



A new framework for identifying and investigating seasonal climate extremes

Matthias Röthlisberger,¹ Mauro Hermann,¹ Christoph Frei,² Flavio Lehner,^{1,3,4} Erich M. Fischer,¹ Reto Knutti¹ and Heini Wernli¹

¹Institute for Atmospheric and Climate Science, ETH Zürich, Zürich, Switzerland

²Federal Office of Meteorology and Climatology MeteoSwiss, Zürich, Switzerland

³Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, New York, USA

⁴National Center for Atmospheric Research, Boulder, Colorado, USA

Rationale of the study

Seasonal climate extremes, such as extremely hot summers or cold winters, have large socio-economic impacts, but due to their rareness they are difficult to study beyond individual case studies. Consequently, climatological characteristics, i.e., characteristics that are shared by a large number of seasonal extremes, are poorly studied and poorly understood.

In this concept study we develop a spatial pooling strategy for seasonal extreme events that allows analysing larger samples of comparable seasonal extreme events, using the example of extremely hot summers and cold winters (hereafter T_{JJA+} and T_{DJF-} events, respectively).

The centrepiece of our approach is an extreme season identification scheme that identifies spatial extreme season objects in reanalysis and climate model data based on grid point wise statistical modelling of seasonal two meter temperature (T2m) means.

Applying the scheme to ERA-Interim and CESM-LENS data yields large sets of T_{JJA+} and T_{DJF-} events that allow studying such seasonal climate extremes in hitherto unexplored ways.

A manuscript about this work is currently in revision and will likely appear in the Journal of Climate (please find the full reference on the last slide).



Home slide

click to navigate through the sections...



1. Rationale of the study

3. T_{JJA+} and T_{DJF-} extreme
seasons in ERAI

5. Example applications

2. Data and Extreme
season identification
scheme

4. Contrasting CESM-LENS
and ERAI T_{JJA+}
characteristics

6. Key points



Data



ERA-Interim (ERA-I): 1979–2018 JJA and DJF seasonal T2m means (**40 values per grid point and season**, Dee et al., 2011)

CESM-LENS: 30 members, 1979-2018 JJA and DJF seasonal T2m means (**1200 values per grid point and season**, Kay et al., 2015)

Both data sets are detrended by removing the forced trend at each grid point, which is estimated as the CESM-LENS ensemble mean anomaly relative to the climatological 1979–2018 ensemble mean.

Extreme season identification scheme (1/2)

