Challenges for the study of extremes in a changing climate

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LSCE

Motivation

- More frequent?
- More intense?
- **Role of human activities**?

Definitions of Extremes

- Mathematics & statistics
  - Annual maximum, peak over thresholds, rare values…
- Physics
  - Typology of events: heatwaves, cold spells, storms, droughts…
- Society & impacts
  - Losses, damages…

☛Risk & vulnerability

Challenges (1)

- Scientific questions
  - Are (climate) extreme events like normal events, but just more intense? (see S.F. Fitzgerald, on *The Great Gatsby*)
  - Have they become more intense?
  - Do they occur more often?
  - What is the role of forcings?
    - Natural
    - Anthropogenic

Challenges (2)

- **Non** scientific questions:
  - Was a specific extreme event (e.g. 2019 summer heatwave) caused by climate change?
  - Do extreme events prove/disprove climate change?

- Epidemiology vs. medecine

New Scientific Challenges

- **Attribution of extreme events**:
  - Can we say something about the exceptionally warm/stormy winter 2013/2014?
  - Very similar to winter 2020!
- Physical mechanisms of extreme events
- **Detection and simulation** of "unprecedented" events
- Clusters of extreme events

Extreme Event Attribution (EEA)

- Detection: how unusual is an event with respect to some background?
- Attribution: Most probable cause(s) of an event
- Challenge: singular event vs. event class
- **Estimate the change of probability distribution of exceeding an observation, between a *factual* and *counter factual* world**

Extreme Event Attribution (EEA)

- Estimate the change of probability distribution of exceeding an observation, between a *factual* and *counter factual* world
- Could the event have occurred (with a similar intensity) without forcings?
  - How intense would such an event be in a climate change scenario?

Extreme Event Attribution (EEA)

- How to characterize the event?
  - Extent, duration, variable?
- Everything else being equal (atmospheric circulation patterns, sea-surface temperature), how does anthropogenic activities alter the features of the event?
- How are the ingredients (e.g. atmospheric circulation) altered by climate change?
  - Storylines, scenario simulations

Necessary Components

- Physical or statistical models
  - Validation of models
  - Ensembles of simulations
- Statistical methods
  - Estimation of probability densities and confidence intervals
  - E.g. Generalized extreme value theory, recurrences & analogues
- Observations

Probability Based Approach

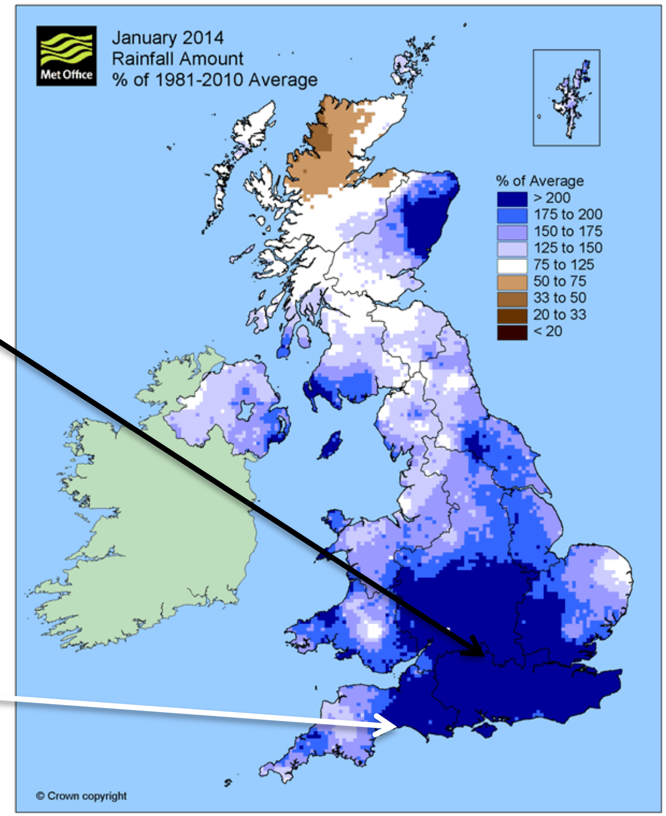
- Given a class of extreme climate event:
  - e.g. Precipitation or temperature exceeds a high threshold
- How does the probability of this class change with external forcings?
- Estimate the probability of exceeding a high value…
  - In a factual world
  - In a counterfactual world

Winter 2013/2014

Did anthropogenic forcing affect the risk of the circulation, heavy precipitation and floods to occur in Southern England?

The Oxford Mail

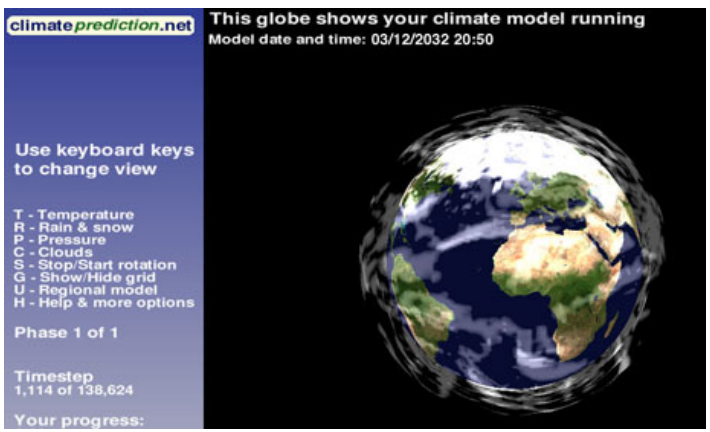
www.metoffice.co.uk

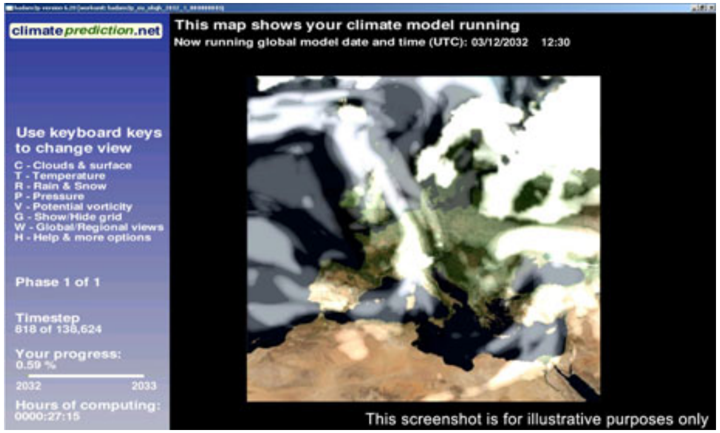


Schaller et al. Nature CC, 2016

Method

- Citizen science project weather@home
- HadAM3P global model with nested HadRM3P regional model
- Extreme events are rare by definition, weather@home allows us to perform the ten thousands of simulations needed to detect a change in risk



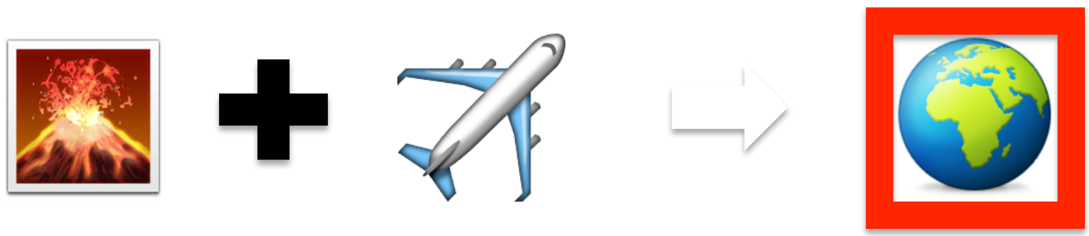


Schaller et al. Nature CC, 2016

Method

- Compare two ensembles of simulations

1) Simulations under “actual” conditions (“factual”): ~10^4 climate model simulations



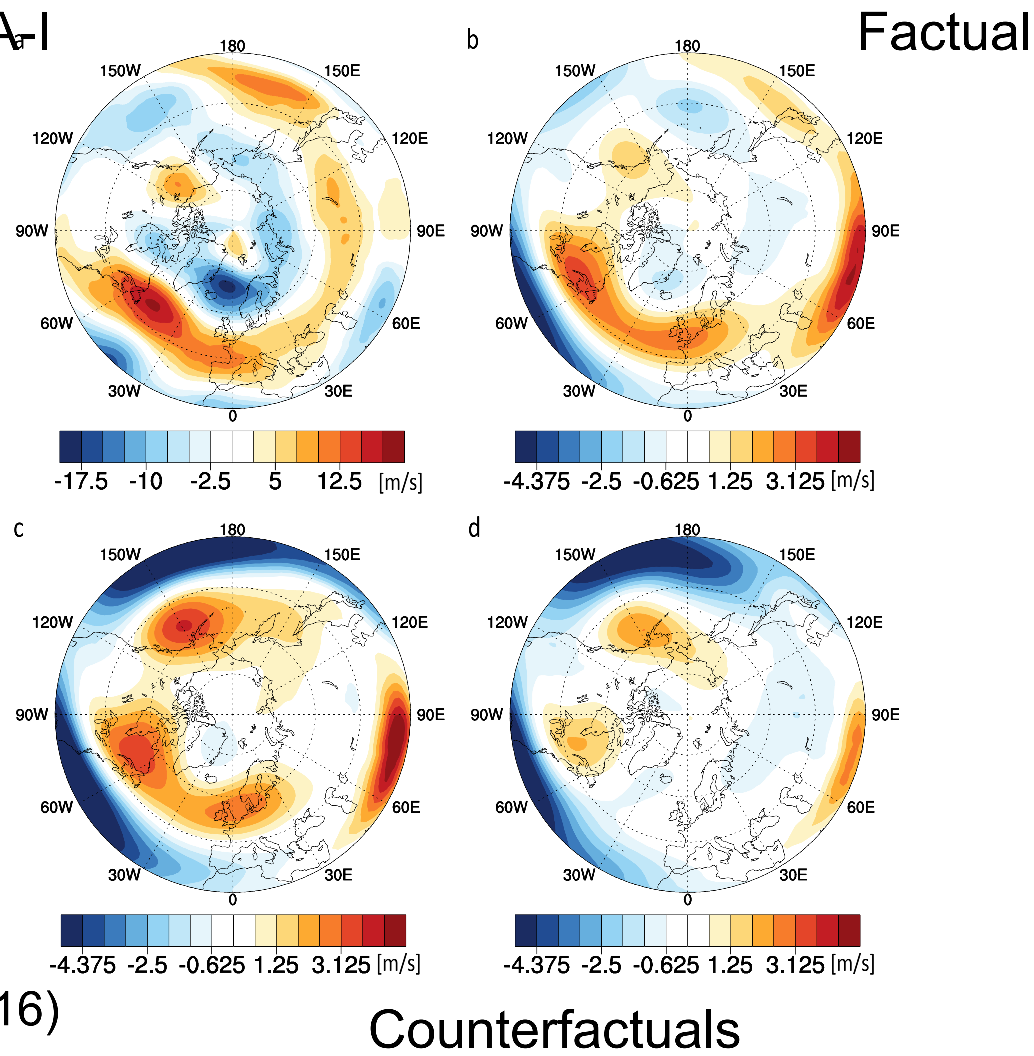
2) Simulations under “world that might have been” conditions (“counterfactual”): 5 10^4 climate model simulations

