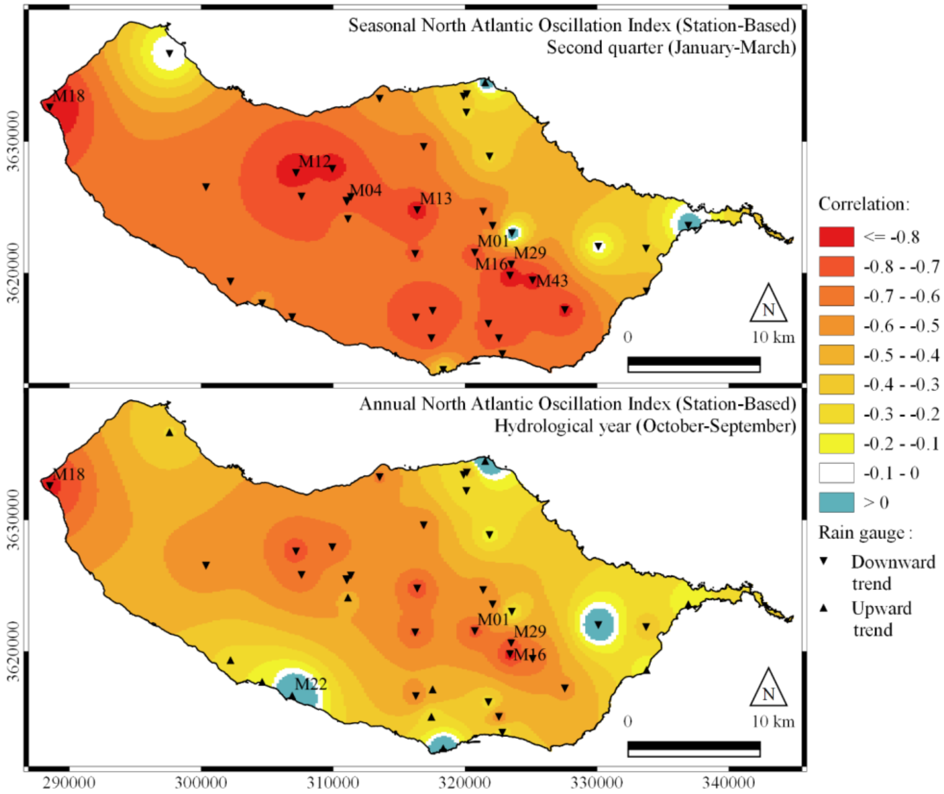
$$t_i = \sum_{k=1}^{i} n_k$$

$$E(t_i) = \frac{i(i-1)}{4}$$

$$\mathrm{Var}(t_i) = \frac{i(i-1)(2i+5)}{72}$$

$$u(t_i) = \frac{[t_i - E(t_i)]}{\sqrt{\mathrm{Var}(t_i)}}$$





2.3
Climate regionalisation

"The regionalisation enabled a dimensionality reduction to three relatively manageable regions of Madeira Island."

Espinosa, L.A., Portela, M. M., & Rodrigues, R. (2019). Spatio-temporal variability of droughts over past 80 years in Madeira Island. Journal of Hydrology: Regional Studies, Volume 25, 2019, 100623, ISSN 2214-5818; https://doi.org/10.1016/j.ejrh.2019.100623

Espinosa, L.A., Portela, M.M.; Pontes Filho, J.D., Studart, T.M.C., Santos, J.F., & Rodrigues, R. (2019). Jointly Modeling Drought Characteristics with Smoothed Regionalized SPI Series for a Small Island. Water 2019, 11, 2489; https://doi.org/10.3390/w11122489

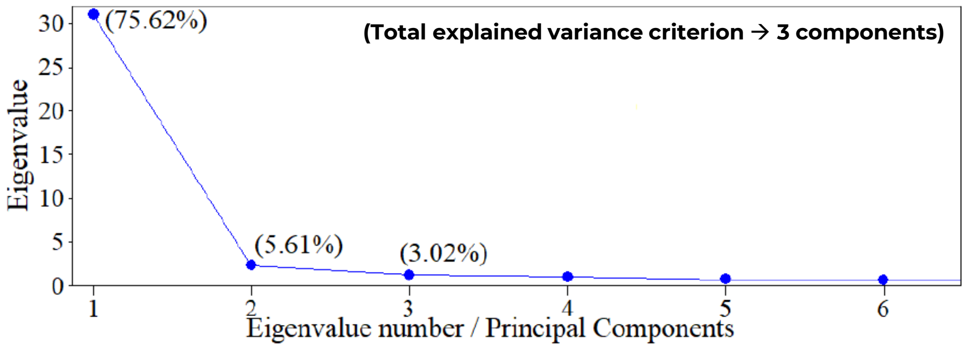
Espinosa, L.A., Portela, M.M., & Rodrigues, R. (2020b). Significant Extremal Dependence of a Daily North Atlantic Oscillation Index (NAOI) and Weighted Regionalised Rainfall in a Small Island Using the Extremogram. Water 2020, 12(11), 2989; https://doi.org/10.3390/w12112989

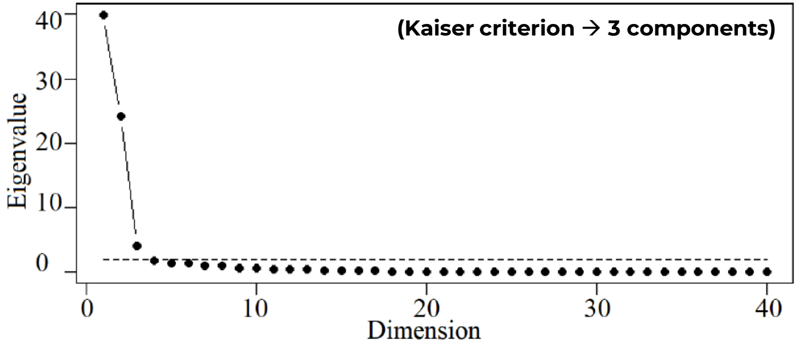
Climate regions were identified based on:

Standardized Precipitation Index (SPI)

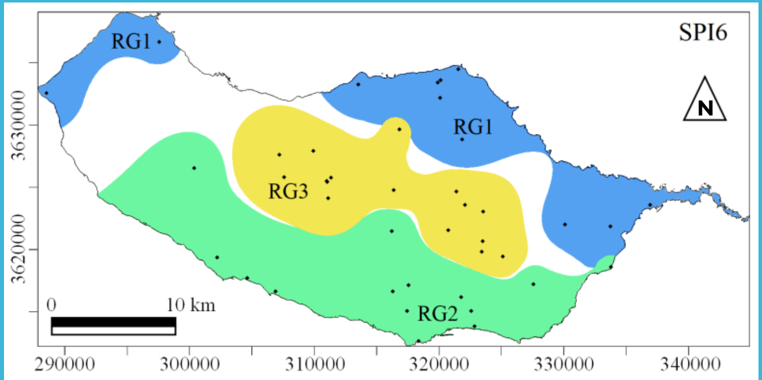
Daily rainfall data

Optimal interpretation of PCA loadings

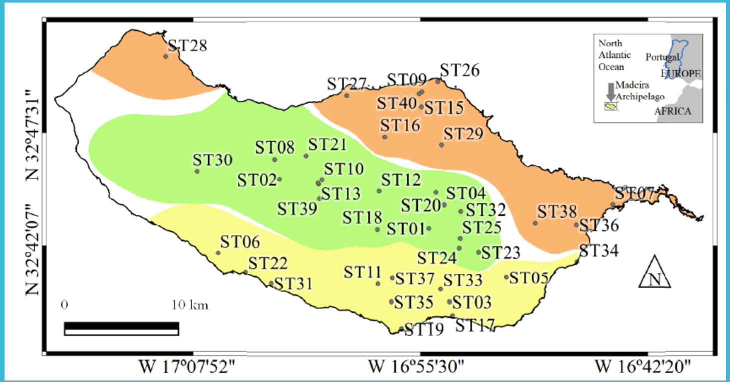




Three identified homogeneous regions



The base for the drought analysis to obtain “new” regionalised SPI series (factor scores)



The base for the extreme rainfall analysis to cluster rain gauges (eigen values)