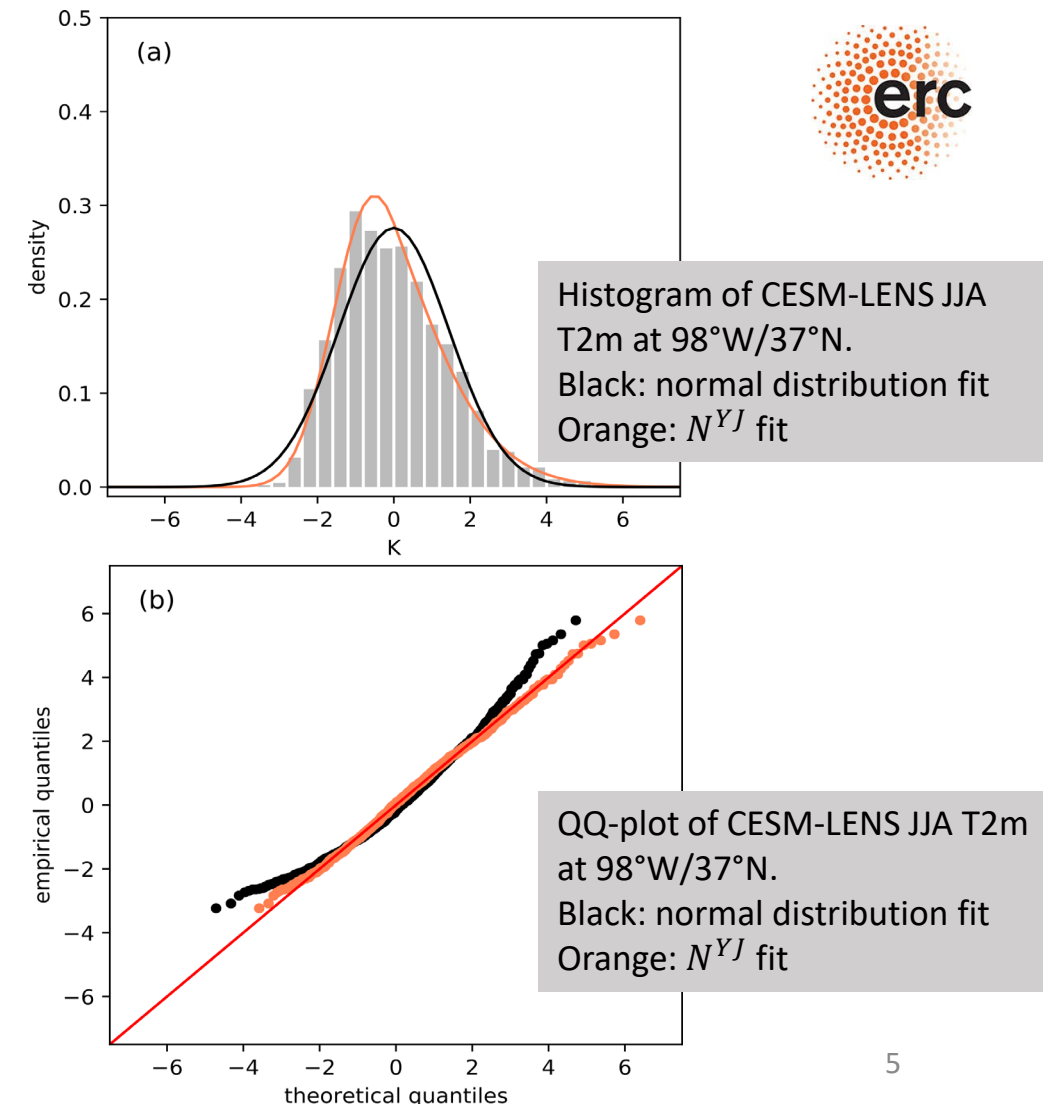


Statistical modelling of seasonal means: Previous studies used a normal distribution to model seasonal mean temperatures (e.g., Chase, 2006; Barriopedro et al. 2011). However, at the grid point scale, seasonal mean T2m distributions are often skewed. Therefore, we incorporate the Yeo-Johnson transform (Yeo and Johnson, 2000) into the normal distribution and model JJA and DJF T2m data with a **Yeo-Johnson transformed normal distribution** (hereafter N^{YJ}) with cdf

$$G(x; \mu, \sigma^2, \lambda) = F(k(x; \lambda); \mu, \sigma^2)$$

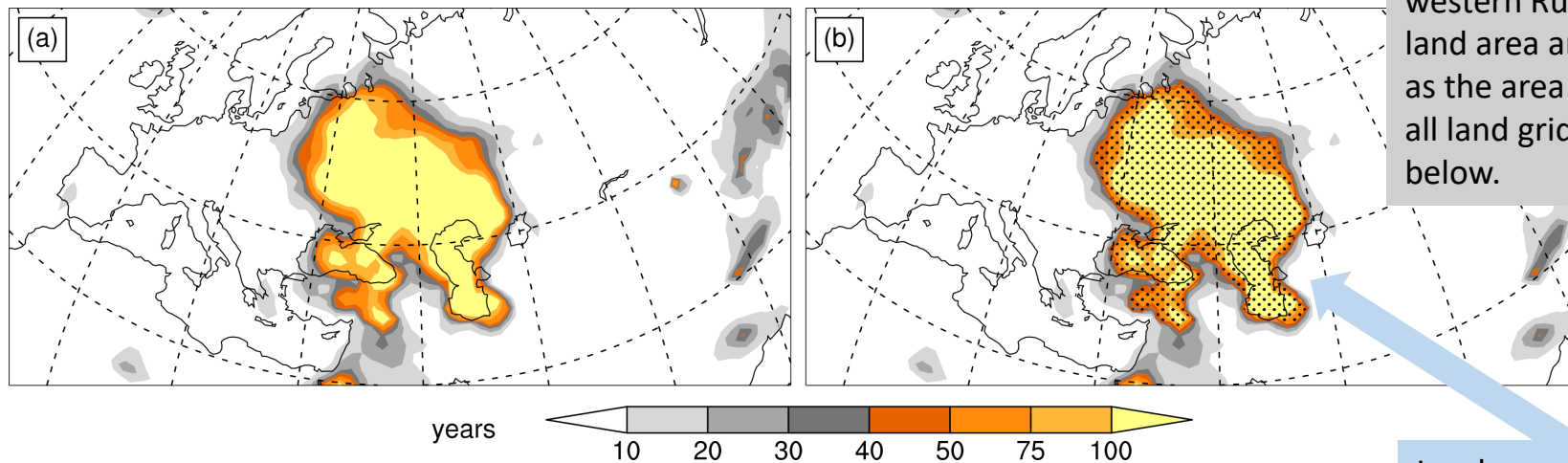
where $k(x; \lambda)$ is the Yeo-Johnson power transform of the variable x with transformation parameter λ , and $F(y; \mu, \sigma^2)$ is the cdf of the normal distribution.

This statistical model allows describing positively and negatively skewed seasonal mean T2m distributions and allows to model seasonal mean T2m over a wide range of climates (an example for a grid point in North America is shown on the right).



Extreme season identification scheme (2/2)

Forming extreme season objects: From the N^{YJ} -fit at each grid point we compute local return periods (LRPs) for each seasonal mean value. Seasonal mean values are deemed “extreme” if their LRP exceeds 40 years. Extreme season objects are then constructed as connected regions where the LRP exceeds 40 years. For each extreme season object we compute a number of characteristics (area, centre of mass, an intensity measure etc.). The formation of extreme season objects is illustrated below for the T_{JJA+} object of the hot western Russian summer in 2010.