x 11

Schaller et al. Nature CC, 2016

Circulation validation

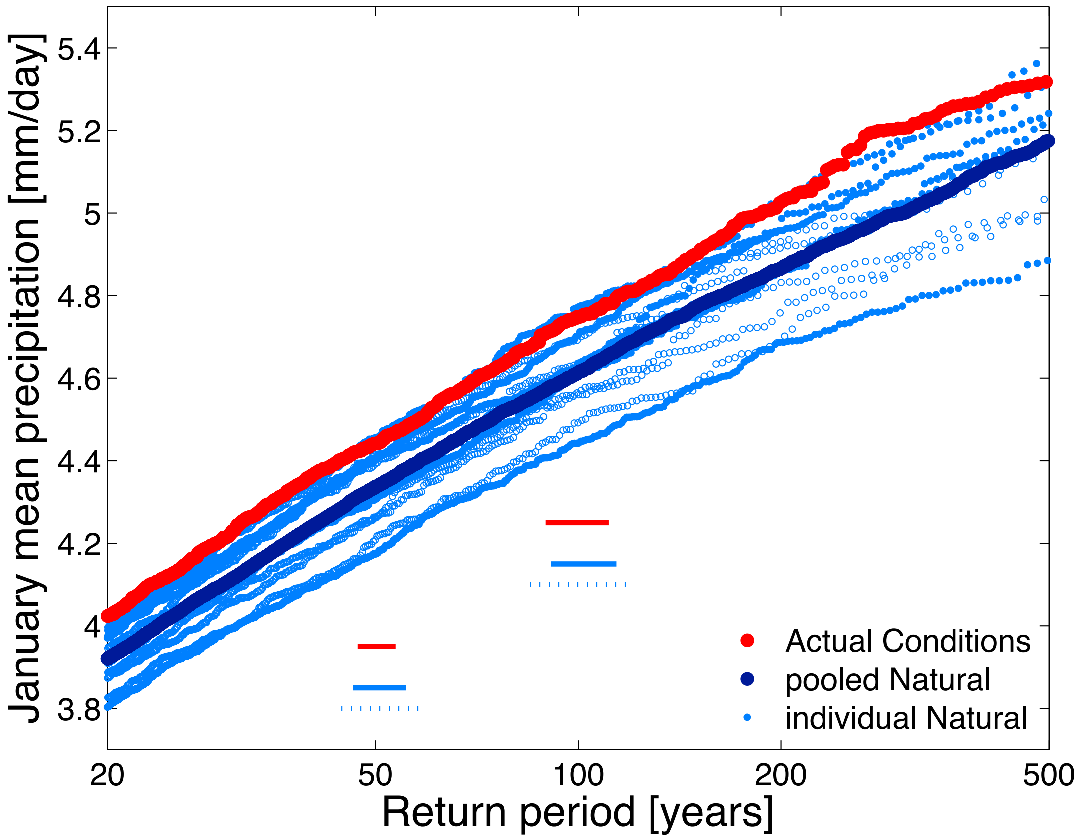
Anomalies of zonal wind at 200 hPa for January 2014



From Schaller et al. (Nature CC 2016)

Results

- Increase in risk of heavy precipitation (FAR):
  - 40% [0%:160%]



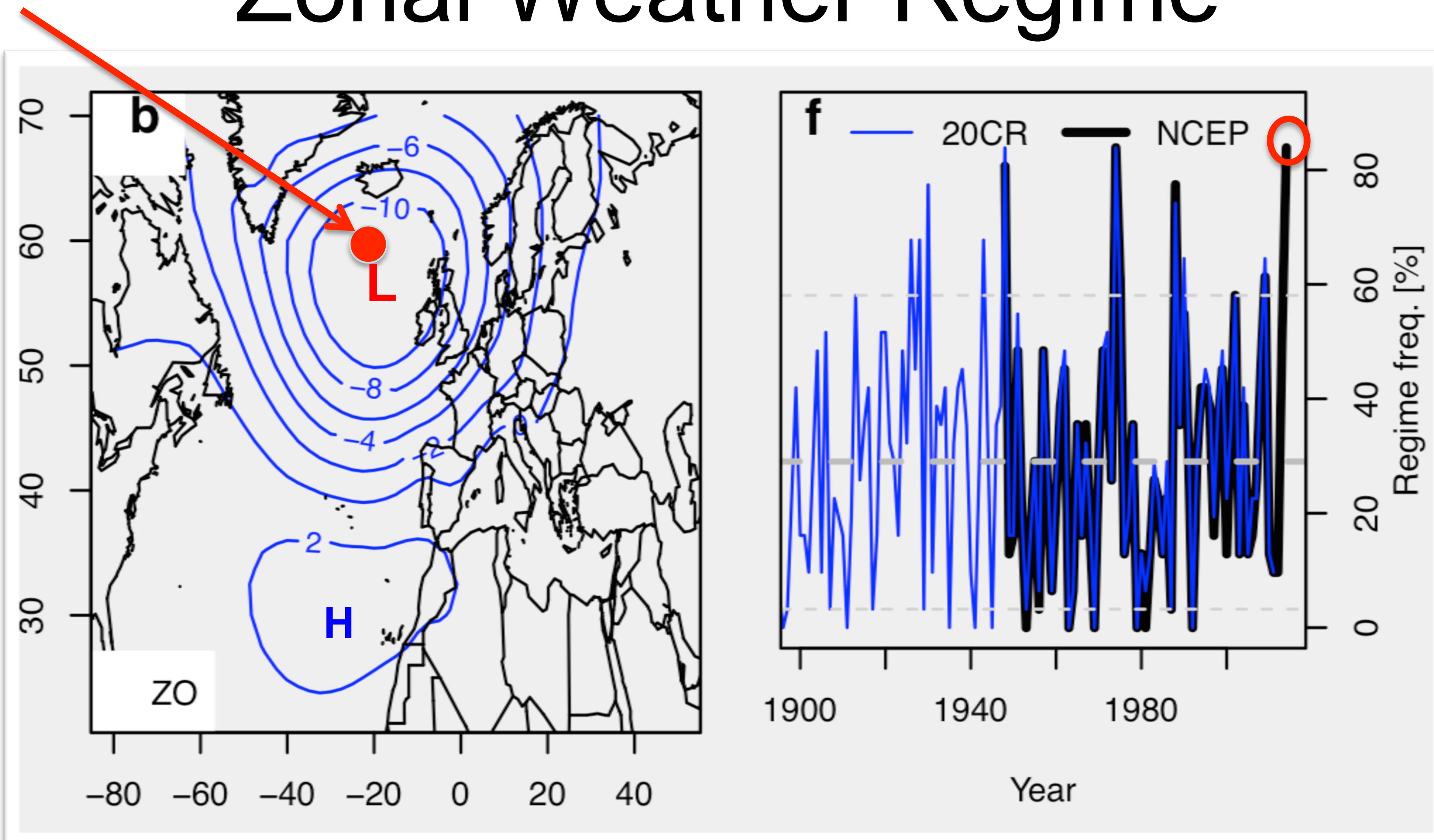
Schaller et al. (Nature CC 2016)

Counterfactual world

$$\mathrm{FAR} = 1 - \frac{p_0}{p_1}$$

Factual world

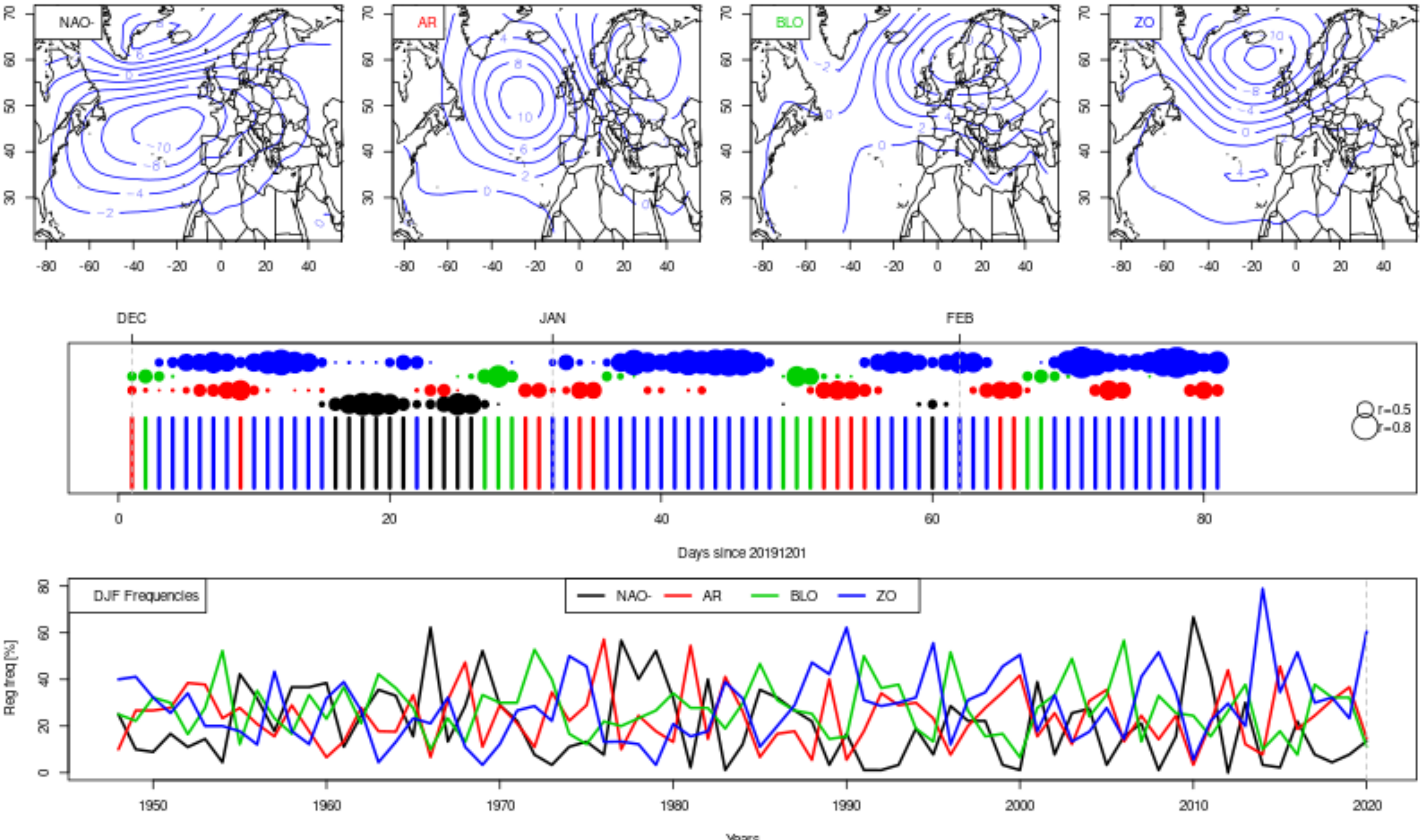
Zonal Weather Regime



SLP Anomaly (hPa)

Zonal WR Frequency (%) in January

Winter 2020?


