Simulating record-shattering cold winters of the 21st century in France

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Abstract

Extreme winter cold temperatures in Europe have huge societal impacts on society. Being able to simulate worst-case scenarios of such events for present and future climates is hence crucial for short and long-term adaptation. In this paper, we are interested in low probability cold events, whose probability is deemed to decrease with climate change. Rather than simulating very large ensembles of normal climate trajectories, rare event algorithms allow sampling the tail of distributions in an efficient way. Such algorithms have been applied to simulate extreme heat waves. They have emphasized the role of atmospheric circulation in such extremes. The goal of this study is to evaluate the dynamics of extreme cold spells simulated by a rare event algorithm. We focus first on winter cold temperatures that have occurred in France from 1950 to 2021. We investigate winter mean temperatures in France (December, January, and February) and identify a record-shattering event in 1963. We find that, although the frequency of extreme cold spells decreases with time, their intensity is stationary. We applied a stochastic weather generator approach with importance sampling, to simulate the coldest winters that could occur every year since 1950. We hence simulated ensembles of worst winter cold spells that are consistent with reanalyses. We find that a few simulations reach colder temperatures than the record-shattering event of 1963. The atmospheric circulation that prevails during those events is analyzed and compared to the observed circulation during the record-breaking events.

1 Introduction

Winter cold spells in the mid latitudes have had wide-ranging impacts, affecting agriculture (Trnka et al., 2011; Vogel et al., 2019), health (Gasparrini et al., 2015; Smith and Sheridan, 2019), infrastructures (Chang et al., 2007), or energy systems (Añel et al., 2017; Bessec and Fouquau, 2008; Van Der Wiel et al., 2019). Cold events are expected to decrease both in terms of intensity and frequency with climate change in most regions of the world (Seneviratne et al., 2021), which could lead to a reduction of their impacts. In the last decades a decrease in intensity has been recorded in the Western European region (Cattiaux et al., 2010; Seneviratne et al., 2021; Smith and Sheridan, 2020; Van Oldenborgh et al., 2019). But even if their probability decreases, extreme cold winter events still occur and can cause major disruptions, like winter 2010 in Western Europe (Cattiaux et al., 2010) or the cold snap of February 2021 in Texas (Doss-Gollin et al., 2021). Winter 2010 was perceived as extremely cold in Europe and rose questions in the media and general public about

the occurrence of extreme cold events under climate change. Cattiaux et al. (2010) showed that winter 2010 was actually not as extreme as records of the previous decades and would have been much more extreme given the same atmospheric conditions if it had occurred in a past climate with a lower influence of climate change. This is consistent with the general upward trend of winter minimum temperatures as shown in Fig. 1a.

However, uncertainties remain about the potential dynamical effects of climate change on severe winter mid-latitudes weather (Cohen et al., 2020; Horton et al., 2015; Overland et al., 2016; Shepherd, 2015). The Arctic Amplification (AA) is a mechanism that may lead to an increase in severe winter weather in the mid-latitudes (Cohen et al., 2014; Francis et al., 2018; Francis and Vavrus, 2012; Vavrus, 2018). But its potential effect is intertwined with other hemispheric drivers of decadal variability and the quantification of its influence remains debated (Blackport and Screen, 2020; Cohen et al., 2020; Francis, 2017). Several studies have also shown that winter warming and winter anomalies trends are not as large as the upward trend of summer warm anomalies in the northern hemisphere (Robeson et al., 2014) and more specifically in France (Ribes et al., 2022). The decrease in winter cold spells would consequently not be as significant as the increase in summer heat waves.

To assess worst case scenario winter temperatures in France, we use the winter 1962-1963 as a reference event. Winter 1963 yielded an exceptionally low mean temperature anomaly over December, January and February (DJF) of -3.4σ (Fig. 1a). 1963 was also extreme by its spatial scale, with negative temperatures covering most of Europe (Greatbatch et al., 2015; Hirschi and Sinha, 2007; O'connor, 1963). This lead to exceptional weather across the continent: large lakes, like Lake Constance or Lake Zurich, froze entirely and widespread and persistent snow coverage was observed in the British Isles. According to the Met office, it was the coldest winter since 1740 in the United Kingdom. In France, a first intense cold wave occurred at the end of December, lasting one week, followed by a second more prolonged cold wave with negative daily mean temperature over France from the 11th of January to the 6th of February (Fig. 1b). Winter 1962-1963 was associated with a negative North Atlantic Oscillation (NAO) index, indicating lower than normal pressure difference between the Iceland low and Azores high-pressure systems (Cattiaux et al., 2010; Greatbatch et al., 2015). A persistent negative NAO phase is usually associated with the development of North-Atlantic atmospheric blockings (Shabbar et al., 2001), and a weakening of the westerlies allowing outbreaks of cold air coming from the Arctic or Russia into Western Europe

(Greatbatch, 2000; Hurrell et al., 2003).

According to the definition of Fischer et al. (2021), winter 1963 was a record-shattering event in France, i.e. the record of low temperatures was broken with a large margin of several standard deviations (Fig. 1a). Therefore, winter 1962-1963 was an extremely low probability event, even considering the colder climate (than in the 21st century) in which it occurred. If the average winter temperature follows a Gaussian distribution, this corresponds to a return period larger than 10^3 years, which is longer than observational periods. The objective of this study is to examine whether such a winter is still possible in the 21st century, considering the warmer climate in western Europe in present times.