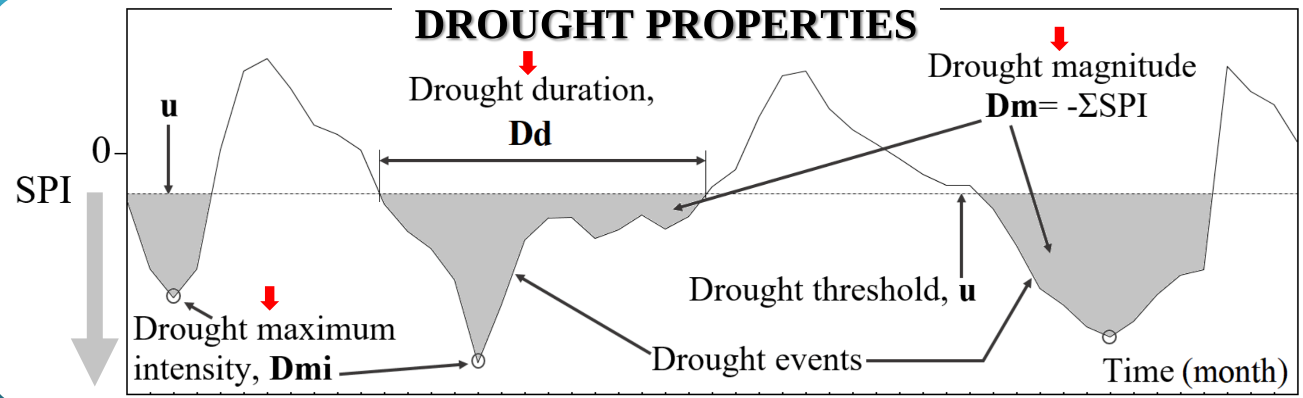
2.4
Drought analysis

"There is strong evidence suggesting that the island, especially its central part, is currently in the midst of the worst drought ever registered which started around the year 2010–2011."

Espinosa, L.A., Portela, M. M., & Rodrigues, R. (2019). Spatio-temporal variability of droughts over past 80 years in Madeira Island. Journal of Hydrology: Regional Studies, Volume 25, 2019, 100623, ISSN 2214-5818; https://doi.org/10.1016/j.ejrh.2019.100623

Espinosa, L.A., Portela, M.M.; Pontes Filho, J.D., Studart, T.M.C., Santos, J.F., & Rodrigues, R. (2019). Jointly Modeling Drought Characteristics with Smoothed Regionalized SPI Series for a Small Island. Water 2019, 11, 2489; https://doi.org/10.3390/w11122489

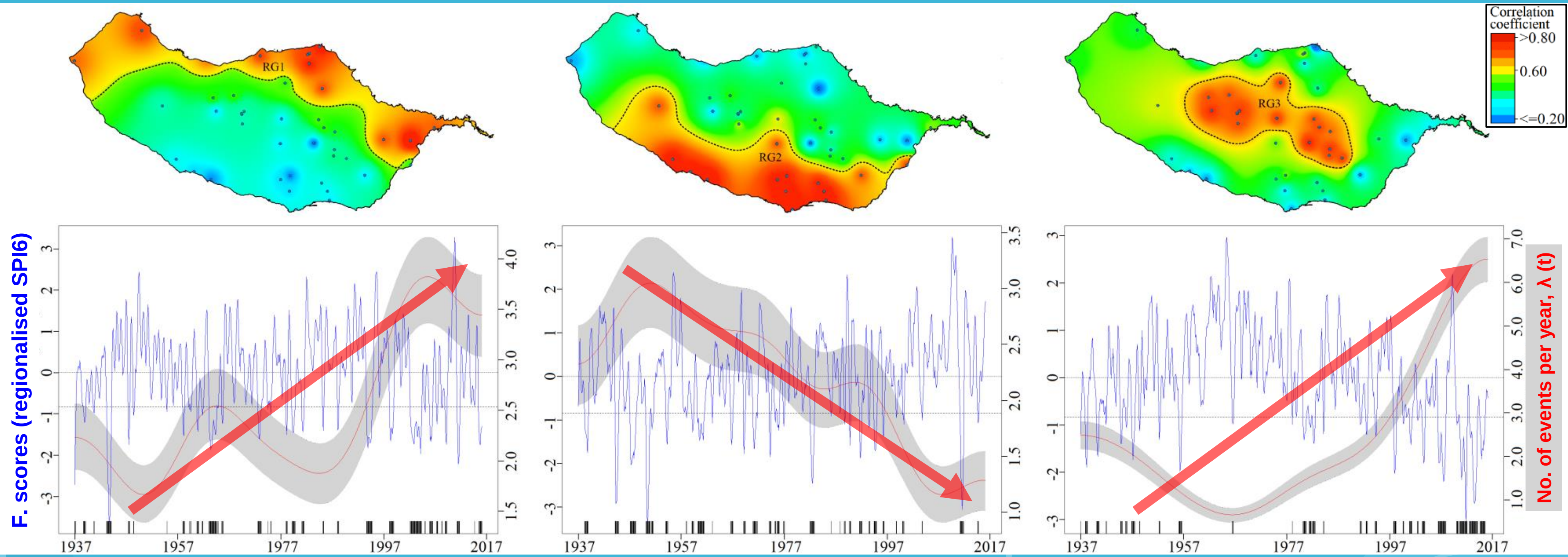
Standardized Precipitation Index (SPI) & drought



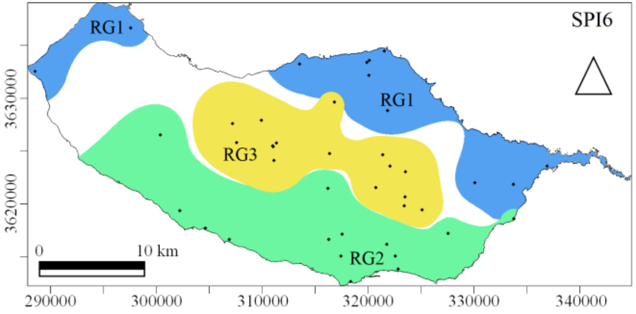
- SPI is the most commonly used indicator worldwide for detecting and characterising meteorological droughts
- For any given region, increasingly severe rainfall deficits are indicated as SPI decreases (negative SPI)
- E.g. 6-month SPI (SPI6) may be associated with anomalous streamflows and reservoir levels

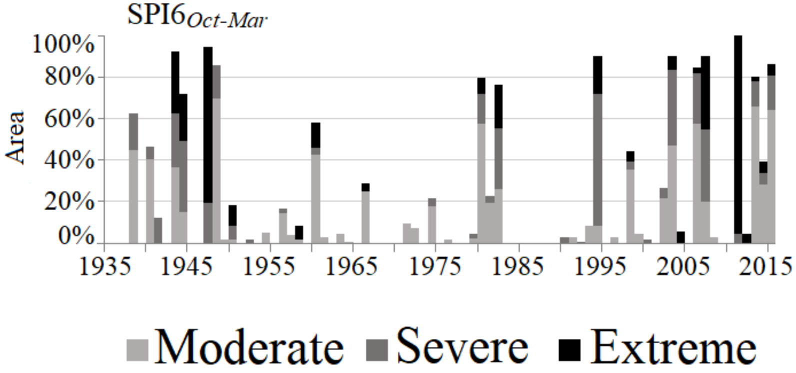
Time-dependent occurrence drought rates (KORE)

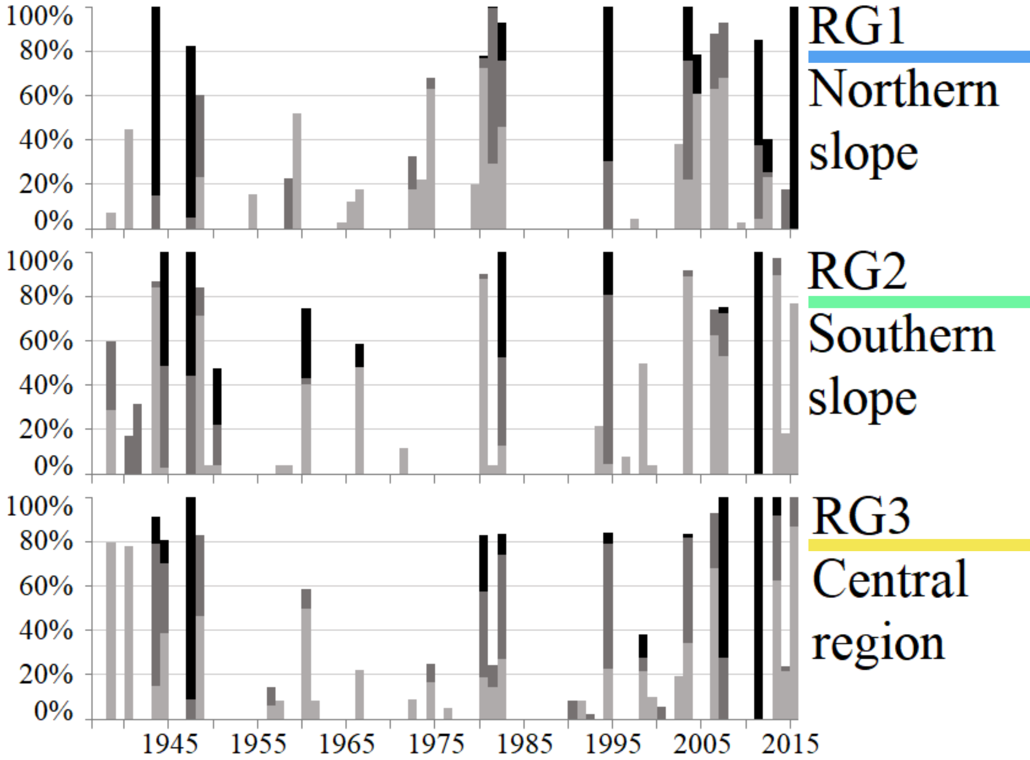
RG1 – Northern slope | RG2 – Southern slope | RG3 – Central region