NAO-
AR
BLO
ZO
DEC
JAN
FEB
r=0.5
r=0.8
Days since 20191201
DJF Frequencies
NAO-
AR
BLO
ZO
Reg freq [%]
Years

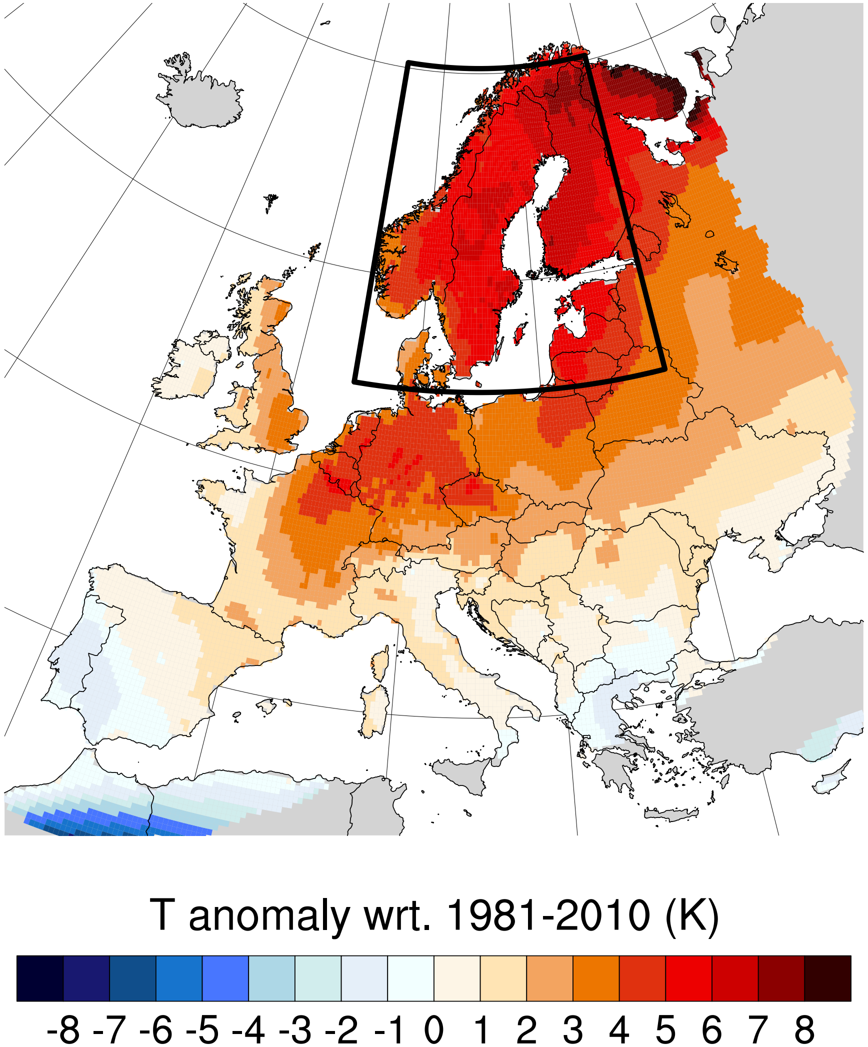
Résultat

- Vers une augmentation de la précipitation, pour une situation météorologique zonale persistente
  - Clausius-Clapeyron (~7%/K)
- Débit de rivières record à cause de la pluie
- Pertes économiques record en Angleterre

2018 Summer Heatwave

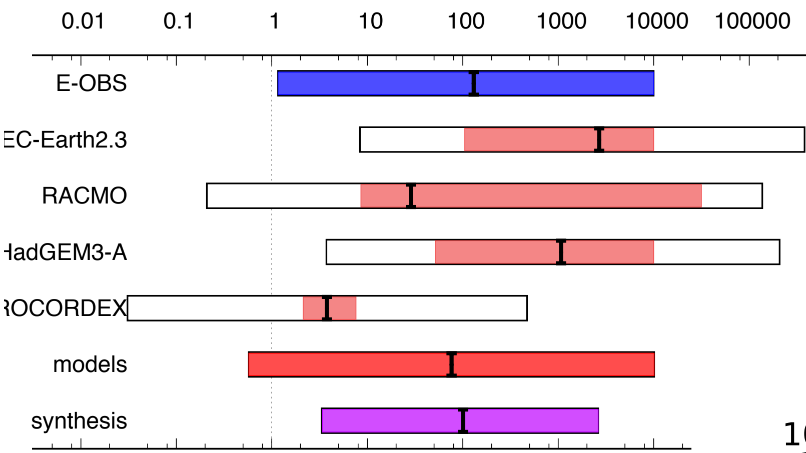
Main anomaly in Scandinavia
Forest fires, drought

Temperature records in Germany and the Netherlands



Yiou et al. (BAMS, 2020)

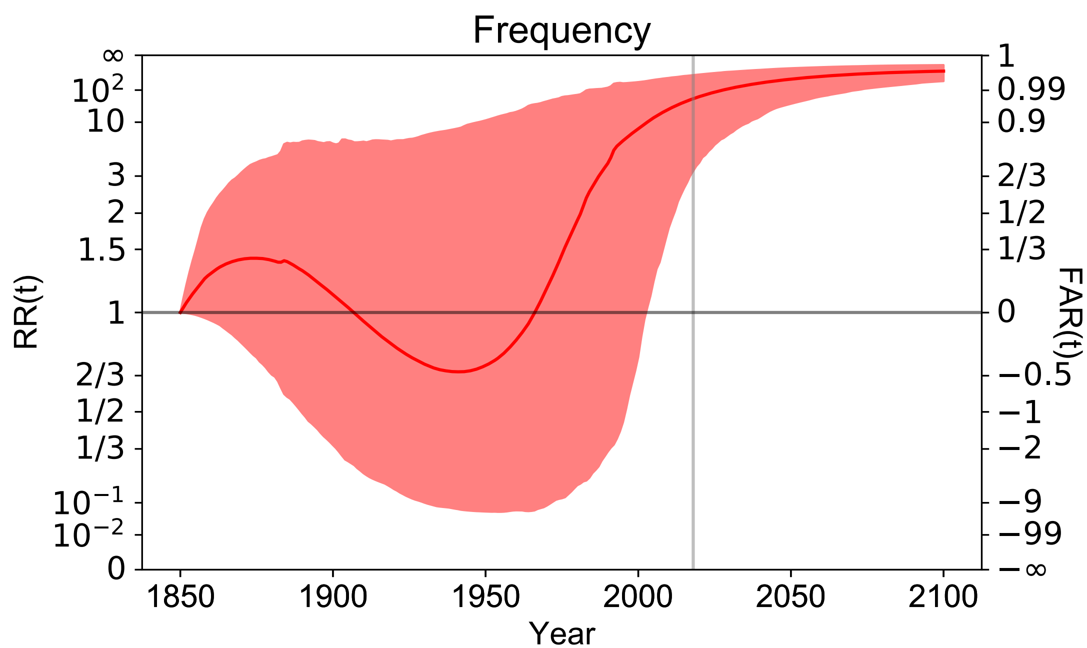
Probability ratios



$$PR = \frac{p_1}{p_0}$$

Proba **avec** activité humaine → p_1

Proba **sans** activité humaine → p_0



Multiplication par 100 de la probabilité d'une vague de chaleur similaire dans les simulations climatiques disponibles.

Simulating extreme events

- Large ensembles of simulations of X(t) and take the most extreme trajectories
  - e.g. Weather@Home: simulate 10000 summers with GCM, to obtain a handful of 2003-like heatwaves, or 100 centennial heatwaves
  - Most (i.e. 9900) trajectories are "normal"
- **How to simulate 100 centennial heatwaves for the cost of 100 trajectories?**

Importance Sampling (1)

- Consider a physical system, e.g.: $$\frac{dX}{dt} = F(X)$$
- How to simulate ensembles of large values of T=g(X(t))?
  - Procedure to guide trajectories towards high values of T=g(X(t))?
- Importance sampling algorithms
  - Evaluate the probability of events from ensemble of optimal simulations
  - Simulate many low probability events

Importance Sampling (2)

- Select N initial conditions of the system X(t), and an observable T(t) to be optimized
- Run trajectories from t0 to t1
- “kill” alpha trajectories for which T(t) is lowest
- Replace them with random perturbations of the remaining ones
- Repeat the procedure K times

Importance Sampling (3)

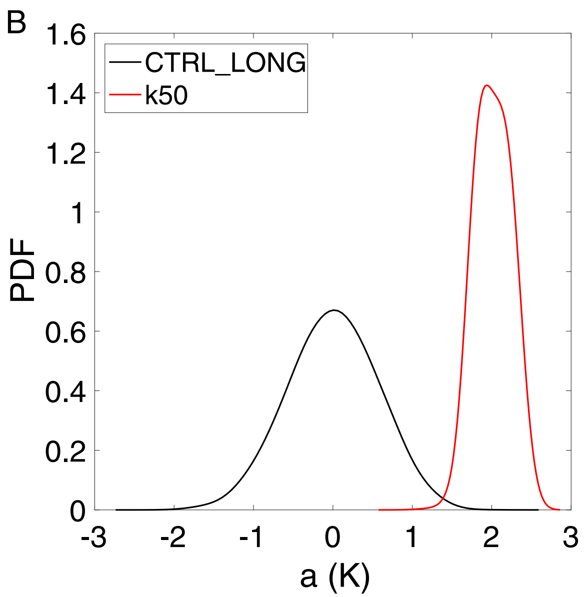
- Probability of final N trajectories after K iterations:

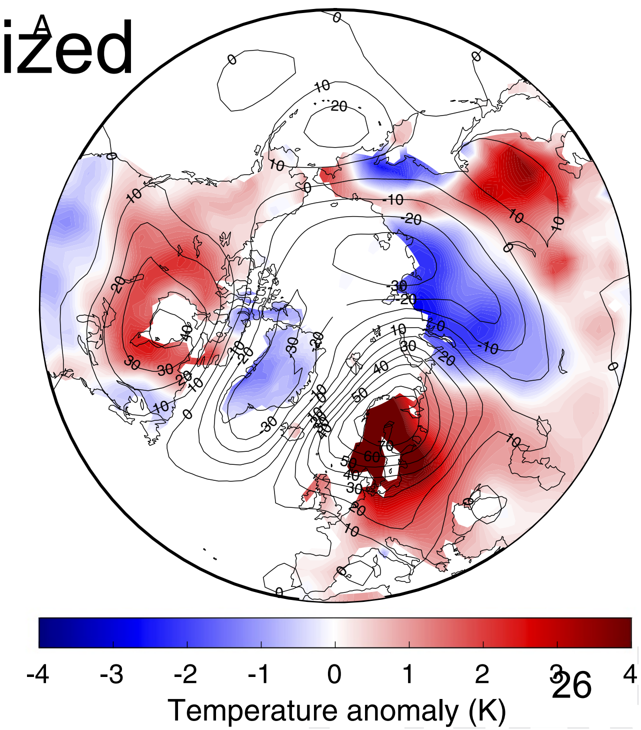
$$p = \left(1 - \frac{\alpha}{N}\right)^K$$

- Note 1: Optimal trajectories fully satisfy the system's equations
- Note 2: You must know the equations!