Simulating ensemble of events whose return period is larger than the observational period, or the typical length of climate model simulations (e.g. $\approx$200 years for CMIP6 (Eyring et al., 2016)) requires intensive computing resources. Several methods based on principles of statistical physics have been developed to provide fast and realistic simulations of large values of atmospheric variables. Rare events algorithm using importance sampling (e.g. Ragone and Bouchet, 2021) have been designed to specifically simulated extreme heat waves from a climate model. An alternative approach is based on Stochastic Weather Generators (SWG). SWGs are Markov processes used to generate large ensembles of atmospheric trajectories with realistic statistical properties, at a low computational cost (Ailliot et al., 2015). Yiou and Déandréis (2019) combined an SWG based on analogs of circulation developed by (Yiou, 2014) and the importance sampling principle exposed in (Ragone and Bouchet, 2021) to specifically simulate extreme summer heat waves from analogs of circulation. This method allows to simulate ensemble of physically consistent trajectories of extreme events at a very low computational cost. In this study, we adapt the analog-based stochastic weather generator with importance sampling of Yiou and Déandréis (2019) to the simulation of extreme cold winter events.

We use SWG simulations based on reanalysis data in order to assess the intensity of the worst-case winter scenario in France in a counterfactual period (with lower influence of climate change) and a factual period representing the present-day climate with more detectable influence of climate change. Therefore, we examine how climate change affects the intensity of worst case cold winters that can hit France.

The paper is organized as follows. Section 2 presents the datasets used in the paper and

details the analog-based stochastic weather generator model for sampling cold winters. Section 3 shows the results of the simulations of extreme winters. Section 4 discusses the main results of the study.

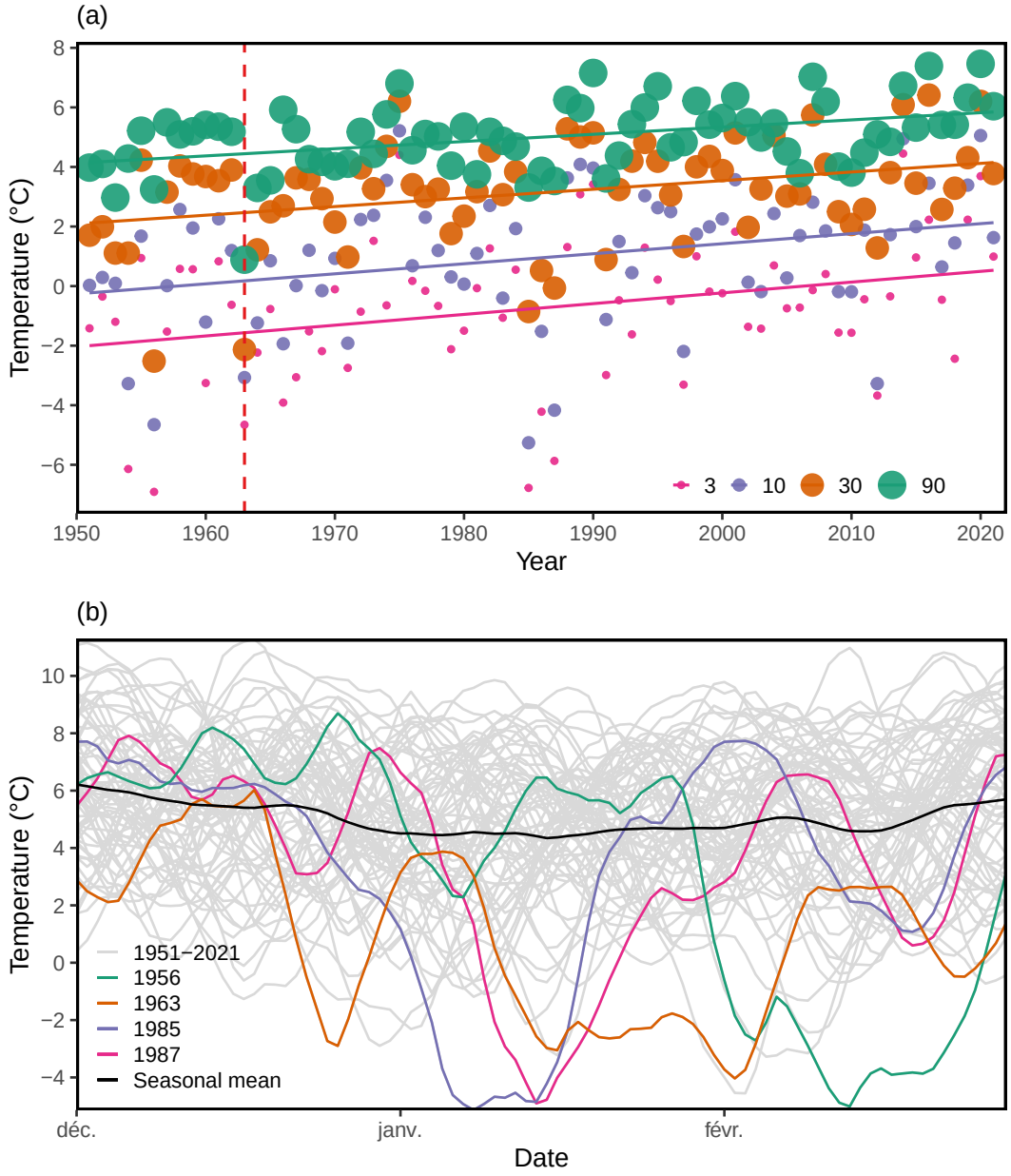

Figure 1: ***(a)*** *Minimum of winter temperatures over DJF for four time scales in continental France. For each winter we compute the n-day running mean of daily mean temperature for* $n \in \{3, 10, 30, 90\}$ *days and select the minimum value. The colored lines are linear regressions of the temperature averages. The vertical dashed line outlines 1963 (coldest winter in France).* ***(b)*** *Time series of DJF 7-days running mean temperature at 2m from 1950-1951 to 2020-2021 in continental France. The curves in colour are for the four coldest years (1956, 1963, 1985 and 1987) and the black curve is for the seasonal mean computed over 1951-2021.*

2 Data and Methods

2.1 Data

Daily mean surface temperature ($t2m$) data were obtained from the 5th version (ERA5) of the atmospheric reanalysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al., 2020). Data from 1950 to 2021 has been retrieved with a spatial resolution of $0.25° \times 0.25°$. Daily temperature fields were averaged over the smallest spatial domain including metropolitan France (5°W – 9°E ; 42°N – 52°N). ERA5 was chosen for its large time coverage and its high horizontal resolution of 0.25°.

