Observational constraints on extremes for estimating the warmest events by the end of the century (and) the IPSL/RTE collaboration framework

Freddy Bouchet - CNRS and ENS (LMD et IPSL)

Within: accord cadre RTE/IPSL for the resilience of the electric system and with:

a) **Yoann Robin and Laurent Dubus (bayesian approach for future extreme statistics)**
b) **Francesco Ragone, Jeroen Wouters (rare event simulations for extreme heat waves)**
Bastien Cozian and Corentin Herbert (extremes of renewable energy production)

Colloque « Adaptation des systèmes énergétiques au changement climatique »
September 2024

SIMONS FOUNDATION

GDR Défis théoriques pour les sciences du climat (theoretical challenges for climate sciences)

- **Identify and work on key theoretical issues that need to be solved for improving the quantitative predictions in climate sciences.**

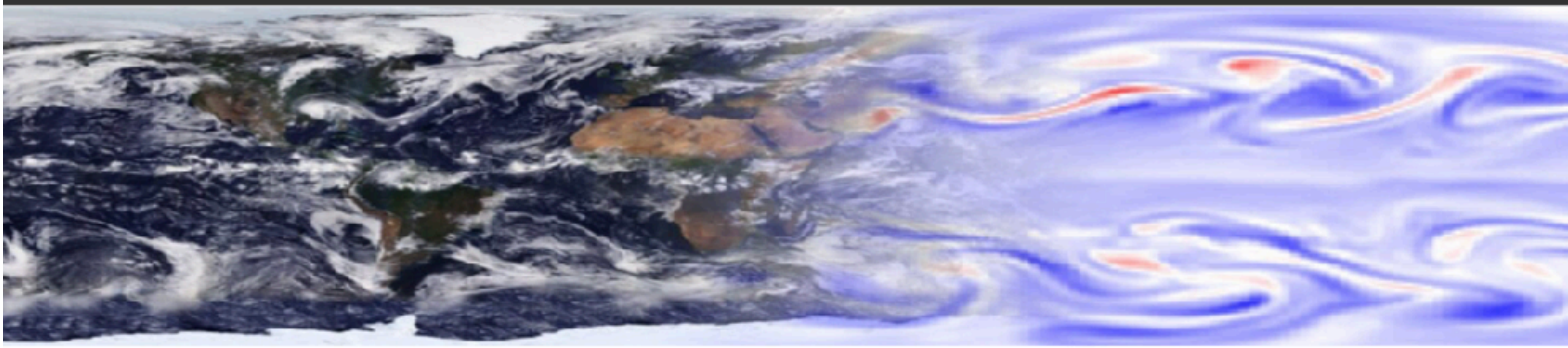
- **A multidisciplinary consortium: climate sciences, mathematics, physics, computer sciences, statistical physics, data sciences.**

- **Examples :** i) How to reduce the uncertainty about climate sensitivity? ii) How to reduce uncertainty when quantifying probabilities of climate extreme events? iii) How to integrate data and theoretical constraints, using machine learning, to build the next generation of climate models? iv) How to make quantitative the study of future and past climate? v) How to build effective coarse-grained descriptions of climate processes?

https://defi-theo-climat.ipsl.fr/

https://defi-theo-climat.ipsl.fr/

cnrs GDR Groupement de recherche **Defis theoriques pour les sciences du climat**



Bienvenue sur le site du GDR Défis théoriques pour les sciences du climat

Le GDR Défis théoriques pour les sciences du climat regroupe la communauté des théoriciens : physiciens, climatologues, océanographes, atmosphériciens, mathématiciens, informaticiens, sciences numériques, machine learning (apprentissage automatique), qui travaillent sur les sciences du climat. Le but du GDR est de développer des outils théoriques et numériques novateurs pour dépasser les limites scientifiques actuelles. Les approches de physique statistique, modélisation de la turbulence, mathématiques, d'apprentissage automatique, permettront d'approfondir la compréhension des mécanismes fondamentaux, améliorer les modèles, et mieux prédire les événements extrêmes pour réduire les incertitudes sur les impacts du changement climatique. Ce GDR a une vocation fortement interdisciplinaire et implique les chercheurs de plusieurs instituts du CNRS, de nombreux autres organismes français et d'entreprises.

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theoretical challenge

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STRUCTURE ▼ APPELS À PROJET ▼ ANIMATION ▼ RESSOURCES

Accord cadre entre l'IPSL et RTE pour l'étude de la résilience du système électrique face au changement climatique (2023-2028)

Coordonné par Freddy Bouchet (LMD/IPSL) et Laurent Dubus (RTE).

Environ 15 chercheurs de RTE et de l'IPSL joignent leurs efforts et partagent leurs compétence pour développer la science permettant l'étude de la résilience du système électrique.

Objectifs :

1. **Production de données climatiques directement actionnables** par RTE pour l'utilisation de ses différents outils de prospective et d'estimation des impacts.

2. Simulation d'événements extrêmes critiques pour le système électrique et impact du réchauffement climatique (impact sur les infrastructures existantes et futures, étude de l'équilibre offre-demande).

3. Analyse de l'interaction entre système électrique, surfaces continentales et climat régional (lien hydrologie/système électrique/utilisation des sols).

IPSL Climate Services and Expertise

L'expertise scientifique de l'IPSL au service des projets d'adaptation aux changements climatiques

Catégories de projets

- Energie
- Agriculture et écosystèmes
- Eau
- Santé
- Assurances - Finance
- Médias - Collectivités - États
- Développements méthodologiques
- Copernicus (projets européens)
- Transfert d'expertise
- Littoral et océans

Projets sur l'énergie

Observational constraints on extremes for estimating the warmest events by the end of the century

Outline

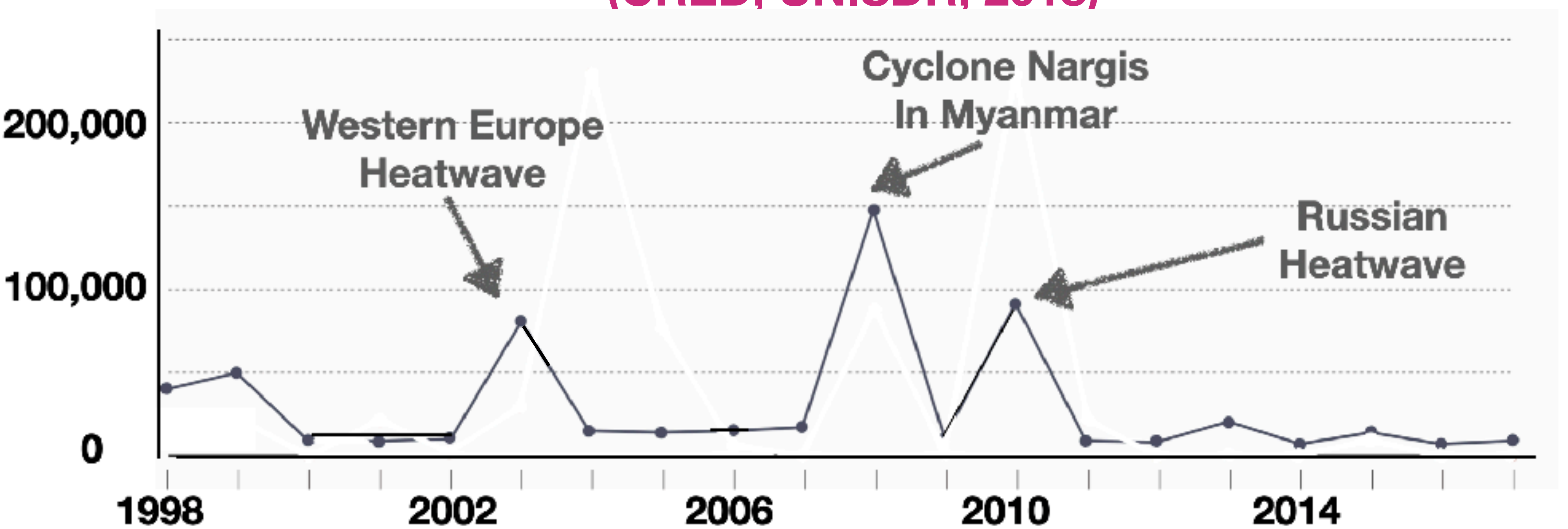
I) Introduction to rare events and new methodologies

II) Estimating future probabilities of extreme events using observations and Bayesian generalized extreme value theory

III) Rare event simulations for extremes of residual loads on the electric system

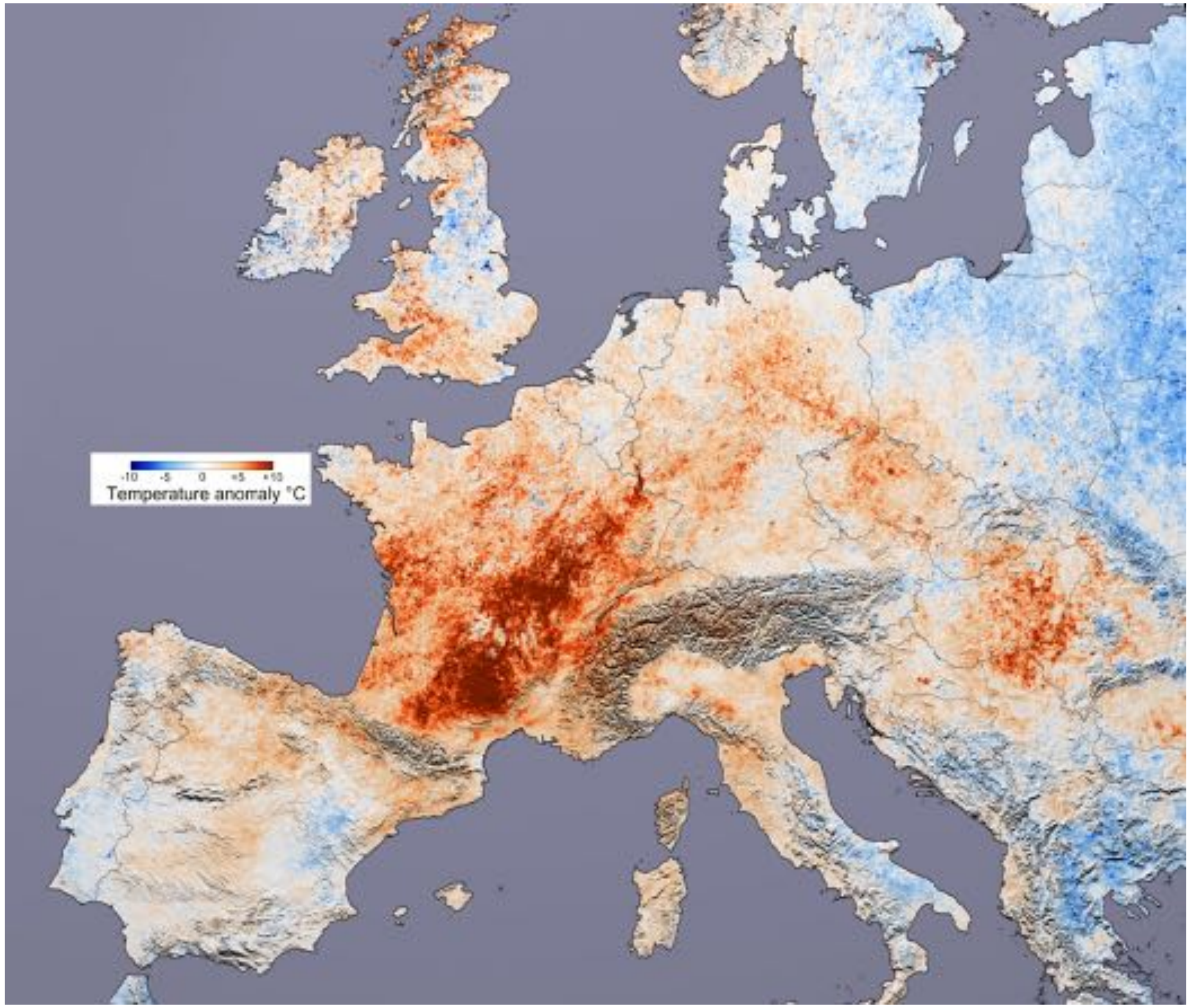
The few most extreme climate events have more impact than all the others

Annual deaths by major climate related disaster
(CRED, UNISDR, 2018)



We need to study extremely rare events. This is a serious scientific challenge.