Importance Sampling (4)

- Ensembles of extreme heatwaves by "pushing" towards high temperatures:
  - F. Ragone et al. (PNAS, 2017)
- Simulate a climate model (PLASIM) so that European temperature is optimized





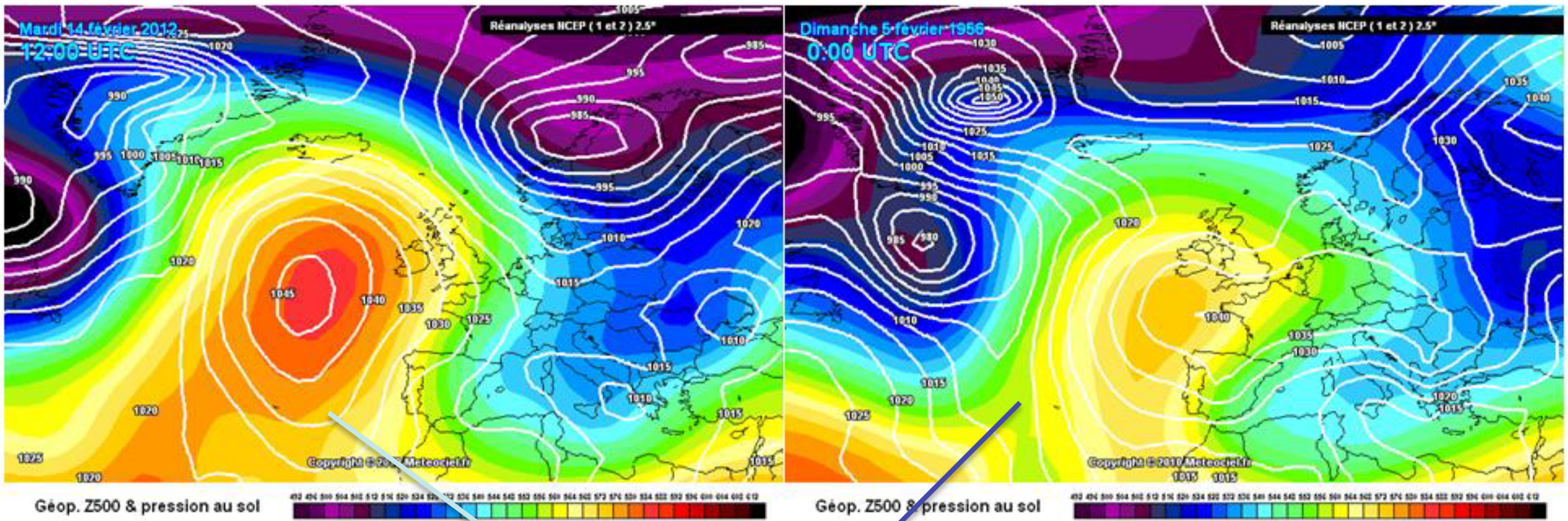
Analogues and Importance Sampling

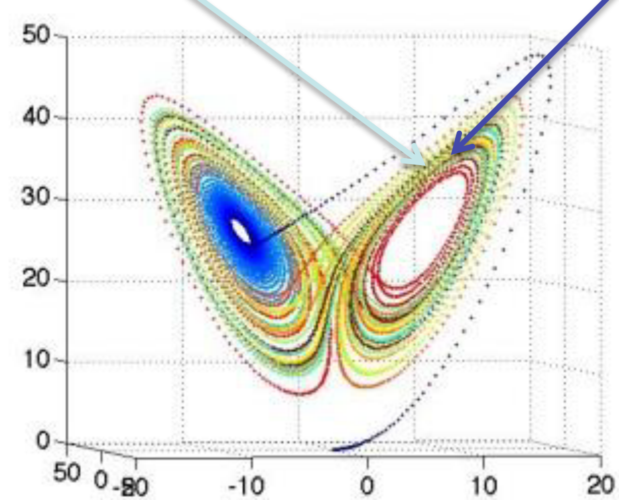
- Adapting Analogue SWG to maximize summer temperature
  - Reshuffling analogues with weight (alpha) towards highest temperatures
- Static WG:
  - warmest summer that could have been, with the same atmospheric circulation
- Dynamic WG:
  - warmest summer that could have been

Circulation analogues

- Synonyms:
  - Recurrences in dynamical systems
  - Nearest neighbors
  - Machine learning: build from experience
- Uses
  - Stochastic Weather Generators: random sampling

Analogues and Recurrences

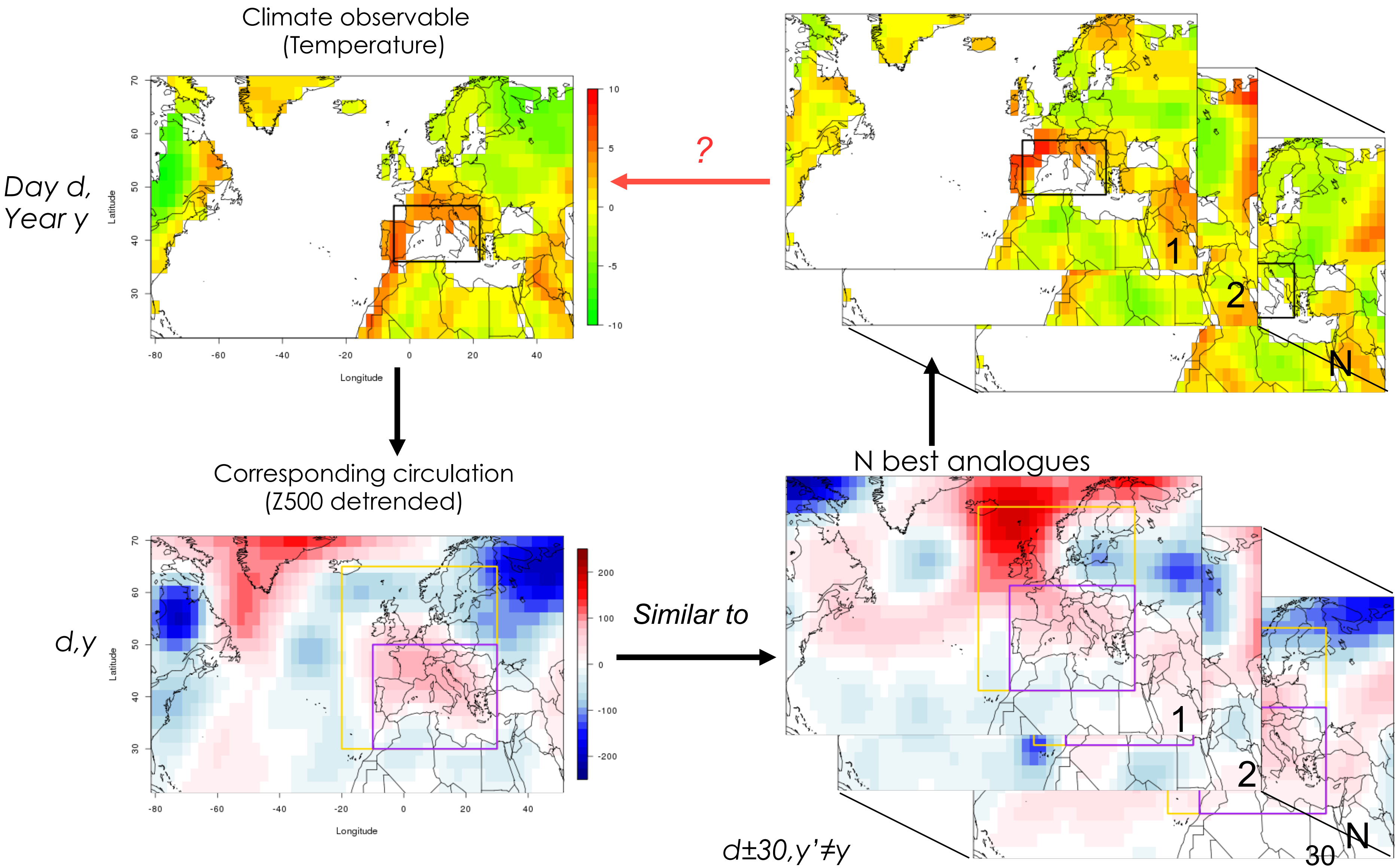




Two analogue maps correspond to close points in phase space

(Courtesy of D. Faranda)

Procedure



(Jézéquel et al., Clim. Dyn., 2018)

Simulation of variables

- Random sampling of analogues
  - Points close in phase space
  - Spatial and temporal correlations
- Simulate monthly/seasonal averages

Algorithm (1)

- Select next analogue with a weight (alpha) proportional to the rank of temperature (R_k)

$$w_k \propto \exp - \alpha R_k$$

$$R_k \in \{0, \ldots, K\}$$

- Does not depend on the units of T
- Same weight values for each time step

Algorithm (2)

