Simulation of UNprecedented Climate Events (UNCLEs)

Pascal Yiou

With: Flavio Pons, Aglaé Jézéquel, Robin Noyelle, Davide Faranda, Camille Cadiou

LSCE, LMD & IPSL

WORK IN PROGRESS!

Why care for (or worry of) UNCLEs?

- When an extreme event occurs, one often hears: “it could have been worse”
  - How worse?
- When President E. M. stated that cyclone Irma (2017) could not have been anticipated, was this true? (or what did that mean?)

- Can we anticipate/imagine events with a probability $< 10^{-N}$ with just a few decades of observations?
  - Storylines
  - <u>Rare event algorithms</u>

General Mathematical Framework

Hypotheses

- We have a physical system (X) with complex dynamics (e.g. climate system)
- We have (partial, finite, etc.) observations of X: $f(X(t))$
- The observed record value of observations $f(X(t))$ is $\widehat{M_X}$.

Questions

- How to obtain the maximum possible (unobserved) value of f(X) ?
- Is it an “inflated” version of $\widehat{M_X}$?

Climate Motivation

- The 2003 French heatwave had a probability $< 10^{-3}$ (and is still the record for JJA temperature)
- Studying the physical properties of such an event require a fairly large sample of similar events (>1000 years)
- There are no observational records that are long enough to provide enough samples
- *Such events can be outliers for Extreme Value Theory!* ("Black Swans")
- We need climate models!
    - What kind?
    - How to use them?

Simulation of rare/extreme events

- Model or Dynamical system: $X(t) : \frac{dX}{dt} = F(X)$
  - Chaotic, multivariate, high-dimensional
- Scalar observable $T(t)$ of the system X
  - $T(t) = f(X(t))$
- How to simulate trajectories of X that maximize $\langle T \rangle_P = \int_0^P T(t)dt$ over a given period P of time?
  - $\max \langle T \rangle_P$? (e.g. max average summer temperature: $P = 90$ days)
  - Simulate trajectories of X for which $\mathbb{P}\left(\langle T \rangle_P > T_{high}\right) > \alpha_{high}$

Brute force methods

Simulating the system

- Monte Carlo simulations of X to obtain a very large sample of $\langle T \rangle$ (larger than observation length)
- Empirical computation of probabilities of extreme values

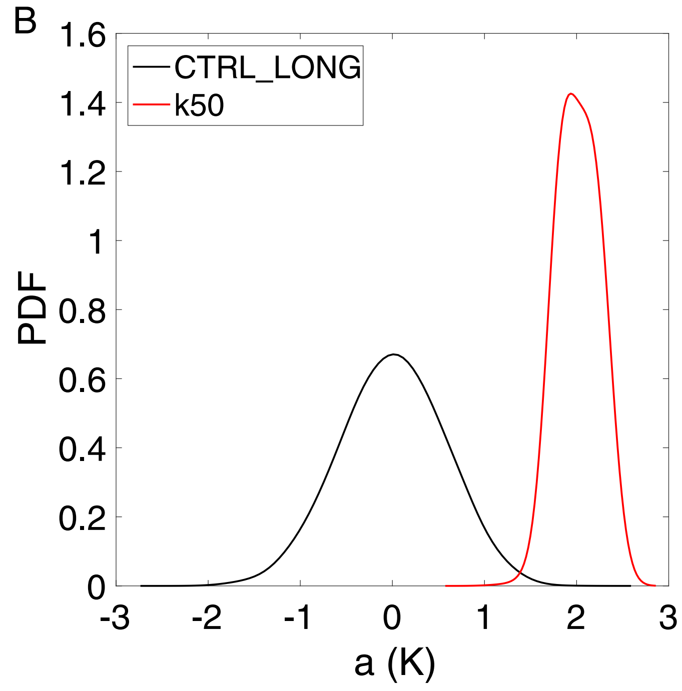
Brute force methods

- Large ensemble simulations
  - Weather@Home: simulate 10^4 summers with a GCM, to obtain a handful of 2003-like heatwaves, or 100 centennial heatwaves
  - Most (i.e. 9900) trajectories are “normal” summers and can be dumped

- **How to simulate 100 centennial heatwaves for the cost of 100 trajectories?**

Rare Event Algorithms (1)

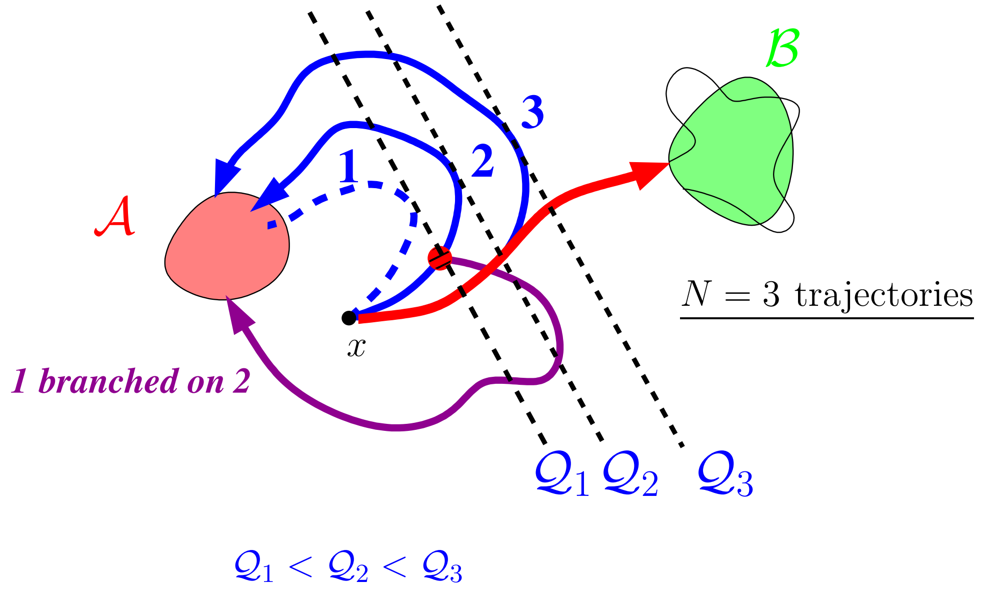
- Consider a physical system, e.g.: $\frac{dX}{dt} = F(X)$
- Procedure to <u>guide</u> trajectories towards <u>high</u> values of $T(t) = f(X(t))$?
- <u>*Rare event*</u> algorithms
  - Evaluate the probability of events from ensemble of optimal simulations
  - Simulate <u>many</u> low probability events



(from Ragone et al., PNAS, 2017)

Example of Rare Event Algorithm (2)

