Reply to Extratropicalcyclones by Raible et al

Anonymous Referee #1

Received and published: 4 July 2018

This paper documented the variability of Extratropical Cyclones (EC) in a 1-deg CESM model during the last millennium and the 21st century under RCP8.5 forcing. They found natural variations on decadal and multi-decadal timescales and substantial changes in cyclone frequency and precipitation under anthropogenic forcing. It is also found that the cyclone-related precipitation changes do not always conform to the CC relationship. The paper is presented in a clear and organized manner. Although most of the analyses are quite generalized and most of the results should be expected, studies of EC in such long-term historical simulations aren't common. I think this could serve as an introductory paper for more detailed studies using the same or similar simulations in the future.

My main comment is about the regression analysis applied in Section 4.3. It seems that the regression is based on the average depth/precipitation index of the entire North Atlantic. Because of the spatial average, it is no surprise that only the most dominant and large-scale circulation pattern (i.e., the NAO) would show up in Figure 5. While such analyses are convenient and easily make sense, the mechanisms that cause the spatial variations of ECs are muddled. Considering the large spatial variability of EC, I would prefer to see results that do not just focus on the regional mean. For example, the authors could try applying EOF analyses to the data to extract some spatial information.

The aim of the regression analysis was to give a broad picture of how mean (over the North Atlantic) cyclone characteristics are connected to other variables illustrating e.g. the mean circulation. The reviewer suggests to apply EOF analysis to the different cyclone characteristics and then assess the spatial pattern obtained in more details. This is in principle a very interesting idea and we thought about it when performing the analysis. Still, there are some issues of concern. The cyclone characteristics make not much sense on the grid point scale (they are mostly measures related to the cyclone center and there are certainly grid points where no cyclones have traveled over which makes the fields very noisy), so some area averaging is necessary (e.g. using all grid points in a circle of 500 or 1000 km around a point). This averaging would induce some spatial dependency which will affect the EOF analysis. Another way to treat this problem is to focus on specific 'impact regions', e.g., Central, Northern or Southern Europe and assess the different cyclone characteristics for these regions and perform a regression-correlation or composite analysis. For the moment we think that such an analysis is a story of its own and is beyond the scope of this study (i.e., to give a broader picture overview). Certainly, we have the plan to focus more on the impacts over Europe in an accompanied study as mentioned at the end of the manuscript. Still, to improve the current manuscript we discuss in more details which mechanistic understanding can be obtained from such an analysis and which not. This is done at the end of section 4.3 and in the conclusions.

Some minor comments:

Line 36: "millennium which" -> "millennium, which", and similar changes throughout

Applied throughout the manuscript as suggested.

Line 37-38: “the external forcing … characteristics” – awkward sentence. Suggest changing it to “the externally forced and internally varying extratropical cyclone activities”

Done as suggested.

Line 135: Would the cyclone statistics change if higher frequency outputs are used? What if time averaged instead of instantaneous outputs are used? Is the ERA data also 12-h instantaneous?

There are several studies which investigated the influence of the higher frequency output. Clearly, the cyclone can be identified more precisely and more cyclones are found when one uses higher frequency output or higher spatially resolved data, as suggested by Blender and Schubert (2000). Though we decided to save only 12-h output for reasons of data storage. It is not common to use time averaged output as this would blur the cyclone center.
We clarified the selection of 12-h output and also added that we have used 12-h instantaneous output of ERA interim.

Line 201: “area North” -> “area of North”

Changed to ‘We focus on the North Atlantic…’

Line 221: “as well as with” -> “as well as between”

Done

Line 267: any references for the improvements?

We relate the statement mainly to the higher resolution, but also several relevant processes in CAM4 (atmospheric part of CESM1) were improved, so we added the reference Neale et al. (2013).

Line 282: “missing volcanic forcing impact”. Do all the volcanic forcings have the same spatial patterns? It is likely that the effect of volcanoes cancels out due to their varying spatial patterns, but the individual volcanoes may still be impactful.

The spatial patterns of the volcanic eruptions are different. As we focus on the strongest eruptions they are all of tropical origin, which diminish the effect mentioned. We also individually analyzed the strongest eruptions and did not find a clear signal in the cyclone characteristics. Note that we focused our analysis on the extremes.
We clarified that the superposed epoch analysis focus on tropical eruptions.

Line 322: “region of minimized” -> “region of reduced”
Done

Line 355: “change of the” -> “change in”; “the latter one” -> “which”

Done

Thank you again for the helpful comments.

Anonymous Referee #2

Received and published: 7 July 2018
Formal review of manuscript for Climate of the Past
Manuscript identification number: CP-2018-58
Title: Extratropical cyclone statistics during the last millennium and the 21st century
Authors: C.C. Raible, M. Messmer, F. Lehner, T.F. Stocker, R. Blender
Recommendation: Minor revision

General Comments:

The authors investigate the variability of extra-tropical cyclone characteristics for the North Atlantic / European region based on a long coupled GCM simulation (850-2100). First, the variability pre-1850 is evaluated, rendering the general result that in spite of the identified multi-decadal variability no external forcing imprint is identified for this period. On the other hand, a general decrease in cyclone numbers (particularly for the Mediterranean) and cyclone related precipitation (e.g. north of 50_N over Europe) is identified for the XXI century. Finally, the authors discuss the possible relevance of thermodynamic vs dynamical processes for the identified trends / variability. The manuscript is well written, the methodologies and statistics are well applied, and the conclusions are largely sound. The consideration of such a long transient run is quite unusual, and the embedded discussion of natural vs anthropogenic forcing is quite interesting. Therefore, I believe the manuscript is a worthy contribution to Climates of the Past. Nevertheless, several minor aspects should be improved / better discussed before the paper is in acceptable form. Therefore, I recommend a minor revision according to the comments given below.