- Expected value is a Laplace transform of T

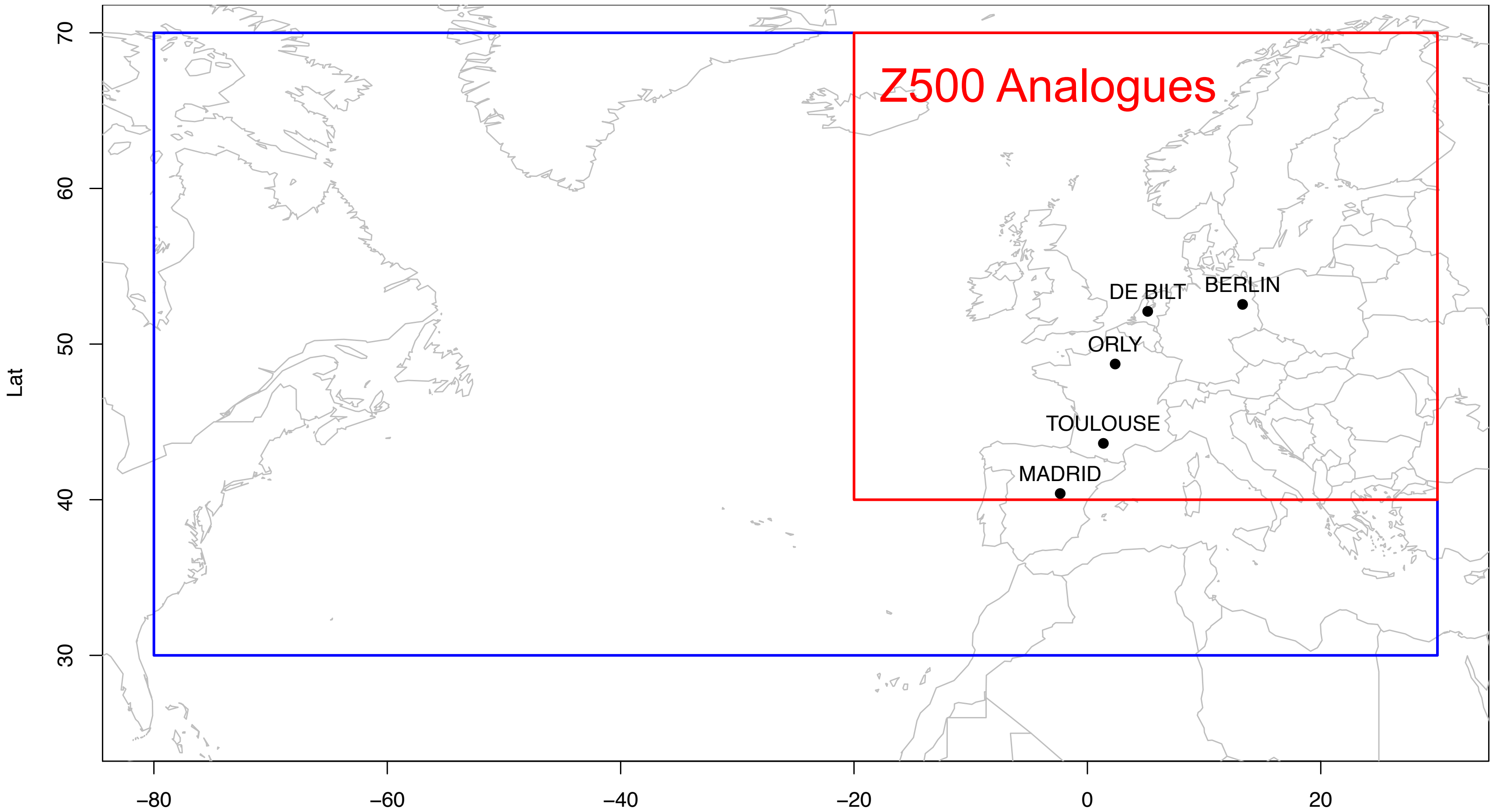
$$E(T) = \sum_{k=0}^{K} \exp(-\alpha R_k) T^{(k)}$$

- Even if T does not follow a Gaussian distribution, the seasonal average of T *does* (approximately)
- One can compare the distribution of simulated T (with parameter alpha) with the empirical distribution of observed T.

Algorithm (3)

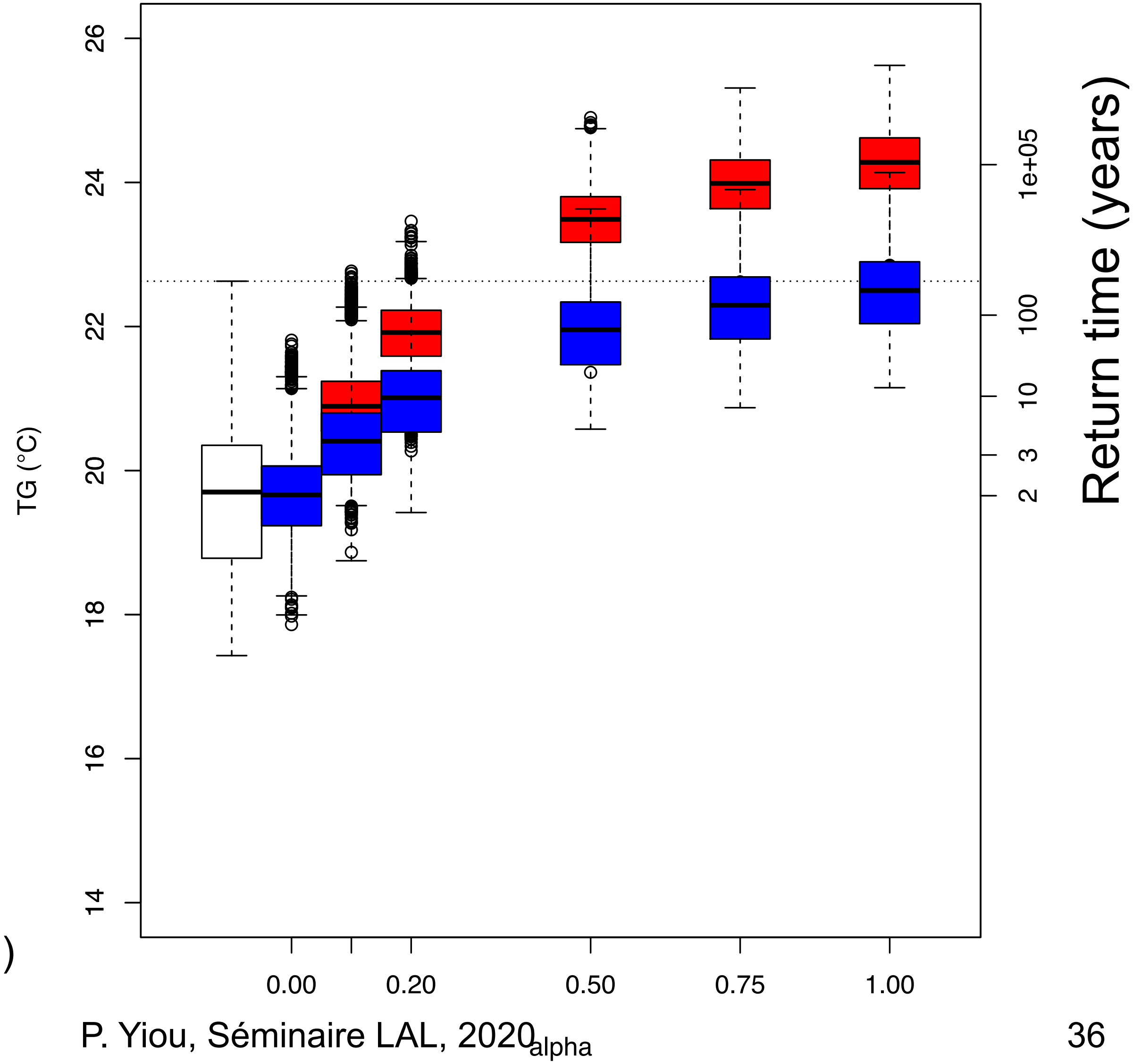
- You do not need to know the equations!
- Variation of a Darwinian mechanism
  – favor the strongest vs. eliminate the weakest
- Beware of the arrow of time & seasonal cycle!
  – Weigh the distance to calendar days to be simulated
- Parameters to be optimized!

Simulations



Return Periods

Static vs. Dynamic SWG simulations



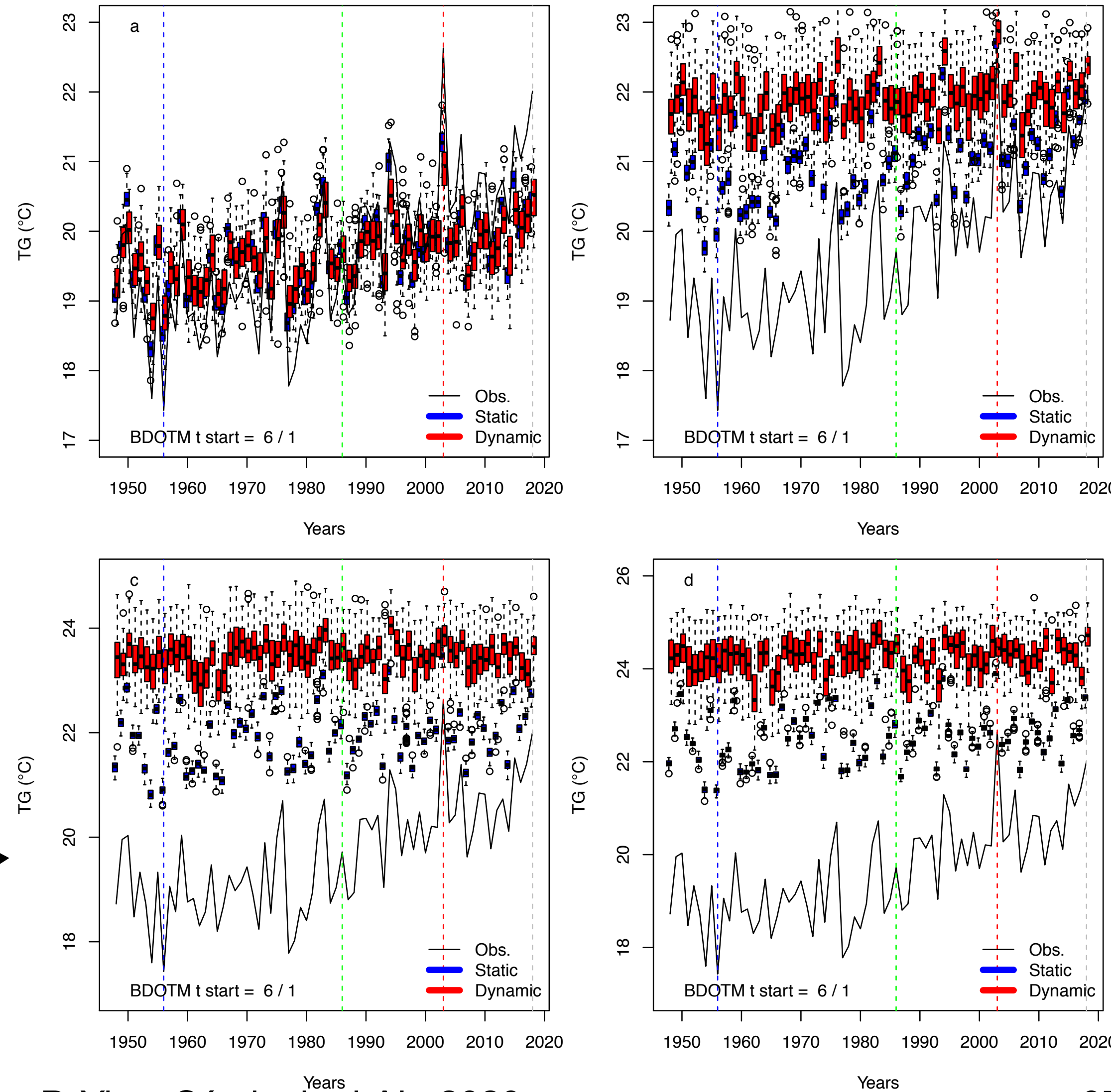
Yiou and Jézéquel, GMD (2020)