What is the probability (return time) of the 2003 Europe heatwave?



July 20 2003-August 20 2003 land surface temperature minus the average for the same period for years 2001, 2002 and 2004 (TERRA MODIS).

Why are return times so hard to estimate?

i) lack of observation data, ii) model biases,

iii) because of rareness, gathering good model statistics is too costly.

Three key problems in the study of climate extreme events

- The historical records are way too short to make any meaningful predictions for the rarest and unprecedented events (those that matter the most).

- Climate models are wonderful tools, but they have biases. The more precise they are, the more computationally costly.

- Because they are too rare, the most extreme events cannot be computed using direct numerical simulations (the needed computing times are often unfeasible).

The practical questions: How to sample the probability and dynamics of rare events in complex models? How to build effective models which are relevant for estimating the probability of rare events?

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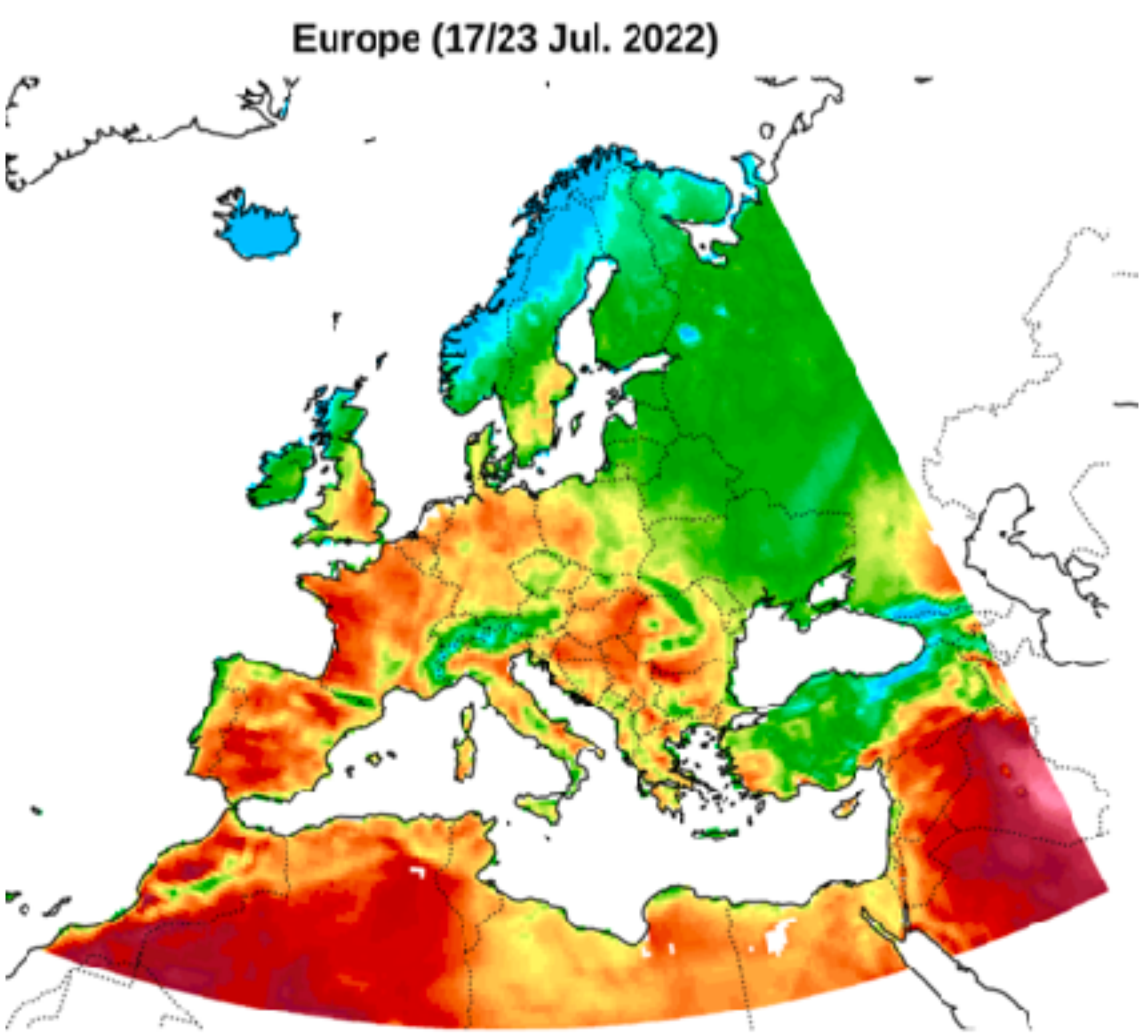
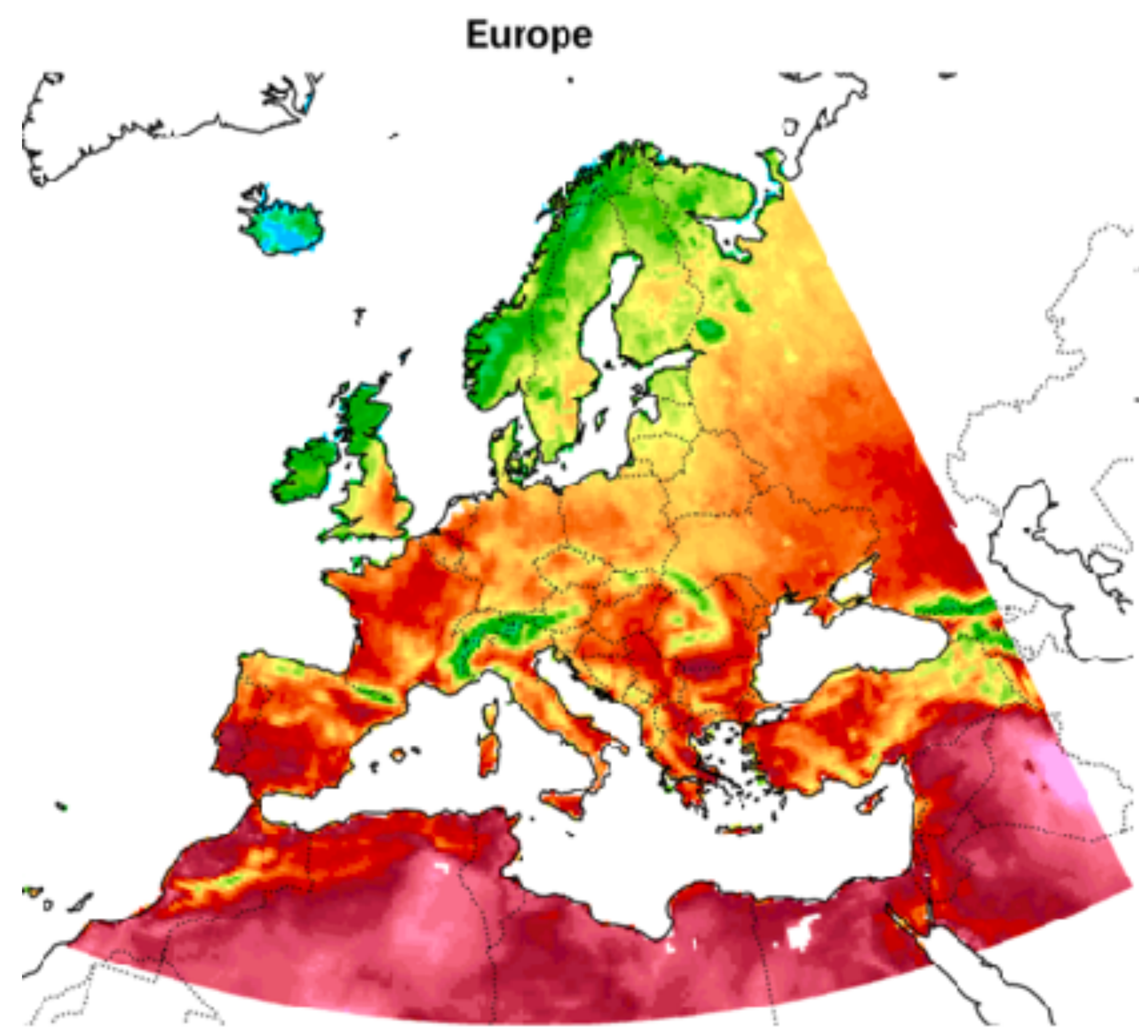
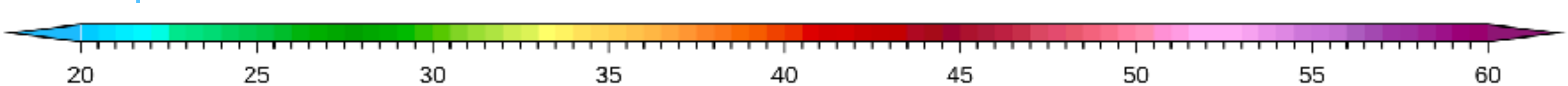
What is the maximum possible temperature ?



Temperature for 2022 heatwave



Maximum observed temperature



How to answer this question ? In current and future climate ?

How to deal with the lack of data issue ?

- **We want to use :**

1. All available observation data
2. The best available climate model outputs, for instance CMIP experiments.

- **The difficulty is to combine present and future datasets, and observation and model datasets, in the best possible coherent mathematical framework.** For this we use :

3. Generalized extreme value theory
4. Bayesian approaches to combine model prediction for the future and past observation data.

Generalized Extreme Value theory

GEV[1]

Hypothesis: yearly maximal temperature follows the Generalized Extreme Value distribution (GEV)

$$\mathbb{P}_t^*(T_t \leq \mathbf{I}) := \exp\left[-\left(1 + \xi_t \frac{\mathbf{I} - \mu_t}{\sigma_t}\right)^{-1/\xi_t}\right]$$

$$\mathcal{Q}_t^*(p) := \mu_t + \frac{\sigma_t}{\xi_t}\left((-\log(p))^{-\xi_t} - 1\right)$$

- Generalized extreme value theory proposed a natural distribution for yearly extrema.
- **Question: how to fit the 3 parameters μ_t, σ_t, and ξ_t using past data ?**

Methodology for a Bayesian fit of future extreme statistics from pas data

- We determine a slow driver X_t (European average temperature) and estimate its evolution with climate change and natural variability.