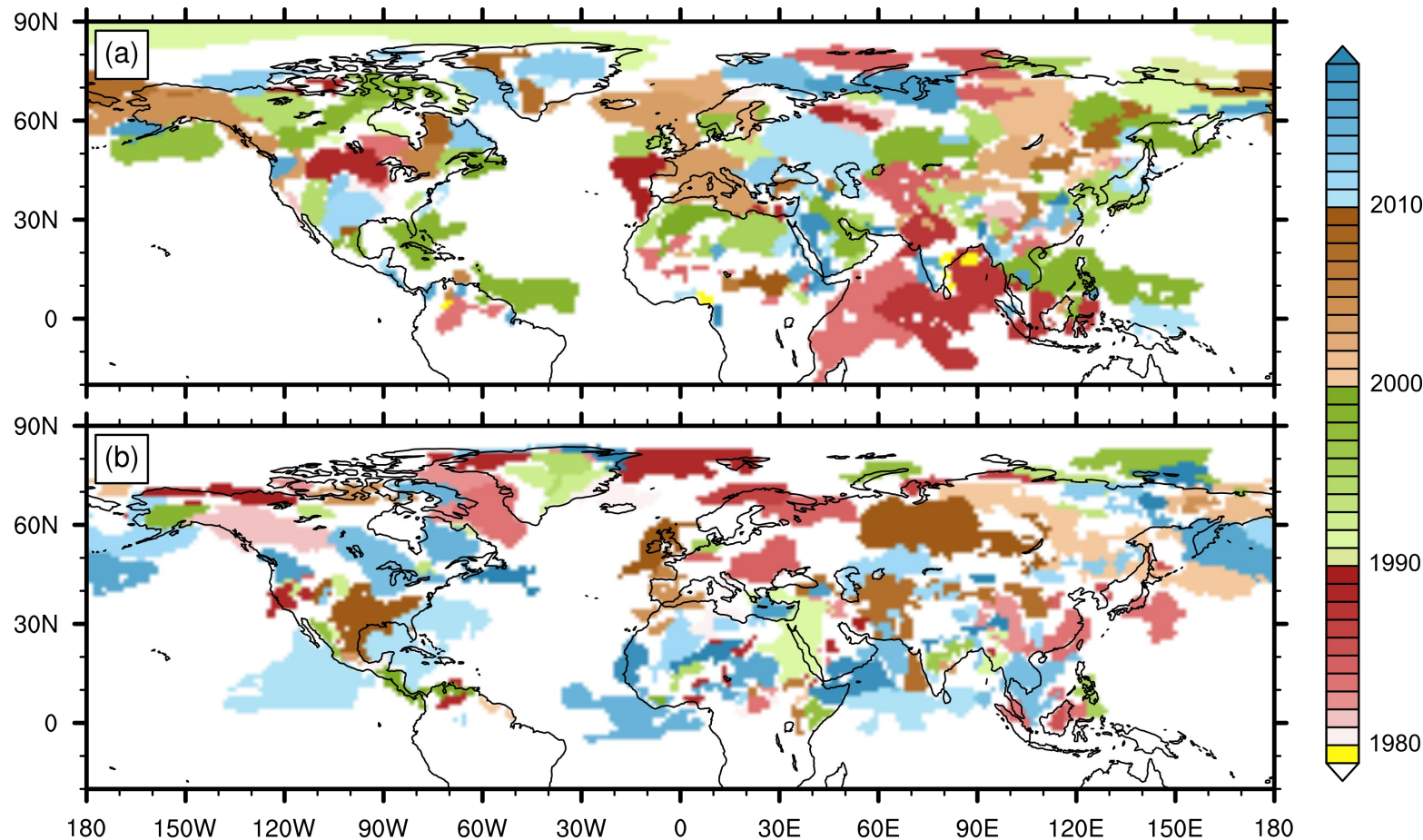


Panels (a,b) show the LRP-field of the 2010 JJA seasonal mean T2m, which is derived from the grid point wise N^{YJ} -fit. In (b) the T_{JJA+} object in western Russia is highlighted with stippling. The land area and an intensity measure, computed as the area weighted mean T2m anomaly over all land grid points of the object, are given below.

Land area: $3.85 \times 10^6 \text{ km}^2$
Land intensity: 2.92 K
Other characteristics: ...

T_{JJA+} and T_{DJF-} extreme seasons in ERAI (1/2)