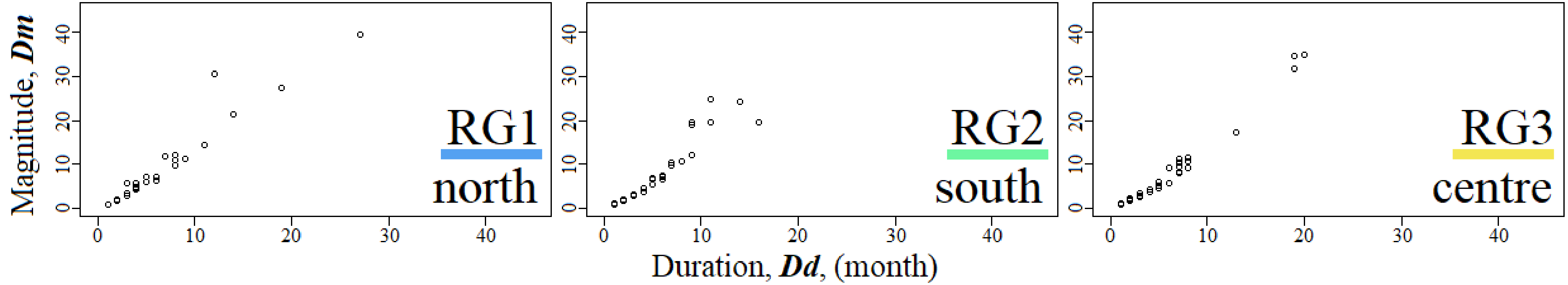
Affected regions by droughts (1937-2017)



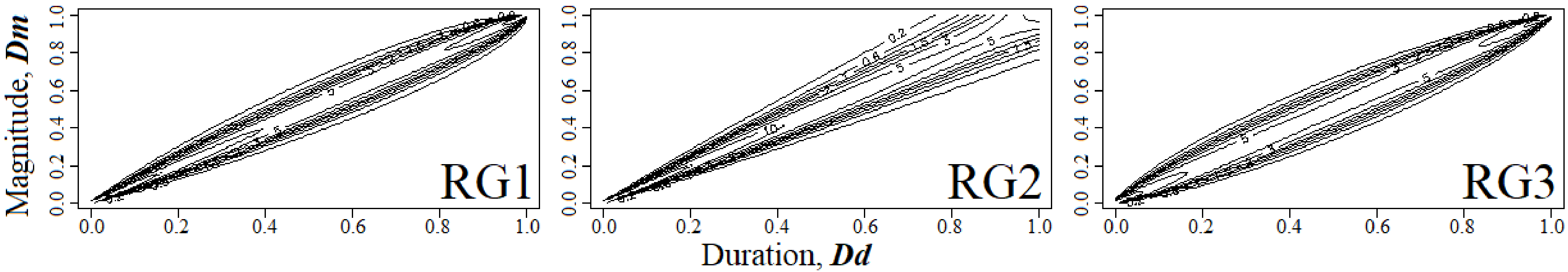




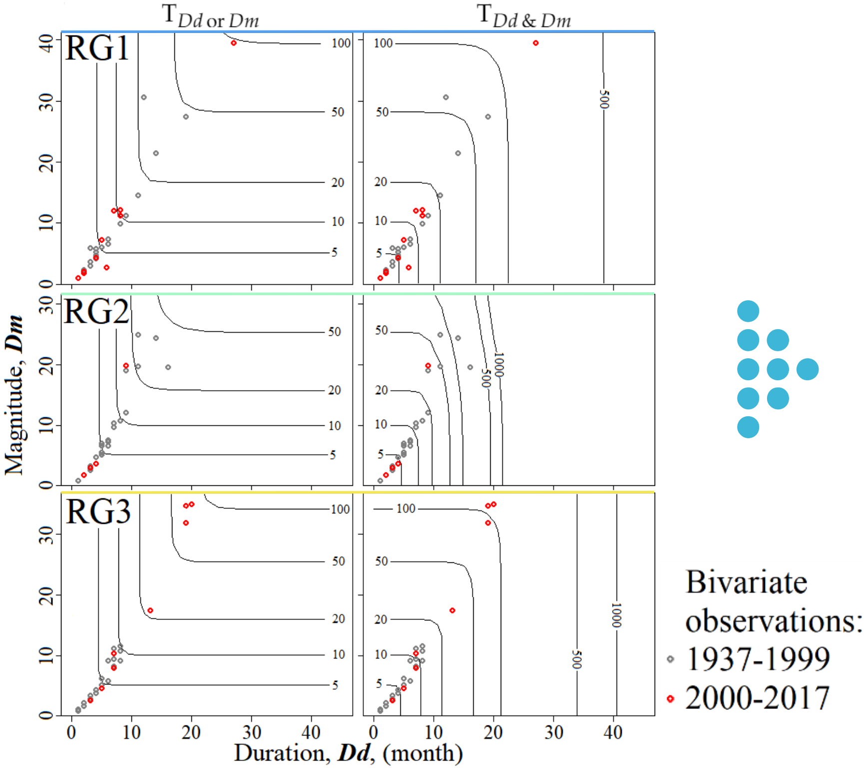
Drought duration, *Dd*, and magnitude, *Dm*, & copulas

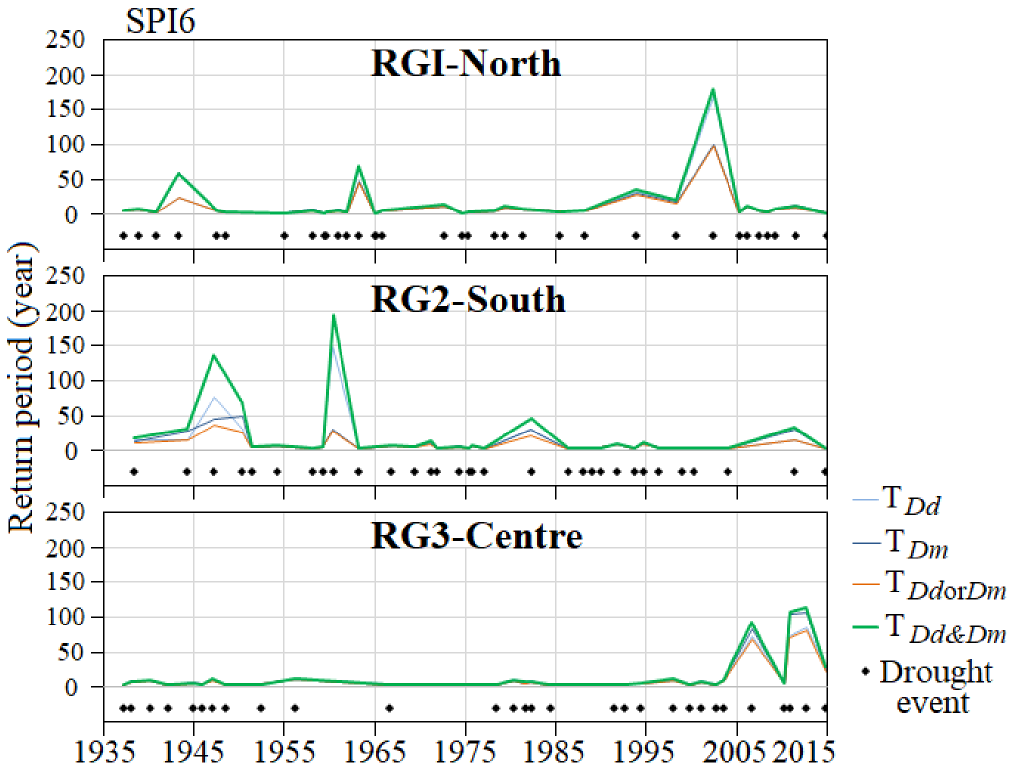


$$C(u_1, u_2) = F(F_1^{-1}(u_1), F_2^{-1}(u_2)) \Rightarrow (u_1, u_2) = \varphi^{[-1]}(\varphi(u_1) + \varphi(u_2))$$