- We use a parametric model for μ_t, σ_t, and ξ_t as a function of X_t

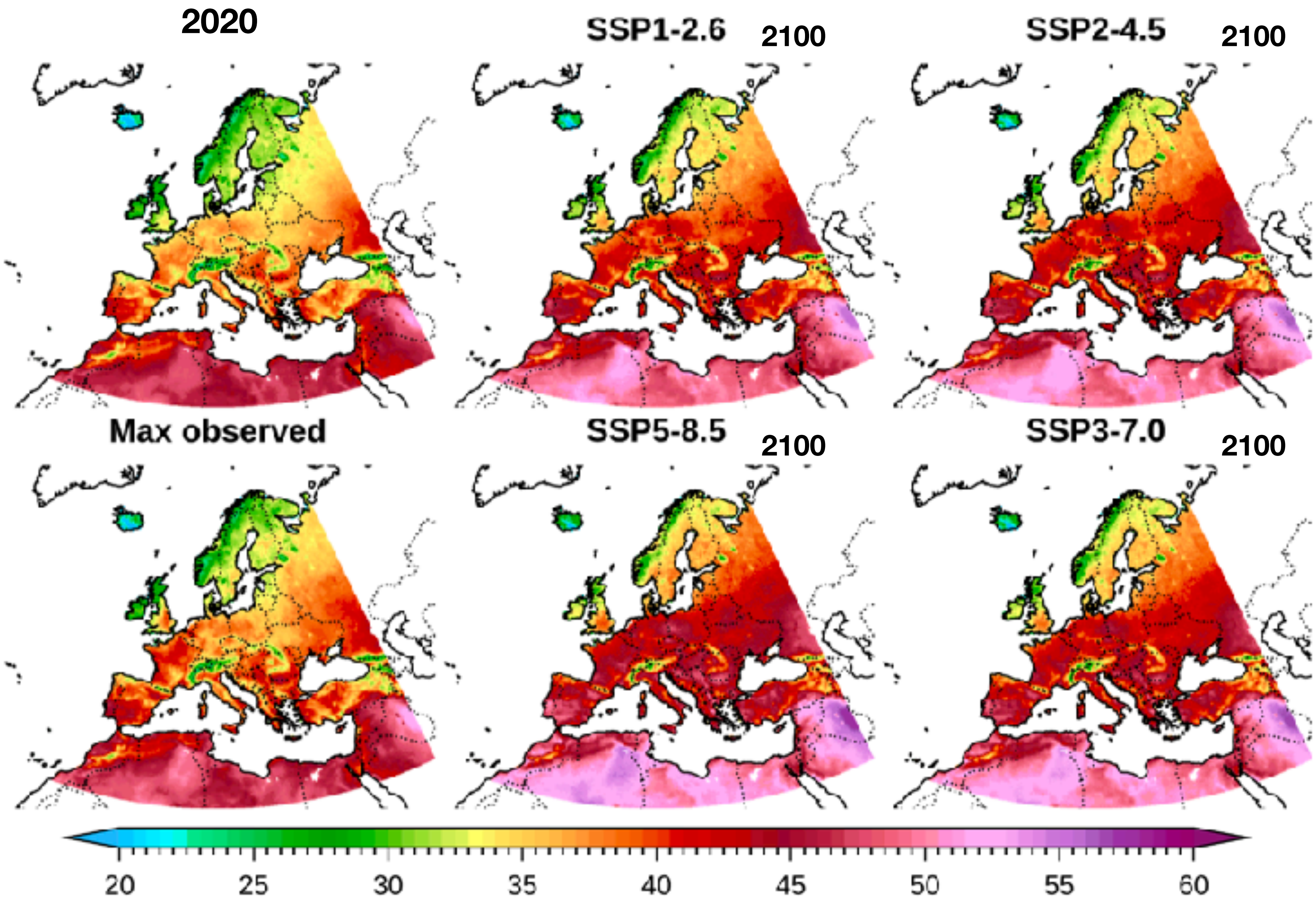
- We determine an a-priori distribution of all parameters using the best available model data with different climate change scenario.

- With a Bayesian approach we use past data to determine an a-posteriori distribution of all parameters.

(Robin and Ribes, 2020)

Result : the best possible probabilistic estimation for future extreme statistics using real data

Maximum possible temperature for different emission scenarios



Maximum possible extreme daily temperature (ensemble median), by 2100

(Figure: Y. Robin)

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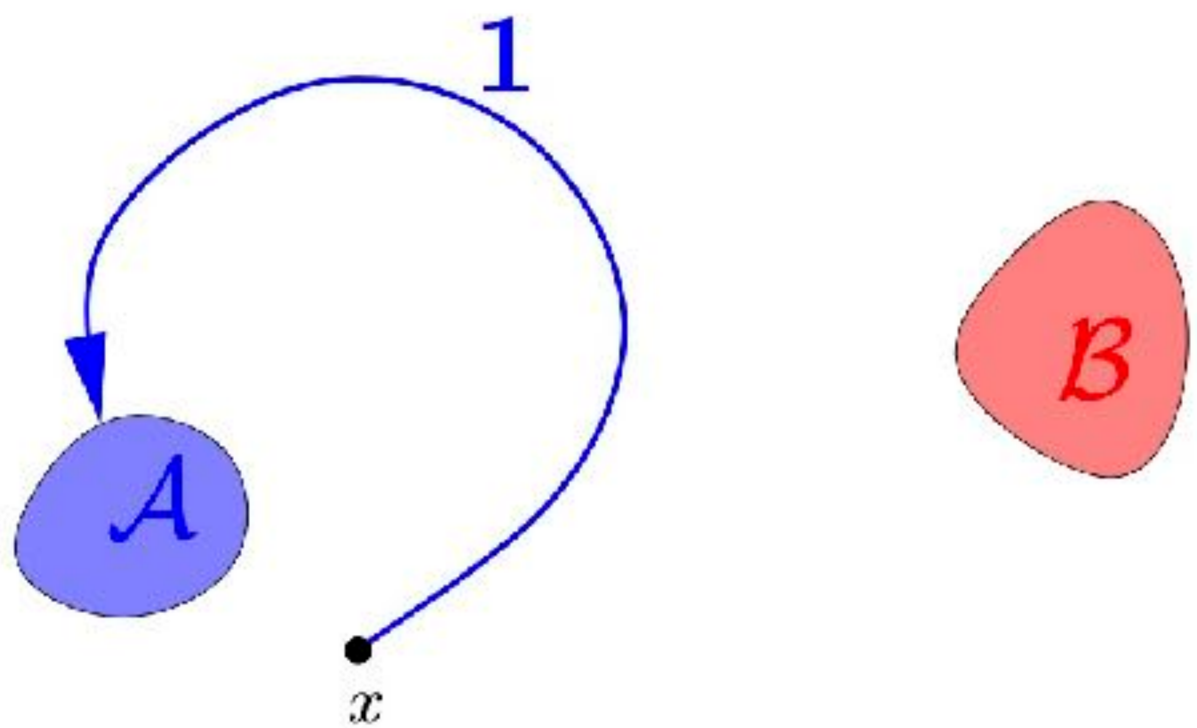
How to study a 10,000 year heat wave with a 200 year simulation ?

- **Because they are too rare, extreme events cannot be computed using direct numerical simulations** (the needed computing times are often unfeasible).
- **Rare event simulations:** Kahn and Harris (1953).
- **Statistical mechanics:** diffusion Monte-Carlo, Wang Landau algorithms, go with the winners, etc.
- **Applied Mathematics:** Chandler, Vanden-Eijnden, Schütte, Del Moral, Dupuis, Lelièvre, Guyader, etc.
- **Rare event simulations and large deviation theory:** the Giardina-Kurchan-Tailleur-Lecomte algorithm
- **For turbulence and climate applications:** J. Weare and D. Abbot, R. Grauer and T. Grafke, E. Vanden-Eijnden, the ENS de Lyon and ENS-LMD group , etc.

How to compute extremely rare trajectories ?

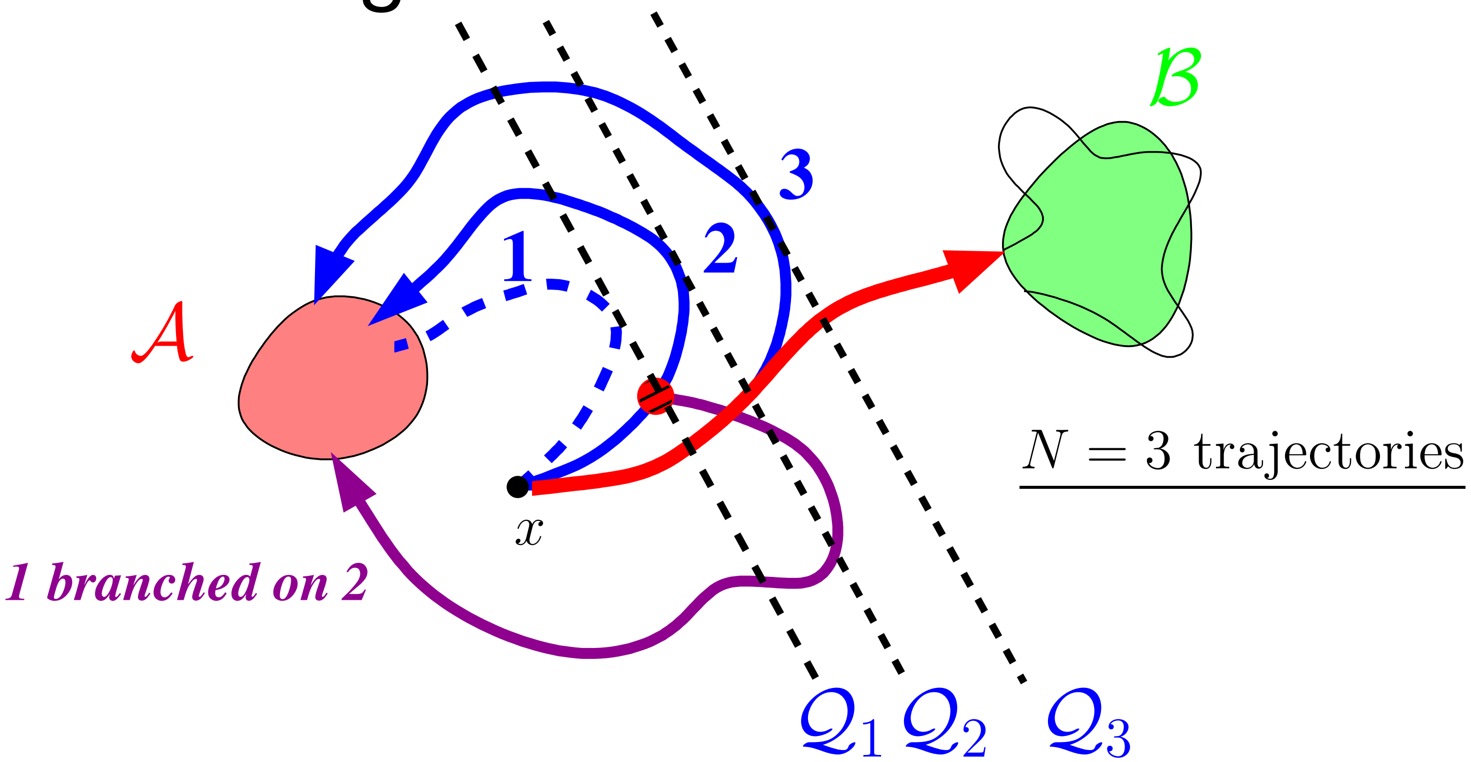


Aim: compute **extremely rare trajectories** from the point x to the rare event set $\mathscr{B}$.

