Tools to Forecast, Anticipate, Attribute Climate Extremes

Pascal Yiou, Camille Cadiou, Meriem Krouma, George Miloshevich, Robin Noyelle, Flavio Pons

LSCE, IPSL

General Motivation

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 $f(X)$?
- What are the precursors of $\widehat{M_X}$?
- Is $\widehat{M_X}$ affected by climate change? (and how?)

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")
  - Fischer et al. (Nature Comm. 2023)

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 $X(t)$:
  - $T(t) = f(X(t))$
- 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 $\mathbb{P}\left(\langle T \rangle_P > T_{high}\right) > \alpha_{high}$

Forecast/Anticipate/Attribute Extreme Events

The system $X(t)$ reaches an extreme state $\mathcal{A}$:

- $\mathbb{P}(X(t) \in \mathcal{A}) = p_{\mathcal{A}} \ll 10^{-N}$

$p_{\mathcal{A}}$ could be very hard to estimate due to the lack of data

- Challenge 1: What is $\mathcal{A}$ for $0 < p_{\mathcal{A}} \ll 10^{-N}$?

- Challenge 2: Estimate conditional probabilities when $\mathcal{A}$ is known
  - $p_t(\tau) = \mathbb{P}(X(t+\tau) \in \mathcal{A} | X(t))$

Challenge 1: What is $\mathcal{A}$ for $0 < p_{\mathcal{A}} \ll 10^{-N}$?

- Rare event algorithms:
  - Simulate rare trajectories of X leading to an extreme
  - Examples: simulate extremely hot summers or extremely cold winters (Ragone et al. PNAS 2017)
- General framework(s):
  - Large deviation theory
  - Ensemble boosting (e.g. Gessner et al. J. Clim. 2021)
- Requirements:
  - Models (physical or statistical)
- End uses:
  - Anticipation of worst case scenarios, e.g. *storylines* (Sillmann et al., Earth's Future, 2021)
  - Does climate change affect $\mathcal{A}$? (Attribution of extremes)

Challenge 2: Estimate $p_t(\tau)$

- Simulations of $X(t)$ for various initial conditions (Ragone et al., PNAS, 2017)
- General framework:
  - Ensemble forecast
- End uses:
  - Identify conditions where $p_t(\tau) > p_0 \gg p_{\mathcal{A}}$ (i.e. precursors of $\mathcal{A}$)
    - Forecast of extremes (Miloshevich et al., 2023)
  - Are those conditions affected by climate change?
    - Attribution of extreme