- Select N initial conditions of the system X(t), and an observable T(t) to be optimized
- Run trajectories from t_0 to t_1
- “kill” alpha trajectories for which T(t) is lowest
- Replace them with random perturbations of the remaining ones
- Repeat the procedure until τ (i.e. K times)



(from Ragone et al., PNAS, 2017)

Features of Rare Event Algorithm (3)

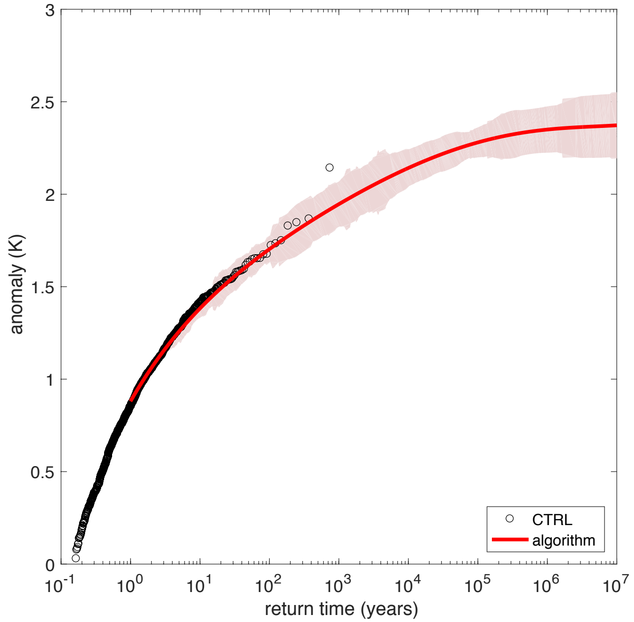
- Probability of final N trajectories after K iterations:

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

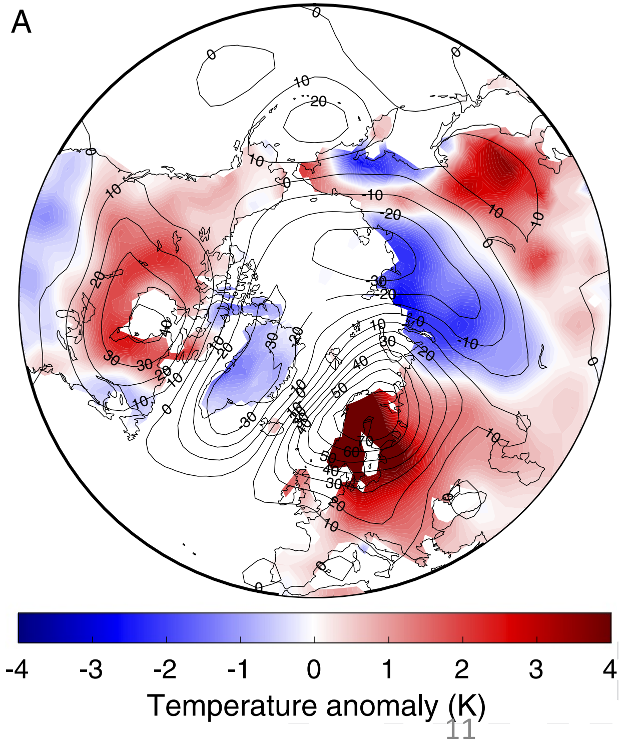
- Note 1: Darwinian procedure
- Note 2: Optimal trajectories satisfy the system's equations of $X(t)$
- Note 3: You must know the equations of the system!

Application to Heatwave simulation (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
- "Regular" control simulation vs. AMS simulations for extremes



Return level plots



Teleconnections during extreme summers

(from Ragone et al., PNAS, 2017)

Properties & Caveats

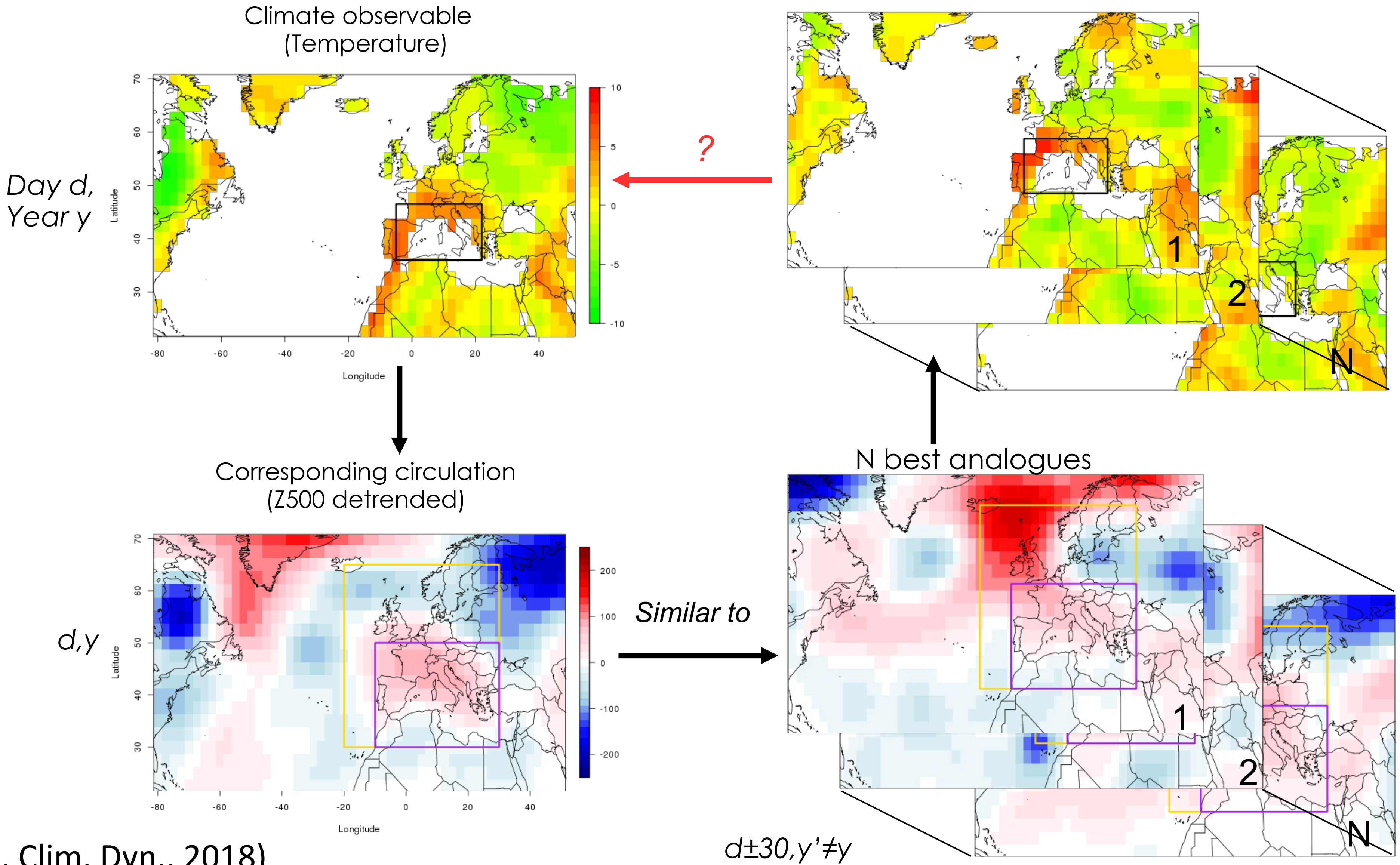
- Control of the return period/probability through α
- No seasonal cycle
  - Requires some adjustments (Ragone et al., GRL, 2021)
- Must simulate the equations of the full system