Most of the times, trajectories that start from x end in $\mathscr{A}$.
The probability to reach $\mathscr{B}$ may be 10^{-3} or 10^{-20}.

The Adaptive Multilevel Splitting (AMS) rare event algorithm

Strategy: **ensemble computation,** selection, pruning and cloning.



Probability estimate:

$\hat{p} = (1 - 1/N)^K,$

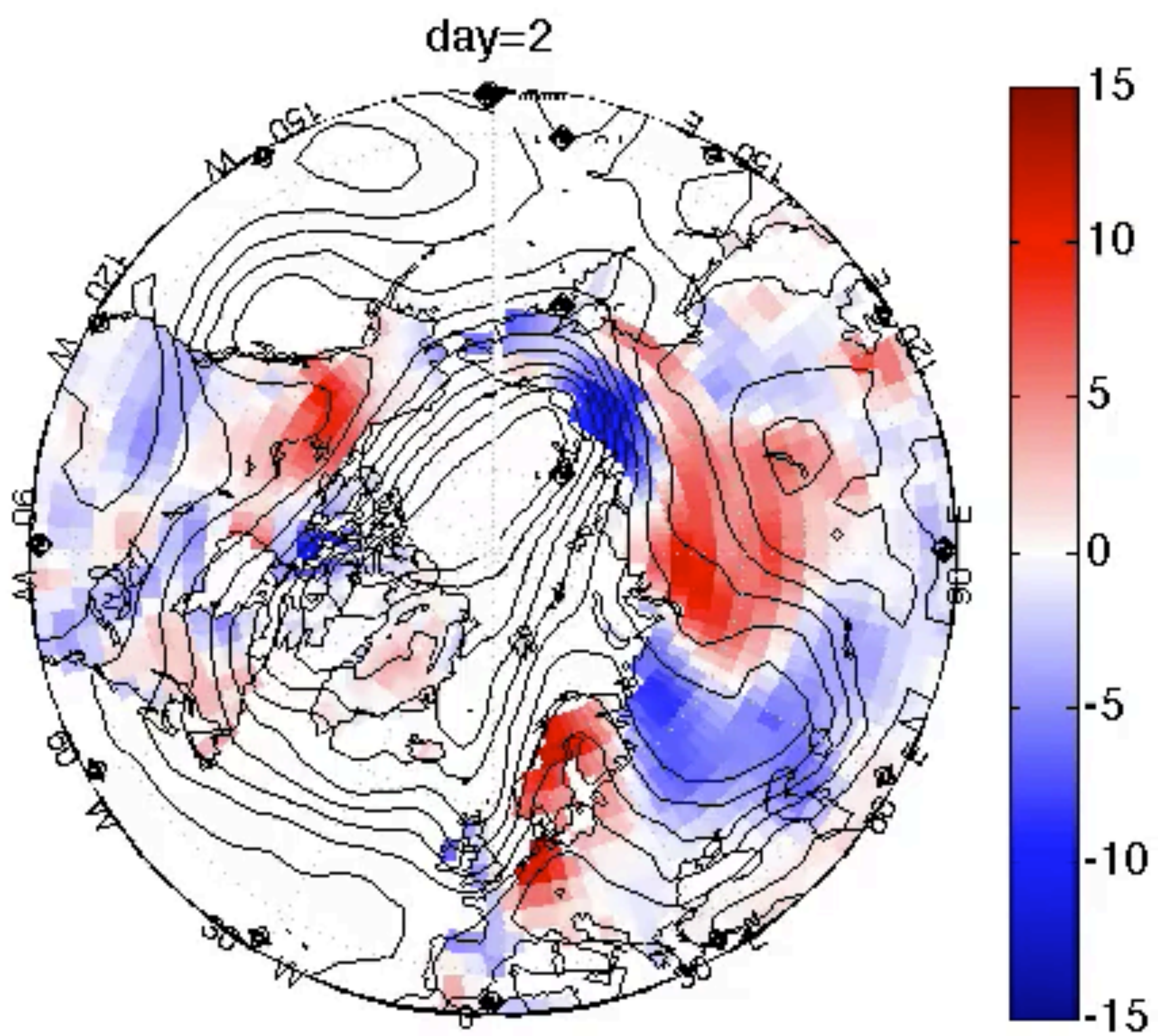
where N is the clone number and K is the iteration number.

Cérou, Guyader (2007). Cérou, Guyader, Lelièvre, and Pommier (2011).
PDEs: Rolland, Bouchet et Simonnet (2016) - **TAMS:** Lestang et al (2018)
Atmosphere turbulent jets: Rolland, Bouchet et Simonnet (2019 and 2021).

Jet stream dynamics

Higher troposphere wind speed. (NASA/Goddard Space Flight Center Scientific Visualization Studio, MERRA reanalysis dataset)

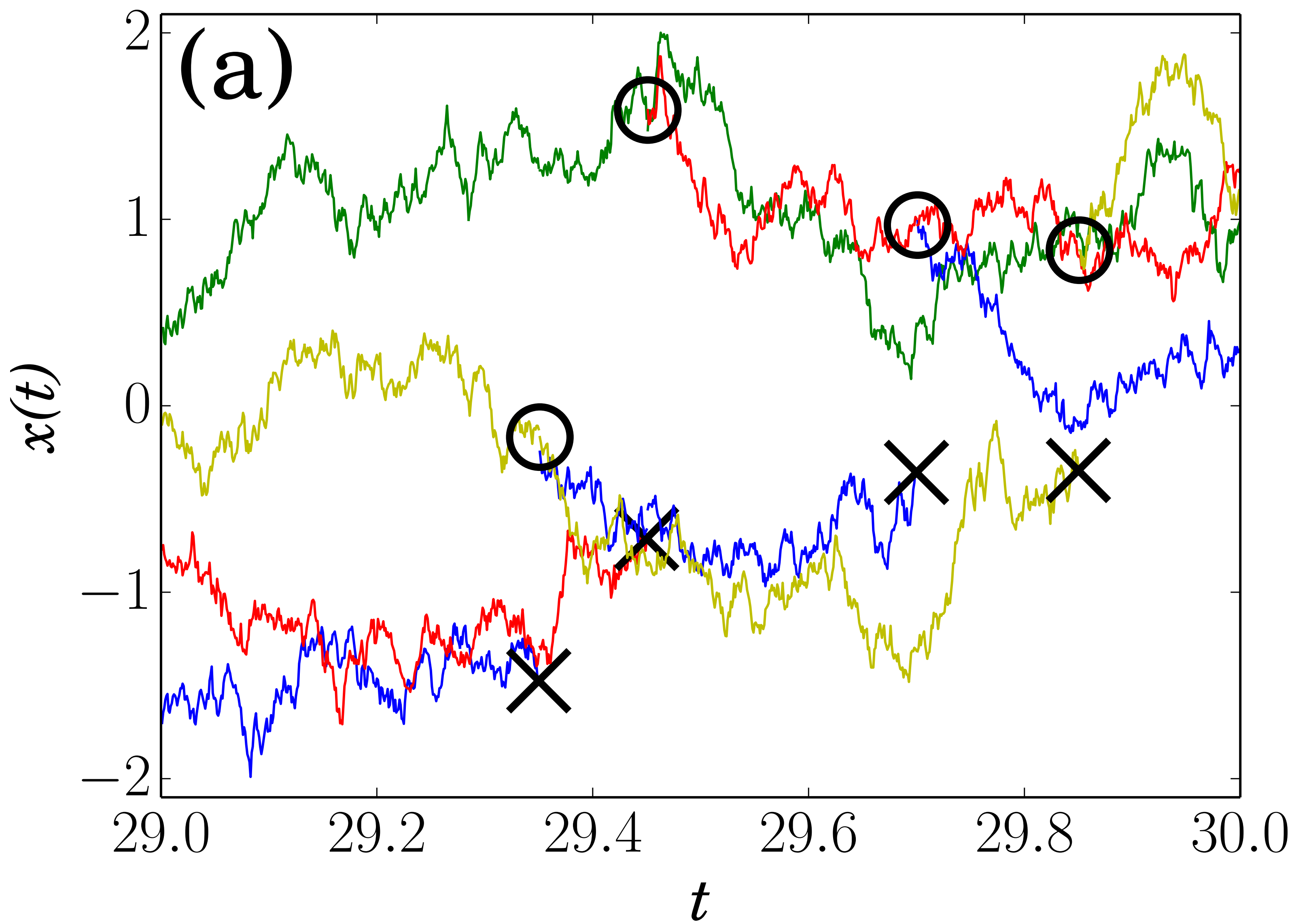
General Circulation Model



Surface temperature (T_s, colors) and 500 hPa geopotential height (Z_g, lines) anomalies

- **Plasim and CESM climate models.**
- **Global.** Coupled atmosphere/land/ocean/vegetation.

Genealogical algorithm: selecting, killing and cloning trajectories

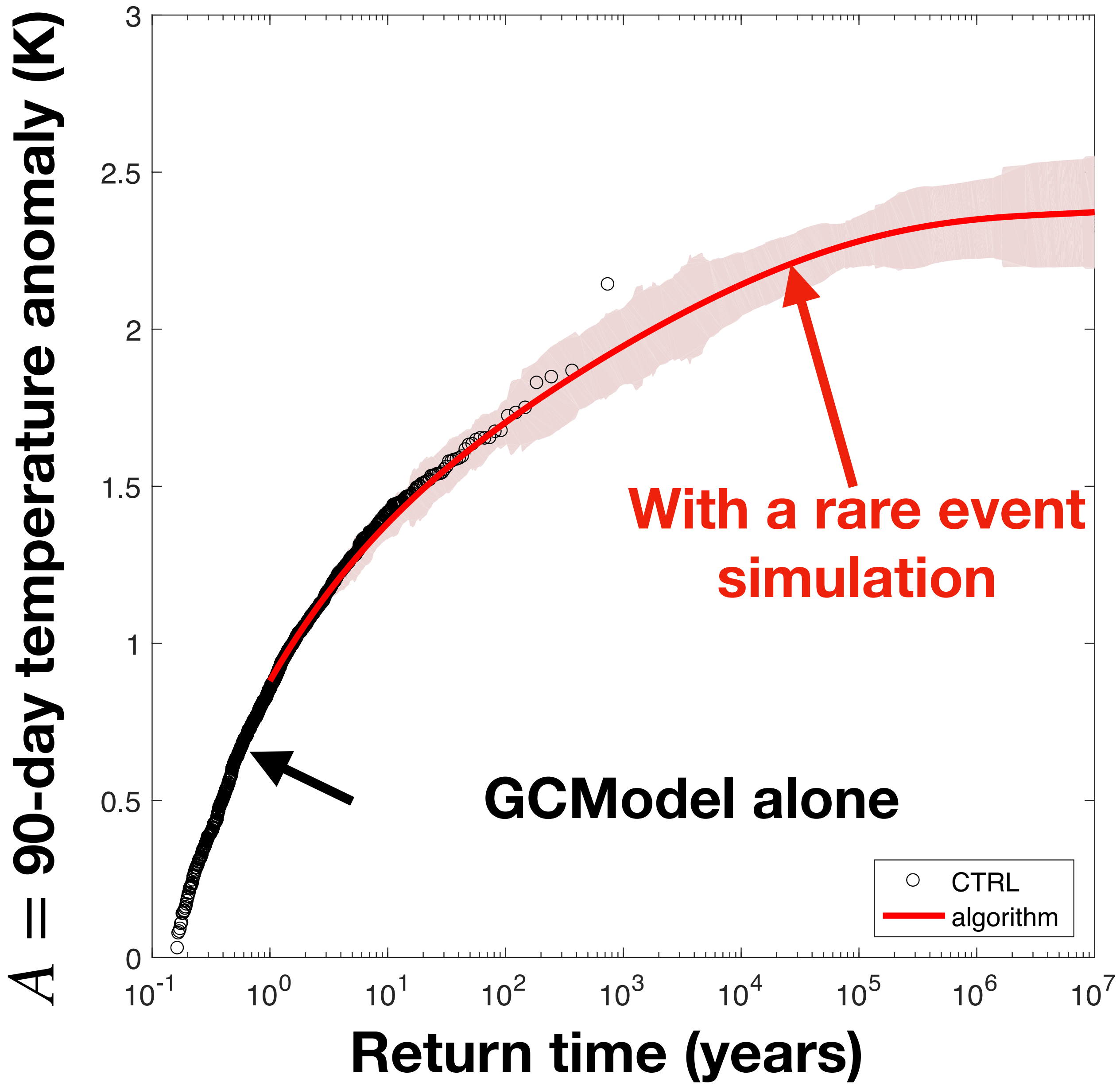


The trajectory statistics is tilted towards the events of interest.