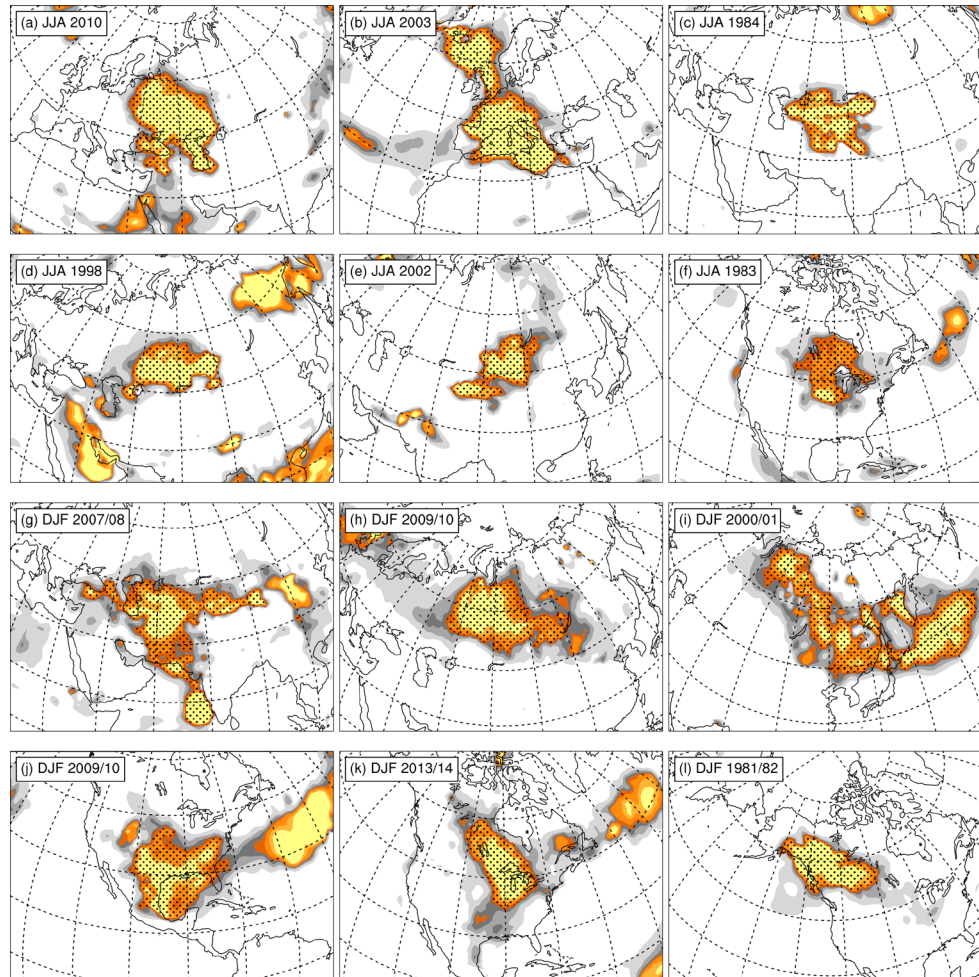
An overview of all Northern Hemisphere T_{JJA+} and T_{DJF-} objects identified in ERAI:



The years of (a) T_{JJA+} and (b) T_{DJF-} extreme seasons with significant land area (>10⁵ km²). Note that not every grid point experienced a summer/winter with LRP > 40 years, while some experience multiple such summers/winters. In the latter case, the year of the latest event is plotted. Overall we identify 175 T_{JJA+} and 147 T_{DJF-} objects with >10⁵ km² land area in the ERAI period in the Northern Hemisphere.

T_{JJA+} and T_{DJF-} extreme seasons in ERAI (2/2)

The largest midlatitude T_{JJA+} and T_{DJF-} objects:

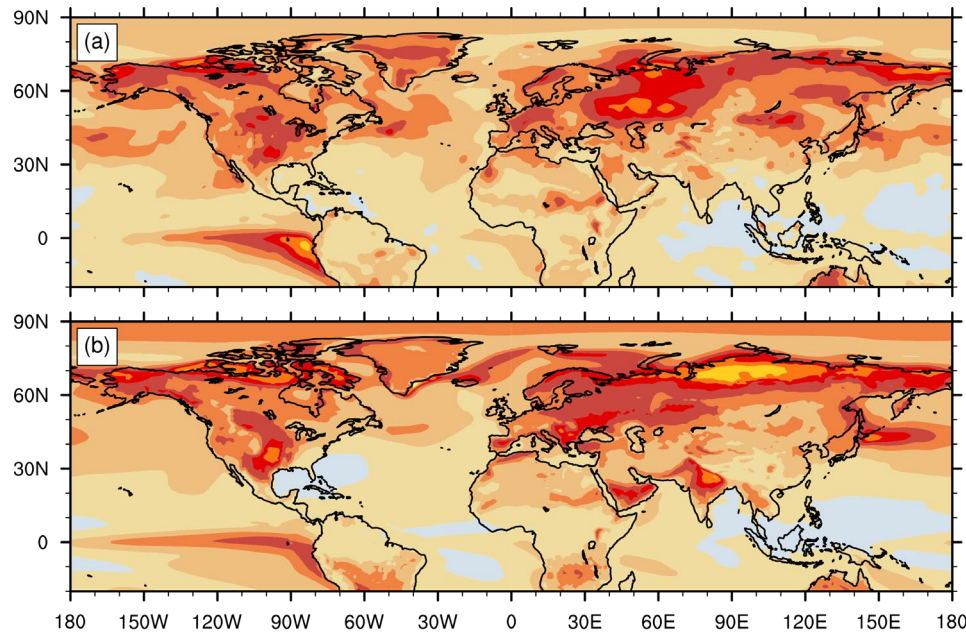


The top 6 midlatitude T_{JJA+} (a-f) and T_{DJF-} (g-l) objects with regard to land area. The shading denotes the local return period (LRP) and stippling indicates the spatial extent of the respective extreme season object.