➢ **How to transpose this into a Stochastic Weather Generator (SWG) framework?**

Analogues and Importance Sampling

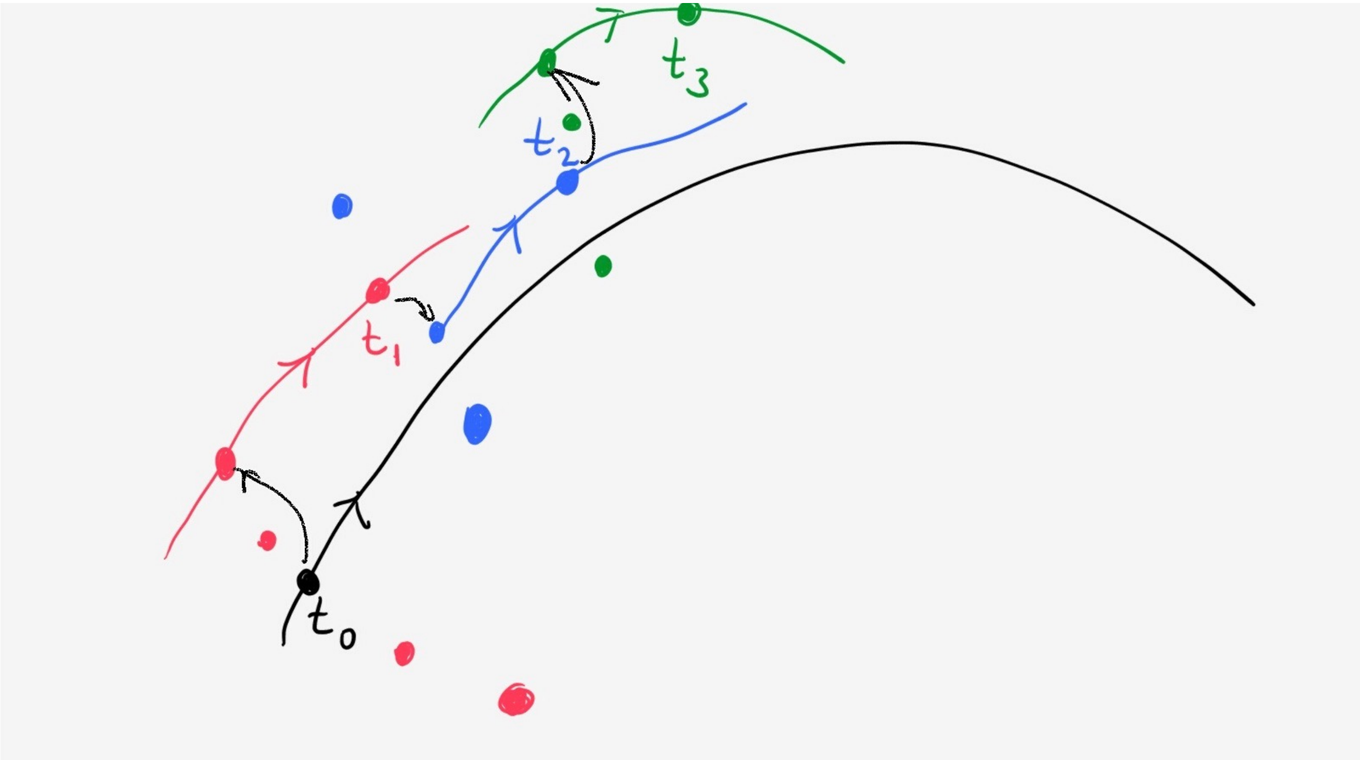
- Adapting Analogue Stochastic Weather Generator to maximize summer temperature
  - Reshuffling analogues of circulation with weight towards highest temperatures
- Static WG:
  - warmest summer that could have been, with the same atmospheric circulation
- Dynamic WG:
  - warmest summer that could have been

Procedure



(Jézéquel et al., Clim. Dyn., 2018)

Analog Stochastic Weather Generator



Random selection of Z500 analogs (among $K = 20$ analogs), with weights that are proportional to the rank of the corresponding day temperature:

$$w_k = \exp(-\alpha \, \mathrm{rank}(T_k))$$

Simulation of ensembles of trajectories that optimize average temperature (e.g. during a season, JJA)

Return period of ensemble is proportional to α

Importance sampling with SWG

Analog SWG: Markov chain with “hidden states” (Z500)

Start at day $t = t_0$ $(= yyyymmdd)$

$\boxed{\text{Z500}(t), T(t)}$

K=20 analogs of Z500

$\boxed{\text{Z500}(t^{(1)}), T(t^{(1)})}$

$\boxed{\text{Z500}(t^{(K)}), T(t^{(K)})}$

$\tilde{t}$: random sample with weights on

- $[t - \tilde{t}|$: move forward in time
- $rank\big(T(t), T\big(t^{(1)}\big), \ldots, T\big(t^{(K)}\big)\big)$
- *Option of* $w = 0$ if $y(\tilde{t}) = 2021$

Take $\tilde{t} + 1$

=1 random trajectory

Iterate $L = 30$ or 60 times

Repeat 100 times

Analog Stochastic Weather Generator

- The analog SWG is a Markov chain of temperatures with hidden states (Z500)
- The rare event algorithm (importance sampling) modifies the probabilistic properties of the ”basic” Markov chain (when $\alpha = 0$) in order to sample realistic trajectories that lead to high temperatures
- Its range of application is for ”long lasting” events
  - The integration time of trajectories has to be large with respect to the integration time step
  - Same constraint as for the paper of Ragone et al. (2017)

Features & challenges

- Variation of a Darwinian mechanism
  - favor the strongest (Yiou and Jézéquel 2019) vs. eliminate the weakest (Ragone et al. 2017)
- Parameters to be optimized!
  - Large-scale predictors in analog pre-computation (Z500, Z500 & RH?, Z500 & SLP?)
  - Which region?
- How to use climate model simulations, e.g. for future climates?
- What "observable" to consider, especially for compound events?