Minor Comments:

#1: lines 47-58: There is quite a lot of additional literature in this topic, so I understand the authors need to do a selection. However, I would recommend to include the two review papers of Ulbrich et al. (2009) and Feser et al. (2015), e.g. on line 48 and 52. If possible, a few more sentences on the different measures of cyclone activity and the regional differences would be excellent.

We included the additional literature and extended the discussion.

2: line 60: Please clearly state here that you mean that the low level meridional temperature gradients are reduced on average. On the upper troposphere, it is the opposite, as the strongest warming occurs in the tropical regions. Please find a suggestion below. This should also be stated more clearly other text passages. “The decrease of the projected low level meridional temperature gradient on average (due to strong high latitude near surface warming associated with polar amplification) implies a decrease of storm activity in the future, (: : :)<”

We agree and clarified that the low level meridional temperature gradients are reduced on average. We clarified it here and in other parts of the manuscript.

3: lines 161-163: While I understand the authors’ idea to consider the 90th percentile of central pressure and cyclone depth as a proxy for windiness, I think it would have been easy to assign peak near surface wind speeds close to the cyclone core (e.g. Zappa et al., 2013) a more adequate measure of windiness associated with the cyclones. What has this not

been done? Was the near-surface wind data not stored? Or was there another reason? This potential shortcoming makes a few statements in the manuscript (e.g. line 338-340) less robust and should at least be discussed as a potential shortcoming.

10 m wind data have not been stored. It is also a diagnostic variable which may suffer from some shortcomings, e.g., how the boundary layer is parameterized in the model. Above the boundary layer, the geostrophic approximation is reasonably fulfilled as we focus on the mid-latitudes. In particular, the cyclone depth measure takes advantage of the geostrophic approximation. Still, we clarified this. Concerning the lines 338-340 we do not see which shortcoming the reviewer refers to. Zappa et al. (2013) showed a slight decrease in extreme wind and an increase in precipitation using CMIP5 model simulation. We only use one model, so the only shortcoming we can see is that the multi model response deviates slightly from just using one model. We added a brief discussion in the conclusions.

4: lines 185-199: It is a bit unusual that the (lower resolution) GCM has a higher cyclone frequency as the ERA-Interim dataset. While I tend to agree with the authors that this may be partially associated with an enhanced number of weak lows in the GCM, I wonder in how far the (bi-linear!!!) re-gridding of the ERA-Interim played a role here. What do the cyclone statistics with the original ERA-interim grid look like? Are the statistics more comparable if one only considers strong cyclones (e.g. exceeding a certain depth)?

As expected the cyclone frequency increases slightly (roughly by 20 %) when using the original resolution of roughly 0.75 degrees. However, the main biases of the CESM simulation remain, namely the overestimation in the Hudson Bay and GIN Seas, so the interpolation does not change this result. We included this in the manuscript. Additionally, we calculated the cyclone frequency maps for strong cyclones, i.e., exceeding the threshold of 200 gpm in cyclone depth once in their lifetime. The threshold represents roughly the 10 % strongest cyclones. As expected the agreement is better for strong cyclones, but biases remain: the overestimation in the Baffin Bay and in the GIN Sea. We extended the discussion in the revised version.

#5: lines 301-310: Given that the main author has co-written a review paper on the NAO variability during the last millennium (Pinto and Raible, 2012), I wonder why so little is discussed about the link well established link between the NAO variability and cyclone variability over the Eastern North Atlantic and Europe (except for this text passage). In my opinion it would be pertinent to strengthen this statement and discuss a bit in how far the NAO variability in the simulation matches (or not) the cyclone variability for various parameters shown in Fig. 4, and in how far this agrees with NAO reconstructions. Even if the authors will surely explore this further in subsequent (and more regional) studies in the future, I suggest expanding the topic a bit here.

Given the results of Pinto and Raible (2012) it is tricky to relate changes in cyclone characteristics linearly to the NAO. In the paper Raible et al. (2007) we found intensified cyclones during a long period (several decades) which was governed by a negative phase of the NAO. For year-to-year variations, a positive phase of the NAO is associated with intensified storms (e.g., Hurrell et al. (1997). So, a clear connection between NAO and cyclone characteristics seems to be time-scale dependent and is not necessarily expected. With the analysis presented in the paper we see that there is a dipole pattern which agrees in some aspects with the canonical NAO pattern but is shifted and the northern center is not barotropic (as the NAO concept suggests). This is the reason why we were cautious about the interpretation and called the pattern ‘NAO-like’. To see whether the NAO has an impact on cyclones one needs to perform a different analysis, i.e. going to more regional scales like a separation in Northern and Southern Europe, composite analysis with respect to the NAO index, etc. This is clearly beyond the scope of this paper, but is certainly of interest in future assessments of the simulation.

6: lines 378-379: I suggest referring to Zappa et al (2013) here, which showed exactly this based on the CMIP5 model ensemble.
Done.