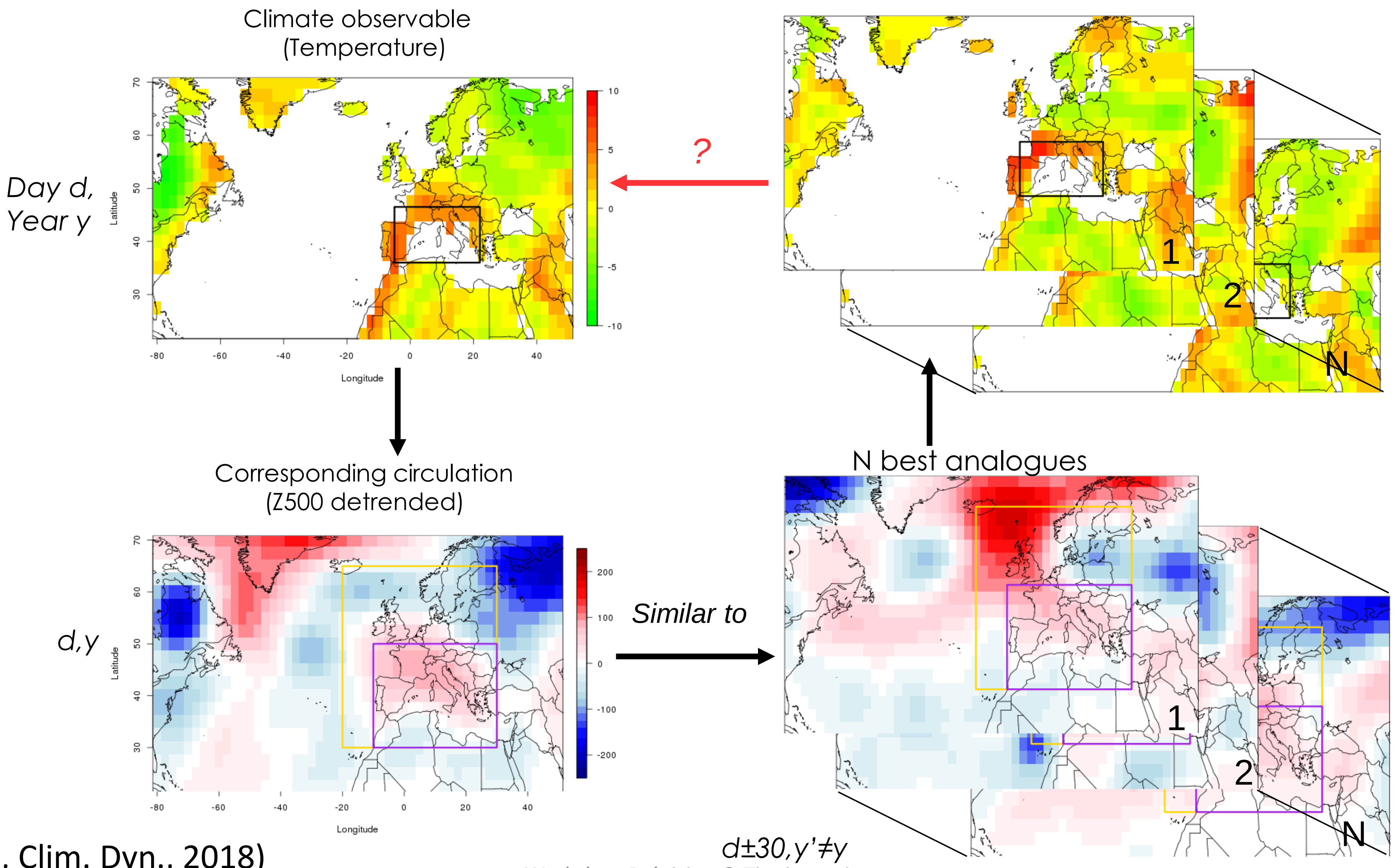
A Cost Effective Framework

- Analogs of circulation to simulate temperatures in the mid latitudes
- Stochastic Weather Generator (SWG) as a climate *emulator* for extremes
  - How to address the challenges of simulating worst cases and the impact of climate change?
- Focus on case studies
  - Paris Olympics in 2024
  - A worst case cold winter

Analogues and Importance Sampling

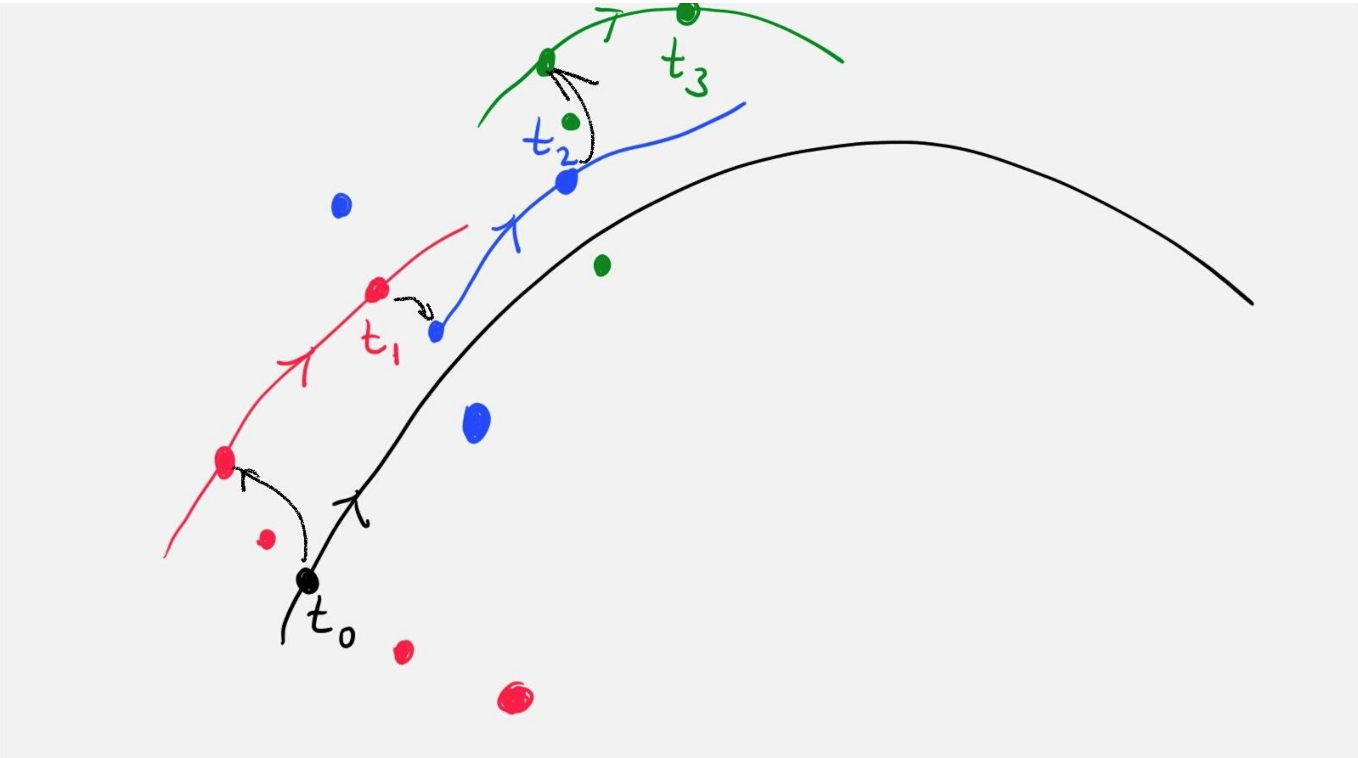
- Adapting Analogue Stochastic Weather Generator (Yiou, GMD, 2014) to maximize summer temperature (Yiou and Jézéquel, GMD, 2021)
  - Reshuffling analogues of circulation with weight towards highest temperatures
- Static WG:
  - warmest summer that could have been, with the same atmospheric circulation
- Dynamic WG:
  - warmest summer that could have been

Procedure



(Jézéquel et al., Clim. Dyn., 2018)