Connexion with the "Committor Function"

- Source set: $\mathcal{A}$, target set: B ($\mathcal{A} \cap \mathcal{B} = \emptyset$), realization of system $X(t)$
- ***Committor function***: probability that $X(t)$ reaches $\mathcal{B}$after leaving $\mathcal{A}$ within lead time τ:
  - $\phi(X_0; \mathcal{A}, \mathcal{B}, \tau) = \mathbb{P}(X(t) \in \mathcal{B}, t \in (t_0, t_0 + \tau] | X_0 = X(t_0) \in \mathcal{A})$

- If the target set $\mathcal{B}$ is a heatwave with probability $p_{\mathcal{B}} \ll 1$,
- $\mathcal{A}$is a set of "normal" initial conditions,

➢we want to optimize $\phi(X_0; \mathcal{A}, \mathcal{B}, \tau)$, i.e. identify initial conditions and trajectories that lead to $\mathcal{B}$ with a probability $p \gg p_{\mathcal{B}}$

Duality with "Ensemble Boosting"

- Ensemble boosting (S. Sippel, E. Fischer, et al.):
  - for a given system $X(t)$ and a target set $\mathcal{B}$ (with low probability), determine a set of initial conditions $\mathcal{A}$ for for which the committor function is maximum (within a lead time τ)
  - Find argmax of committor function ϕ
  - Then "replay" perturbed trajectories from $\mathcal{A}$
- Importance sampling:
  - for a given system $X(t)$ and a target set $\mathcal{B}$ (with low probability), how to reach $\mathcal{B}$ from any initial condition $\mathcal{A}$?
  - Estimate committor function ϕ

Instantons and extreme events

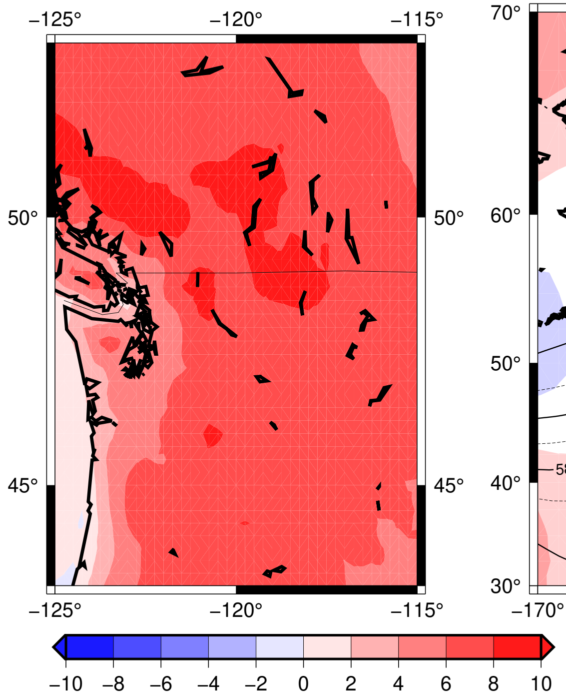
Anna Karenin (L. Tolstoï): “Happy families are all alike; every unhappy family is unhappy in its own way”

- If climate extreme/rare events (e.g. heatwaves) are like “happy families”, is their pathway unique?
- Theory of *instantons* (Freidlin and Wentzell, 1984): if set $\mathcal{B}$ has sufficiently low probability, there is only one way to reach it, which is provided by optimizing a committor function
- Is this true? Caveats? Counterexample?