7: lines 381-401: The interesting thing here is that the increase in cyclone related precipitation is particularly clear north of 50_N (notably over Europe), while elsewhere reduced precipitation is often found, particularly at lower latitudes. Recent studies (e.g. Santos et al. 2016) have identified that there may be a “circulation independent” increase of precipitation north of _ 45_N over Western Europe and comparative drying around 35-45_N (cf. their Figure 9). This may imply that for the latter the increase of humidity is overcompensated by temperature (thus lower relative humidity) or hampered by increased subsidence. I think that present statement for the whole region regarding the Clausius-Clapeyron relationship is too general, and a more differentiated regional discussion would be quite interesting.

Thank you for this comment. It seems that the reviewer has overlooked one important detail. In Fig. 7 we showed the mean precipitation and not the extreme cyclone-related precipitation. So, we can certainly compare this result with the one of Santos but for the discussion of the CC relationship, this might be a bit misleading. Realizing that this is a problem we tried to be more clear.
Concerning a more regional discussion of the CC relationship we implicitly have the regional scale included as we compare the extreme cyclone-related precipitation with the cyclone-related temperature. Again, we clarified this in the manuscript.

11: line 424: Please add Ulbrich et al (2009) and Zappa et al. (2013) here.
Done

12: line 429: see discussion in #10, please enhance, maybe adding “at least north of 50_N” or similar.
We think that adding north of 50N would be not supported by our analysis. See #10.

We thank the reviewer for his helpful comments and suggestions.

References (not exhaustive):

Feser F., et al. (2015). Storminess over the North Atlantic and Northwestern Europe: A review. QJRMS, 141, 350-382. doi:10.1002/qj.2364.

Pinto JG, Raible CC (2012) Past and recent changes in the North Atlantic Oscillation. WCC, 3, 79–90. doi:10.1002/wcc.150

Santos JA, (2016) Understanding climate change projections for precipitation over Western Europe with a weather typing approach. JGR-A, 121, 1170–1189. doi:10.1002/2015JD024399

Ulbrich U, et al (2009) Extra-tropical cyclones in the present and future climate: a review. TAAC, 96, 117–131. doi:10.1007/s00704-008-0083-8

Zappa G., et al. (2013) A multimodel assessment of future projections of North Atlantic and European extratropical cyclones in the CMIP5 climate models. JCLIM, 26, 5846– 5862. doi:10.1175/JCLI-D-12-00573.1, 2013.

Anonymous Referee #3

Received and published: 11 July 2018

This manuscript investigates a long integration of the 1deg version of the CESM, from 850-2100 (with RCP8.5 forcings). The authors use 12-hourly data to track extratropical cyclones (ETCs) over the North Atlantic. Results are dominated by interannual-todecadal scale fluctuations of cumulative ETC metrics (count, intensity, precipitation) but no obvious external forcing signal is noted. After 2100, strong increases in ETC precipitation and decreases in ETC count are noted, with authors applying a regression analysis to demonstrate that these changes are mostly thermodynamic in nature, in line with previously published work. Some regional variations are also considered, particularly over the Mediterranean and Scandinavia.

In general, I feel the manuscript is clear and crisp, albeit not with overly novel conclusions. As a scientist who deals mostly with future storminess associated with climate change, I think this type of analysis is relevant to our understanding of climate models and the dynamics of the features themselves within the climate system over long time periods. Where I do have one concern is the results of the tracking algorithm, particularly with regards to CESM, that may be somewhat influencing the results. Before final publication, I feel these should be addressed by either retracking the storms or running a sensitivity analysis. Assuming the authors have a pipeline that performs the subsequent analysis in Figs. 4-8, this should be fairly trivial to undertake.

As one who has used CESM data in the past, if the authors are using the in-line 1000hPa geopotential (Z1000) as a variable (versus calculating Z1000 using the hybrid coefficients and topography) they are likely having issues with the fact that CESM will not automatically interpolate "below ground." Therefore, while the true Z1000 is likely negative over high-terrain areas (e.g., Greenland) the Z1000 reported from CESM is anomalously positive since the code will not go below the lowest model level (at least, according to my recollection). This is a quirk of the CESM in-line interpolation and is likely causing the issues (high cyclone count near high-terrain areas) seen in Fig. 2b since the "background" Z1000 field is biased very high. This can probably be rapidly verified by just comparing the time-mean Z1000 in both ERA-Interim (ERA-I) and CESM. The optimal correction for this would be to use some sort of offline solver with the 3-D Z field and Python/NCL/IDL/etc.