Analog Stochastic Weather Generator



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

Return period of ensemble is proportional to α

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

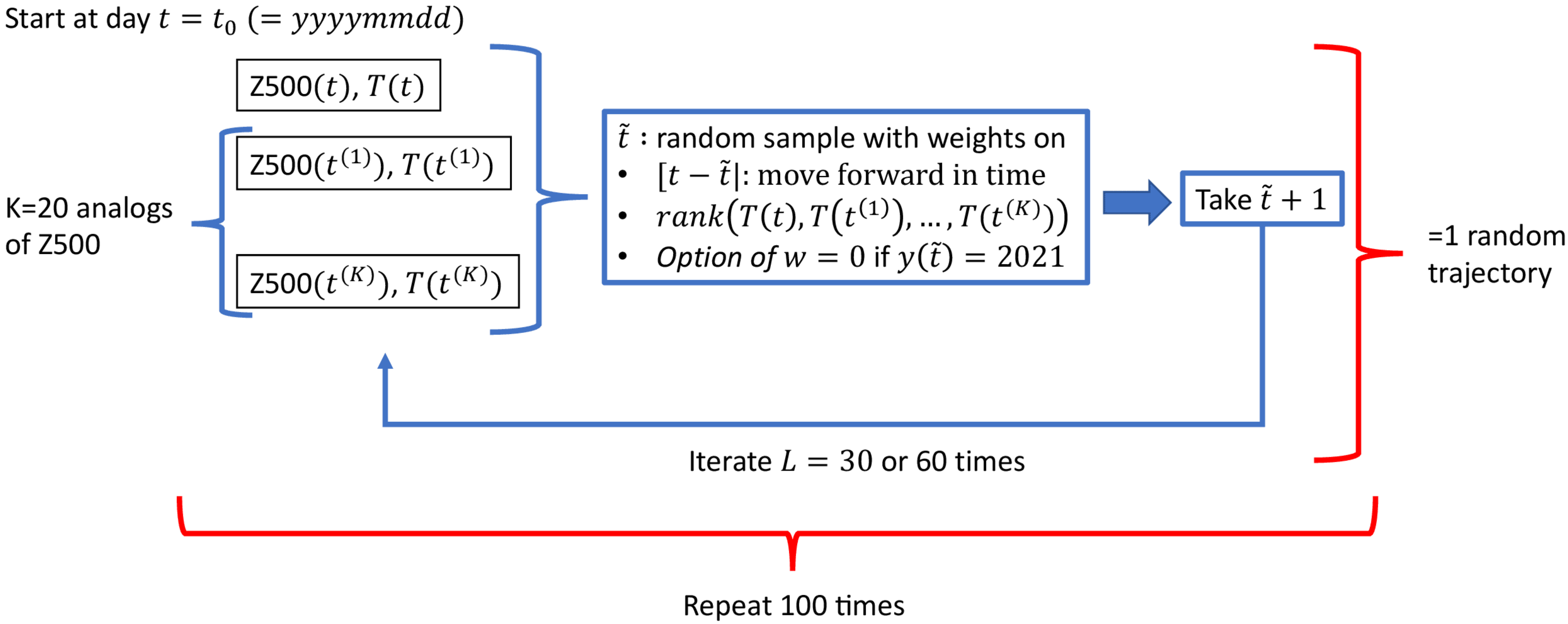
$$w_k = \exp(-\alpha_T \,\mathrm{rank}(T_k))$$

Weights on the distance to the calendar day to be simulated

$$w_k = \exp(-\alpha_{cal} \,|t_k - t|)$$

(Yiou and Jézéquel, GMD, 2021)

Importance sampling with SWG



Analog Stochastic Weather Generator

- The analog SWG is a Markov chain of temperatures with latent 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 (months, seasons)
  - 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. (PNAS, 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?

Simulating worst case heatwaves during the Paris 2024 Olympics

Pascal Yiou

With: C. Cadiou, D. Faranda, A. Jézéquel, N. Malhomme, G. Miloshevich, R. Noyelle, F. Pons, M. Vrac

LSCE, LMD & IPSL

Challenge: Paris Olympics 2024

- Paris 2024: 26/07 to 11/08 2024
  - Apex of the temperature seasonal cycle
- **Can the record shattering event of 2003 be broken in 2024?**

- Consider TG15d in JJA (max of T15d in JJA)
- Four SSP scenarios of CMIP6 (2015-2050) + historical (1950-2014) simulations, with R2D2 bias correction