Sample paths of the Giardina Kurchan algorithm

(from Bouchet, Jack, Lecomte, Nemoto, 2016)

Return time plot computed using a rare event simulation (PlaSim)



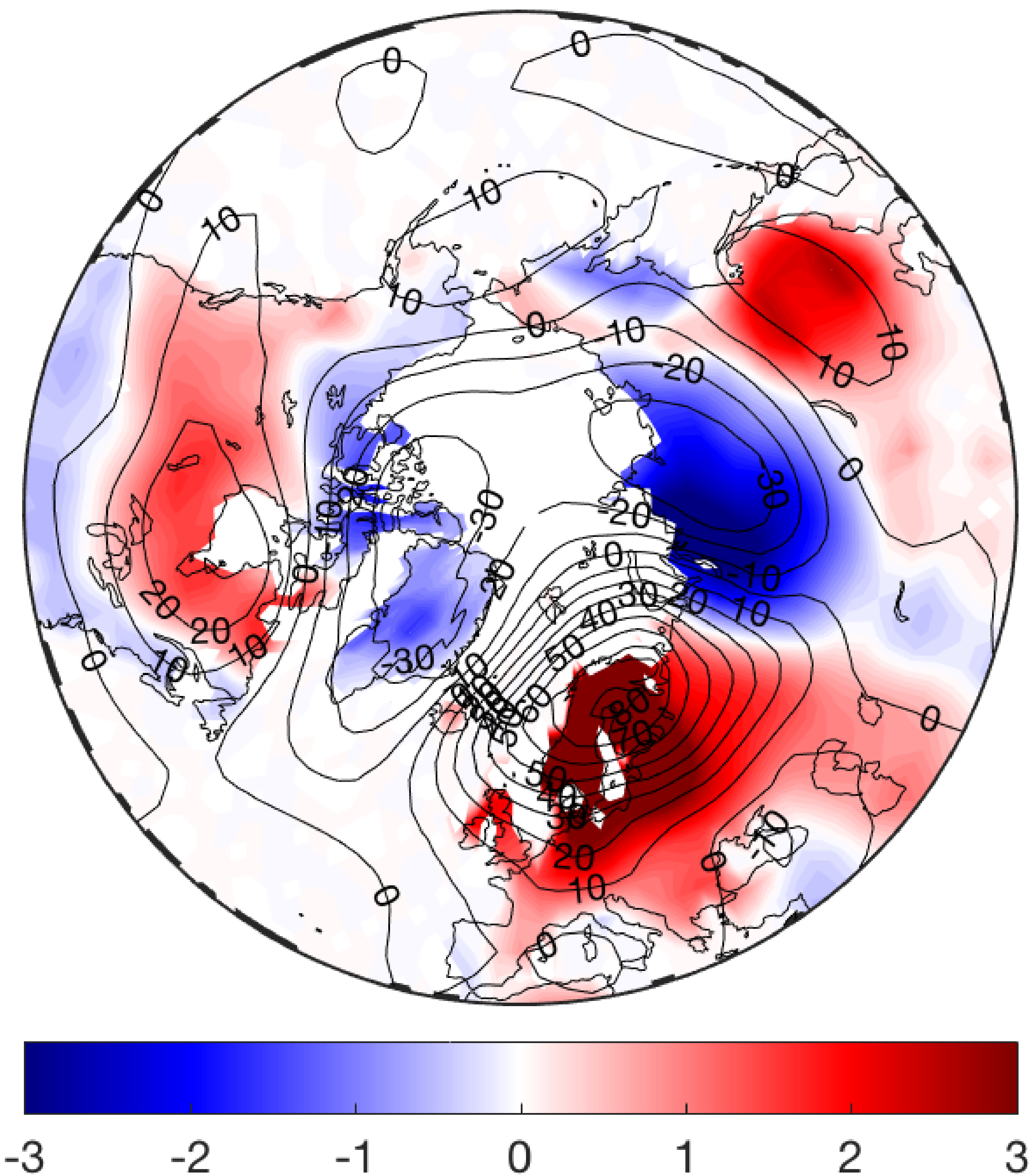
Extremes of 90-day Europe heatwaves

PlaSim model.
No seasonal cycle.
Del-Moral—Garnier (or Giardina—Kurchan) algorithm.

F. Ragone, J. Wouters, and F. Bouchet, PNAS, 2018

At a fixed numerical cost, we can study events which are several orders of magnitude rarer.

Extreme teleconnection pattern



500 hPa geopotential height and temperature anomalies

Extreme teleconnection patterns = conditional averages with

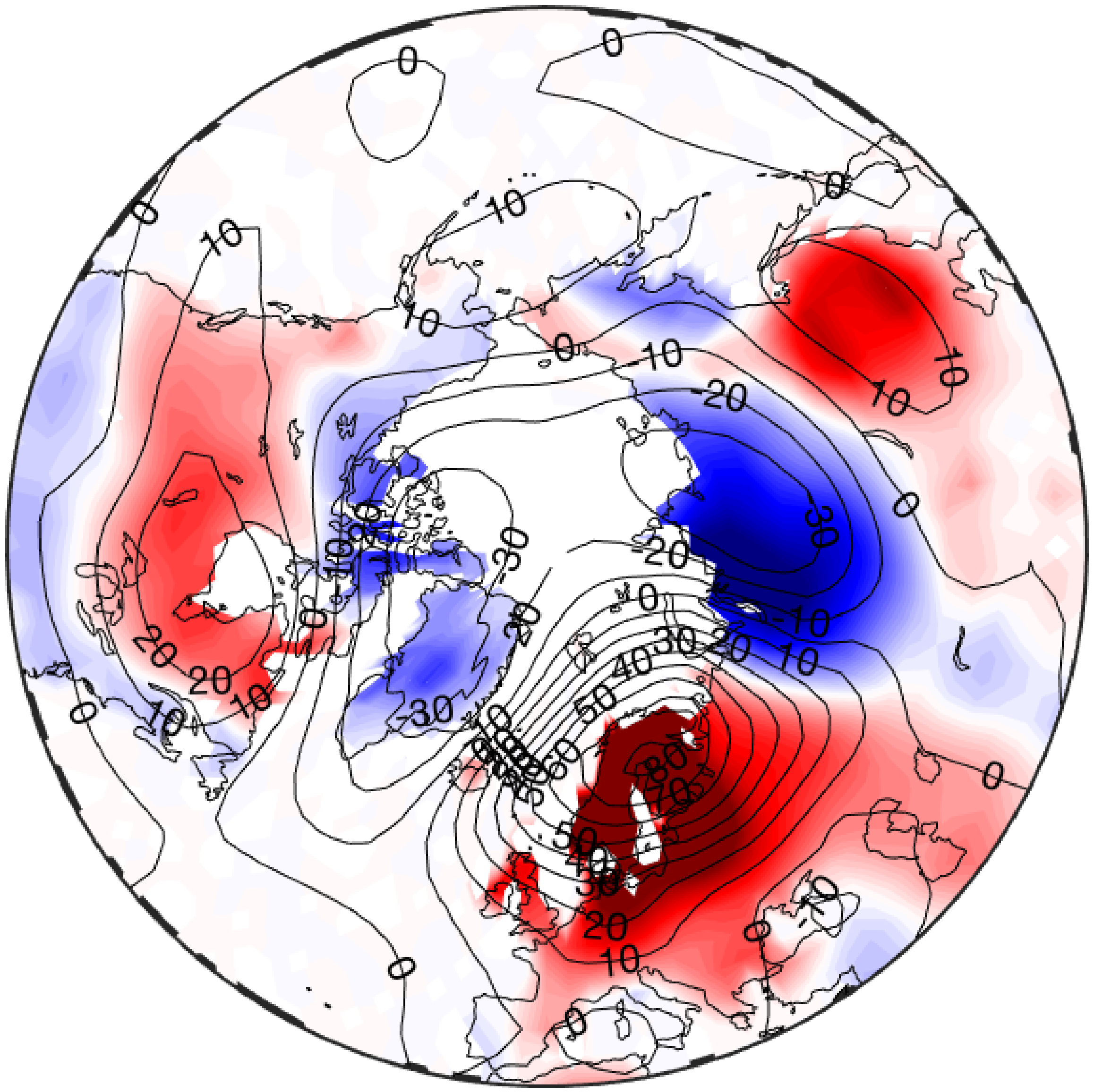
$$\frac{1}{T}\int_0^T \mathrm{d}t \frac{1}{|\mathcal{A}|}\int_{\mathcal{A}} \mathrm{d}\mathbf{r}\ \mathrm{T_S}(\mathbf{r},t) > 2\ \mathrm{K}$$

and $T = 40$ days.