Actually we used the 3-D field of geopotential height and some NCL routines offline to interpolate the Z1000 field. The exact routines are:

```
;**********************************************
; This script interpolates sigma to pressure coordinates
; in outputs the geopotential height (for all plevs chosen)
;**********************************************
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_code.ncl"
load "$NCARG_ROOT/lib/ncarg/nclscripts/csm/gsn_csm.ncl"
;**********************************************
begin
;**************************************************
; read in data
;**************************************************

;******only years
;******year has to be given with the function call: 'for a in { }; do ncl
;******year=... Interpolation_... ;done'

path1="/BPRD_trans/atm/hist/BPRD_trans.cam2.h1.$yy-01-01-00000.4.nc"

in = addfile(path1,"r")


;------------------------------------------------------------------------
```

```
; read needed variables from file
;-----------------------------------------------------------------------

Z3 = in->Z3      ; select variable to be converted
P0mb = 1000.
hyam = in->hyam    ; get a coefficiants
hybm = in->hybm    ; get b coefficiants
PS = in->PS      ; get pressure
TBOT = in->TS    ; get temperature at lowest layer (closest to surface)
dims = dimsizes(Z3)
nlevs= dims(1)
PHIS = Z3(:,nlevs-1,:,:)*9.81   ; get geopotential [m^2/s^2] at the bottom (lowest layer)

;-----------------------------------------------------------------------
; define other arguments required by vinth2p
;-----------------------------------------------------------------------

; type of interpolation: 1 = linear, 2 = log, 3 = loglog
interp = 2

; is extrapolation desired if data is outside the range of PS
; extrap = False
extrap = True

; A scalar integer indicating which variable to interpolate: 1 = temperature,
; -1 = geopotential height, 0 = all others.

varflg = -1

; create an array of desired pressure levels:
plevs =(/ 1000.0 /)

plevs!0 = "plevs"
plevs&plevs = plevs
plevs@long_name = "Pressure"
plevs@unit = "hPa"


intVar_PS = vinth2p_ecmwf(Z3,hyam,hybm,plevs,PS,interp,P0mb,1,extrap,varflg,TBOT,PHIS)

intVar_PS!0 = "time"
intVar_PS!1 = "lev"
intVar_PS!2 = "lat"
intVar_PS!3 = "lon"
intVar_PS&time = in->time
intVar_PS&lev = plevs
intVar_PS&lat = in->lat
intVar_PS&lon = in->lon
intVar_PS@units = "m"
intVar_PS@long_name = "Geopotential Height (above sea level)"

;system("echo saving")
;setfileoption("nc","Format","NetCDF4Classic")
;fileout=getenv("FZ")

fileout="BPRD_trans.cam2.h1.$yy-01-01.z1000.nc"


system("rm " + fileout)        ; remove any pre-existing file


fout=addfile(fileout,"c")

fout->Z3 = intVar_PS ; write into new file
system("echo new file for GPH")  ; print path and new file to screen as confirmation
```

Therefore, we think that a retracking is not necessary. To convince the reviewer we added an analysis of Z1000 and SLP in this point-to-point response:

Comparing the Z1000 with the SLP averaged for the period 1980-2009 a small positive difference over the center of Greenland is found (Fig R1, below). However, this difference between Z1000 and SLP does not affect the two regions where CESM overestimates cyclones (see manuscript Fig. 2), namely in the Hudson Bay and in between Iceland and Spitzbergen. We additionally made a visual test (movie of Z1000 field) and see that CESM simulates more cyclones traveling to these two regions than ERA interim. So there are no stationary cyclones in these regions which may be a hint that the interpolation of Z1000 leads to some artificial cyclones. Note also the effect of the slightly coarser resolution of ERA interim (here in Fig. R1 1.5 degree) which leads to a less pronounced meridional pressure gradient in the North Atlantic. So some of the bias might be due to weak cyclones (we will give more arguments for this in the revised version), but certainly CESM also overestimates cyclones. We added the treatment of the vertical interpolation in the revised version.

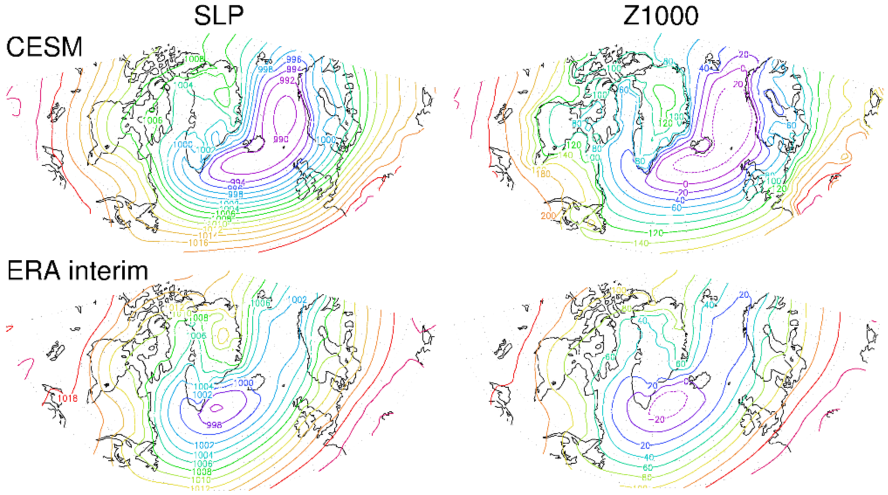

Fig.R1: Comparison of mean SLP and Z1000 field for winter DJF for the period 1980 to 2009: (top) CESM, (bottom) ERA interim.

In this vein, it is not clear why the authors are not tracking on sea level pressure (PSL), which is essentially a prognostic quantity in most climate models (technically PS is prognostic, but the correction to PSL primarily uses other prognostic variables like T and the surface topography field). PSL is a much more widely-used quantity when evaluating climate models and would likely alleviate the issues.

As seen above there is no strong difference between PSL and Z1000 so that we think it is not necessary to redo the analysis with PSL. Also from a dynamical point of view the geopotential height is more relevant than the PSL and there is a direct relation to the geostrophic wind. In most publications, which apply the cyclone detection and tracking method of Blender et al. (1997), Z1000 is used as input rather than sea level pressure. For consistency, we would like to stay with Z1000.