Data: TG15d in Ile de France

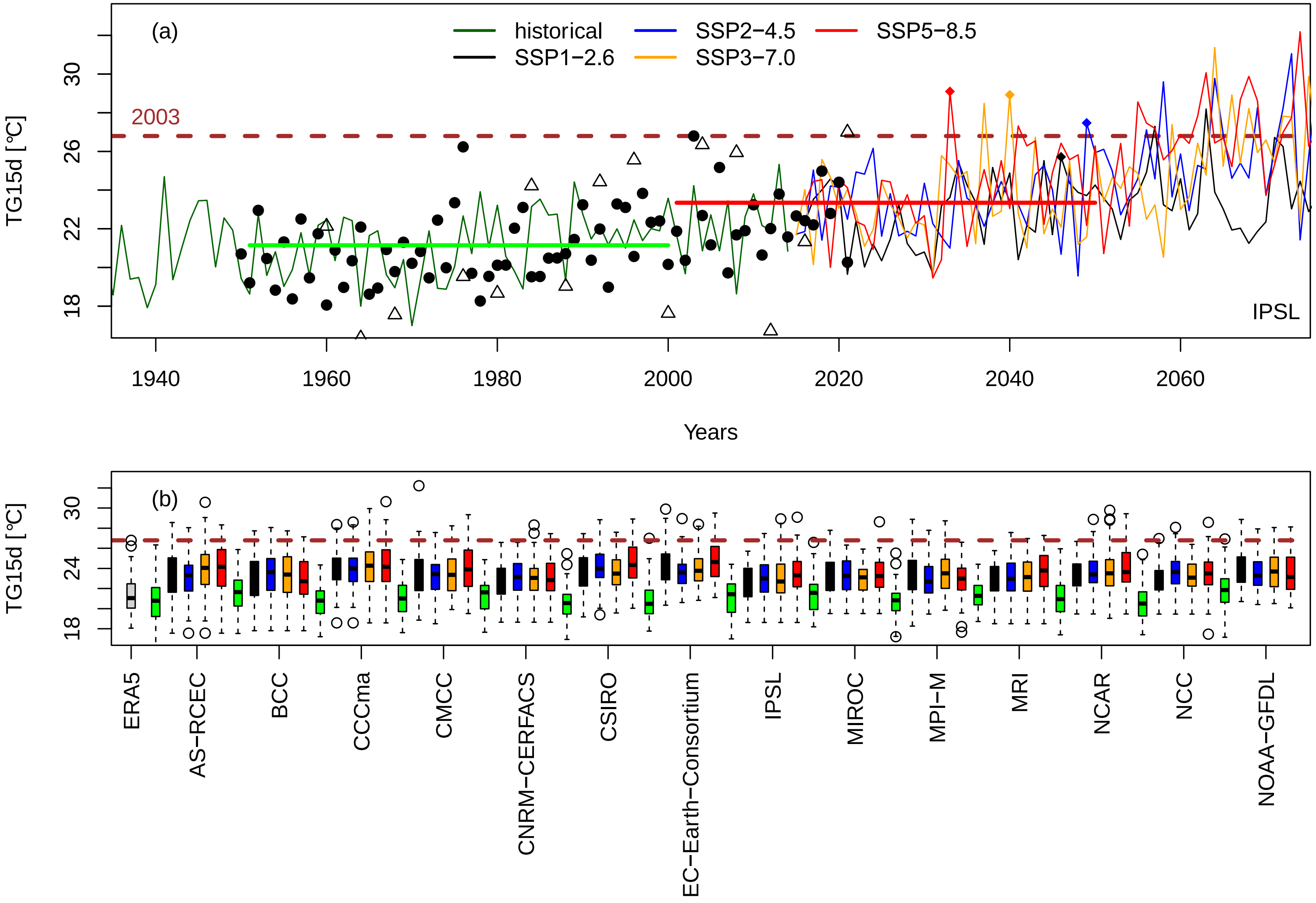
TG15d in
- ✓ historical,
- ✓ SSP1-2.6, 2-4.5, 3-7.0 and 5-8.5