Trends of simulations

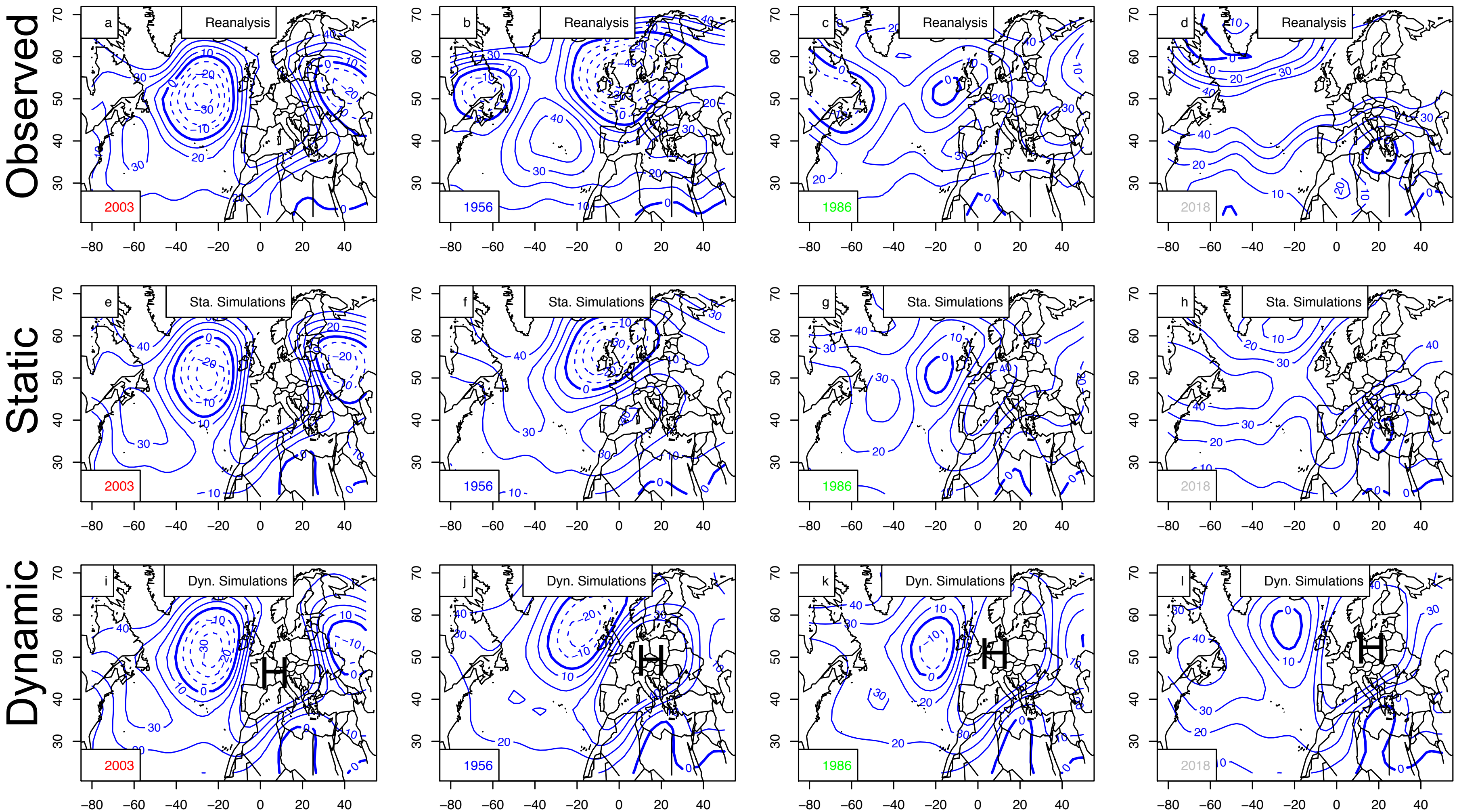
Warmest: 2003
Coldest: 1956
Median: 1986
2^{nd} warmest: 2018

$\alpha = 0.5$

Yiou and Jézéquel, GMD (2020)



Atmospheric circulation (Z500)



Conclusions

- Achievement:
  - Simulate 100 events with RP of ~1000 years, for the price of 100 events.
- PoC to simulate ensembles of extreme temperatures that are coherent with the atmospheric circulation
- Storyline of atmospheric circulation (here "blocking")
- Combine with other types of events:
  - e.g., wet spring and hot summers
- Other types of (long lasting) events:
  - Cold summers, hot winters, etc.

Service Climatique d'Attribution

Fiche Juin 2017 pour les décideurs

Fiches EXTREMOSCOPE

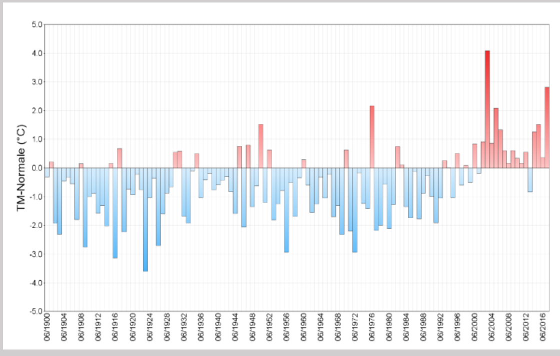
Le mois de juin 2017 exceptionnell chaud

L'essentiel

La France a connu des températures très élevées au cours du mois de j classiques pour une vague de chaleur de milieu d'été, les températures très exceptionnelles pour un mois de juin, et des valeurs record se sont p Une analyse à partir des simulations climatiques montre que de telles très peu probables sans la modification du climat par les activités hur aussi que, dans le futur, des températures aussi élevées au mois de juir A cette période d'activité économique intense, une adaptation de professionnels à ces températures est donc nécessaire.

L'événement

Le mois de Juin 2017 a été exceptionnellement chaud en France. Il se situe en seconde position, avec une température moyenne de 21,2°C après le record de 2003 dont la température moyenne était de 22,4°C, et avant Juin 1976 (20,5°C). De plus, la France a connu du 18 au 22 juin une vague de chaleur remarquable par sa précocité et son intensité. Les hautes valeurs de pression sur l'Europe de l'Ouest ont favorisé le maintien d'un dôme d'air chaud, de l'Afrique du Nord à la France. Avec une température moyenne sur la France (1) de 26.4 °C, le 21 juin est la journée la plus



Comment un tel événement est-il lié au changement climatique ?

Pour répondre à cette question de façon quantitative, nous utilisons ici les simulations régionales du climat issues du projet EURO-CORDEX. Ces simulations calculent une dizaine d'évolutions possibles du climat en Europe, en utilisant à chaque fois des modèles différents. Cet ensemble de simulations peut être utilisé pour calculer des probabilités de dépasser les valeurs de l'indicateur qui ont été observées pour la moyenne du mois de juin en France (21,2°C), voir la Figure 1-a.

Des probabilités différentes sont obtenues durant des périodes climatiques différentes, permettant d'estimer l'influence des activités humaines sur ces probabilités. Seule une dizaine de modèles est utilisée pour faire cette étude, et ces modèles ne représentent pas tout le spectre des possibilités. Nous savons en particulier que les modèles ont une sensibilité aux gaz à effet de serre qui se situe dans une fourchette haute de l'ensemble des modèles utilisés dans le monde, en particulier pour les

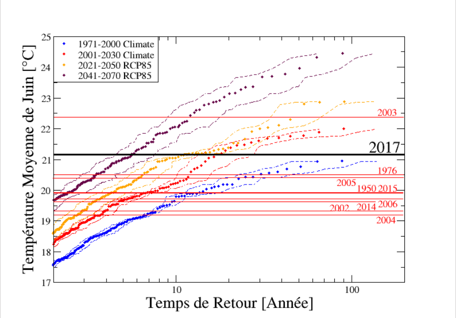


Figure 2 : Temps de Retour d'un mois de juin dont la température moyenne en France dépasse une valeur donnée, pour différentes périodes climatiques: la fin du 20ème siècle, la période actuelle [2001-2030], et deux périodes futures selon le scénario sans politique climatique RCP8.5. La figure est obtenue à partir de 10 simulations climatiques issues du projet EURO-CORDEX. Les intervalles de confiance 5-95% sont indiqués en tirets, les 5 mois de juin les plus chauds sont montrés.