The fact that CESM simulates far more cyclones than ERA-I is therefore questionable. While there are certainly some differences in effective resolution, etc. of the datasets, a factor of almost 2x (Line 202) in the total number of storms between CESM and ERA-I seems quite high at first blush. The authors hypothesize this is due to weak C2 storms, but that is not clear to me from Fig. 3. For example, the SLP distribution shows more weak storms for CESM, but also more strong ones. Having a smaller radius distribution is also not necessarily indicative of weaker storms, as aspects of the model configuration such as numerical diffusion and how grids are interpolated may contribute to differences here. This is somewhat hinted at in Figs 3c-d. As an additional example, one could make an argument that 1deg ETCs would be "smaller" than 4deg ETCs, but 1deg ETCs *should* be more intense based on being better resolved.

We agree with the reviewer that the number of cyclones are strongly overestimated in CESM. One reason is that CESM shows more short-lived cyclones. When comparing the cumulative cyclone presence, the difference is already reduced (CESM: 22993; ERA interim: 15590). Though, CESM still overestimates cyclones. We further agree with the reviewer that some of the argumentation explaining this difference was not clear and Fig. 3 does not always support the line of evidence given. Therefore, we reformulated the entire paragraph. We also performed additional analysis, e.g., conditional distributions for short-lived cyclones which show that they can explain some of the difference in the number of cyclones. Also we find that short-lived cyclones have a smaller radius and are less intense (based on central pressure and cyclone depth). We also redid part of the analysis with the ERA interim in 0.75-degree resolution. As expected, we find more cyclones (roughly 20 %) in the higher resolution compared to the lower one. Also the mean radius is increased by roughly 10 % in the high resolution ERA interim. However, the biases discussed above and in the manuscript still remain present when comparing CESM to the high resolution ERA interim results.

I would like the authors to consider "retracking" the storms if PSL is available. They could easily modify their algorithm to search for prognostic deficits in PSL as in other trackers within the IMILAST project (of which the lead authors of this manuscript already contributed to). If that is not available, I would like the authors to try and evaluate whether or not the issues of additional ETCs tracked in CESM are related to the Z1000 issue noted above. One option would be to run CESM for a short period (perhaps a few decades) and compare the results of using the inline Z1000 with PSL or a more accurately diagnosed Z1000.

As seen by the analysis above, the mean PSL and Z1000 pattern are very similar. The suggested use of PSL in the detection and tracking method of Blender et al. (1997) induces substantial changes. It would involve testing and adjusting several parameters of the method and given the fact that the mean pattern in Fig. R1 look very similar, we think it is not necessary to "retrack" the cyclones.

Minor comments:

Line 122: "So called" is too colloquial, would just say "this is the 1deg version of the model used in CMIP-class experiments" or thereabouts.

Done

Line 123-124: Would include a sentence or two about the subgrid physics package used in this version of CESM (in the atmospheric model) since that would have the largest impact on the results here, particularly thermodynamic ones.

The main changes of CAM (atm. model) are described in the Neale et al. (2013). We added a brief description in this section.

Line 245: Are there changes in mean storm-track, basin-wide surface pressure, etc. that may be relevant here?

The SLP can be affected by a basin wide surface pressure trend (as it is part of it), but the cyclone depth (as a relative measure) is not sensitive to such a change. As results from both measure agree with each other, we do not expect an influence of basin-wide surface pressure trend on this result.

Line 262: 4deg models certainly underresolve synoptic scale features, which ETCs are.

We clarified this.

Line 299: Is this a basin-wide metric? I question a bit about correlating the spatial pattern with basin-wide metrics as then I'd expect large scale North Atlantic patterns that control ETCs to dominate this analysis (e.g., the NAO).

Yes, basin-wide metrics are used to get a first more general impression. We expected to see NAO-like patterns which is (to some extent) true for the cyclone depth metric but not for the cyclone-related precipitation.

Line 312: The spatial field remains quite noisy, I would be a bit careful about being too conclusive since, even with a multi-century simulation, I'm not sure we can be completely confident very small (O(10deg)) spatial patterns are tremendously significant in a model whose effective resolution is probably _6deg (see Skamarock 2004 for discussion of effective resolution in numerical models).

It is expected that the Figs. 5c and d are noisier than a and b as we assess cyclone frequency and precipitation. We are aware that one should only interpret significant areas of a certain larger extent so we modified the description of Fig. 5c,d accordingly. We also realized that not always the region of the significant change was mentioned. This is also clarified.

Line 321: This reads as a bit "hand-wavy;" I'd formalize and clean up the text a bit.

We tried to reformulate this part.

Line 332: These "barotropic pressure structures" could be underresolved warm core storms (e.g., tropical cyclones) moving to mid-to-high latitudes. 1deg models are capable of starting to simulate these features, albeit far weaker than what is observed (e.g., Wehner et al., 2014, Walsh et al., 2015).

We realized that this was not clear. The barotropic structure we refer to is over Central Europe. So, we have high pressure when the cyclone related precipitation index is enhanced. As most of the correlation coefficient in the Z1000 and the Z500 field are not significant we removed this part. Note that hurricanes cannot play a major role as we focus on season DJF.

We thank the reviewer for his helpful comments and suggestions.