simulations of IPSL-CM6-LR

TG15d in ERA5

TG15d during preceding Olympics

Boxplots of TG15d of Ile de France in CMIP6 with R2D2 (*) bias correction



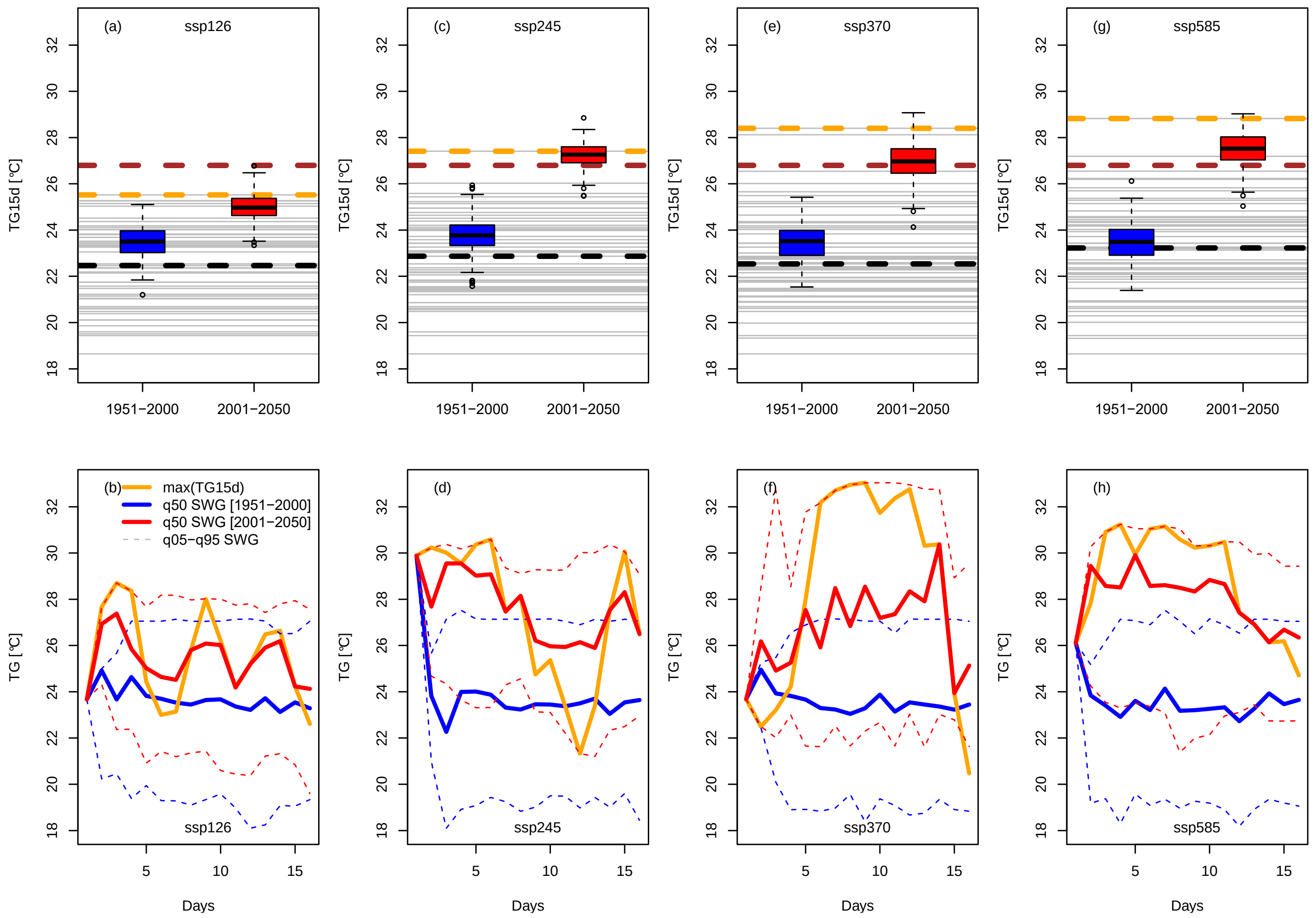
(*) Vrac, M., and S. Thao, GMD, 2020

SWG simulations based on IPSL model

Step 1: Find the highest TG15d in 2001-2050 (and its first day)

Step 2: Simulations start on the highest TG15d of IPSL-CM6-LR with analogs in 1951-2000 and 2001-2050

2003 record exceeded in 3 SSP scenarios

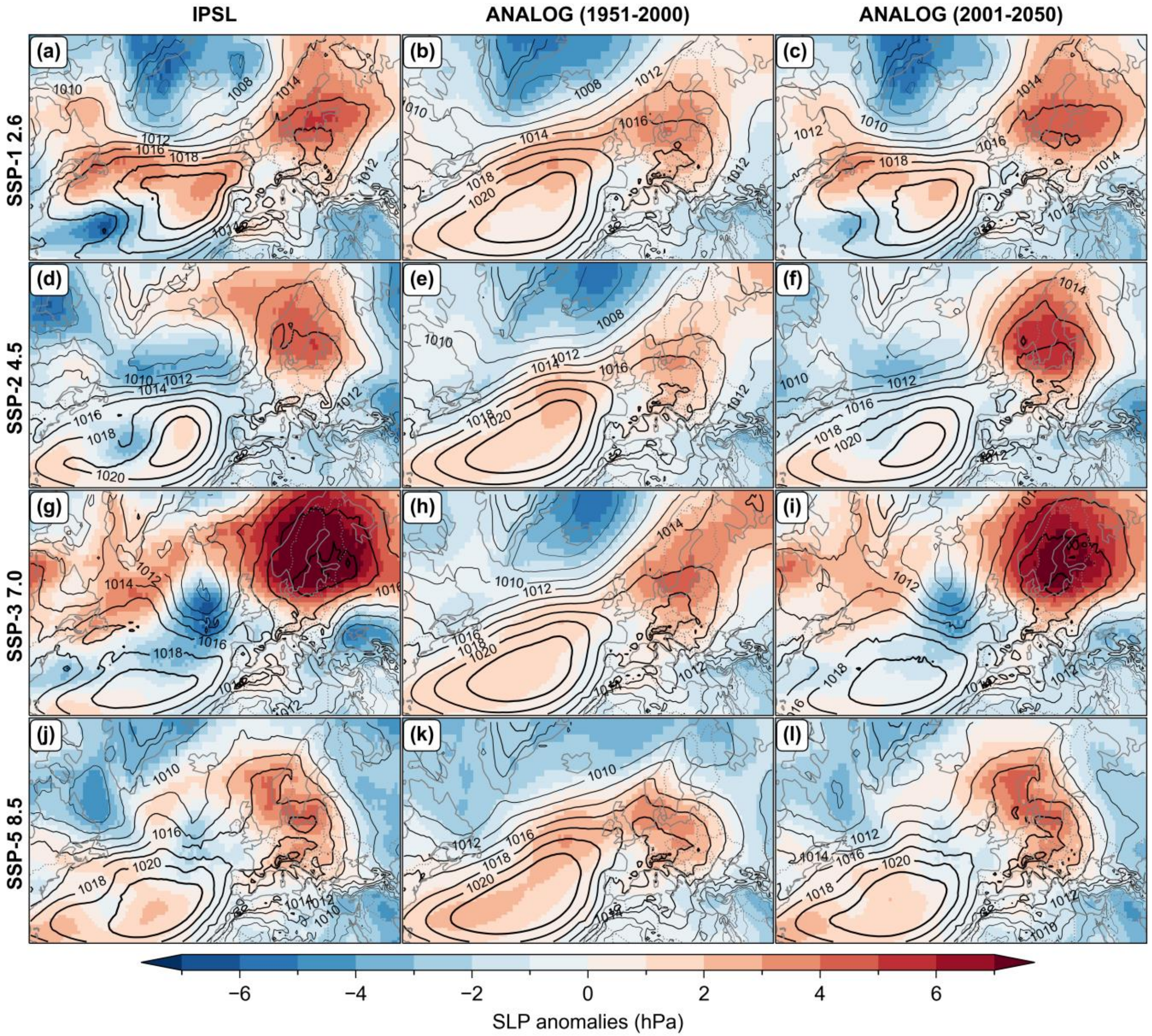


SLP composite pattern

Composites of SLP for identified records of TG15d (between 2001 and 2050)