We compute running averages of temperature for four time scales (r = 3, 10, 30 and 90 days) and determine the minimum value for each winter (from December to February). This corresponds to identifying the coldest r-day period for each year, or TNrd. Fig. 1a shows the variations of TNrd time series for France. We observe a upward trends of TNrd at the four time scales r. The records at each time scale occurred before 1990. However, extreme cold events still happened in the 21st century: winter 2012 witnessed the 5th coldest 10-day and the 8th coldest 3-day cold spells of the 1950-2021 period. At the 30-day time scale, February 1956 and January 1963 were two very extreme events, with temperature anomalies to the 1950-2021 trend of respectively -2.9σ and -2.8σ. One event really stands out in the 90-day winter temperatures: winter 1963 is at 3.7σ from the trend of winter mean temperatures and 2.2σ under the second coldest winter in 1950-2021, winter 1952-1953. For conciseness, this paper focuses on TN90d, i.e. DJF average temperatures.

For the computation of analogs of circulation, we use daily geopotential height at 500 hPa (Z500) from ERA5 reanalysis from 1950 to 2021. Z500 was chosen over SLP because of its lower sensibility to perturbations from the surface roughness and its common use on weather regime studies (Corti et al., 1999; Yiou and Nogaj, 2004; Jézéquel et al., 2018; Dawson et al., 2012). Jézéquel et al. (2018) also showed it was better suited to simulate temperature anomalies, although that study investigated warm temperatures. Z500 data were regridded on a $1° \times 1°$ grid to reduce computation time since a higher resolution has little impact on the analogs calculation because of the smooth spatial variability of Z500 fields. We considered the Z500 field over the North Atlantic region (20°W – 30°E ; 30°N – 70°N) to compute circulation analogs. This domain offers a compromise between a spatial coverage large enough to study the role of the synoptic circulation but small

enough not to drown out the signal in the too complex hemispheric circulation.

2.2 Methods: Analogs of circulation

We first compute a database of analogs of circulation following the procedure of (Yiou and Jézéquel, 2020). For a given day t, we compute the Euclidean distance of the Z500 fields between t and all days t' that are not in the same year or season (astride two following years) and within a calendar distance to t inferior to 30 days. The K analogs days of t are the K days for which the distance from t is the smallest. We chose $K = 20$ analogs, as advocated in previous studies (Krouma et al., 2022; Platzer et al., 2021).

The circulation analogs were computed using the "Blackswan" Web Processing Service (Hempelmann et al., 2018). We consider three different analog data sets, depending on the time period in which the analogs are selected:

1. 1950-2021: the whole length of available ERA5 data,
2. 1950-1999: the past period, as a counterfactual, with less influence of anthropogenic climate change.
3. 1972-2021: the present period, as a factual, with a significant signal from climate change.

The analog periods were chosen to have sufficient length to be representative of all the possible states of the atmospheric patterns while being characteristic of climate periods that are significantly different. We were constrained by the length of the ERA5 data available (only 71 years). Therefore we chose a compromise between analog depth and low overlap by considering two 50-year periods (1950-1999 and 1972-2021).

2.3 Methods: Stochastic Weather Generator and importance sampling

The analog-based stochastic weather generator (hereafter referred as SWG) developed by Yiou (2014) uses stochastic reshuffling of daily atmospheric fields to generate atmospherically-consistent alternative trajectories of climate events. This algorithm was adapted by Yiou and Jézéquel (2020) to simulate extreme heat waves using a principle of importance sampling. The goal is to simulate L day trajectories of a model while optimizing an observable. Here, the observable is the average temperature over France. For simplicity, this paper focuses on $L = 90$ day events, starting on a 1st of December, i.e. the whole winter (December-January-February).

Here we focus on the so-called "dynamic" type of simulations, developed by Yiou (2014), which computes alternative atmospheric trajectories starting with the same initial conditions as an observed event. We start at an initial condition t_0. To simulate temperature for the day after t_0 ($t = t_0 + 1$), we randomly pick one analog among the K best analogs of t. This analog day is the simulated day t'. For the next time step, t is replaced by $t' + 1$, the day following t'. This random process is repeated sequentially for L time steps, the length of the simulation. This defines a Markov chain with hidden states provided by the analogs of Z500.

At each time step, the selection of the analog day follows several constraints and weights controlled by the parameters that are described hereafter. To better follow the seasonal cycle of the simulated season, we use K weights $\omega_{cal}^{(k)}$ ($k \in \{1, \dots, K\}$) on the analog selection that depend on a parameter α_{cal} which favours analog days that are closest to the calendar date of time step t :

$$\omega_{cal}^{(k)} = A_{cal} e^{-\alpha_{cal} d_k} \tag{1}$$

where A_{cal} is a normalizing constant, $\alpha_{cal} \geq 0$ is the calendar weight and d_k is the number of calendar days between the k^{th} analog day and t. We simulated ensembles of trajectories of 90 days starting on Dec. 1st of each year, with different values of parameter α_{cal}. Figure 2a shows the percentage of simulations for which the last day of the simulations falls after the 15th of February. With too low calendar weight (e.g. $\alpha_{cal} = 1$), fewer than half of the simulations end with a calendar day after the 15th of February. This means that the trajectories of the simulated events with $\alpha_{cal} = 1$ are less consistent with the seasonal cycle. With an α_{cal} parameter greater than 5, more than 75% of the simulations have their last day falling after the 15th of February. Therefore we use $\alpha_{cal} = 5$ in the following.