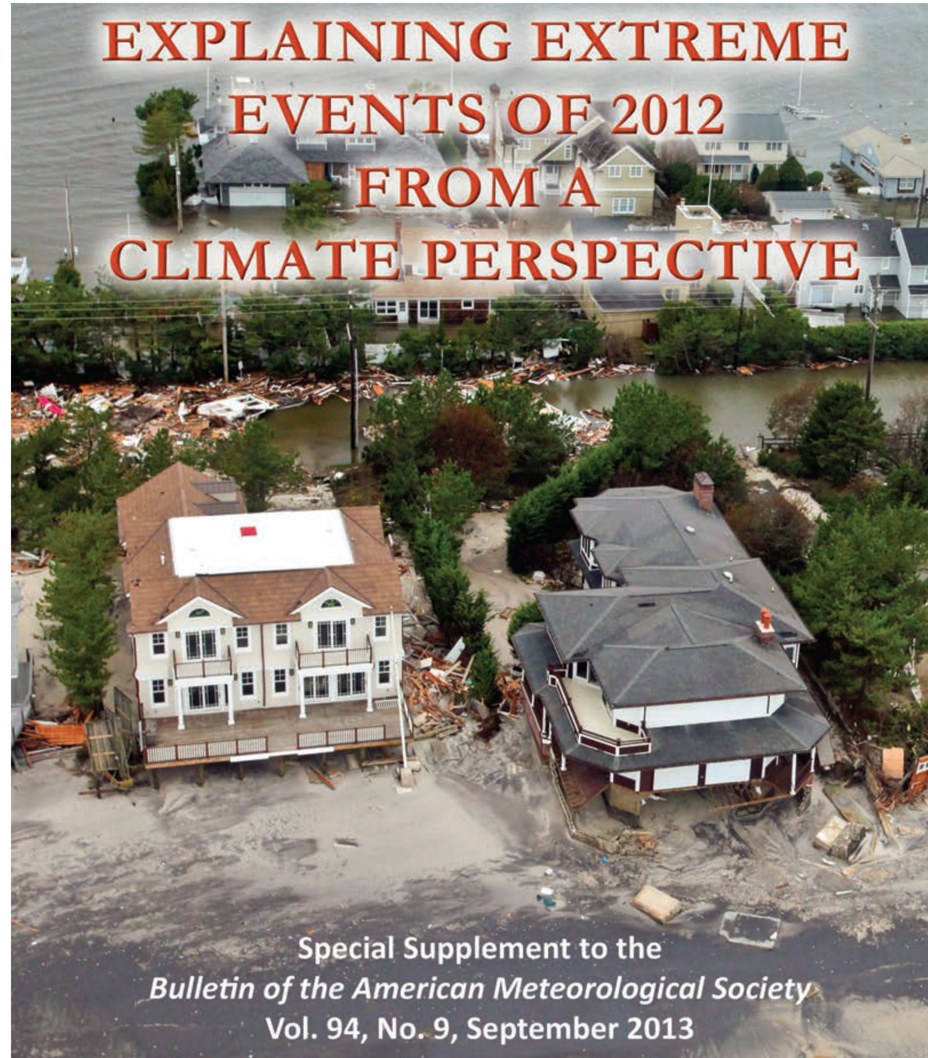
Que peut-on en conclure ?

Compte tenu des limitations concernant

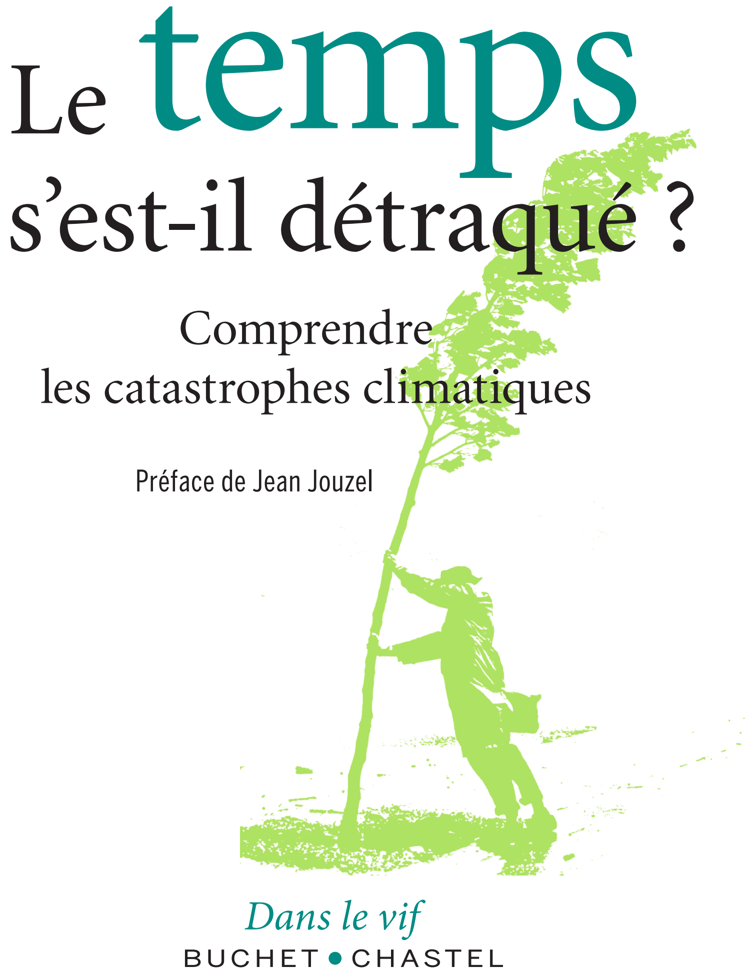
Convention de Service Climatique pour l'attribution (COSC) au niveau français
MF, IPSL, BRGM, CERFACS, CIRED

To know more about extremes

BAMS special report on extremes



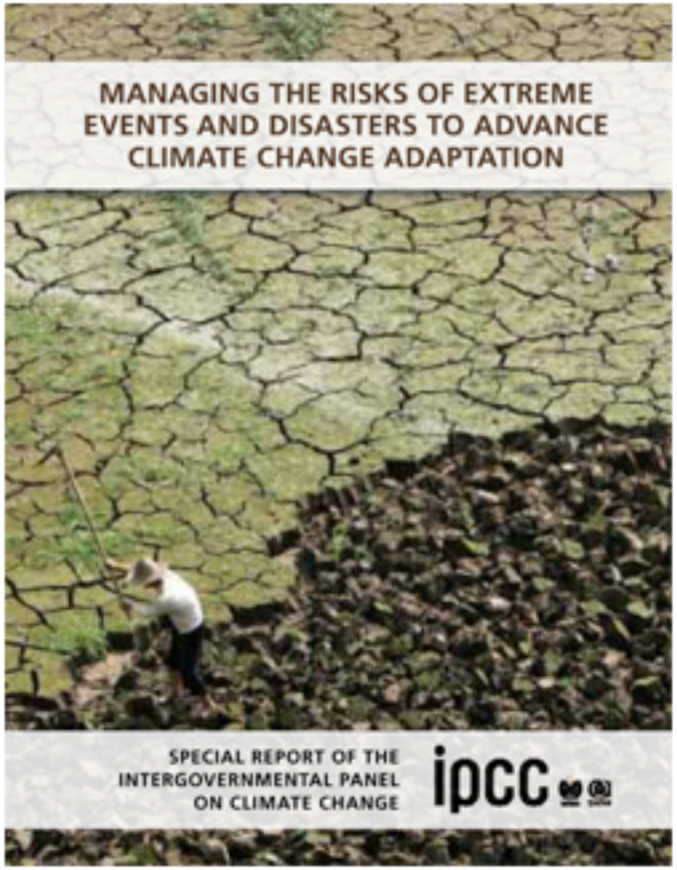
To know more about extremes



« Se familiariser avec les fondements scientifiques des décisions de société est un acte démocratique :
on passe d'un monde de croyances dominé par quelques personnalités,
à un monde où chacun fait un choix éclairé. »

PASCAL YIOU

To know more about extremes



FULL SREX REPORT

PDF - 594 pages - 31MB

SUMMARY FOR POLICYMAKERS

PDF - 20 pages - 11.8MB

Analogues and Dynamical Systems

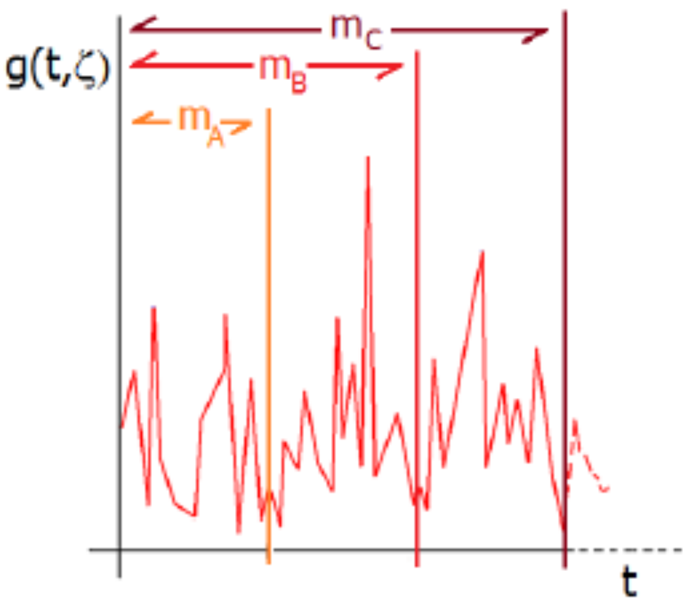
Blow up of Lorenz (1963) attractor

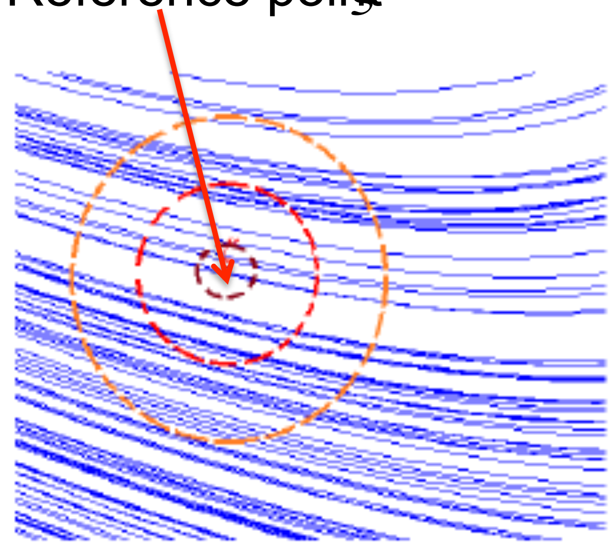
$$g(t;\varsigma) = -\log(d(X_t,\varsigma))$$

$$\frac{dX}{dt} = T(X),$$

$$X_t = (x_t, y_t, z_t)$$

Reference point ς





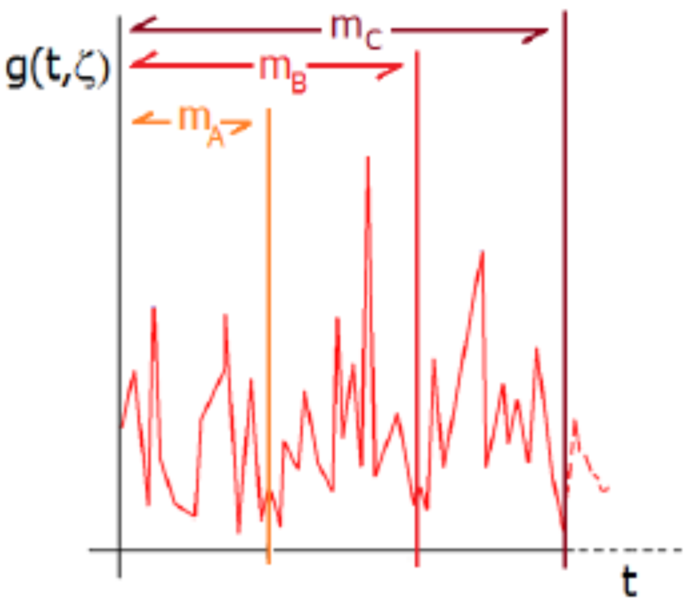
(Courtesy of D. Faranda)