Composites of SLP for SWG simulations with analogs in 1951-2000 and 2001-2050

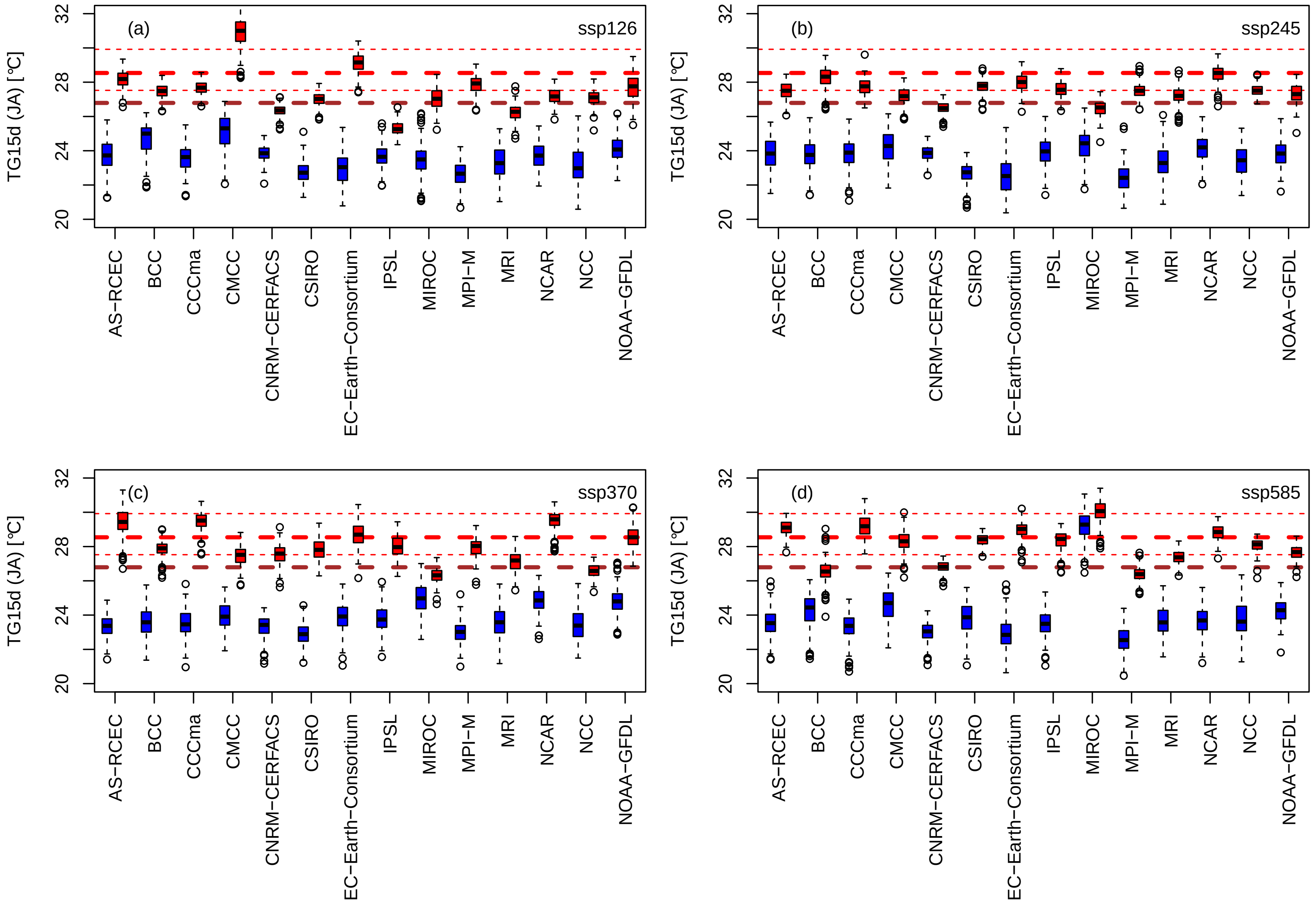
Anticyclonic conditions + cut-off low?



CMIP6 SWG

Initialize SWG from warmest TG15d conditions (Y < 2050) for all CMIP6 models, all SSP. Compare with analogs

- in 1951-2000
- In 2001-2050



Cold winters in Europe

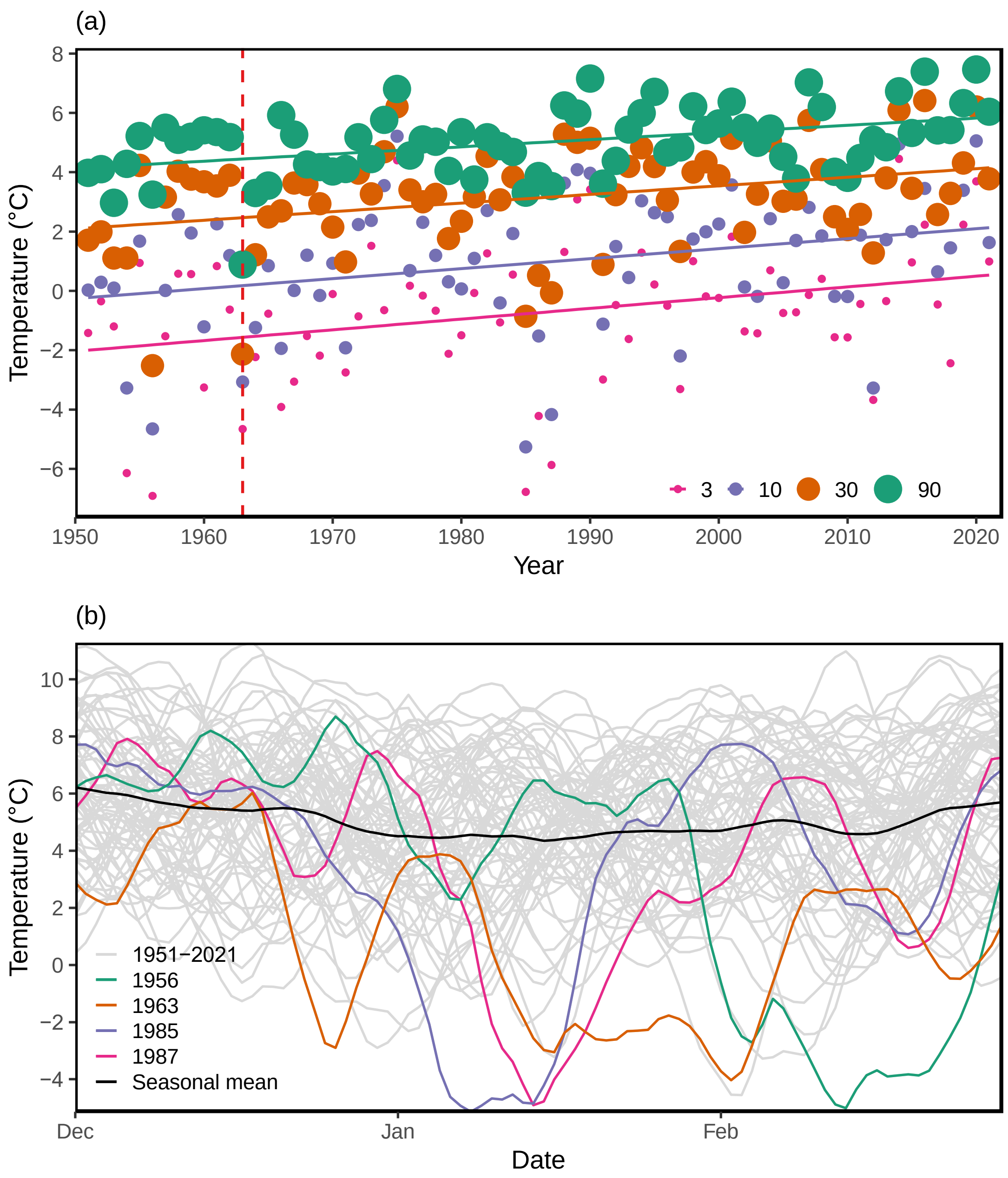
Dependence on time scale (from 3 days to whole winter)
Impacts on the energy & health sectors