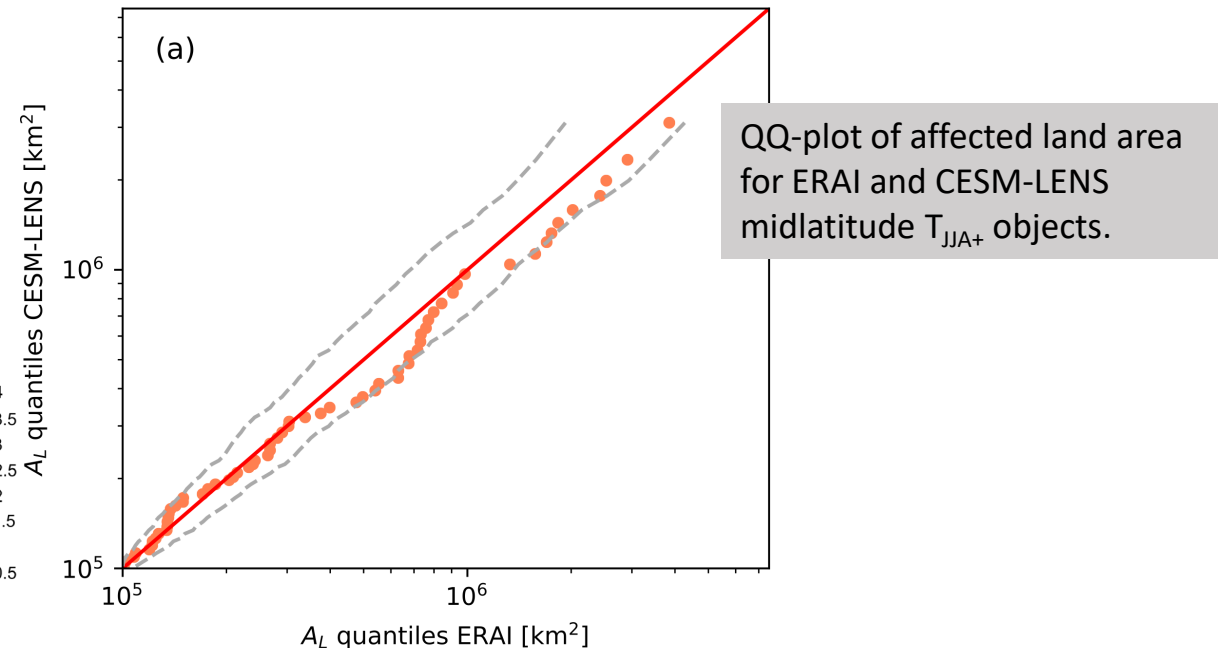
The top six midlatitude objects of both types of extreme seasons contain well known events such as the European and western Russian hot summers in 2003 and 2010, or the cold winters in the US in 2009/10 as well as 2013/14.

Contrasting CESM-LENS and ERAI T_{JJA+} characteristics

Model evaluation is fundamentally important: Large ensemble simulations such as CESM-LENS allow us to substantially enlarge the sample of events comparable to those on the previous slide, which yields enormous potential for climatological analyses of events comparable to even the most extreme observed ones. However, inferences drawn from such analyses are meaningful only to the extent that the simulated characteristics of extreme seasons align with reality.



Comparing 40-year return levels for JJA T2m anomalies in (a) ERAI and (b) CESM-LENS.



QQ-plot of affected land area for ERAI and CESM-LENS midlatitude T_{JJA+} objects.

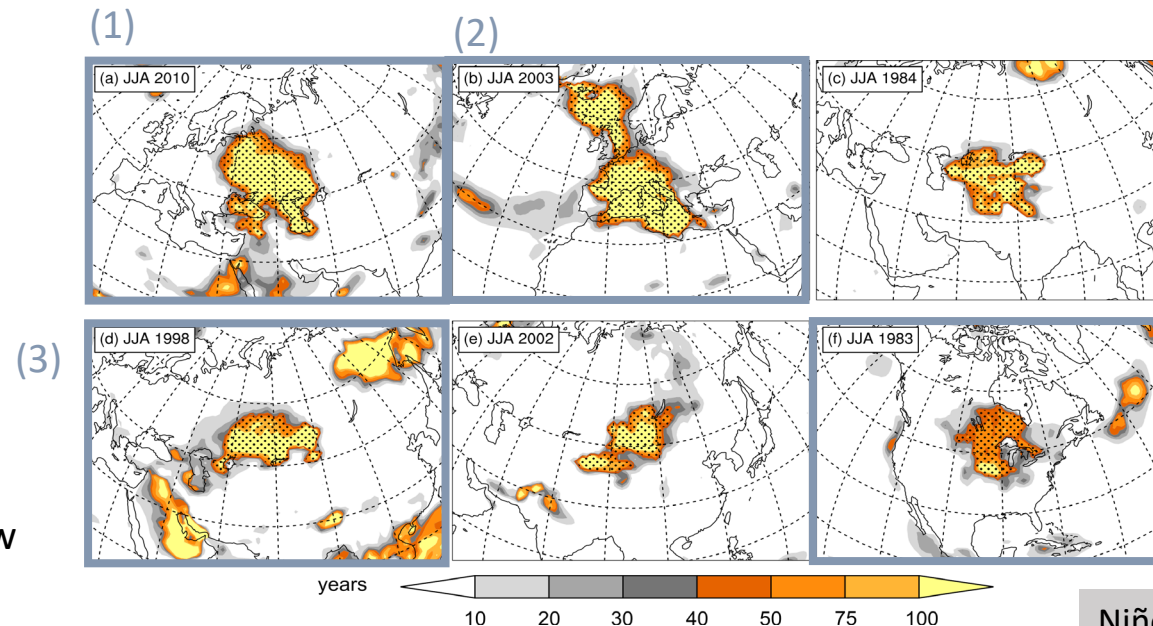
Overall, the statistics of CESM-LENS and ERAI extreme season characteristics agree reasonably well, even though there are clear but geographically confined model biases in the 40-year return levels of hot summers and cold winter T2m anomalies (e.g., Siberia, high Arctic).