To favour the simulation of the most extreme events, importance sampling weights $\omega_T^{(k)}$ are introduced, with a control parameter $\alpha_T \geq 0$. The higher α_T, the more the stochastic weather generator favours analog days with extreme temperatures. The K analogs of t are sorted in ascending order of temperature with ranks R_k ($k \in \{1, \dots, K\}$), so that the coldest analog day has a rank of 1. Hence the weight associated to the k^{th} analog day of t is:

$$\omega_T^{(k)} = A_T e^{-\alpha_T R_k} \tag{2}$$

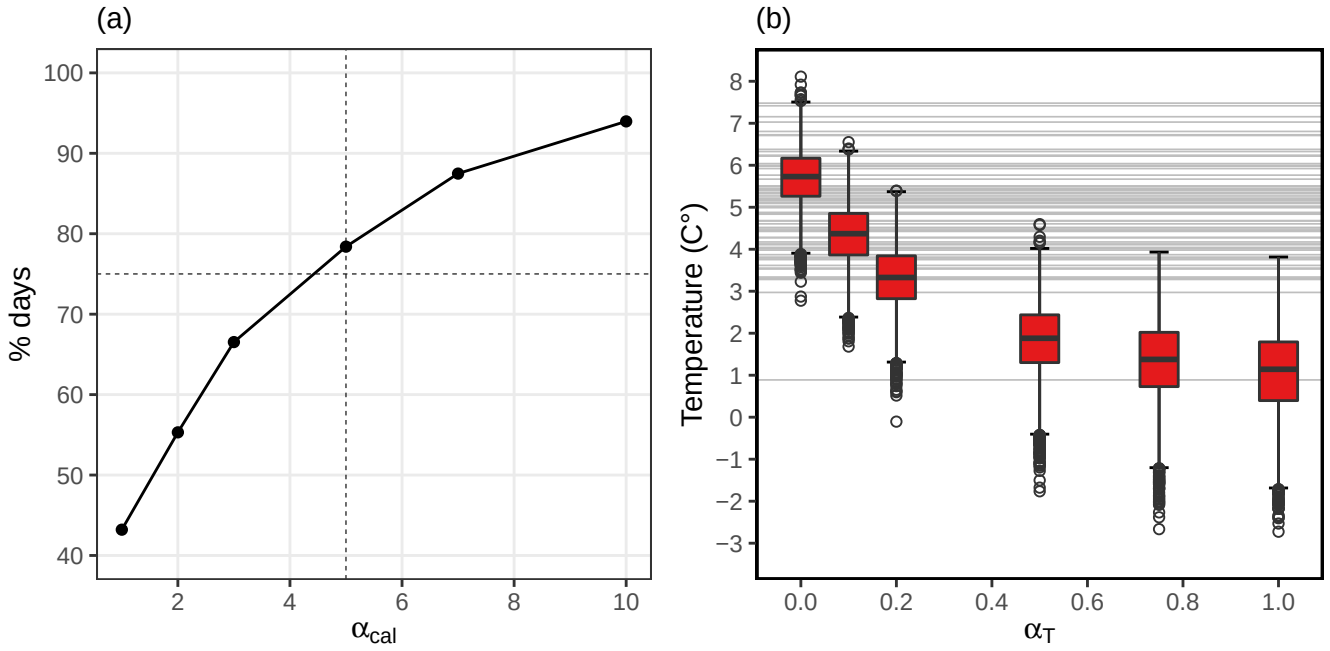

Figure 2: ***(a)*** *Percentage of simulations of extreme winters for which the last day falls after the* 15^{th} *of February, as a function of the* α_{cal} *parameter.* ***(b)*** *Temperature distribution of 100 simulations (method 2) for each winter between 1950-1951 and 2020-2021 (*$100 \times 70 = 7000$ *simulations total per box-plot) done for various values of the* α_T *parameter (*$\alpha_T \in \{0, 0.1, 0.2, 0.5, 0.75, 1\}$*). Horizontal lines represent the winter mean temperature of each winter from 1950-1951 to 2020-2021 in ERA5 data. The boxes of the boxplots represent the 25th (q25), median (q50) and 75th (q75) quantiles of the distribution. The upper whisker is* $\min\{\max(TN90d), q50 + 1.75 \times (q75 - q25)\}$*. The lower whisker corresponds to the lower symmetrical formula.*

where A_T a normalizing constant, α_T is the importance sampling weight and R_k is the rank (in ascending order) of the k^{th} analog day among the K analogs.

We run the SWG with parameter values $\alpha_T \in \{0, 0.1, 0.2, 0.5, 0.75, 1\}$, starting on each 1st of December, between 1950 and 2021. If $\alpha_T = 0$, there is no importance sampling and the SWG is the same as in (Yiou, 2014). Figure 2b shows that for $\alpha_T = 0$, the SWG simulates events covering the range of winter mean temperatures from 1950-1951 to 2020-2021, apart from winter 1962-1963. For $\alpha_T = 0.2$, a few outlier simulations reach winter 1963 temperatures. A value of α_T greater than 0.5 allows the simulation of a greater proportion of extreme events. The difference for α_T greater than 0.5 being less significant, we chose for the following $\alpha_T = 0.5$ as a compromise between the extreme character of the simulations and their quality.

The SWG with importance sampling is obtained by combining the weights on the calendar and importance sampling. The k^{th} analog day of day t has a probability of:

$$\omega_k = A e^{-\alpha_{cal} d_k} e^{-\alpha_T R_k} \tag{3}$$

where A is a normalizing constant so that $\sum_{k=1}^{K} \omega_k = 1$.

2.4 Simulation protocole

We adapted this stochastic weather generator from the one of (Yiou and Jézéquel, 2020), which was designed to simulate summer heat waves, to the version used in this analysis simulating winter cold spells. Consequently, the importance sampling weights favour the coldest analogs instead of the warmest. Furthermore, as the event analysed straddles two years, it is impossible to exclude analogs from the year of the event as it was the case simulating summer heat waves. Thus for winter simulations, analogs of the all length of the observed event are excluded and their weights are put to $w_k = 0$.