References:

Skamarock, W.C., 2004: Evaluating Mesoscale NWP Models Using Kinetic Energy Spectra. Mon. Wea. Rev., 132, 3019–3032, https://doi.org/10.1175/MWR2830.1

Walsh, K.J., S.J. Camargo, G.A. Vecchi, A.S. Daloz, J. Elsner, K. Emanuel, M. Horn, Y. Lim, M. Roberts, C. Patricola, E. Scoccimarro, A.H. Sobel, S. Strazzo, G. Villarini, M. Wehner, M. Zhao, J.P. Kossin, T. LaRow, K. Oouchi, S. Schubert, H. Wang, J. Bacmeister, P. Chang, F. Chauvin, C. Jablonowski, A. Kumar, H. Murakami, T. Ose, K.A. Reed, R. Saravanan, Y. Yamada, C.M. Zarzycki, P.L. Vidale, J.A. Jonas, and N. Henderson, 2015: Hurricanes and Climate: The U.S. CLIVAR Working Group on Hurricanes. Bull. Amer. Meteor. Soc., 96, 997–1017, https://doi.org/10.1175/BAMS-D-13-00242.1

Wehner, M. F., K. A. Reed, F. Li, Prabhat, J. Bacmeister, C. Chen, C. Paciorek, P. J. Gleckler, K. R. Sperber, W. D. Collins, A. Gettelman, and C. Jablonowski (2014), The effect of horizontal resolution on simulation quality in the Community Atmospheric Model, CAM5.1, J. Adv. Model. Earth Syst., 6, 980–997, doi: 10.1002/2013MS000276.

Anonymous Referee #4

Received and published: 13 July 2018

I have reviewed this manuscript cp-2018-58 entitled "Extratropical cyclone statistics during the last millennium and the 21st century" by Christoph C. Raible et al. In this manuscript, the authors studied the extratropical cyclones and their changes in the 20th and 21st centuries using a unique CESM1 simulation from 850-2100 with high temporal output. They found that the variations of the cyclones over the North Atlantic and Europe sector before industrialization are mainly related to the internal variability, not directly related to either volcanic or solar forcing (nature forcing). Towards the 21st century, two of the cyclone metrics show significant trends. They also show that the Clausius-Clapeyron relation is not always followed by the changes of the cyclones and the global mean temperature. I found this manuscript is very interesting and worth to be published subject to some minor revision.

Comments:

1. the authors using a 30-year running correlation to show whether changes of solar forcing will affect the cyclone activity and found there is no relationship. Since one of the major solar cycle is 11-years, with a 30-year running window, it will not show the effect of solar forcing on the cyclone activities. The authors could do a spectrum analysis for the cyclone activities and check with the solar forcing cycles (11-year or other cycles). This could give a better sense on whether solar activity would or would not affect the cyclones.

We perform an analysis using yearly data for solar forcing and the cyclone characteristics. We applied the wavelet cross spectral method (Fig. R2). Clearly, the method identifies the 11-yr cycle in the solar forcing used for the simulation (left column). The middle column shows the wavelets of the cyclone characteristics. The right column shows the corresponding cross wavelet spectra. These cross spectra show enhanced common variability between the solar forcing and corresponding cyclone characteristic. However, the arrows, which illustrate the phase relationship (e.g., to the right means in phase, to the left out of phase), show for the 11-yr period no coherent picture, i.e., sometimes we see an in phase relationship, sometimes the solar forcing and the cyclone characteristic are out of phase. This means that there is no connection to the 11-yr cycle. We mention the analysis in the revised version, but will not include a figure, as it only confirms our results.

2. Line 351, "The former is due to polar amplification, induced by a strong sea ice reduction and the reduced heat capacity of the land surface compared to the ocean", in this sentence, it is not clear to me why the heat capacity of land reduces? it is because the ocean heat capacity increases? or something else. It would be nice that the authors could explain this a bit better or add some references.

This was indeed misleading and we clarified this in the revised version.

3. Overall, it seems that the physical explanations are a bit weak in this manuscript.
We tried to be more precise in the revised version of the manuscript and extended some of the physical explanations.

We thank the reviewer for his helpful comments and suggestions.