Example applications (1/3)

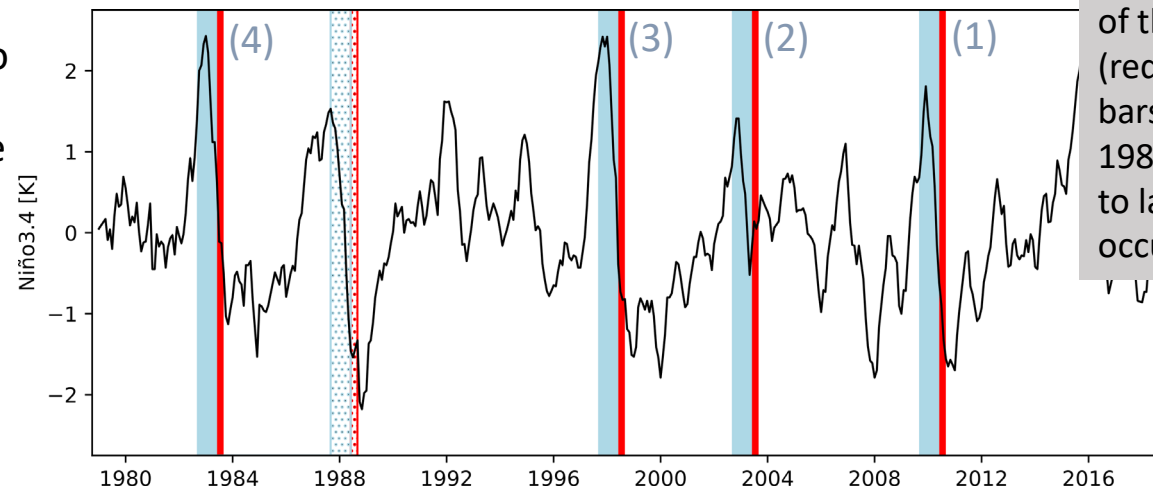
Contrasting the characteristics of the "most extreme" observed events:

Five out of the seven largest midlatitude T_{JJA+} events in 1979–2018 occurred within nine months after a major El Niño event. Thus, despite their occurrence in completely different regions, these events share characteristics in their physical storyline. Our approach now allow identifying and further investigating these commonalities.

The mechanisms by which El Niño to La Niña transitions possibly foster the occurrence of major midlatitude T_{JJA+} events are so far not well understood.



(4) Blue rectangles indicate the events highlighted in the lower figure.



Niño 3.4 time series and the periods of the four events indicated above (red bars: period of the events, blue bars: nine preceding months). The 1988 event ranks seventh with regard to land area in the midlatitudes and occurred in North America.

Example applications (2/3)