Bivariate observations & return periods (1937-2017)





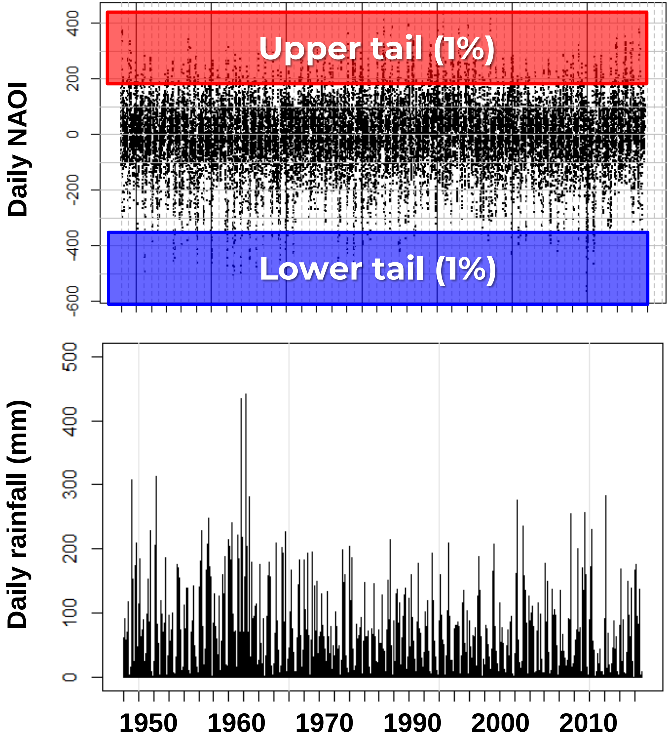
2.5
Analysis of extreme rainfall

"This suggests that previous negative NAO is the main trigger of the winter extreme daily rainfall, and that contains information regarding the antecedent atmospheric conditions in Madeira."

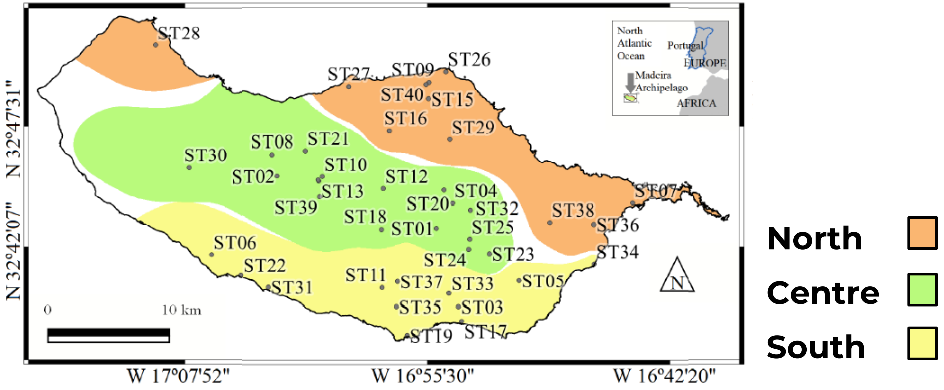
Espinosa, L.A., Portela, M.M., & Rodrigues, R. (2020b). Significant Extremal Dependence of a Daily North Atlantic Oscillation Index (NAOI) and Weighted Regionalised Rainfall in a Small Island Using the Extremogram. Water 2020, 12(11), 2989; https://doi.org/10.3390/w12112989

Espinosa, L.A., Portela, M. M., Pontes Filho, J. D., & Zelenakova, M. (2021). Bivariate Modelling of a Teleconnection Index and Extreme Rainfall in a Small North Atlantic Island. Climate, 9(5), 86 ; https://doi.org/10.3390/cli9050086

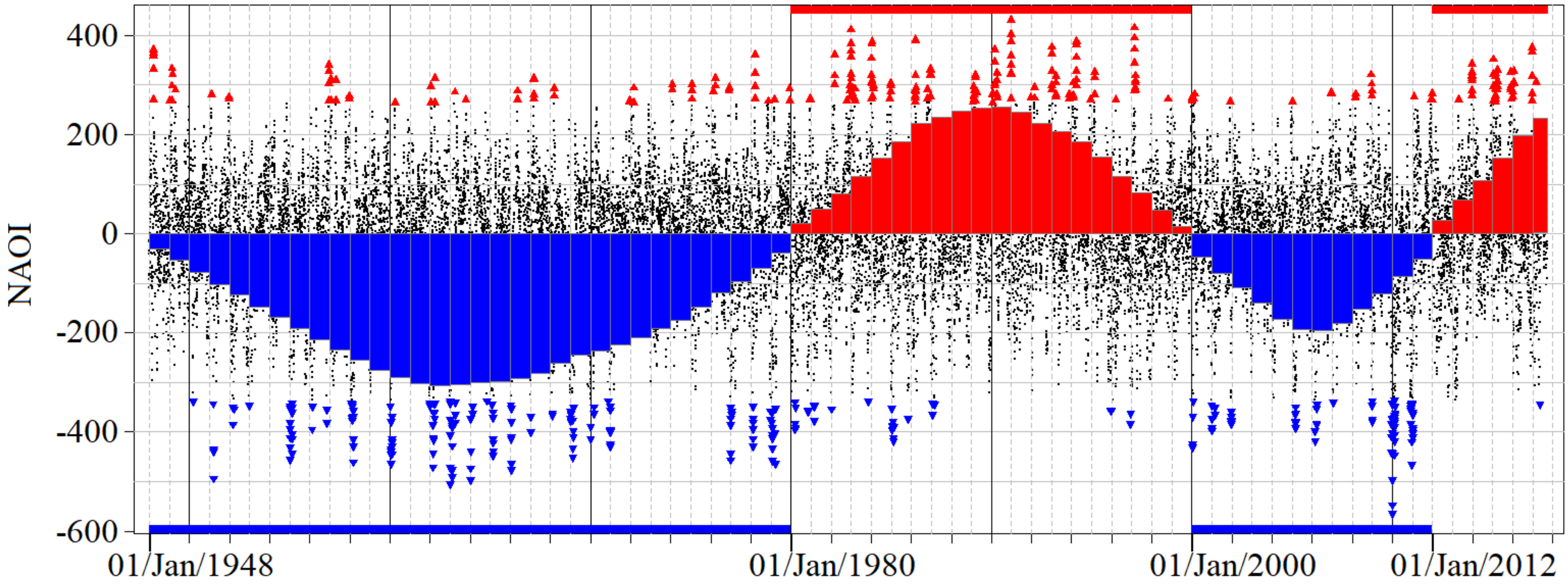
Extremal dependence of NAO and rainfall (1948-2017)



Upper tail of regionalised daily rainfalls (1%)