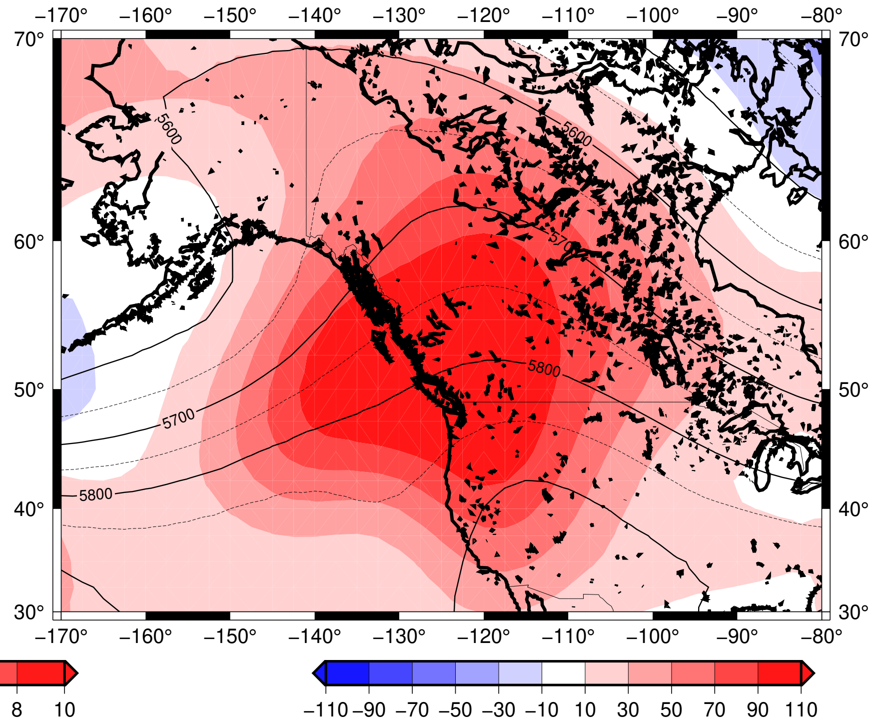
Summer 2021 in North West America

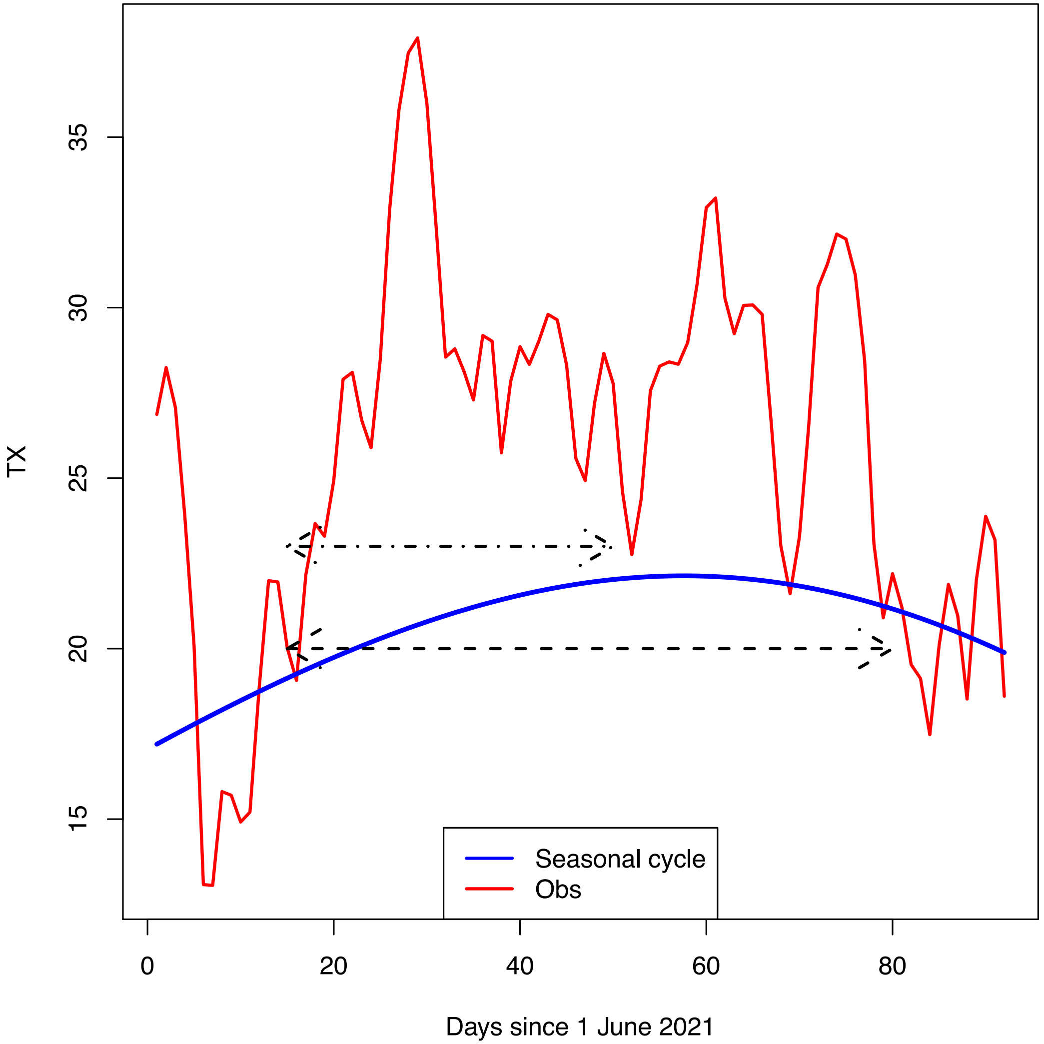
ERA5 (from climate explorer)

TX anomalies

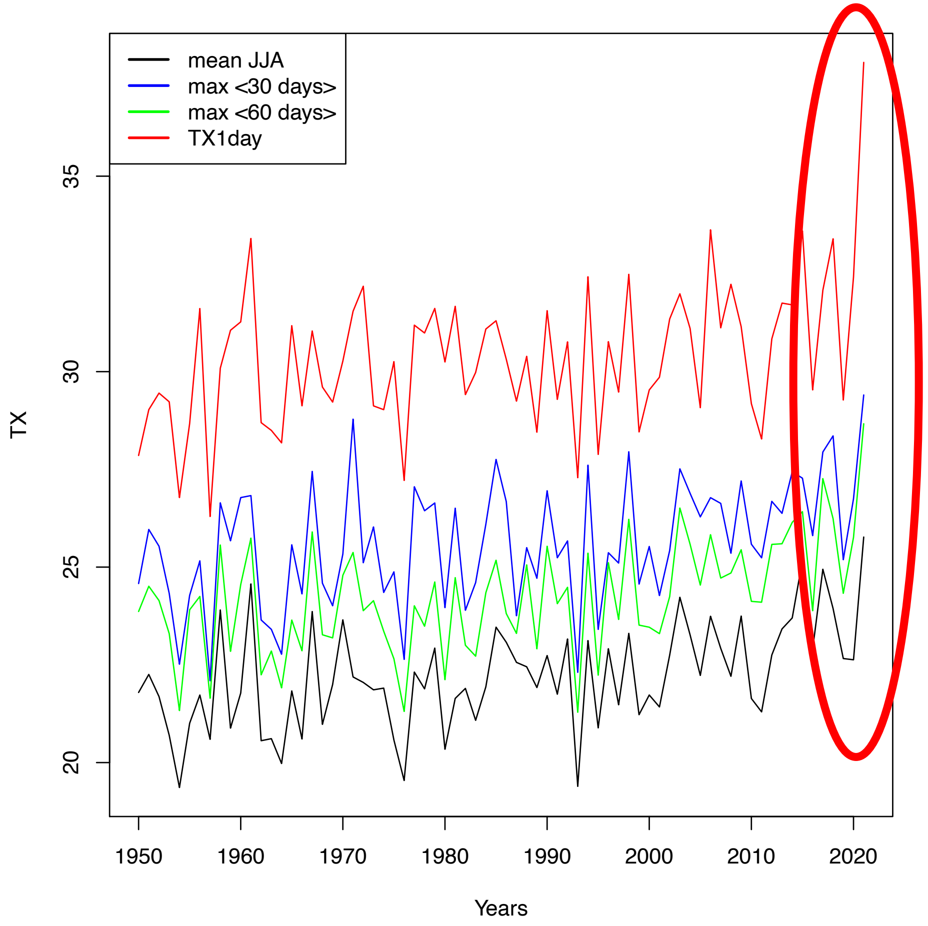


Z500 (+ JJA anomalies)