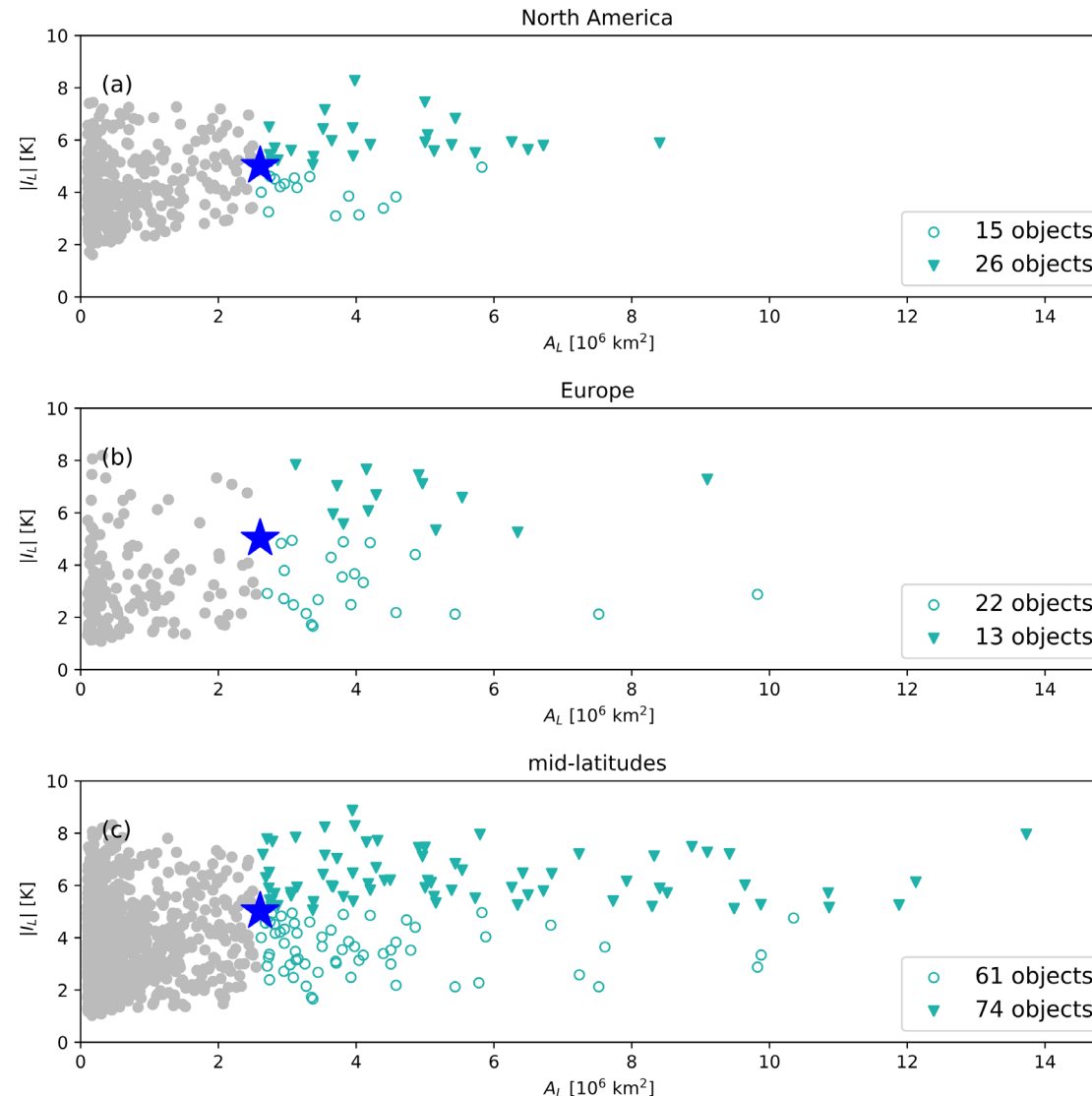


Regional return periods (RRPs):

What is the return period of a T_{DJF-} event with at least the same area and/or intensity as the cold winter 2013/14 in the US (hereafter NA2013/14 event)

anywhere within a certain region, e.g., North America, Europe or the entire midlatitudes?

A simple counting exercise using our set of CESM-LENS T_{DJF-} events suggests that a T_{DJF-} event at least as large as the NA2013/14 event occurs roughly every 29 years in North America, every 34 years in Europe and every 9 years anywhere in the midlatitudes.



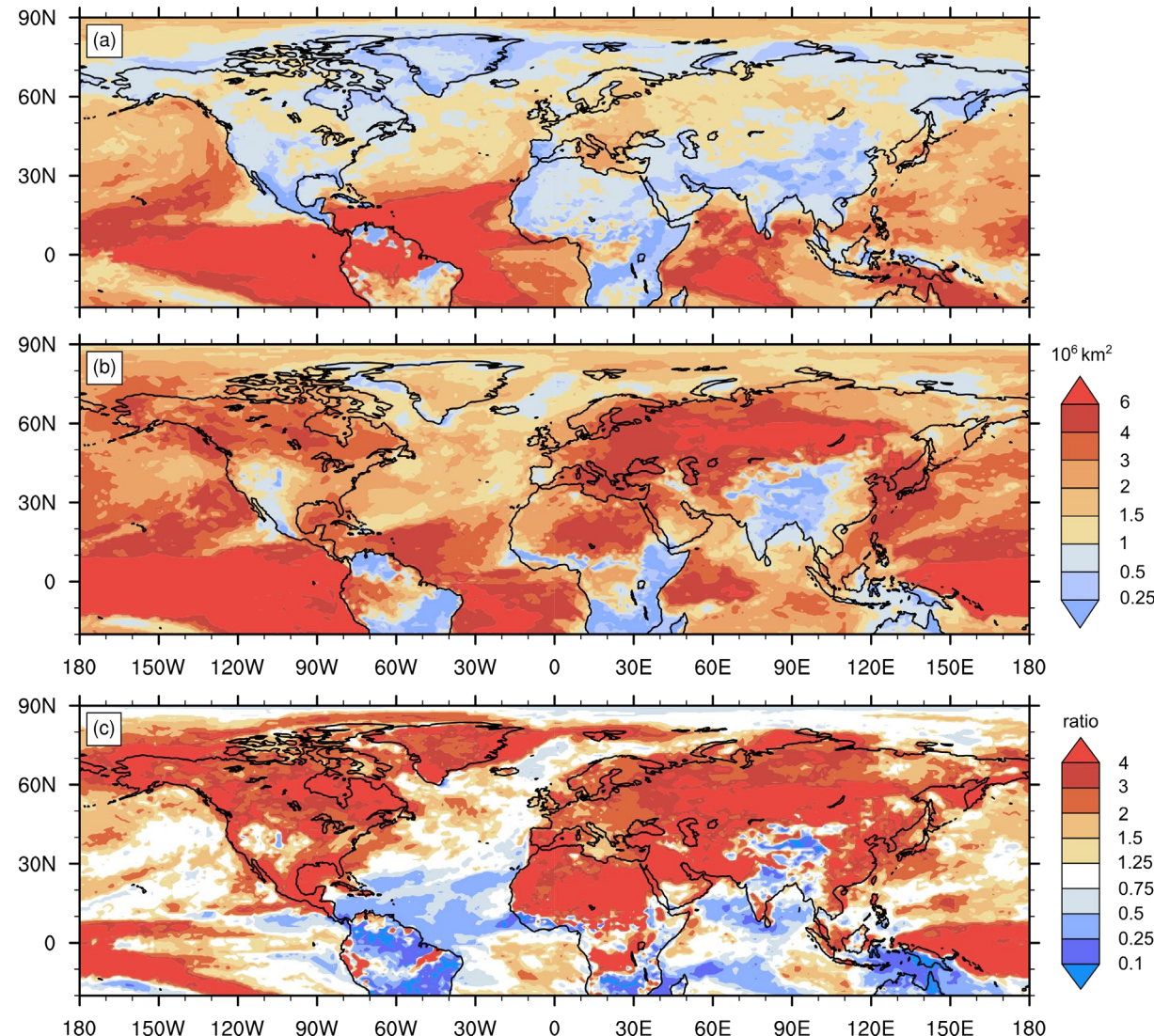
Scatter plots of the land area and the intensity of T_{DJF-} objects in CESM-LENS for three different regions. The NA2013/14 event is indicated with a blue star. Turquoise markers indicate CESM-LENS T_{DJF-} objects with a land area exceeding that of the NA2013/14 event. For the objects denoted with filled triangles both the intensity and the land area exceed that of the NA2013/14 event.