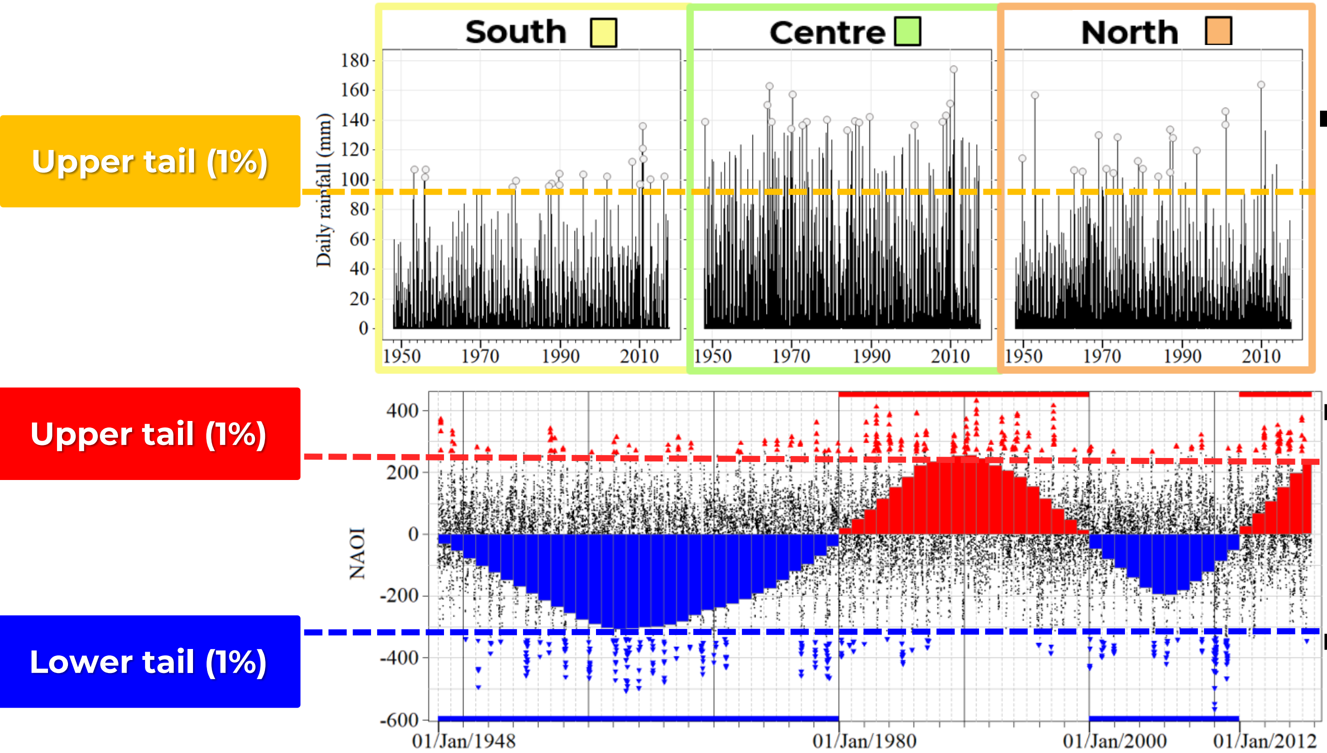


–Negative & +positive NAOI dominance periods*



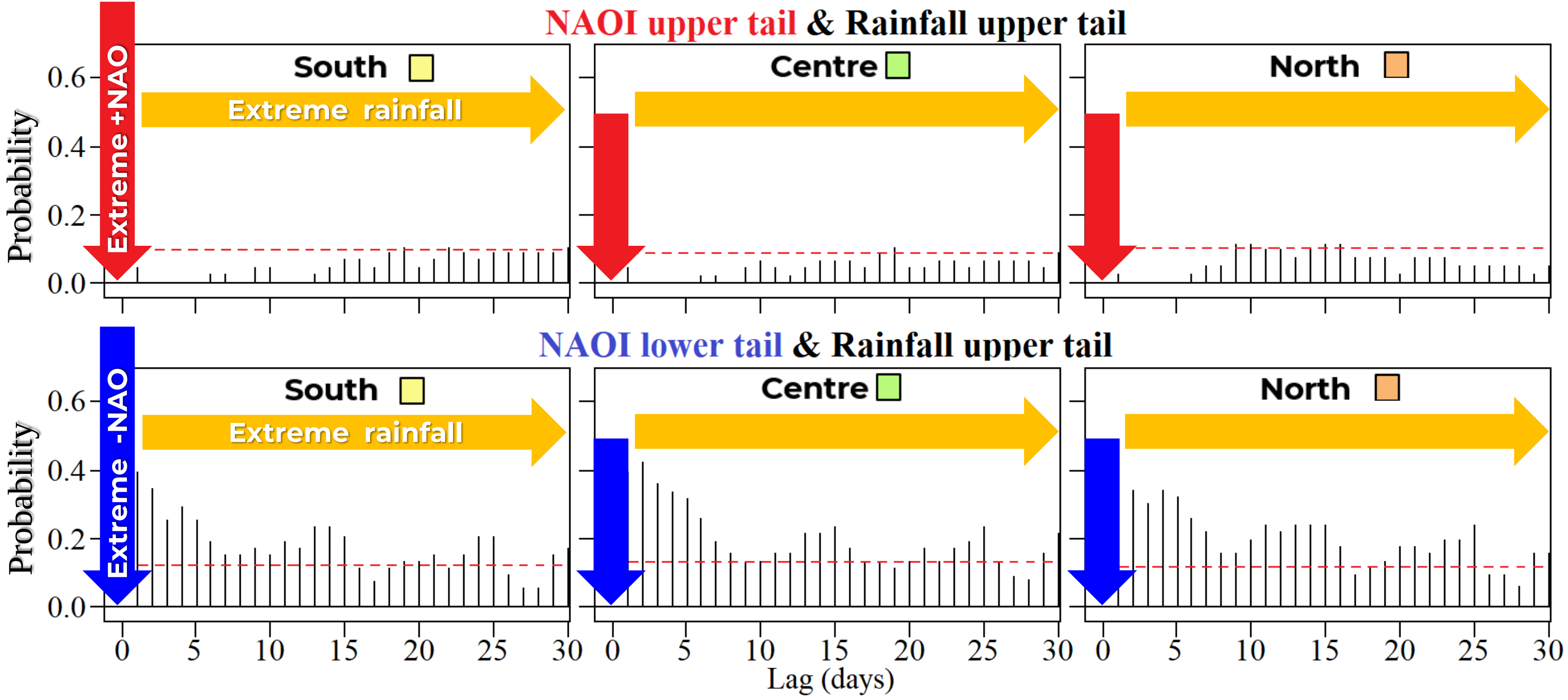
*The lower and upper tails' daily NAOI (blue and red triangles, respectively) fitted into a LOWESS curve (vertical blue/red bars).

The bivariate NAOI-extreme rainfall problem



$$\frac{\sum_{t=1}^{n-h} I_{\{a_m^{-1}Y_{t+h}\in B,\, a_m^{-1}X_t\in A\}}}{\sum_{t=1}^{n} I_{\{a_m^{-1}X_t\in A\}}}$$

Cross-extremograms of NAOI-rainfall



Extremal dependence links

+NAOI dominance has a weak effect on extreme rainfall events

-NAOI dominance has a strong effect on extreme rainfall with wetter conditions and higher extreme rainfall events

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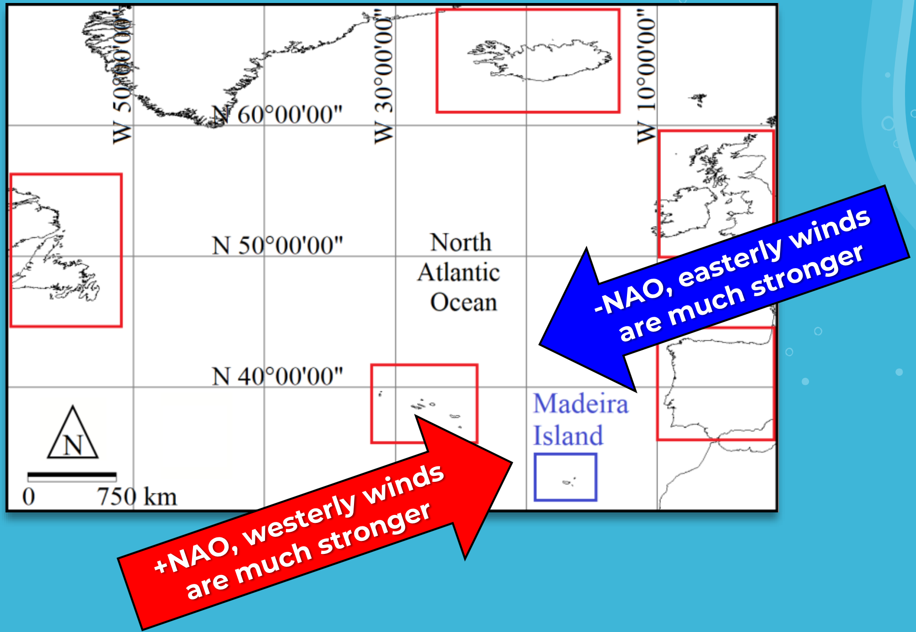
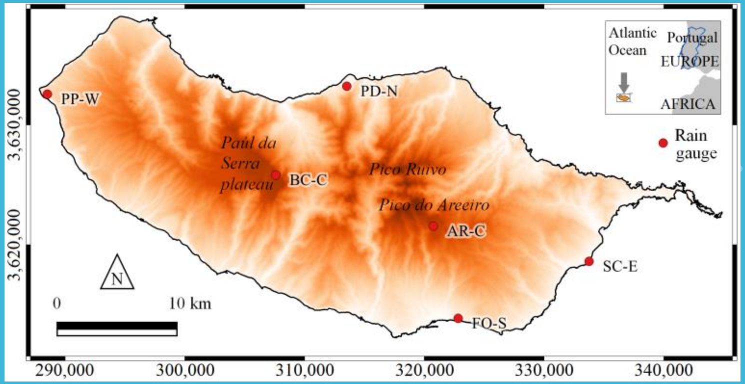