We refine the original approach of Yiou and Jézéquel (2020) by proposing two different methods simulate SWG trajectories:

1. Method 1 (*cum data*): At each time step, the simulated day is selected among the $K = 20$ analogs and the corresponding day in the observed event (e.g. Dec. 12th 1962 for a simulation initialized on the 1st of December 1962).

2. Method 2 (*sine data*): At each time step, the selection is made only among the K analogs (the day of the observed event is not considered), and analogs days falling in the observed event are excluded from the selection (e.g. if we initialize a simulation on Dec. 1st 1962 running for $L = 90$ days, all analog day between Dec. 1st 1962 and March 1st 1963 will be excluded). With this method, the simulations use no information from the observed event apart from the initial condition.

Method 1 allows the simulation of events that are more like the observed event, while Method 2 aims to simulate an ensemble of events possible considering the initial condition and the analogs set only. Therefore, if the SWG is initiated on Dec. 1st 1962 (beginning of the coldest winter), it does not use further information on that record shattering event.

The SWG is used to simulate worst-case winter scenario from 1950 to 2021. For each winter from 1950-1951 to 2020-2021, the simulation starts at t_0 — the 1st of December — and run for $L = 90$ days over DJF (December, January and February). $n = 100$ simulations are run by winter year, hence 100×71 events are simulated for each experiment. The α_T and α_{cal} parameters are

respectively set to 0.5 and 3.

The same process is made using method 1 and method 2. Simulations are also made using the two sets of analogs — the counterfactual and factual periods. Hence the simulated events are events that could have occurred in the analog period used for the simulations. This allows simulating worst case events from the same initial conditions but considering different states of the climate. In other words, we assess whether a record shattering event can be deduced from the information of less intense extremes.

In this paper, we focus on winter 1963. We run 1000 simulations starting in December the 1st 1962, using as previously, the factual and counterfactual sets of analogs and the two methods. This allows having a wider ensemble of the winter temperature possible starting from the initial conditions of winter 1962-1963.

3 Results

3.1 Sensitivity to SWG configurations

In this subsection, we simulate cold winters of 90 days starting on a 1st of December of each year from 1950 to 2021. Analogs can be selected in any year from 1950 to 2021. We evaluate the impact of the possibility to sample analogs from the starting year (SWG method 1 vs. method 2) on the winter average temperature. We then evaluate the impact of analog periods on the simulated temperatures.

Figure 3 shows the results of simulations from 1951 to 2021 using respectively method 1 (Fig. 3a) and method 2 (Fig. 3b) in Section 2, with analogs sampled in 1950-2021. The SWG successfully simulates extremely cold winters, with simulations being respectively 3.9°C (Fig. 3a) and 3.1°C (Fig. 3b) colder overall compared to the ERA5 temperatures time series. 40% of all simulations reach a mean temperature as cold as the 1963 record with method 1, while only 13% of them are as cold using method 2.

The variability of the simulations performed with method 1 follows closely the variability of historical winter temperatures due to the possibility of selecting analogs of the observed event with this method. The medians of simulations made with method 1 are highly correlated ($r = 0.88$) to the observed temperatures. With method 2 there is no correlation between the median of simulations