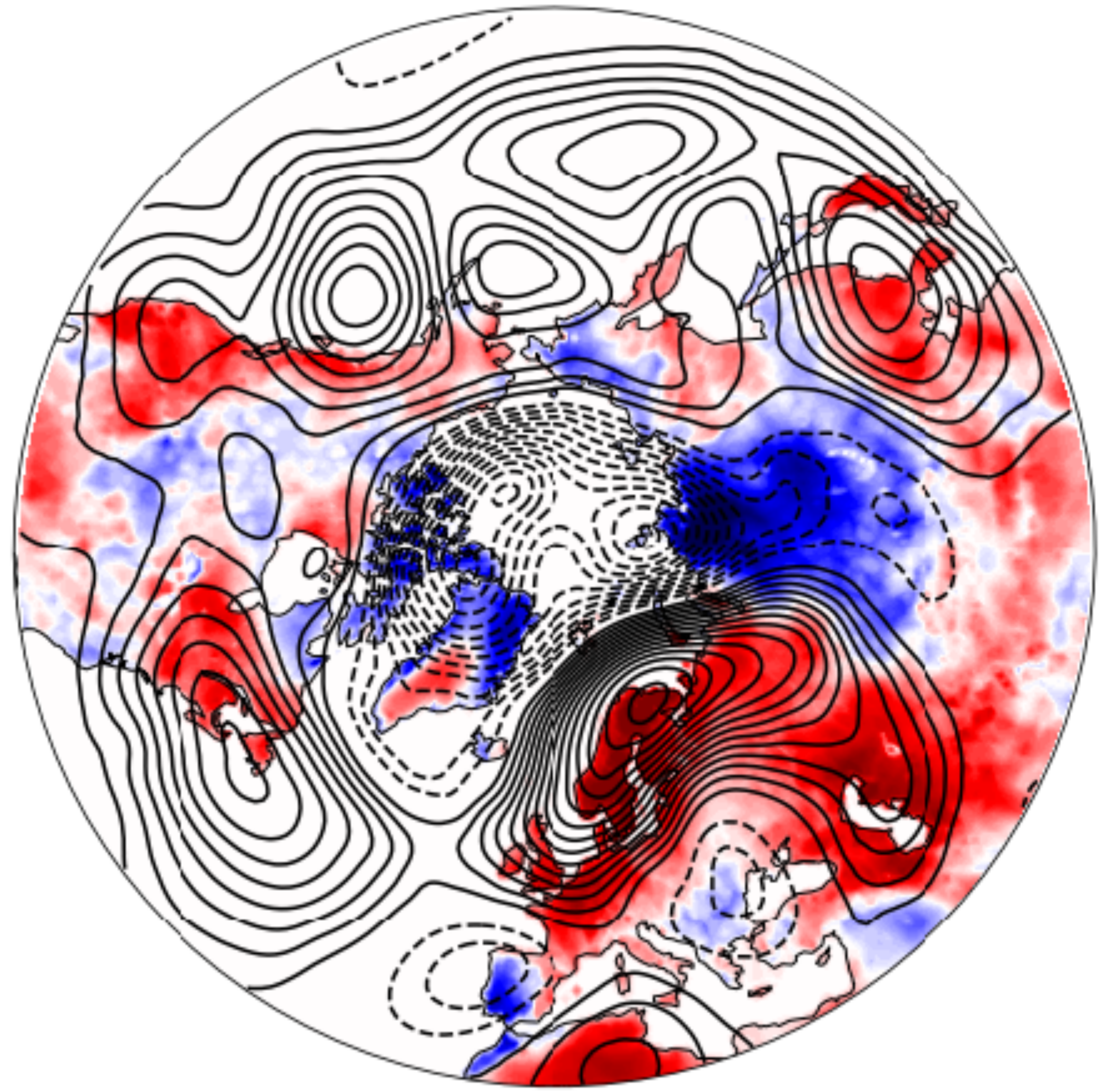
Plasim model.
Summer Scandinavian heatwaves.

F. Ragone, J. Wouters, and F. Bouchet, PNAS, 2018

2018 heatwave over Scandinavia



Published in January 2018
(PLASIM model)

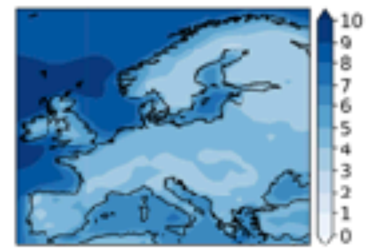


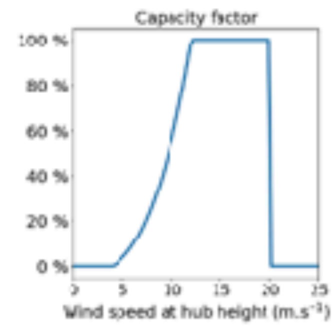
Observed in July 2018 (ERA5)

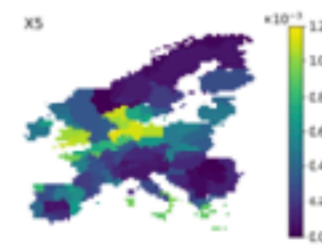
Climate models correctly predict extreme teleconnection patterns.

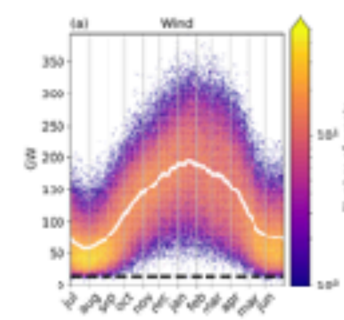
Wind production model

1. **Near-surface wind speed**
2. **Capacity factor**
3. **Scenarios of installed wind turbines**
4. **Time series of wind production**

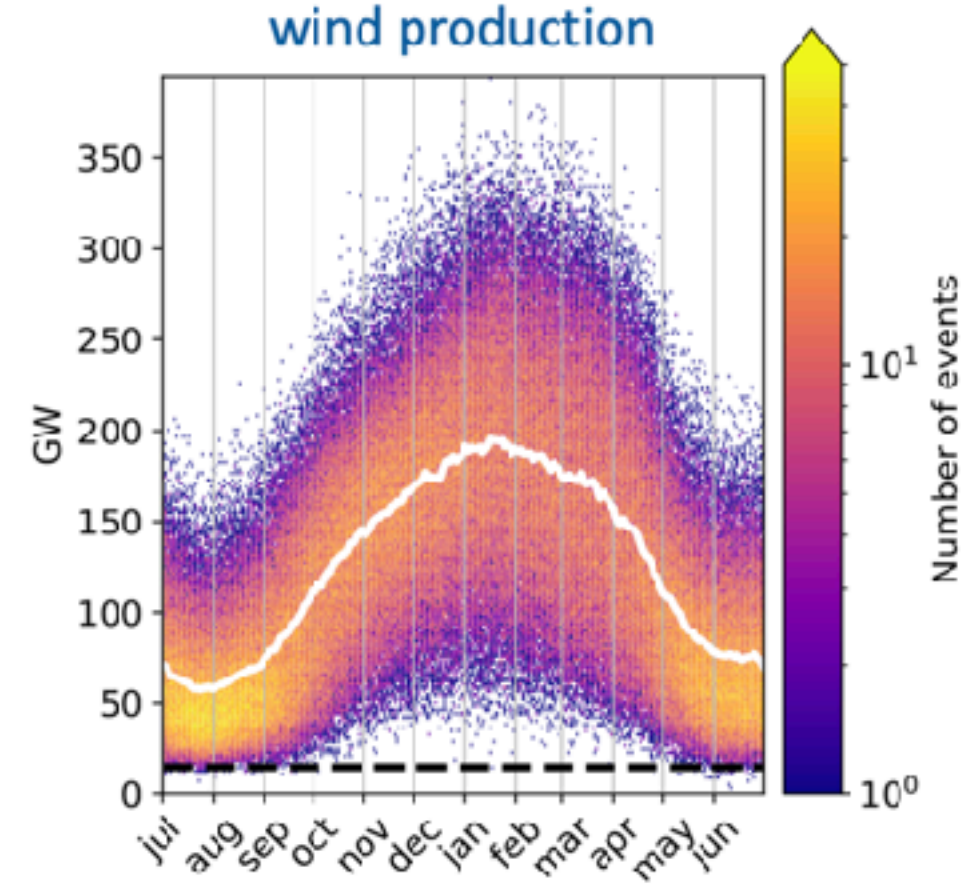






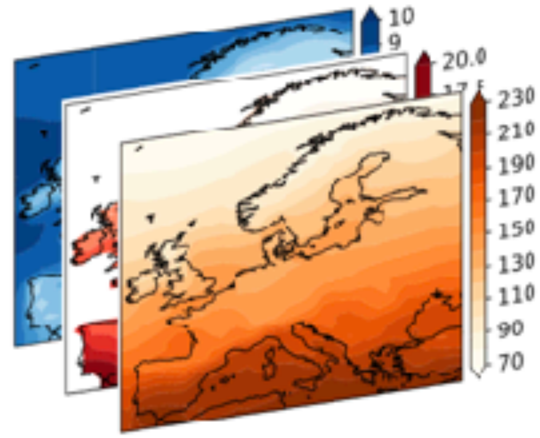


Histogram of wind production

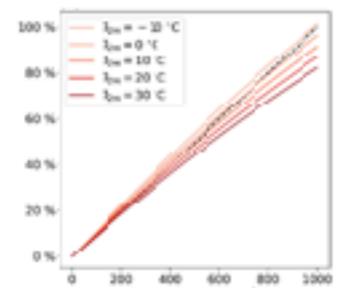


Solar PV production model

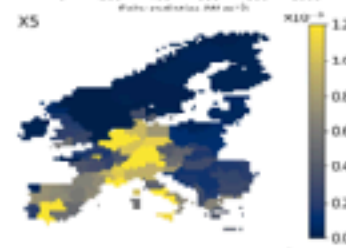
1. **Solar radiation, temperature wind speed**