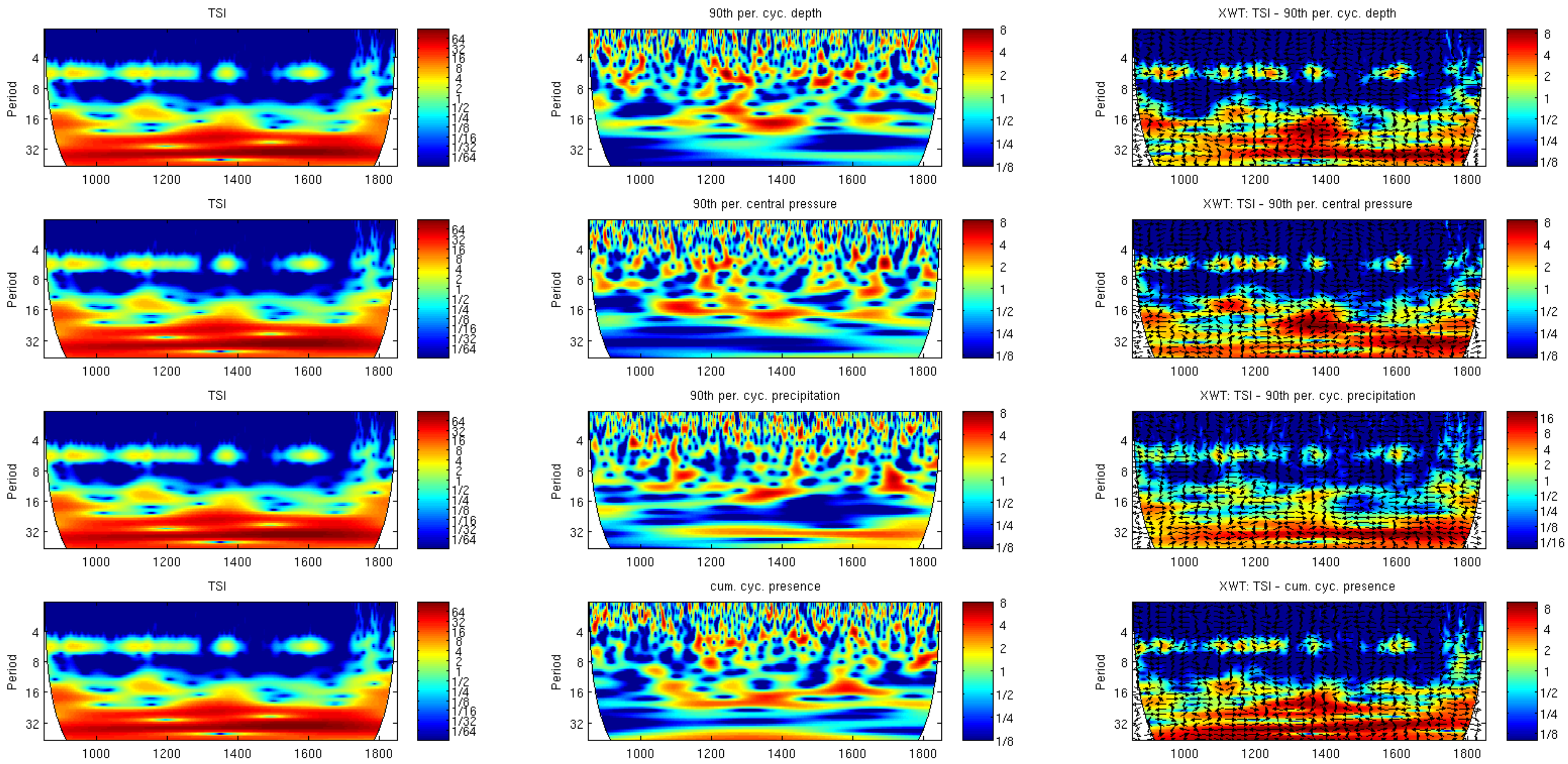

Fig. R2: Wavelet (left and middle column) and crosswavelet (right) spectra. The relative phase relationship is shown as arrows in the right panels (with in-phase pointing right, anti-phase pointing left, and solar forcing leading the cyclone charcteristic by 90° pointing straight down). The method is taken from Grinsted et al. (Nonlinear Processes in Geophysics, 2004, 11: 561–566).

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Extratropical cyclone statistics during the last millennium and the 21st century

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Abstract. Extratropical cyclones in winter and their characteristics are investigated in depth for the Atlantic European region, as they are responsible for a significant part of the rainfall and extreme wind and/or precipitation-induced hazards. ~~Here, we use~~ The analysis is based on a seamless transient simulation with a state-of-the-art fully-coupled Earth System Model from 850 to 2100 CE~~as basis for the analysis~~. The RCP8.5 scenario is ~~applied~~ used in the 21st century. During the Common Era, cyclone characteristics show pronounced variations on interannual and decadal time scales, but no external forcing imprint is found prior to 1850. Thus, variations of extratropical cyclone characteristics are mainly caused by internal variability of the coupled climate system. When anthropogenic forcing becomes dominant in the 20th century, a decrease of the cyclone occurrences mainly over the Mediterranean and a strong increase of extreme cyclone-related precipitation become detectable. The latter is due to thermodynamics as it follows the Clausius-Clapeyron relation. An important finding, though, is that the relation between temperature and extreme cyclone-related precipitation is not always controlled by the Clausius-Clapeyron relation, which suggests that dynamical processes can play an important role in generating extreme cyclone-related precipitation - for example in the absence of anomalously warm background conditions. Thus, the importance of dynamical processes, even on decadal time scales, might explain the conundrum that proxy records suggest enhanced occurrence of precipitation extremes during rather cold periods in the past.

1 Introduction

Extratropical cyclones are fundamental phenomena of the day-to-day weather variability. Extreme extratropical cyclones have a strong impact on society and economy and are one of the major natural hazards of the mid-latitudes (e.g., Schiesser et al., 1997; Beniston, 2007; Etienne et al., 2013). Thus, a better understanding of variations of cyclone characteristics is essential and has led to a variety of studies, which assess recent and future changes in cyclone characteristics (e.g., Ulbrich et al., 2008; Bengtsson et al., 2009; Pinto et al., 2009; Raible et al., 2010; Schneidereit et al., 2010; Zappa et al., 2013; IPCC, 2013). Still, considerable uncertainty remains of how extratropical cyclones react to changes of external forcing, especially in the 21st century (Harvey et al., 2012; IPCC, 2013) as confounding and partly canceling processes are difficult to disentangle (O'Gorman, 2010; Woollings et al., 2012b). Additionally, low-frequency internal variability might be important, e.g., a potential influence of the Atlantic Meridional Overturning Circulation (AMOC) on cyclones has been discussed (Woollings et al., 2012a, 2015). Some of the uncertainties also arise from the fact that the observed time period is rather short, making it difficult to validate model-simulated decadal variability in cyclone statistics. Further, there are only a few modelling studies, which put changes of extratropical cyclone characteristics in a long-term perspective (Fischer-Bruns et al., 2005; Raible et al., 2007; Gagen et al., 2016). A possibility to overcome this is the last millennium, which enables us to study the ~~external forcing imprint on extratropical cyclone characteristics and the interaction of internal variability of the climate system with these characteristics~~ externally forced and internally varying extratropical cyclone activities (Bothe et al., 2015; Smerdon et al., 2017).