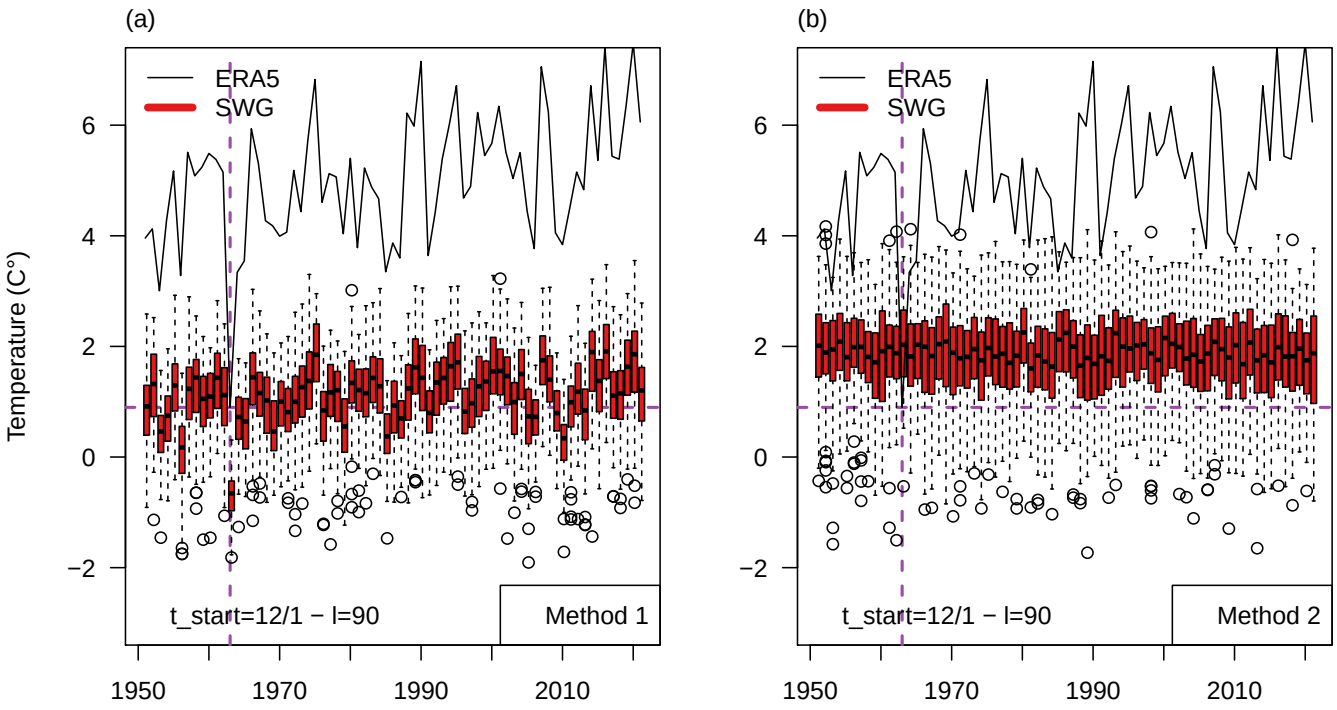

Figure 3: *Results of 100 SWG simulations from winter 1950-1951 to winter 2020-2021 with method 1* ***(a)*** *and method 2* ***(b)****. The black continuous line represents the time series of winter mean 2m-temperature over France from ERA5 data. The box plots represent the ensemble variability of the simulations for each year. The boxes of box plots indicate the median ($q50$), the lower and upper hinges indicate the first ($q25$) and third ($q75$) quartiles. The upper whiskers indicate $min[max(T), q75 + 1.5 \times (q75 - q25)]$. The lower whisker has a symmetric formulation. The points are the outlying values that are above or below the defined whiskers. The vertical purple dashed line highlights winter 1963 while the vertical purple dashed line shows the mean temperature of the same winter.*

and the observed temperature, which is the consequence of method 2 not using information from the observed event apart from the initial conditions. The simulation length of 90 days being higher than the decorrelation time of atmospheric dynamics, the resulting events should not be highly influenced by their initial conditions. The standard deviation of the medians of the boxplots obtained with method 2 is also very low: 0.15°C, compared to the 0.44°C obtained with method 1. This is coherent with the chaotic internal variability of the climate system, resulting in simulated events being representative of the climate analogs period used rather than the initial conditions.

The mean of boxplots median is also higher by 0.77°C with method 2 compared to method 1, which can be explained by the fact that method 1 allows more days to be picked during the importance sampling process so that the coldest days can be selected during the simulations by construction, while some analogs days are excluded when using method 2.

Simulating winter with Method 2 using analogs either in the factual (1972-2021) or counter-

factual (1950-1999) periods gives an overview of the range of the most extreme winter temperatures possible in those two climate periods. With method 2, winter simulations in the factual period are overall warmer of 0.73°C compared to the counterfactual period. This difference has the same order of magnitude as the observed warming of 0.52°C between winter mean temperatures in the factual and counterfactual periods. This is also consistent with a current warming rate of 0.36°C per decade in metropolitan France, as estimated by Ribes et al. (2022), which corresponds to a warming of approximately 0.72°C between the factual and counterfactual periods. For 1963, method 2 excludes the use of any analog day in winter 1962-1963 for simulating the events. The only information of winter 1962-1963 used is the initial condition of the 1st December 1963. By excluding all information from this exceptional event of the 1950-1999 simulations, the difference between simulations using 1972-2021 analogs compared to 1950-1999 analogs is of only 0.16°C, which is lower than for other years.

3.2 Focus on winter 1963

In this subsection, we simulate winter 1962-1963, starting on Dec. 1st 1962, and consider circulation analogs in the counterfactual and factual periods. Here, 1000 simulations are done for that winter. Figure 4a shows the focus on 1963 simulations using methods 1 and 2 and the factual and counterfactual analogs periods. As seen in Section 2, the simulations are overall colder using method 1 than method 2. This is also the case for 1963; as displayed in Figure 4a for both the factual and counterfactual period. All events simulated with method 1 reach a mean temperature over DJF colder than the value reached in 1963 whether using 1950-1999 or 1972-2021 analogs.

The probability of reaching winter 1963 temperatures is lower with method 2. The first quantile of simulations does not reach 1963 mean values both in the factual and counterfactual periods. 1963 was already a very rare event in the 1950-1999 climate but remains reachable using only 1971-2021 analogs, in a climate with more global warming.

Figure 4b displays the time series associated with 1963 simulations using method 2. The temperatures of winter 1962-1963 are below the seasonal cycle for most of the season. The temperatures of simulated events for both the factual and counterfactual periods are also overall well below the seasonal mean for the all length of the event. The median fluctuates around 2°C while the 5_{th} percentile of all simulation reaches -5°C during most of the winter. The 95_{th} percentile stays under 2°C above the seasonal average while the 5th percentile reaches -4°C during most of

the event, which corresponds to the coldest daily mean temperatures observed in 1963. Overall the range of daily winter temperatures as simulated for extreme winter temperatures matches the range of daily mean temperatures observed in 1962-1963 extreme winter event in both the factual and counterfactual periods. Hence a winter like the one of 1962-1963, even if of very low probability, could still be possible under a warmer climate of the 21st century.