Example applications (3/3)

Contrasting extreme season characteristics across regions:

The small number of observed seasonal extreme events at any location precludes comparing climatological event characteristics across regions. Using a large ensemble simulation such as CESM-LENS, however, such analyses are possible. This figure reveals (1) the considerable spatial variability in the median size of CESM-LENS extreme season objects and (2) that CESM-LENS T_{DJF-} objects are larger than T_{JJA+} objects over land, while over the extratropical ocean they are roughly of the same size.

These results are relevant since the affected area is likely correlated with the expected impact of a seasonal extreme event.



Median area of all CESM-LENS T_{JJA+} (a) and T_{DJF-} (b) objects covering the respective grid point. Panel (c) depicts the ratio (b) divided by (a).

Key points



In this concept study we develop **an extreme season identification scheme** that is applicable to short reanalysis data sets as well as large climate model simulations and **allows identifying spatial extreme season objects based on local return periods**.

Extremely hot summer and cold winter objects are identified in ERAI and CESM-LENS, which allows

- (1) Comparing and contrast physical characteristics of the most extreme observed events.
- (2) Evaluating the climate model with regard to simulated extreme season characteristics.
- (3) Studying numerous so far unexplored climatological aspects of seasonal extremes which cannot be assessed with observational data alone.

The **major limitation of our approach is the short observational record** which leads to:

- (1) Considerable uncertainties in the estimation of unusually large LRPs.
- (2) A small sample of observed events, which complicates evaluating the ability of climate models to realistically simulated seasonal extreme events (their statistics and relevant physical mechanisms), due to too few observed events to compare with.

Nevertheless, we conclude that our approach offers vast potential to study seasonal extremes in hitherto unexplored ways. We hope that the present work will enable numerous such analyses in the future.

References



Barriopedro, D., E. Fischer, J. Luterbacher, R. Trigo, and G.-H. Ricardo, 2011: The hot summer of 2010: RRedrawing the temperature record map of Europe. *Science*, **332**, 220–224, doi:10.1126/science.1201224.

Chase, T. N., K. Wolter, R. A. Pielke, and I. Rasool, 2006: Was the 2003 European summer heat wave unusual in a global context? *Geophys. Res. Lett.*, **33**, L23709, doi:10.1029/2006GL027470.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Q. J. R. Meteorol. Soc.*, **137**, 553–597, doi:10.1002/qj.828.

Kay, J. E., and Coauthors, 2015: The Community Earth System Model (CESM) Large Ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Am. Meteorol. Soc.*, **96**, 1333–1349, doi:10.1175/BAMS-D-13-00255.1.

Yeo, I.-K., and R. A. Johnson, 2000: A new family of power transformations to improve normality or symmetry. *Biometrika*, **87**, 954–959, doi:10.1093/biomet/87.4.954.

This study:

Röthlisberger, M., M. Hermann, C. Frei, F. Lehner, E.M. Fischer, R. Knutti and H. Wernli (2021): A new framework for identifying and investigating seasonal climate extremes. *In revision for J. Climate*.