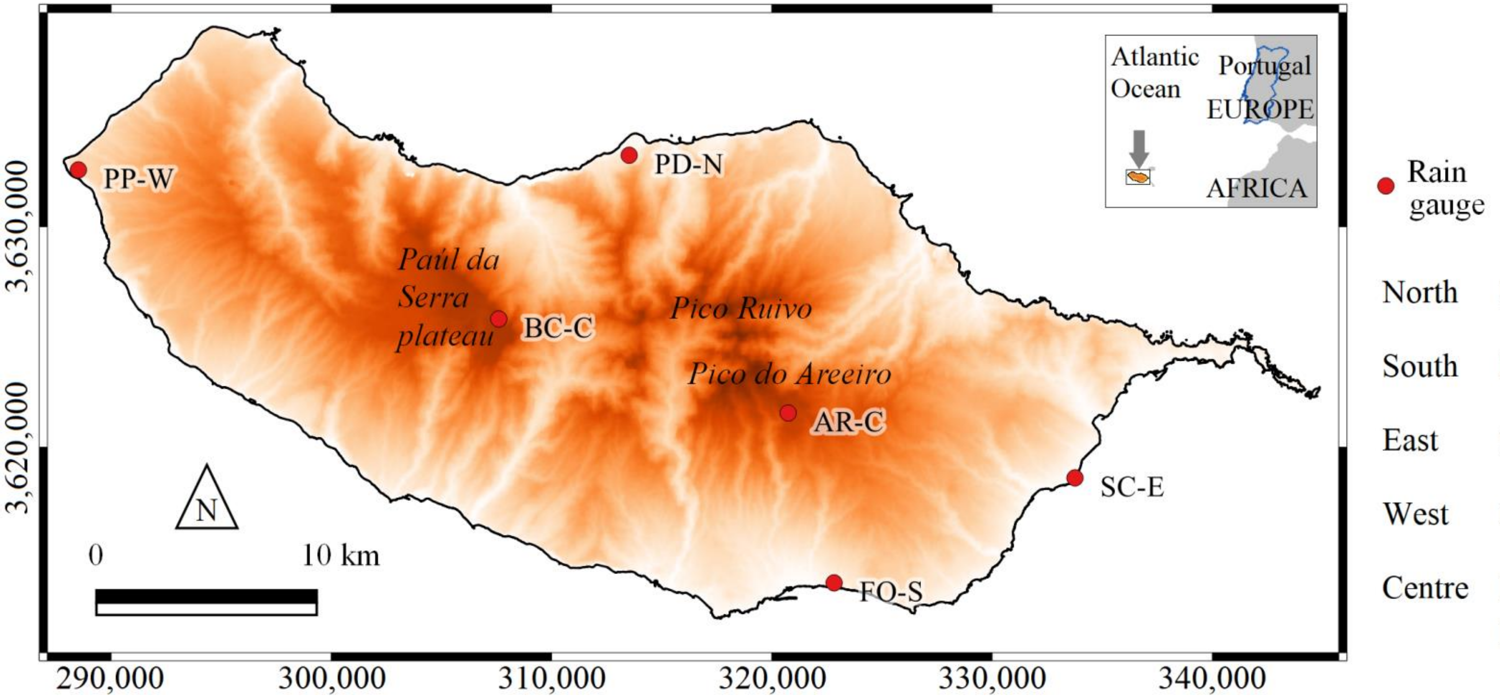
Connecting the dots...

The extremal dependence study (Espinosa et al., 2020b) focuses on short term climatic fluctuations in the NAO and claiming the existence of systematic evidence of statistical dependence over Madeira between exceptionally daily negative NAO and rainfall which is stronger in sustained −NAOI year long periods

Modelling the NAOI-extreme rainfall problem

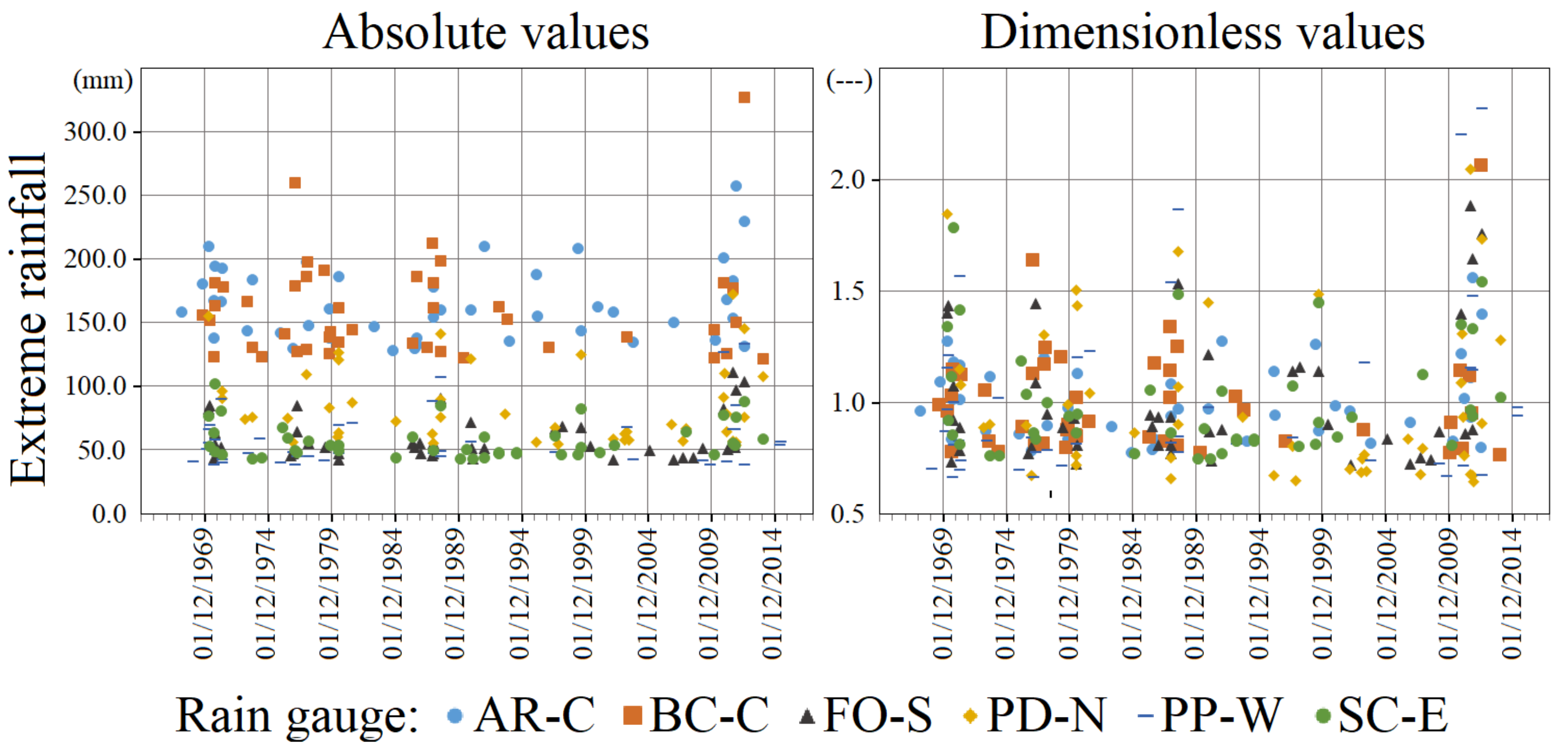


The winter (DJF) extreme daily rainfalls (1967-2017)