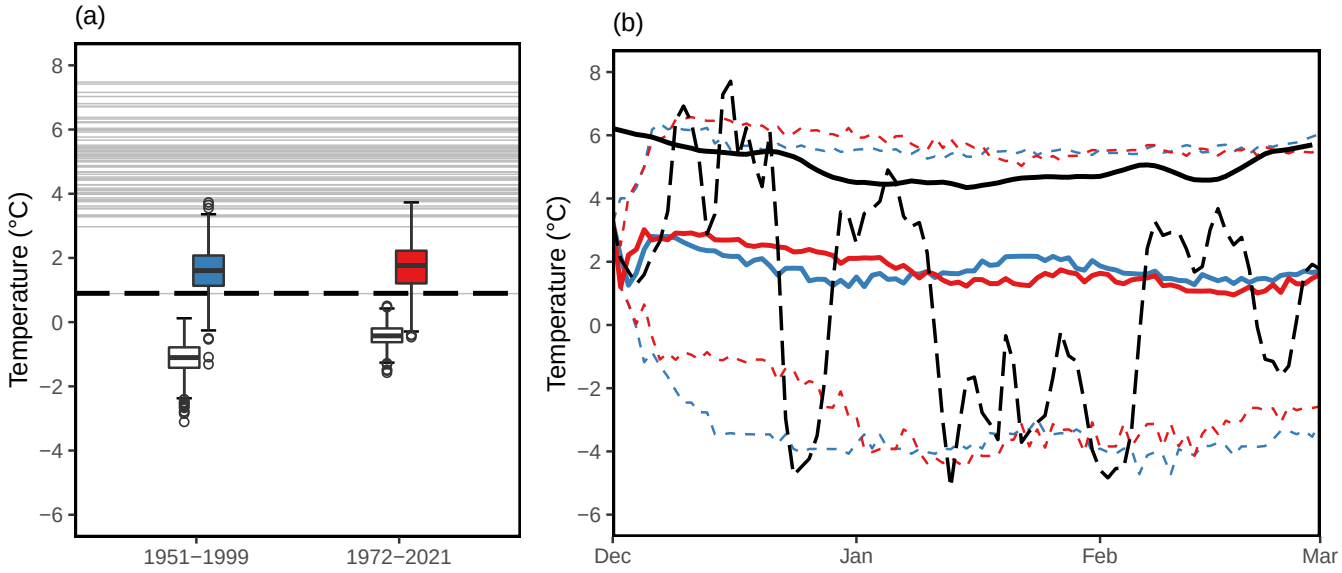

Figure 4: ***(a)*** *Temperature distribution of 1000 SWG simulations of winter 1962-1963 with analogs from 1950-1999 (left) or 1972-2021 (right) in ERA5 data using method 1 (white filled boxplots) and method 2 (color filled boxplots). Horizontal lines represent the winter mean temperature of each winter from 1950-1951 to 2020-2021 in ERA5 data. The dashed black line is the value that was observed in 1962-1963.* ***(b)*** *Time series of 7-day running mean of daily mean temperatures for winter 1962-1963 (dashed black line), SWG median (plain line), q05 and q95 (dashed lines) temperatures of the thousand 1962-1963 simulations with Method 2 using 1950-1999 analogs (blue lines) and 1972-2021 analogs (red lines).*

3.3 Atmospheric dynamics during winter 1963

A strong and persisting anticyclonic anomaly prevailed over Iceland. It was associated with a negative Z500 anomaly over continental Europe, the Azores and the Glacial Arctic Ocean, leading to a weakening of the westerlies and advection of cold air from the Arctic (Fig. 5a).

Here, we compute the composites of Z500 and Z500 anomalies over a region that is larger than the region for which the analogs are computed.

The Z500 composite over DJF does not correspond directly to a North Atlantic weather pattern, as for instance obtained by Cattiaux et al. (2010). The low over Europe is located more to the East than for an NAO− weather pattern, while the positive Z500 anomaly over Iceland is located more to the north than it would be in an Atlantic ridge weather regime. The respectively

positive and negative Z500 anomalies over Iceland and the Azores are however characteristic of a negative NAO index which is often, even if not systematically, an indicator of colder than usual winter temperature over Europe (Hirschi and Sinha, 2007).

Z500 anomalies of SWG simulations for winter 1963 are smoother than the ERA5 field for the same winter. This can be explained by the fact that the map is averaged over 100 (10% of 1000 simulations) different simulations and that simulations are less auto-correlated than observed events would be, thus having more spatial variability. Hence, we compute the Z500 and Z500 anomaly composites of SWG simulations for the 10% coldest members of the ensemble starting on Dec. 1st 1962. For comparison purposes with winter 1963, this selection is reasonable because 75% of simulations are warmer than this record event (Fig. 4a), and we want to focus on the coldest members of the ensemble. We find that the pattern of a strong negative anomaly over Western Europe and a positive anomaly over Iceland is still reflected in the 10% coldest events simulated with the SWG in both the counterfactual (Fig. 5b) and factual (Fig. 5c) simulations. The intensity and position of the Z500 low over the Barents sea and the high over western Russia seen in ERA5 seem to have a lower contribution to the intensity of the event as they are weaker and less marked in the SWG simulated events.

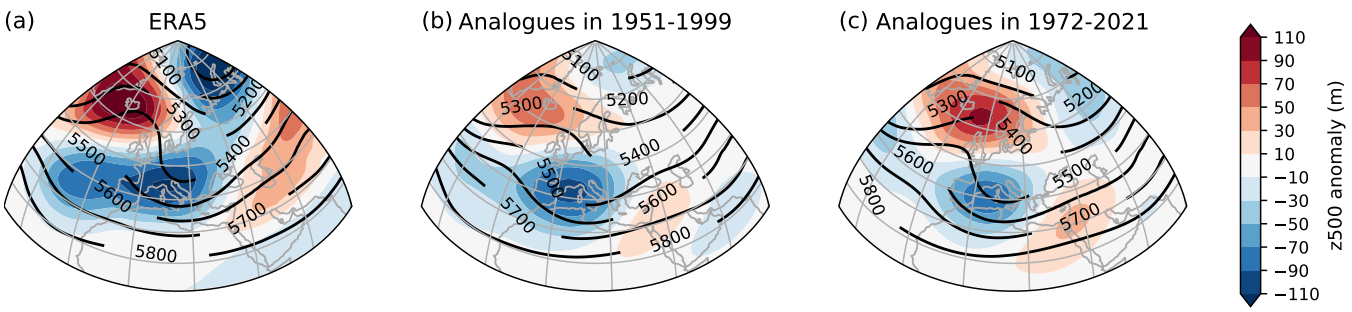

Figure 5: *Absolute values (contours) and anomalies with respect to 1950-2021 (shaded areas) of 500-hPa geopotential height (Z500) average over DJF for winter 1963 as observed in ERA5 (a) and simulated by the SWG with counterfactual (b) and factual (c) analogs using method 2 (*sine data*). For the simulations, the composite maps are computed from the 10% coldest simulations among the 1000 (i.e. 100 simulations per map).*

4 Discussion and conclusion

This paper presents how an analog stochastic weather generator can be used to simulate ensembles of extreme cold winters in continental France. We adapted the method developed by Yiou and Jézéquel (2020) (to simulate extreme heat waves) to the simulation of extreme cold

events. The paper displays a proof of concept using ERA5 data for the simulation of extreme winter temperatures in France between 1950 and 2021.