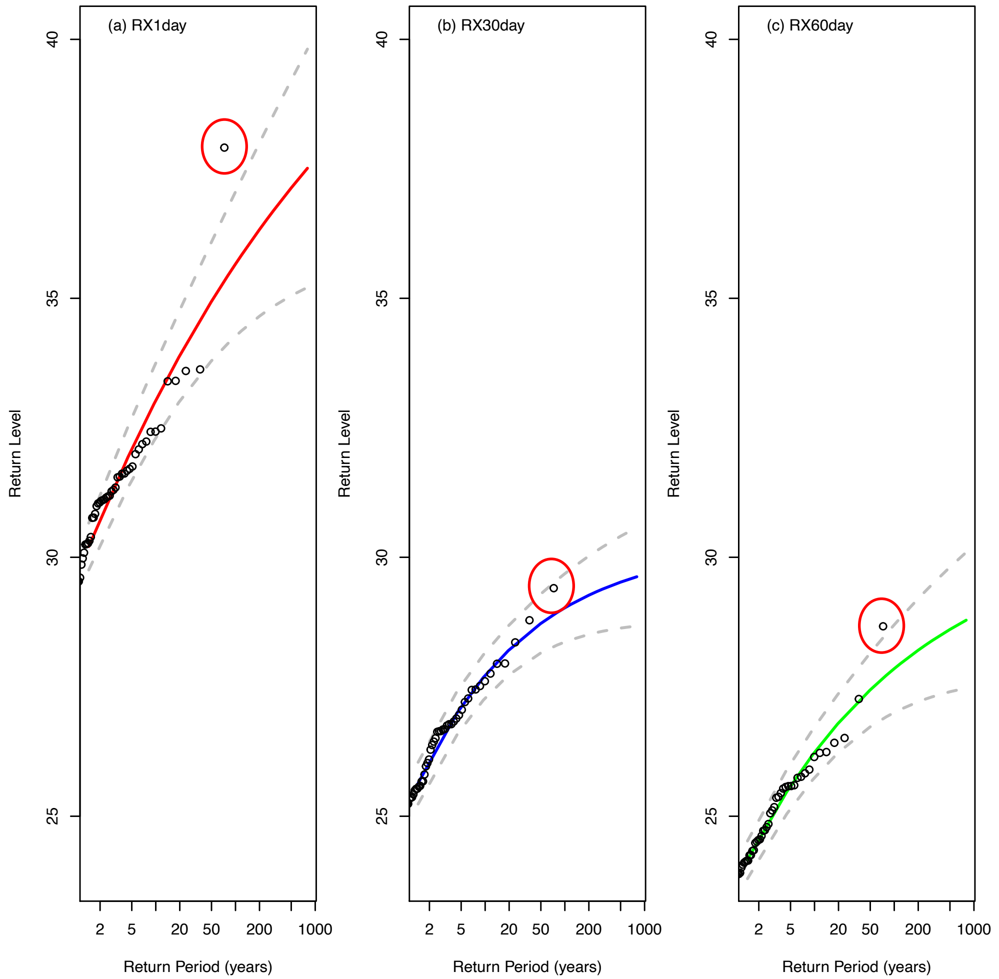




Record breaking/shattering?



Return levels from GEV fits of TX1d, TX30d, TX60d



Out of the distribution event (Gaussian and GEV)?

Challenge

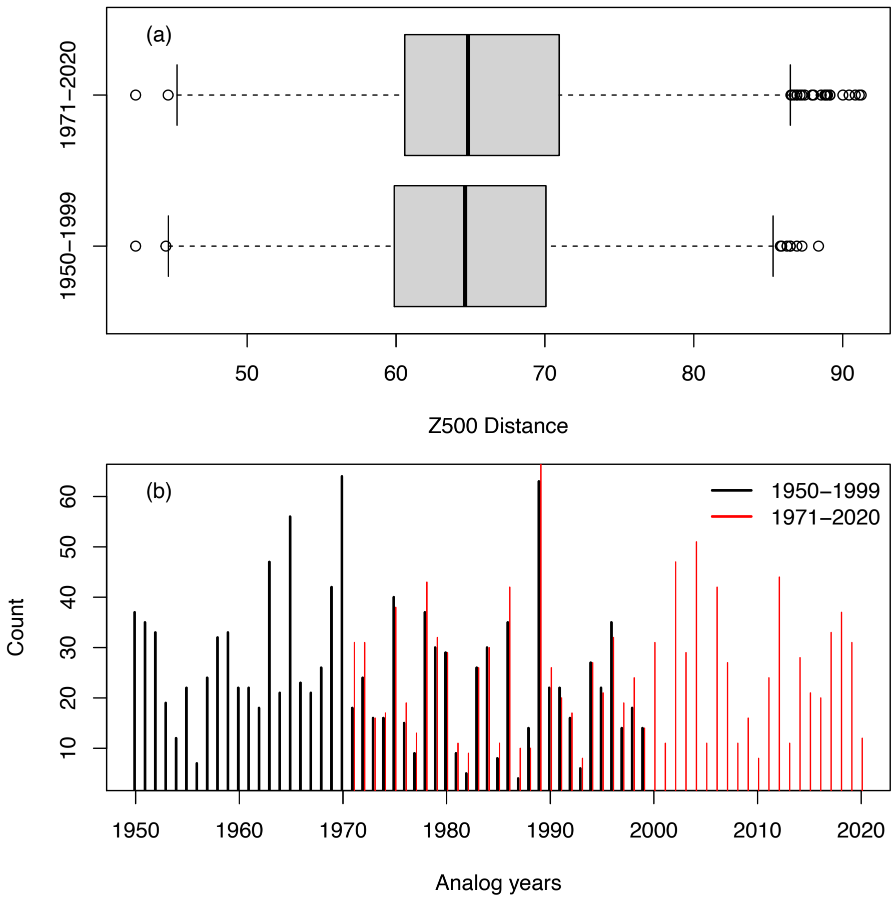
- For short or longer time scales the Summer 2021 is a record:
  - Outside of N σ of distribution with a Gaussian hypothesis
  - Outside of GEV fit
- If a Generalized Extreme Value distribution cannot reach such an event, can we do this with a model?

➢ Simulate an outlier event with a statistical Markovian model (Stochastic Weather Generator: SWG) with a rare event algorithm