Record breaking cold winter in 1962/1963

- a record shattering event: more than 2σ colder than average
- Several cold spells during the winter

In spite of the increasing temperature, can such a cold winter be reached?

Cadiou and Yiou (2023)



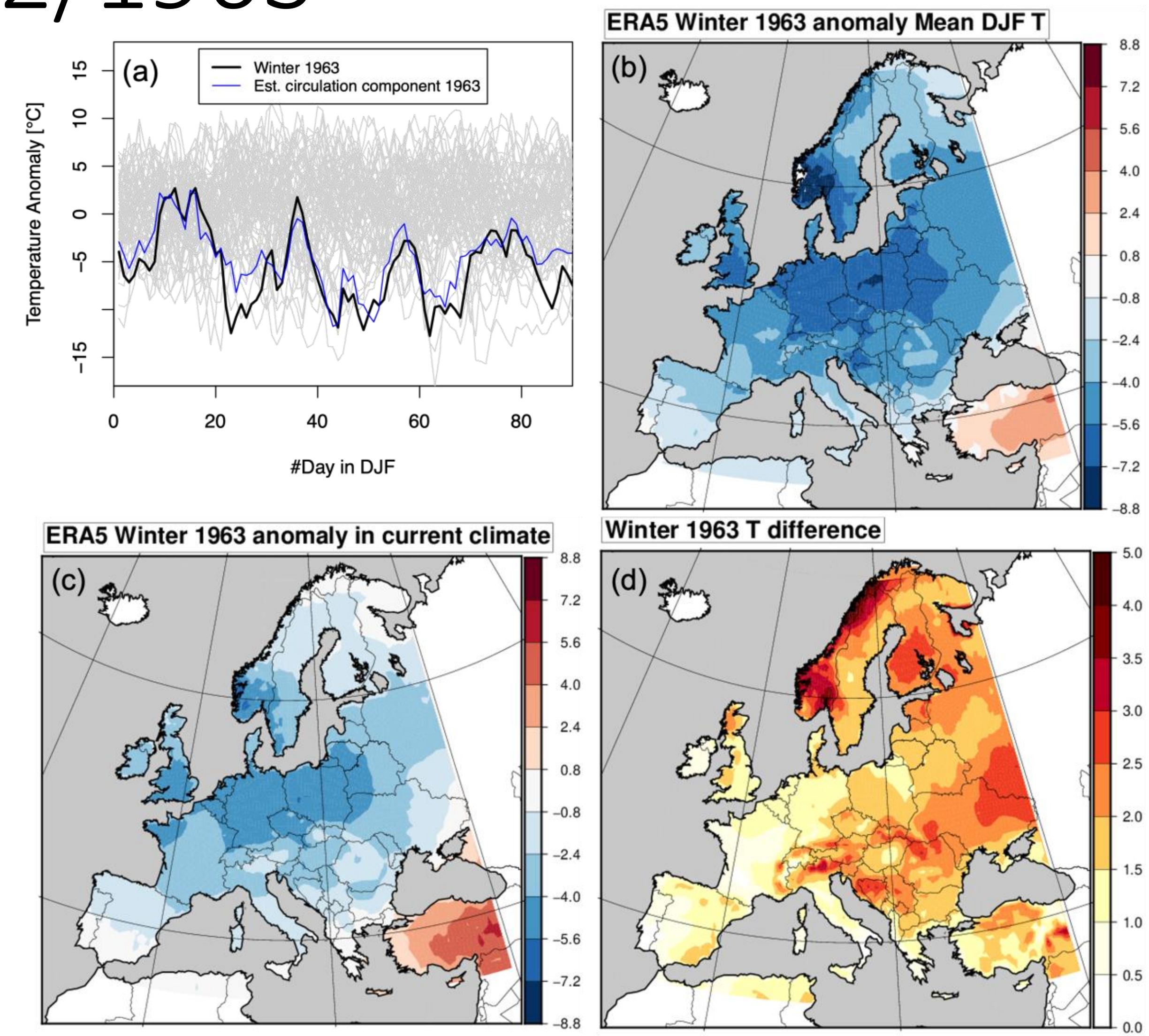
The Cold Winter of 1962/1963

How cold would be a winter with a similar atmospheric circulation in present-day climate?