The SWG for the simulation of extreme cold spells inherits some of the technical caveats already pointed out by Yiou and Jézéquel (2020) for the simulation of extreme heat waves. This SWG method is limited by the length of the data set used as input, so that it may not sample completely the atmospheric dynamics of the climate system. The average of resampled analogs is however bounded to a lesser extent and can reach values far more extreme than the most extreme ones in the input data set. The SWG allows simulation of extreme events outside the observed range but is still limited by the length of available data.

The length of the factual and counterfactual periods considered was a compromise between the length of available data (70 years), the non stationarity of temperatures and the overlapping of the two periods. We needed periods of sufficient length to sample correctly the climate considered. But to have significant differences between the factual and counterfactual periods it was better that they would overlap as little as possible. The non stationarity of climate also means that the longer the periods, the less homogeneous they are in terms of level of warming. 50-year long periods yield good results in terms of both extremeness (the data set is large enough to simulated very rare events) and significant enough difference between the factual and counterfactual periods. Moreover we verified that the analog days are evenly distributed over the two climate periods and evenly picked during the simulation process. Therefore we consider that the events simulated are representative of the entire analogs period used in the SWG.

This method does not allow to disentangle anthropogenic warming from others forcings and natural multi-decadal variability of the climate system. But it gives an estimation of the worst-case winter temperatures scenario for a given climate as sampled is the input. Another caveat is that the method is mainly based on the use of flow analogs to assess temperatures. It focuses on the link between atmospheric circulation and temperatures and does not take into account other drivers and feed-backs. For instance, snow cover is not considered in the simulations even though it can have a significant impact on extreme winter temperatures (Orsolini et al., 2013).

We showed that winter as cold as the record event of 1963 or even colder could still occur in the current climate, at a higher level of warming. This does not mean than such an event will happen in the future but it remains possible at the considered level of warming and is relevant

from an adaptation point of view. A winter as cold as 1963 would indeed have major impacts on society, especially on the energy system (Añel et al., 2017). For instance, Doss-Gollin et al. (2021) showed that the February 2021 Texas cold snap, which resulted in major failures of the energy system causing energy, food and water shortages, was actually not unprecedented both in terms of temperature anomalies and resulting heating demand per capita. The lack of preparedness and greater exposure of the energy system due to increasing population and electrification led to disproportionate impacts. In France, the electricity transmission system operator RTE (Réseau de Transport d'Électricité) estimates the sensitivity of electricity consumption to temperature to be 2400 MW/°C in winter (RTE, 2021). Hence, it might be desirable that energy systems and logistics are scaled for worst case winter scenario in the current or future climate conditions and exposure as the ones simulated in this study.

The possible occurrence of unprecedented cold winter temperatures in France as simulated in this paper is not inconsistent with the already observed decrease in cold spells intensity in the northern mid-latitudes as exposed by Van Oldenborgh et al. (2019). We focus here on low-likelihood long-lasting events, with a return period of over 10^3 years. This is not representative of cold waves defined as the exceeding of a threshold over a few days, which can be a yearly event.

The absence of significant changes in the atmospheric circulation leading to the extreme winters simulated is in line with the *typicality* of large and persistent temperature anomalies as shown using large deviation theory (Galfi and Lucarini (2020); Gálfi et al. (2021)). The same atmospheric conditions usually lead to the most extreme events. However these results are valid in a stationary system and obtained using steady state model simulations. Climate change can lead to important shifts in atmospheric dynamics that could affect the frequency and intensity of extreme events, as well as the dynamics leading to them. The present paper shows no significant shift in the atmospheric circulation of record-breaking winters between the factual and counterfactual periods, which have a difference $0.72°C$ in terms of level of warming. However these results cannot be extended to a higher shift in global warming level. Simulations of extreme cold spells using of the Coupled Model Intercomparison Project phase 6 (CMIP6) simulations (Eyring et al., 2016) would therefore be an extension of this study in order to further explore the evolution of extreme winter temperatures in the mid-latitudes in the future — according to different emissions pathways (Riahi et al., 2017) — and the associated atmospheric trajectories.

In this paper, we focused on cold winters (90 days: TN90d) in France. The method can be adapted to simulate cold events of different duration, or in other regions. The worst cold spells recorded in France were February 1956 — the coldest month of the 20^{st} century (Andrews, 1956; Dizerens et al., 2017) — and January 1985 (Météo France, 2022a,b). These events caused major disruptions and had a wide health impact (Huynen et al., 2001). The energy sector has been sensitive to 15-day events. The cold spell of 3rd – 17th January 1985 is used as the event of reference by the French electrical network company. A similar event triggered an unprecedented impulse of solidarity, following Abbé Pierre's call in France for the help of the homeless during winter 1954.

Winter 1963 was the coldest winter recorded in France and a record-shattering event. Using an analog stochastic weather generator with importance sampling for the simulation of an extremely cold winter, we show that winter 1963 temperatures were already exceptional in the lower level of warming in which it occurred. Estimations of the possibility of such an extreme event occurring in the recent climate show that it is still possible to have a winter as cold, even if would remain a highly exceptional event. This paper hence provides a *storyline* for extremely cold winters in France (Sillmann et al., 2021).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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