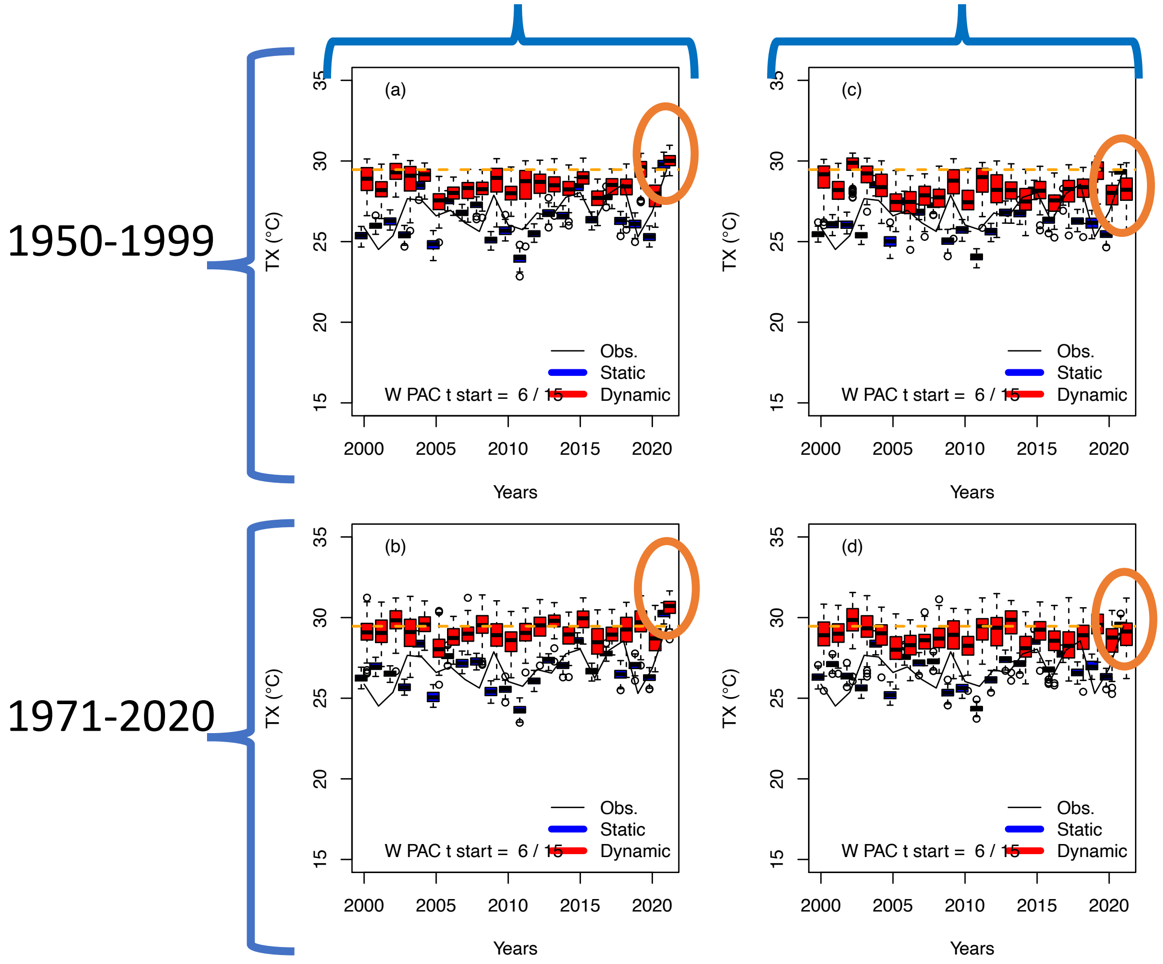
Simulation set-up

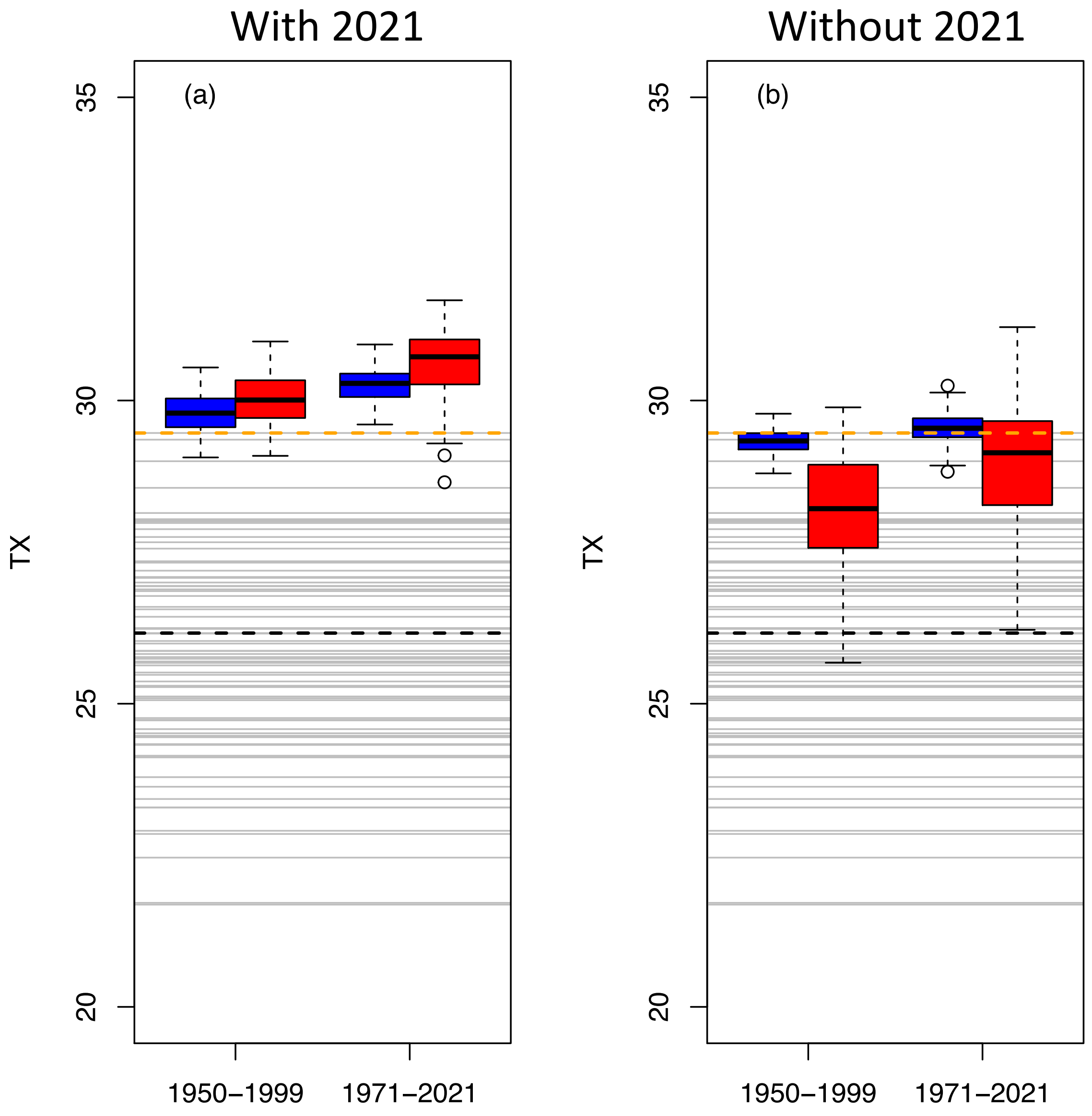
- Z500 analogs of 2000-2021 in 1950-1999 & 1971-2020
  - Here: ERA5 (for T and Z500)
- TX averaged over W America
  - Here: ERA5 [125-115W; 44-52N]
- Flavors of *dynamic* simulations:
  - Initial condition: 15th June
  - Using information on 2021
  - No information on 2021 (even to simulate summer 2021)