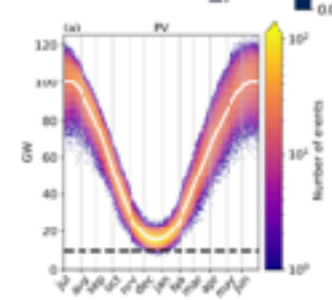
2. **Capacity factor**

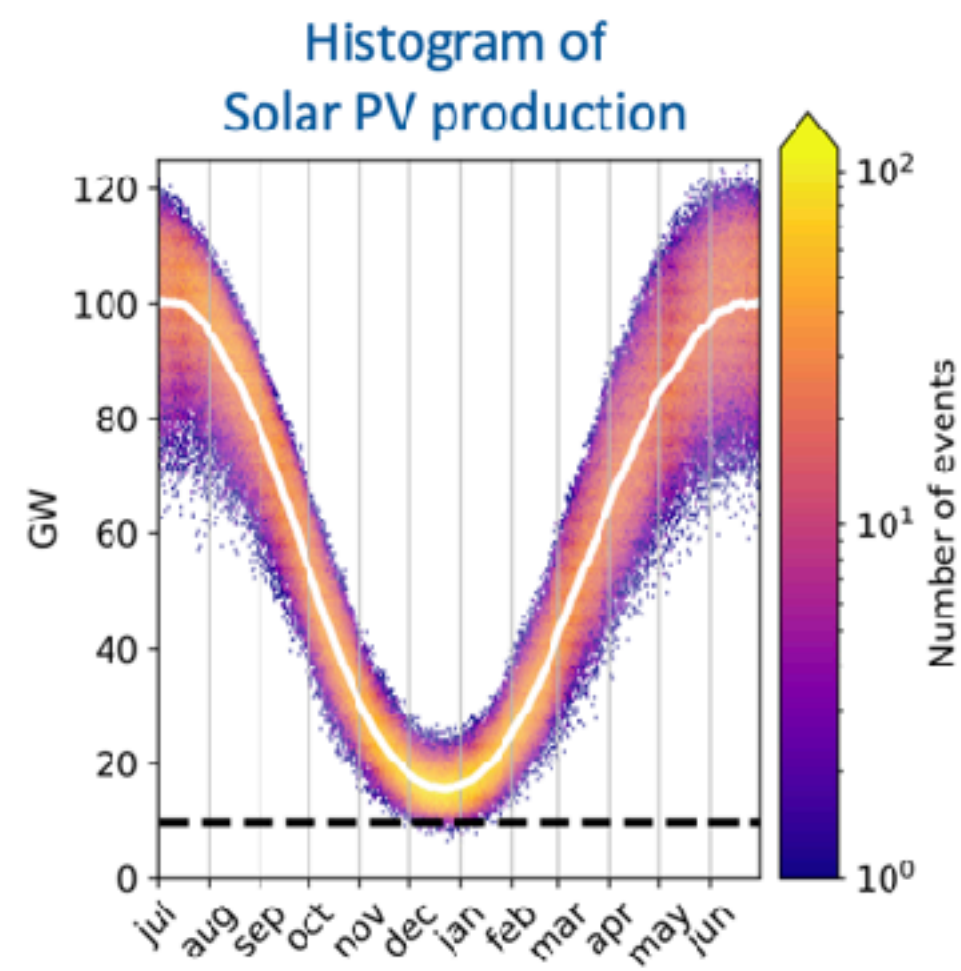


3. **Scenarios of installed solar cells**



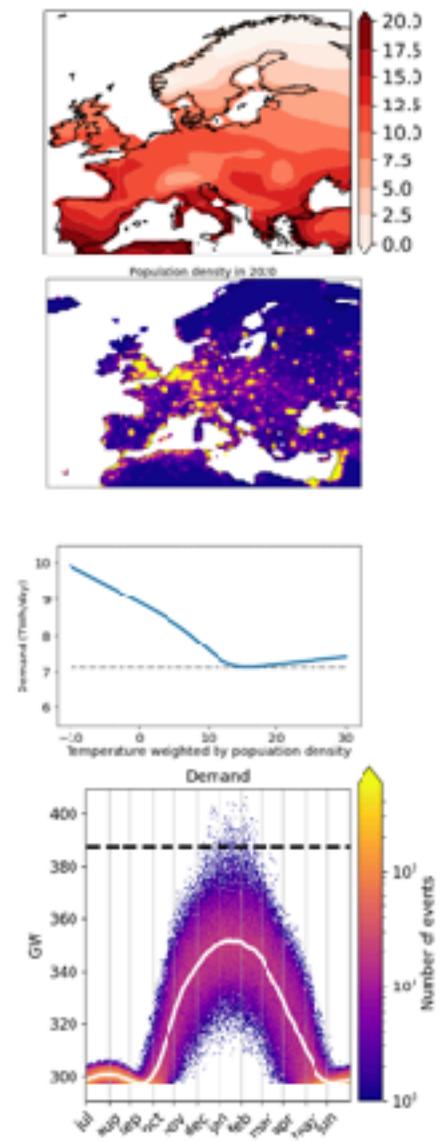
4. **Time series of solar PV production**

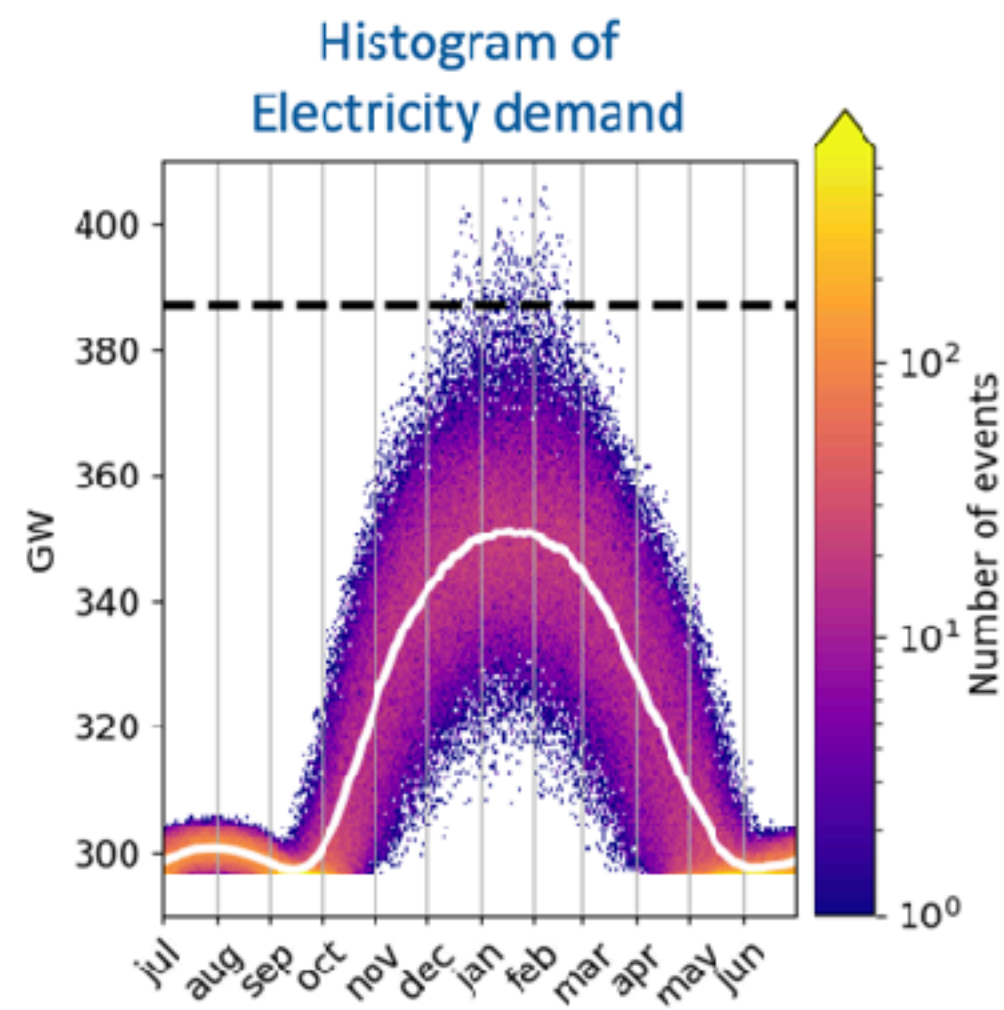




Demand model

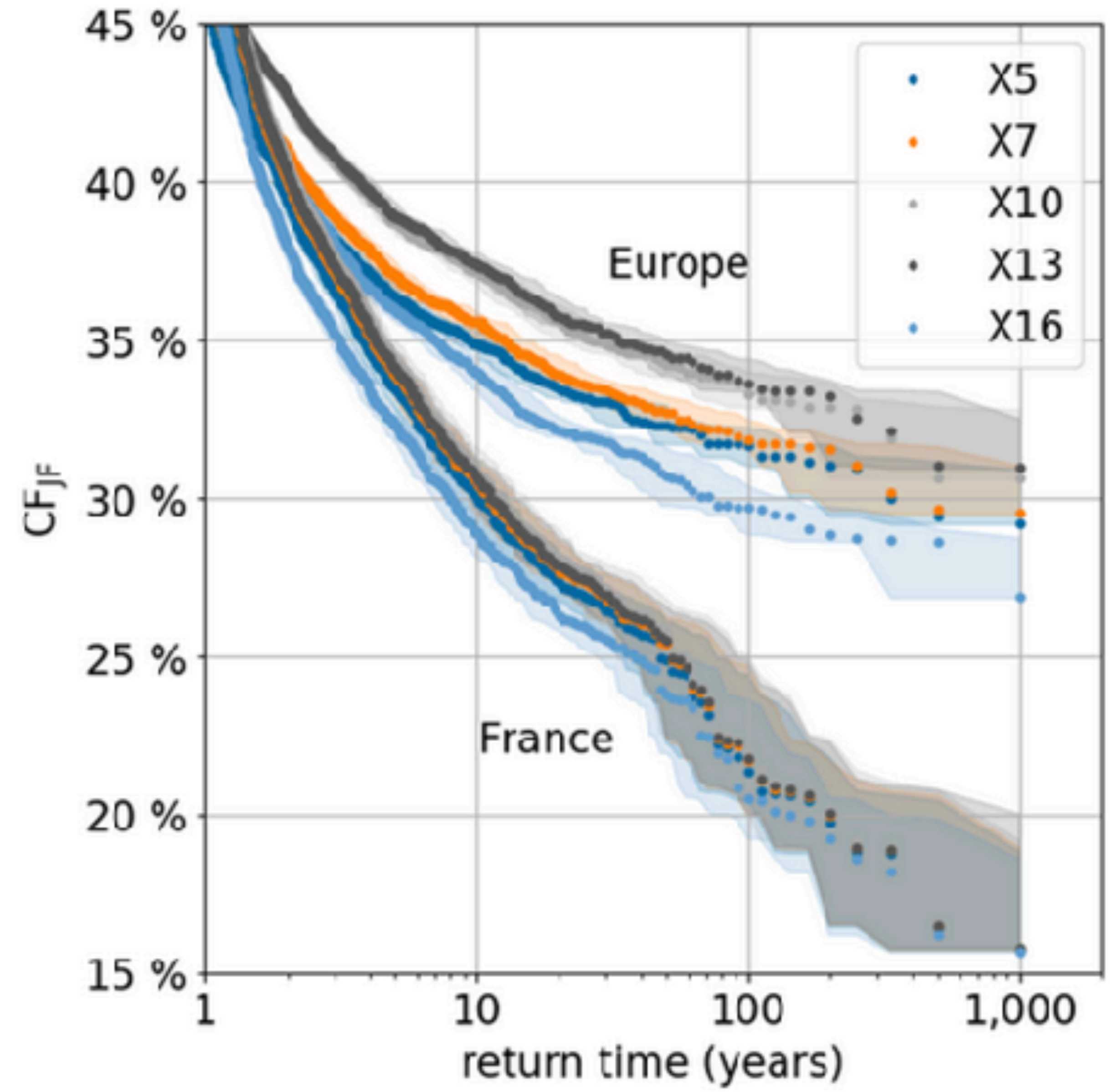
1. **Surface temperature**
2. **Population density**
3. **Demand model**
4. **Time series of demand**