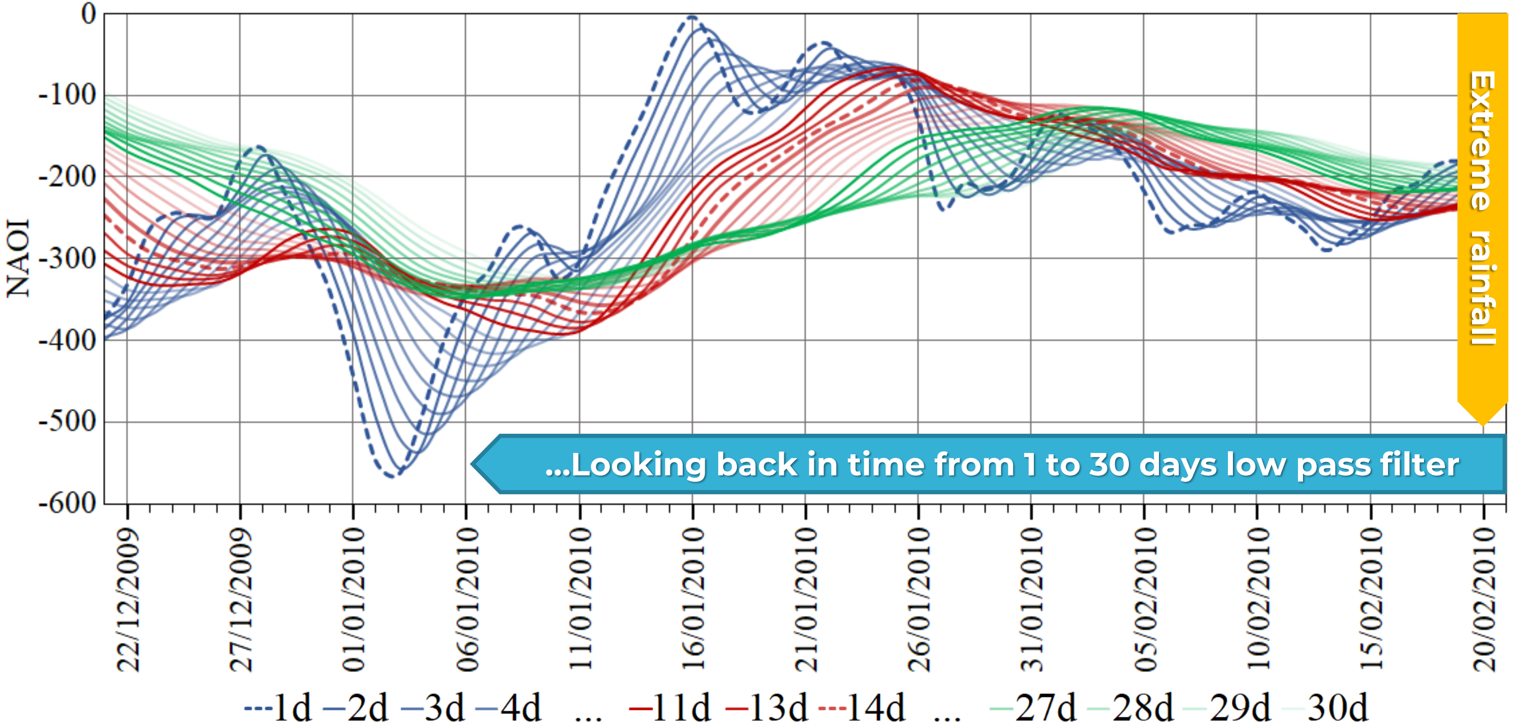


North	Ponta Delgada (PD-N)
South	Funchal Obervatório (FO-S)
East	Santa Catarina (SC-E)
West	Ponta do Pargo (PP-W)
Centre	Bica da Cana (BC-C)
	Pico do Areeiro (AR-C)

The winter (DJF) extreme daily rainfalls (1967-2017)



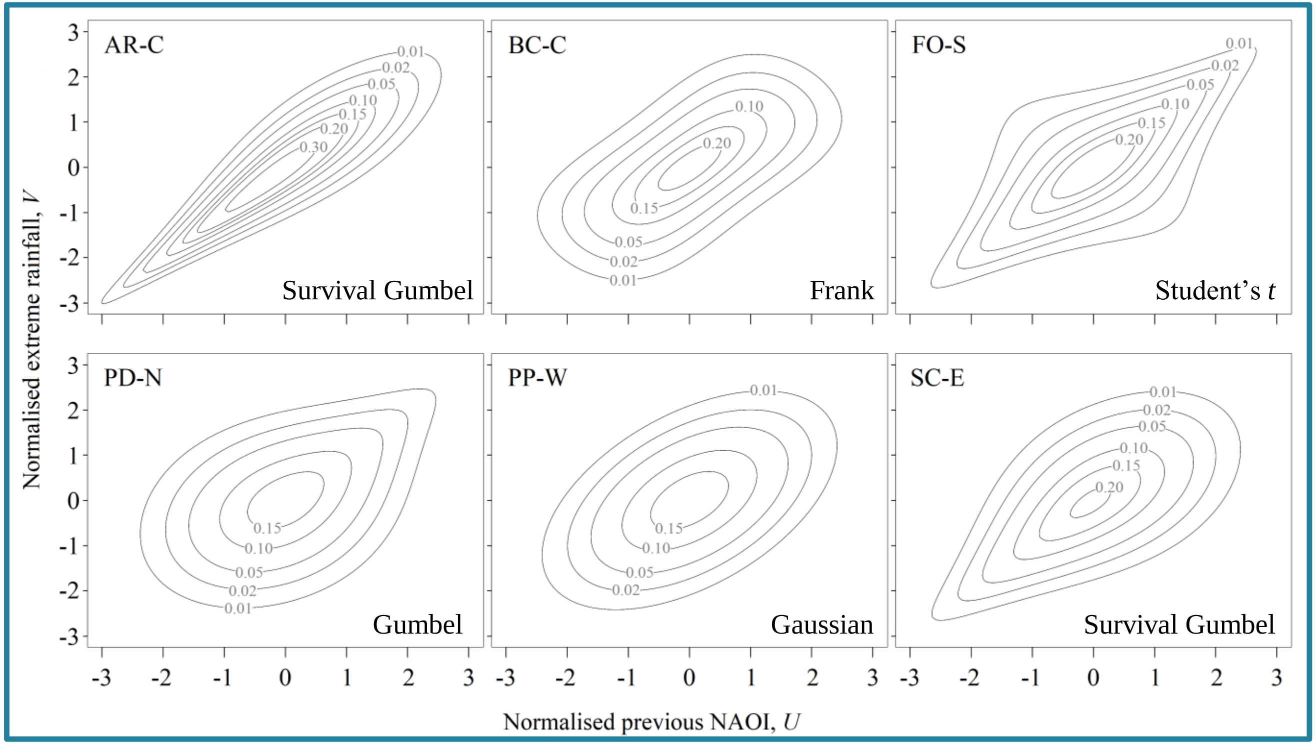
Example of the (non) filtered daily NAOI series prior to the 20 February 2010 flash floods/debris



Normalised contour plots of the bivariate copulas

Copula family	Mathematical formulation
Gaussian	$\phi_\rho(\phi^{-1}(u), \phi^{-1}(v))$
Student's t	$T_{\rho,v}(T_v^{-1}(u), T_v^{-1}(v))$
Clayton	$(u^{-\theta} + v^{-\theta} - 1)^{\frac{-1}{\theta}}$
Frank	$-\theta^{-1}\log\left[1 + \frac{(e^{\theta u}-1)(e^{\theta v}-1)}{(e^{\theta}-1)}\right]$
Gumbel	$\exp\{-[(-\ln u)^{-\theta} + (-\ln v)^{\theta}]^{\frac{1}{\theta}}\}$

North	Ponta Delgada (PD-N)
South	Funchal Obervatório (FO-S)
East	Santa Catarina (SC-E)
West	Ponta do Pargo (PP-W)
Centre	Bica da Cana (BC-C)
	Pico do Areeiro (AR-C)