Analogues and Dynamical Systems

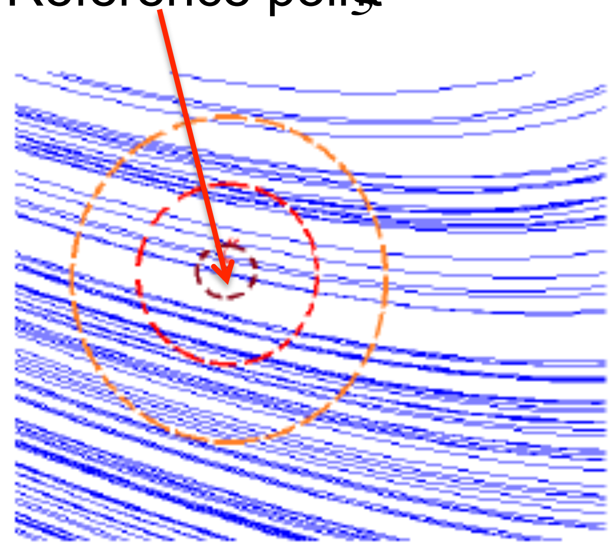
Under general conditions (e.g., ergodicity, mixing), g(t,z) follows a *Gumbel* distribution (Theorem of Freitas-Freitas-Todd, 2010)

➢ **Interpretation of analogues for chaotic systems**

$$g(t;\varsigma) = -\log(d(X_t,\varsigma))$$



Reference point ς



(Courtesy of D. Faranda)

Sp

Extreme ev

- Black swa
  – Evéneme devienne
    - E.g. SID Europe

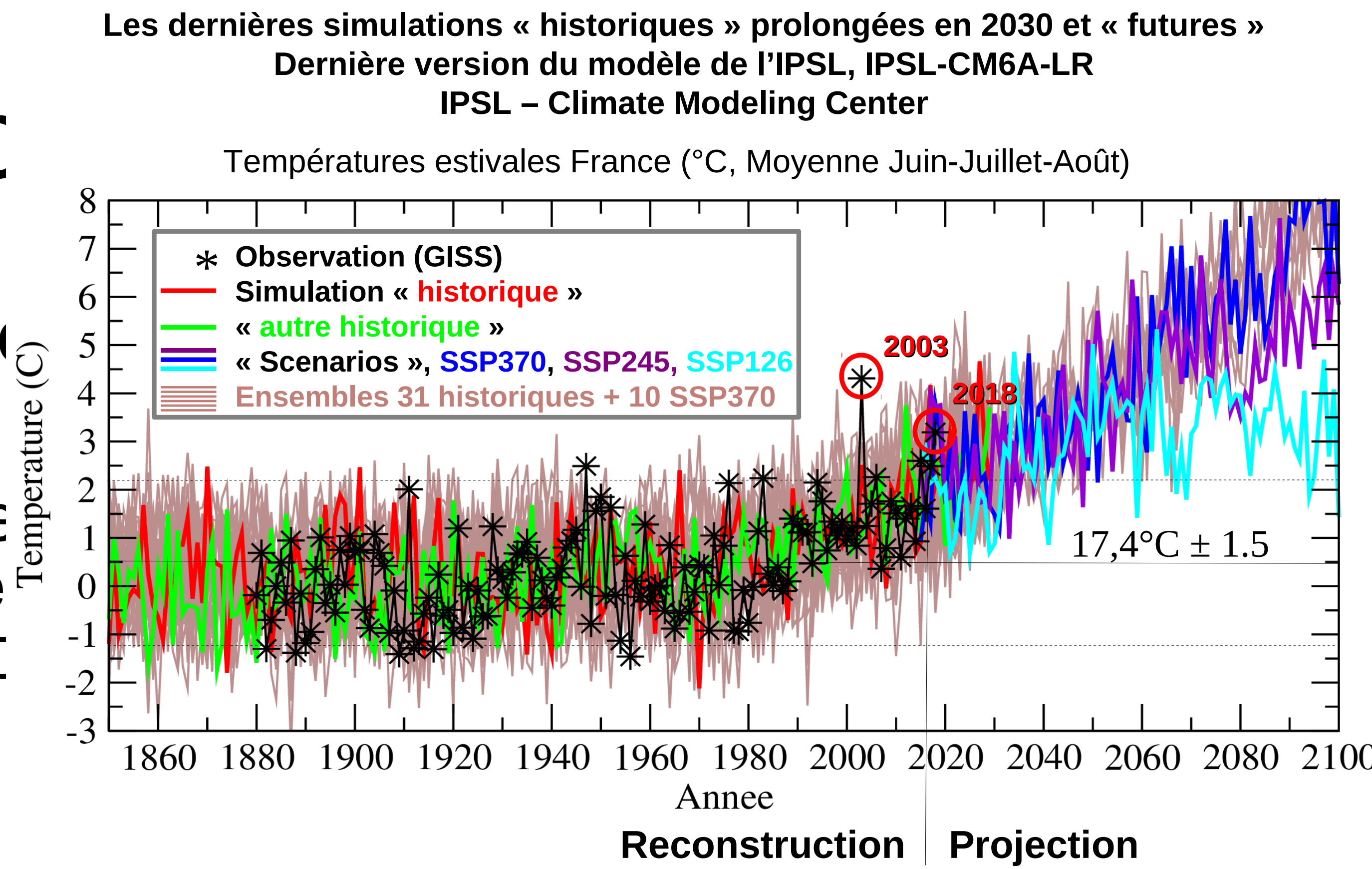


Fig. F. Hourdin, mai 2019

- Dodos
  – Evénements extrêmes “habituels”, mais qui disparaissent dans le futur
    - E.g. vagues de froid extrêmes (?)

Special Extremes (2)

- *Perfect storms (or <u>compound events</u>)*
  - Combination of two or more events without serious consequences, when taken individually, but with a devastating sum
  - E.g., Tohoku earthquake, tsunami and Fukushima plant failure (March 2011)
  - Record crop yield losses in France (2016) due to warm winter followed by a wet spring

Conditional EEA

- Is an extreme *climate* event (e.g. European winter of 2007, UK precipitation in Jan. 2014) explained by the atmospheric variability?
- Estimate the probability of exceeding a high value (monthly or seasonal T, Precip.)…
  - In a factual world (or "new" world 1950-2015)
  - In a counterfactual world (or "old" world 1900-1950)
- ***… Conditional to the atmospheric circulation.***

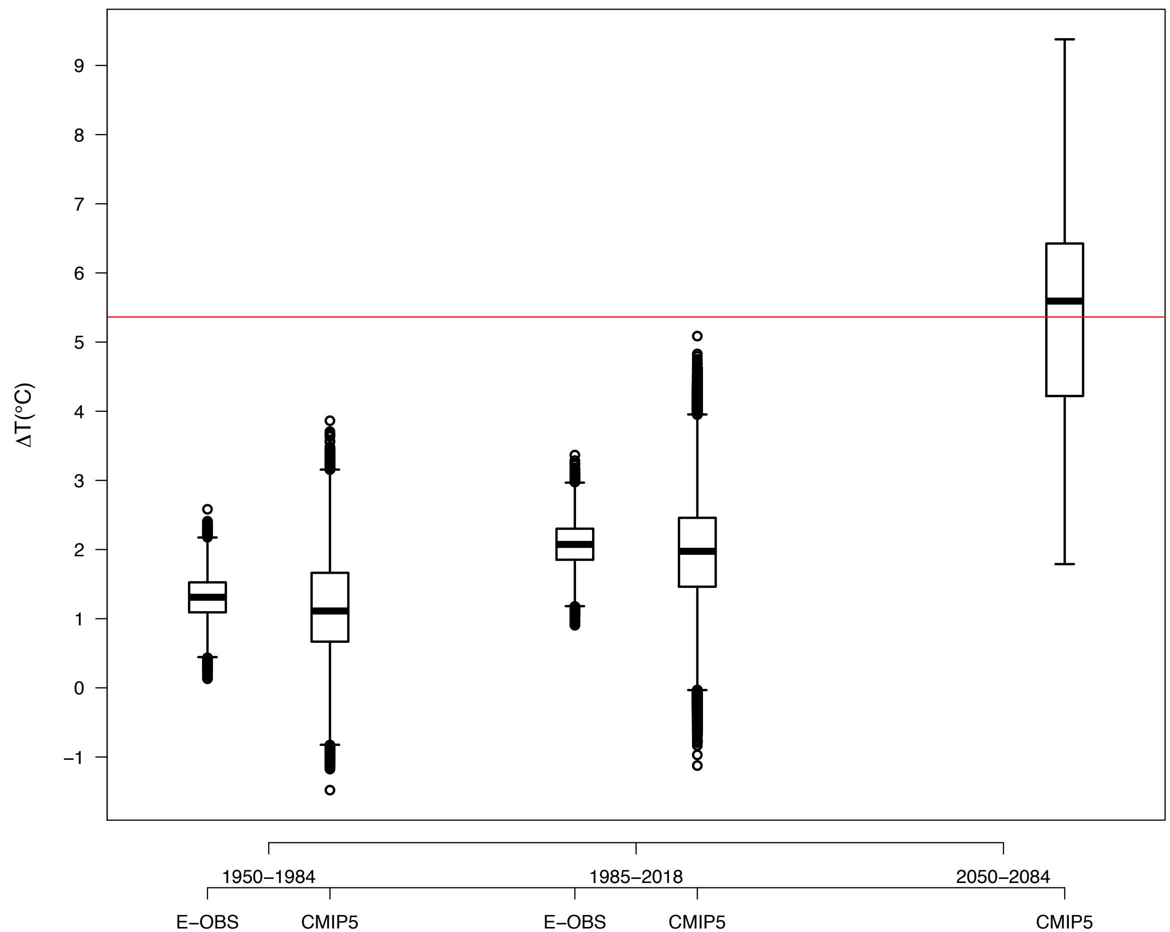
Conditional EEA

- Conditional attribution with atmospheric circulation:
  - Heatwaves, cold spells, winter heavy precipitation
- Analogues of circulation and weather regimes
- Dynamical vs. Thermodynamical contributions

Attribution conditionnelle

Pour une même circulation atmosphérique, quel est l'impact du CC sur la température moyenne de l'événement?

Un événement pratiquement impossible au 20ème siècle devient "typique" à la fin du 21ème siècle.



Daily variations