Return times for seasonal wind production

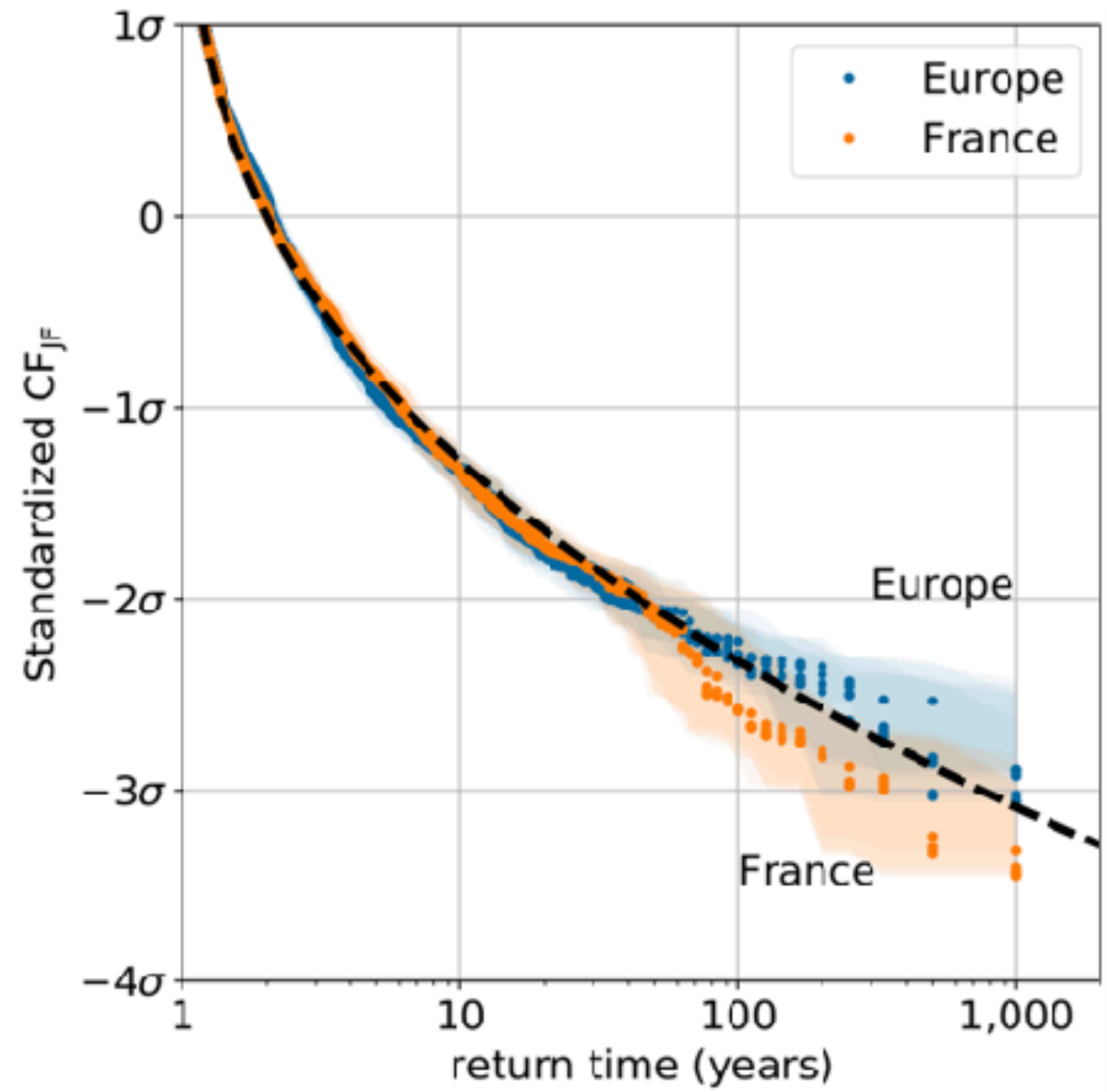
- CF_T with T = 2 months (January-February)
- Interpretation:
  « European wind capacity factor reaches 32% once in 100 years in scenario X5 »
- The location of wind turbines is important for both typical and extreme events
- Aggregating production on a European scale greatly reduces the amplitude of the most extreme events



CF_T = Time averaged during T days of the capacity factor for wind electricity production

Universal Gaussian curve explains rare fluctuations

- **Standardized capacity factor :** $\dfrac{\mathrm{CF}_{JF} - \mu}{\sigma}$
- **Amplitude of extreme events are simply explained by the mean and variance**

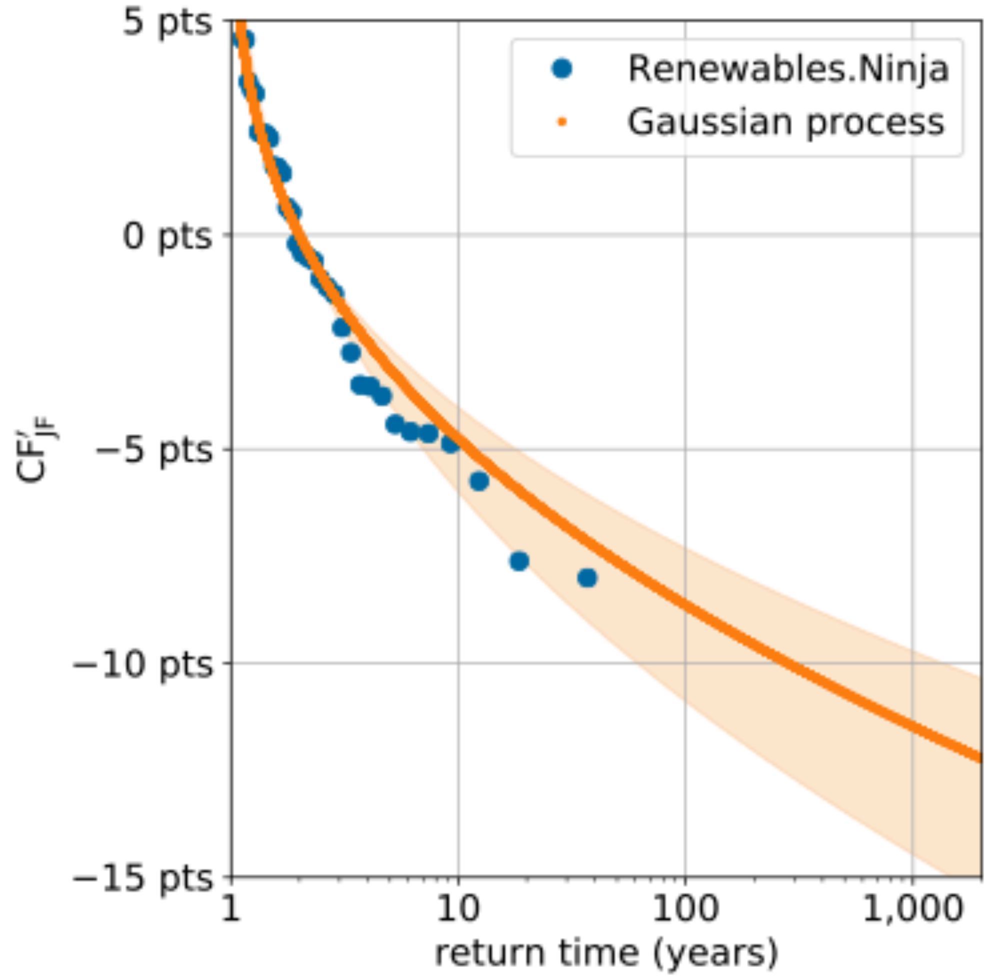


CF_T = Time averaged during T days of the capacity factor for wind electricity production

(B. Cozian, C. Herbert and F. Bouchet, ERL 2024)

Extremes of renewable electricity production and demand at the European scale

Relation between energy and climate is a critical issue for the future energy transition



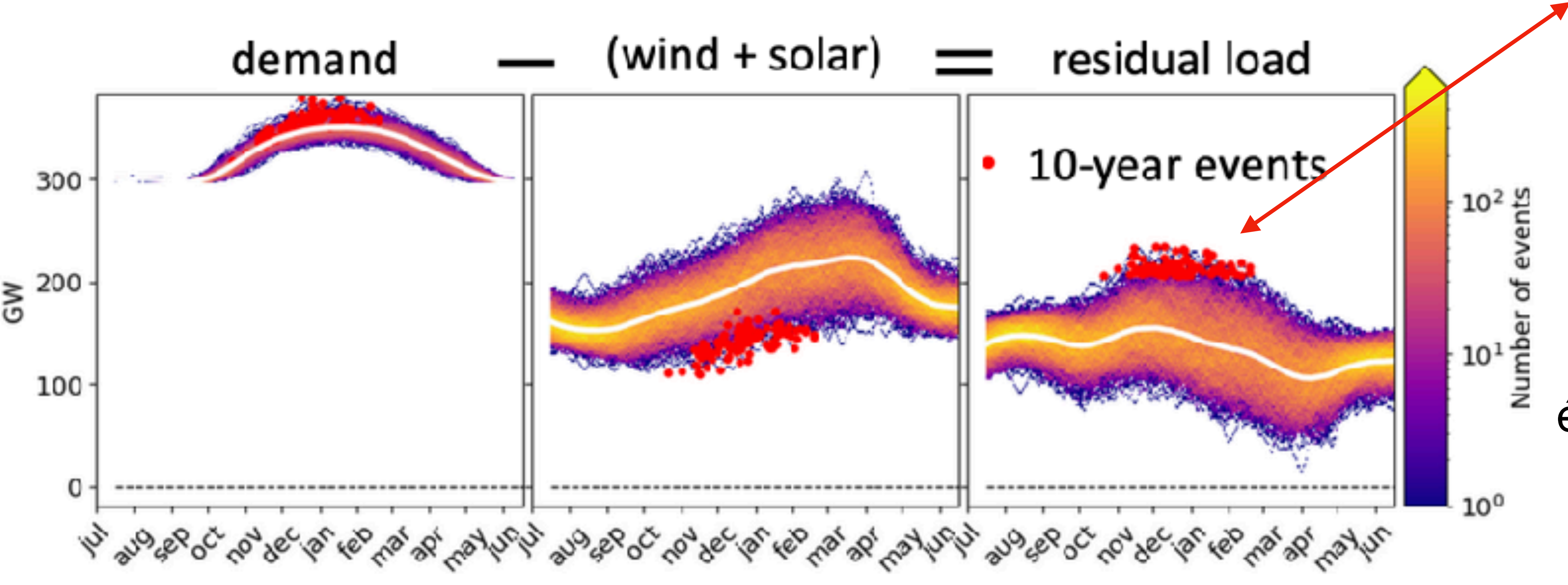
59 days time average = January / February

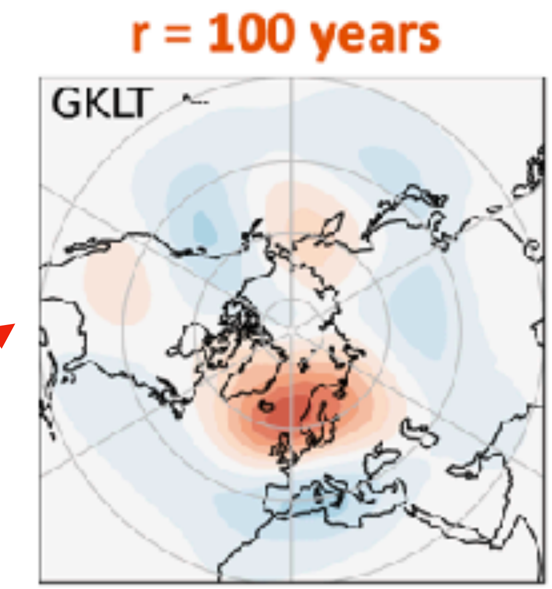
Return time plot for wind energy production at European scale

(B. Cozian, C. Herbert and F. Bouchet, ERL 2024)

Etude des situations extrêmes de demande résiduelle (forte demande combinée à des faibles productions renouvelables)

Simulation de 1000 années de demande électrique et de production éolienne et solaire à l'échelle de la France et de l'Europe (modèles de climat + modèles électriques).





Conditions météorologiques pour les 10 évènements avec un temps de retour de 100 ans (composite de la hauteur du géopotentiel à 500 mbar)

Avec des algorithmes d'événements rares, nous pouvons multiplier par 100 ou 1000 (en fonction du type d'événements) le nombre d'événements les plus extrêmes dans les simulations.

(Thèse de B. Cozian dirigée par F. Bouchet)

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Conclusions

- Within **the framework program RTE/IPSL** for the resilience of the electric system we develop the key tools for RTE (and beyond) to study climate/energy relation. We work more specifically on rare and extreme events

- We (Yoann Robin et al) use **the best available tools to estimate future extreme statistics (with climate change)** from past observations **(Bayesian estimation of Generalized Extreme Value statistics)**

- We can use **rare event simulations** to gather an amazing statistics for extreme events, for instance **extremes of residual loads on the electric system**

Opened post-doc positions