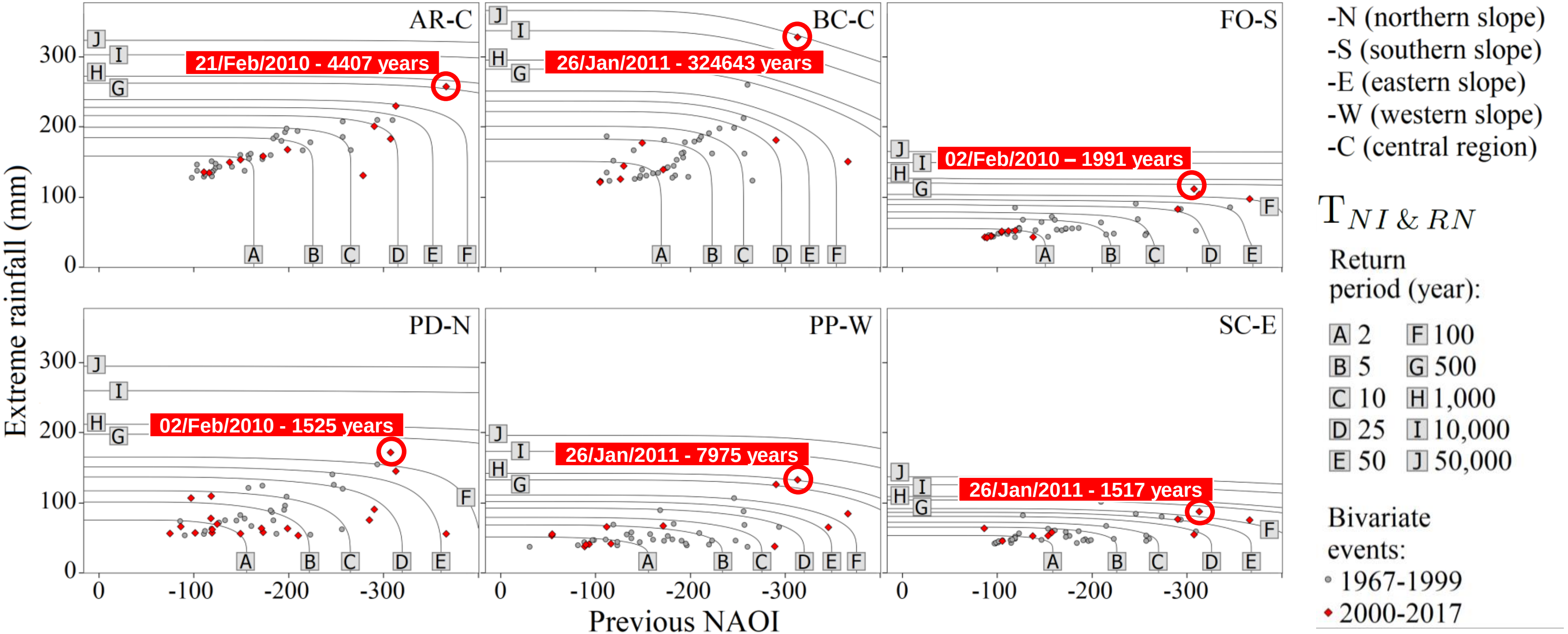


How "EXTREME" were the extremes?

With the hypothesis that the NAO can explain extreme rainfall, and assuming that the phenomenon has a multivariate nature, the return periods of the bivariate problem were computed as joint return periods using the constructed copulas ($\mathbf{C}$):

$$\mathrm{T}_{NI\,\&\,RN} = \frac{E(L)}{P(NI \geq ni, RN \geq rn)} = \frac{E(L)}{1 - F_{NI}(ni) - F_{RN}(rn) + \mathbf{C}(F_{NI}(ni), F_{RN}(rn))}$$

Joint return periods NAOI-Extreme rainfall (1967-2017)



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Major findings of the research

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Challenges and developments

1. The remarkable identified bivariate events of winter 2009/2010 and 2010/2011 (some of the most intense events ever recorded) further emphasise the challenges for climate variability assessment for the small island of Madeira.

2. It is essential to study variability of rainfall at shorter (longer) time scales along with atmospheric observations from a multivariate perspective.

This in turn may help to understand the atmospheric physics and the mechanisms that can shift the current hydrological conditions into extreme rainfalls or even droughts.

4
Summary

The coupling of the results from the research with other published studies over the past sixty years provides evidences that in Madeira Island:

(1) seasonal and annual rainfall has shown a gradual decrease since the late 1960's with the uncertainty regarding to whether rainfall will continue to decrease or it will counterbalance the already experienced rainfall deficits;

(2) the variability of seasonal and annual rainfall is highly correlated with the large scale atmospheric circulation pattern of NAO;

(3) droughts in the island have become worse (higher magnitude and longer duration in recent years); and that

(4) extreme rainfall is clearly intensified by the persistent changes in the NAO mainly during negative NAO phases (recently more recurrent and "extreme")

5
Further developments

Different aspects related to both the effects of climate change and abrupt climate variability on droughts and rainfall have been comprehensively addressed. However, some of those aspects can be studied from other perspectives. Also, new aspects and challenges could be raised for the small island environments, in general, and for Madeira Island, specifically. Further research could include:

- assignment of uncertainties to the detected trends;
- evaluation of uncertainties of the return periods of the analysed hydrological extremes;
- attribution research of extreme rainfall events i.e., signal identification of the human influence in general indicators of climate change (e.g. increasing global mean temperature); and
- improved downscaling of Global Circulation Model outputs aiming at a refinement, or even at a gap-filling, of ground-based rainfall data at shorter time-scales (e.g. daily, hourly)

Changes in Hydrological Extremes:

Advances in climate-induced extremes, focusing on a small North Atlantic island

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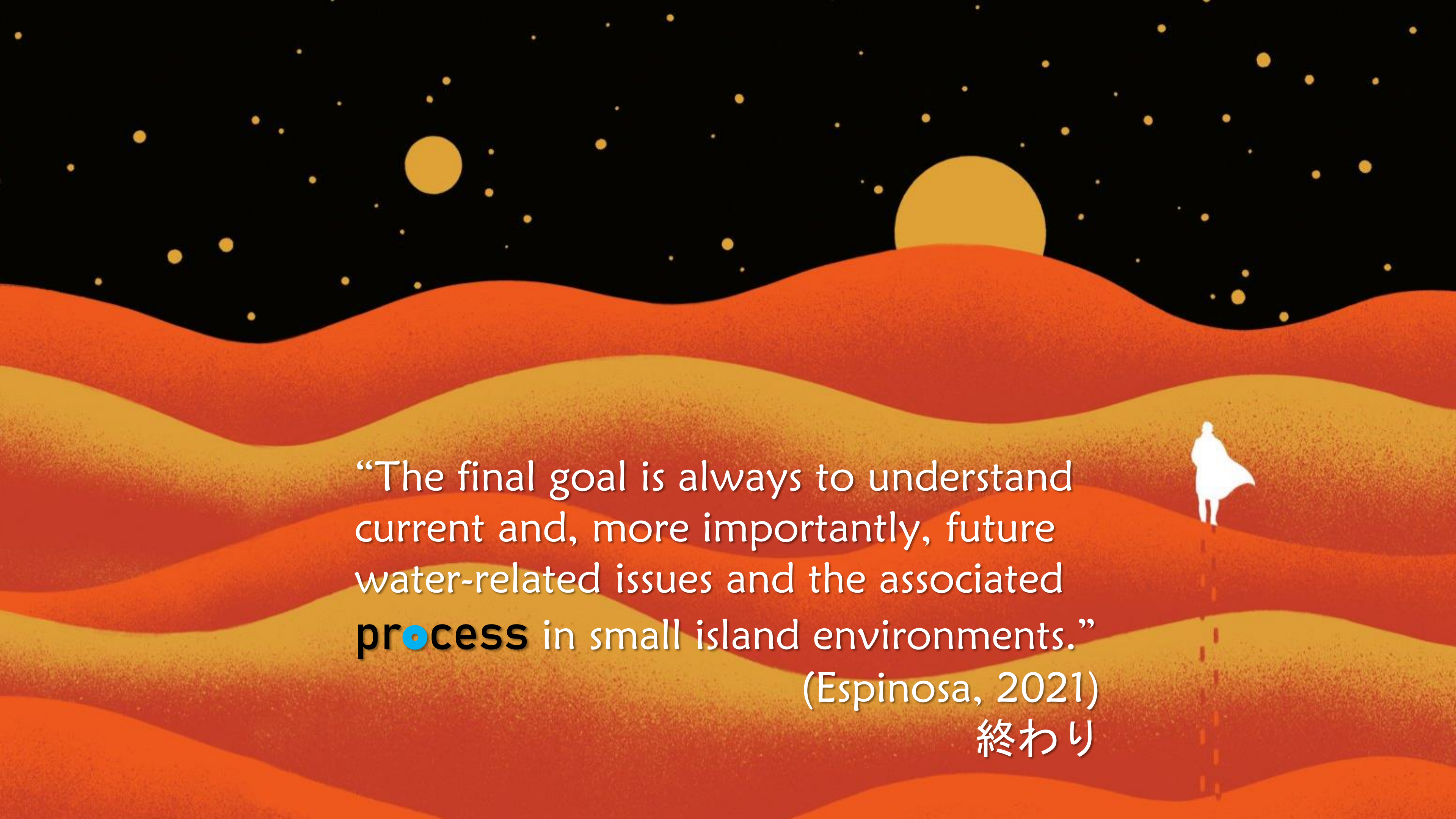
3rd February 2022

swarm TÉCNICO LISBOA


"The final goal is always to understand current and, more importantly, future water-related issues and the associated process in small island environments."
(Espinosa, 2021)
終わり