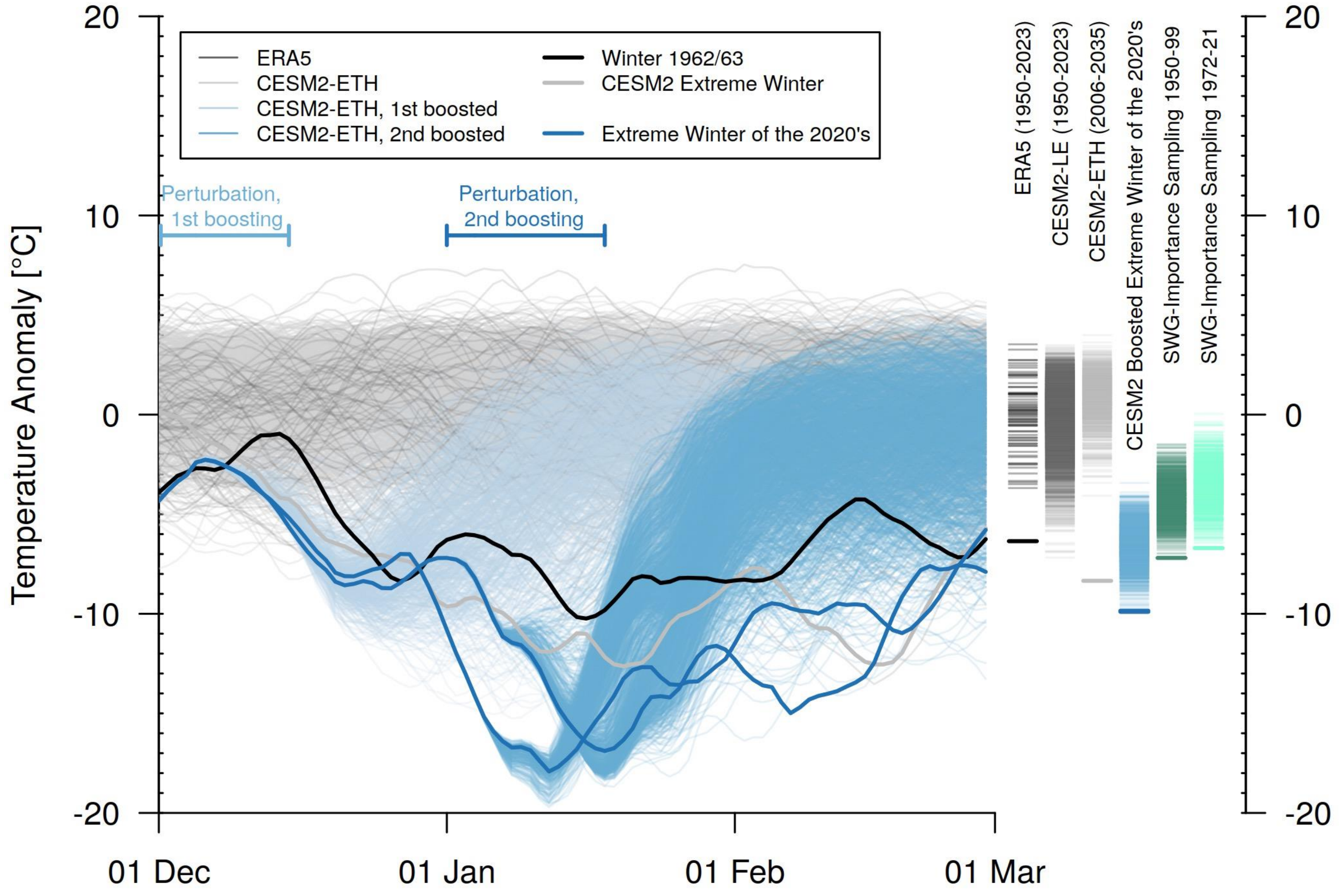
Strategy

- Simulate a climate model with initial conditions close to Dec. 1st 1962
  - CESM2 (ETH Zurich): boosting by selecting cold trajectories
  - SWG (IPSL)

Sippel et al. (2023)



Simulating the coldest winters in Germany



Sippel et al. (2023)

Model boosting "à la" ETH Zurich (Gessner et al., J. Clim. 2021):

- Start on Dec. 1st 1962
- 900 simulations of 90 days
- 2nd boosting in Jan. 1963: restart from the coldest simulation (strong convergence to seasonal cycle)

Colder winters than 1963 are possible in present day climate with CESM2 boosting and SWG simulations (based on ERA5)

Conclusions

- Heatwave during the Olympics?
  - ~~Forecast~~
  - Anticipation
  - Attribution: 2003 record can be exceeded with analogs in 2001-2050, hardly with analogs in 1950-2000.
- A record breaking cold winter in Europe in 2024?
  - Lower probability than in the 20th century BUT still possible
  - December 1962 initial conditions can lead to such cold winters

Perspectives?

- Can heatwaves be predicted: Estimation of committor function from SWG (G. Miloshevich):
- How to reach the upper bound of maximum daily temperature (R. Noyelle)