No change in analog distance pdf



30 day Simulations



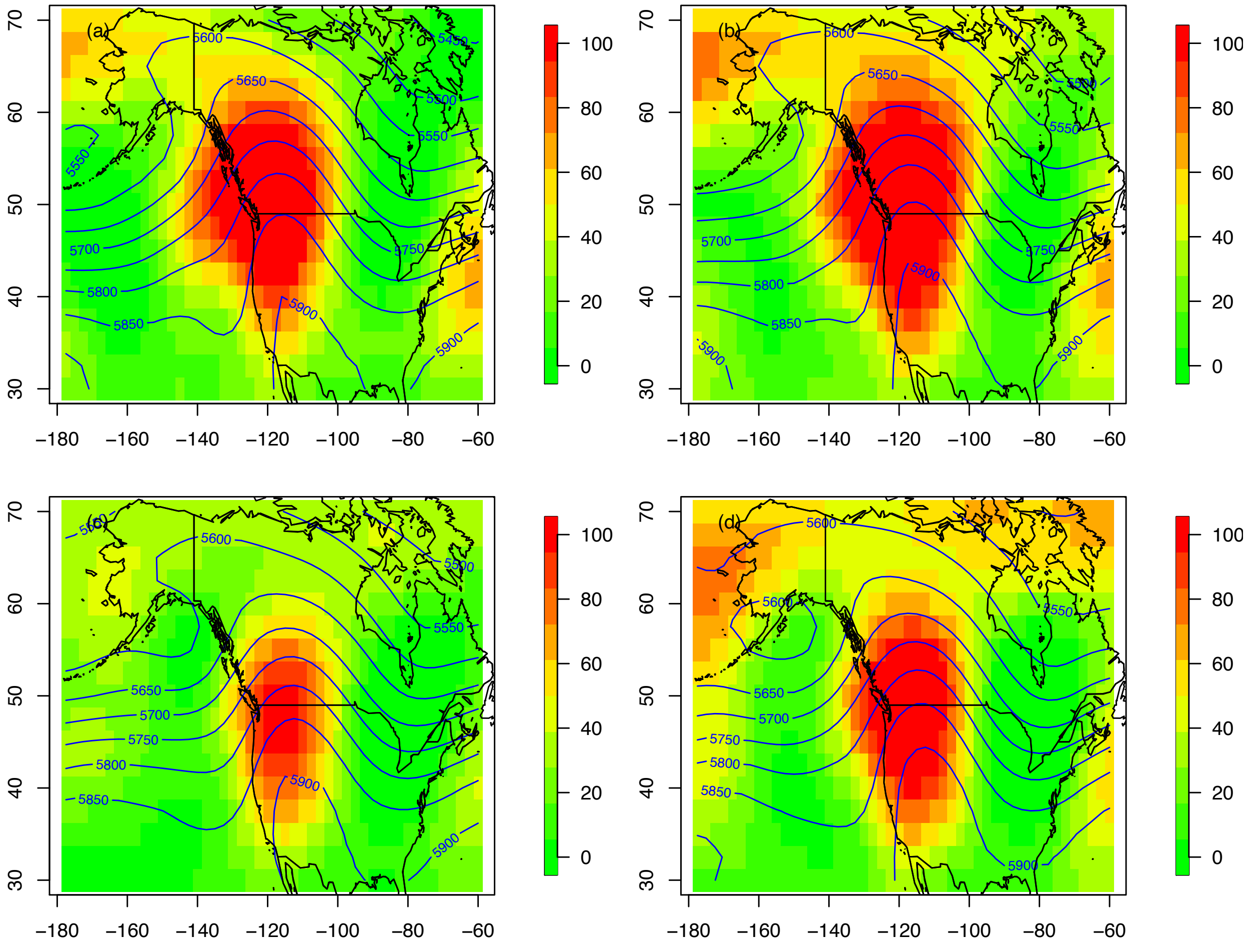


Composite Z500 during 30 day simulations

1950-1999 | 1971-2020

With 2021

Without 2021



- Slight enhancement of anticyclonic patterns between 1950-1999 to 1971-2020
- Strong enhancement of anticyclonic pattern with 2021
- Extreme high temperatures necessitate Omega shaped circulation

Conclusion

- Difficult to exceed 2021 temperature values in 1950-1999 without information on 2021
- The increase of the pdf for extremes is larger than mean (local) climate change
- Necessity of Omega shaped Z500 pattern for extremely high temperatures
    - Unique pathway to reach such an event (instanton)?

Hackathon 09: Simulation of worst cases

- West Pacific Heatwave of 2021
- A heatwave around (continental) France
- A heatwave in Paris during the 2024 Olympics
- Questions:
  - Can we top or exceed the records with present day conditions?
  - What is the atmospheric circulation during those heatwaves?

Hackathon 09: Plan

- Precomputed analogs of Z500 or SLP (from reanalyses or CMIP6)
- Daily time series of temperatures
- Code (R and shell script) on github
  - For windows-ers: please use the code provided on the ICTP dropbox

Some references

- Jézéquel, A., Yiou, P. & Radanovics, S., Role of circulation in European heatwaves using flow analogues, Clim Dyn (2017) 50: 1145. https://doi.org/10.1007/s00382-017-3667-0
- Pfleiderer, P., Jézéquel, A., Legrand, J., Legrix, N., Markantonis, I., Vignotto, E., and Yiou, P.: Simulating compound weather extremes responsible for critical crop failure with stochastic weather generators, Earth Syst. Dynam., 12, 103–120, 2021, https://doi.org/10.5194/esd-12-103-2021.
- Ragone, F., J. Wouters, and F. Bouchet, 2018: Computation of extreme heat waves in climate models using a large deviation algorithm. Proc. Nat. Acad. Sci., 115, 24–29.
- Ragone, F., and F. Bouchet, 2021: Rare event algorithm study of extreme warm summers and heatwaves over Europe. Geophys. Res. Lett., 48, e2020GL091197, https://doi.org/10.1029/2020GL091197
- Yiou, P., Jézéquel, A., 2019. Simulation of Extreme Heatwaves with Empirical Importance Sampling. Geosci. Model Dev. Discuss. 2019, 1–26. https://doi.org/10.5194/gmd-2019-16
- Yiou, P.: AnaWEGE: a weather generator based on analogues of atmospheric circulation, Geosci. Model Dev., 7, 531-543, doi:10.5194/gmd-7-531-2014, 2014.