The purpose of this study is to establish a long-term, pre-instrumental perspective for cyclone characteristics. In particular, we evaluate the future of these characteristics under the RCP8.5 scenario and compare it to natural variability during the last millennium. We take advantage of a transient simulation for the last millennium in high resolution (approx. $1° \times 1°$), which provides 12-h output — a necessity to investigate extratropical cyclones and their characteristics, such as cyclone-associated wind and precipitation extremes. The focus of the analysis is on the North Atlantic region and winter (December to February).

Various studies have analyzed the climate change response of extratropical cyclones and some of their characteristics ~~(e.g., Ulbrich et al., 2008; Zappa et al., 2013; IPCC, 2013)~~ (e.g., Ulbrich et al., 2008, 2009; Zappa et al., 2013; Feser et al., 2015; IPCC, 2013). A robust finding is that the warmer atmosphere in the future leads to a moistening of extratropical cyclones and thus to more precipitation (Bengtsson et al., 2009; Zappa et al., 2013). In the North Atlantic, an extension of the storm track into Europe is suggested under future climate change ~~(e.g., Bengtsson et al., 2006; Catto et al., 2011; McDonald, 2011; Zappa et al., 2013)~~ (e.g., Bengtsson et al., 2006; Ulbrich et al., 2009; Catto et al., 2011; McDonald, 2011; Zappa et al., 2013; Feser et al., 2015).

For the Mediterranean a decrease in winter cyclone activity is projected (e.g., Ulbrich et al., 2009; Raible et al., 2010; Zappa et al Further modelling studies suggest that the wind intensity of extratropical cyclones in the North Atlantic is projected to be enhanced north of 55°N in the future compared to today (e.g., Feser et al., 2015), leading to a higher potential of future losses (Pinto et al., 2012). A process relevant for this intensification is a local minimum in the warming of the North Atlantic Ocean due to a reduction of the AMOC (Rahmstorf et al., 2015). This temperature anomaly leads to stronger low-level temperature gradients within the North Atlantic basin than today and thus to enhanced low-level baroclinicity (Laine et al., 2009; Catto et al., 2011; Woollings et al., 2012b).

Substantial uncertainty remains in future projections of extratropical cyclone characteristics because of the processes involved (Harvey et al., 2012). The decrease of the projected low-level meridional temperature gradient on average (due to strong high latitude near surface warming associated with polar amplification) implies a decrease of storm activity in the future, but at the same time the vertical temperature gradient decreases over the Atlantic and Arctic, which induces a reduced static stability and thus a favoring of storm growth (Harvey et al., 2012). Additionally, the moisture changes also influence the cyclone formation as latent heating arising from moist condensation often strengthens cyclones due to diabatic potential vorticity anomalies (e.g., Gutowski et al., 1992; Li et al., 2014), such that one would expect an intensification of cyclones in a warmer, moister climate (Willison et al., 2013). However, increased moisture, and therefore latent heat content in the global circulation leads to a more efficient poleward transport of energy, and therefore to a weakening of cyclonic activity in the mid-latitudes (e.g., O'Gorman and Schneider, 2008; Schneider et al., 2010; Li et al., 2014). Additionally, other processes like changes in the wave-wave interaction (James and James, 1989; Riviere, 2011) and in the eddy length scale (Kidston et al., 2011) might play a role for the response of extratropical cyclones to future anthropogenic forcing changes and for the uncertainty of the response in different climate model simulations.

The past can serve as a test bed to place future projection of extratropical cyclone characteristics into context and to assess multi-decadal variability. Climate states completely different from the present, like the Last Glacial Maximum show pronounced differences in extratropical cyclone behavior. Hofer et al. (2012a,b) showed that cyclones tend to move more zonally over the North Atlantic leading to enhanced precipitation in Southern Europe in winter. The reason is a southward shift of the eddy driven jet due to the Laurentide ice sheet (Merz et al., 2015). However, in the last interglacial, the Eemian (130 ka ago), the jet positions and thus the cyclones are similar to present (Merz et al., 2015). More relevant is potentially the recent past, i.e., the last millennium including the Medieval Warm Period (approx. 11th to the 13th century) and the Little Ice Age (LIA, approx. 14th to the 19th century; e.g., Bradley and Jones, 1993; Broecker, 2000; McGregor et al., 2015), as these periods are precursors of the Anthropocene (Zalasiewicz et al., 2010) and, thus, provide a rich and highly resolved proxy network (e.g., PAGES 2k Consortium , 2013). In multi-century preindustrial climate model simulations, Fischer-Bruns et al. (2005) suggested that natural variability of extratropical cyclones is unrelated to external forcing like total solar irradiance (TSI), or volcanoes. This is in contrast to the modelling study of Raible et al. (2007) who found a significant intensification of cyclones in the North Atlantic during the Maunder Minimum (a period of reduced TSI from AD 1640-1715) compared to today, although part of the signal is already of anthropogenic origin. They further showed that low-level baroclinicity is enhanced due to the increased low-level meridional temperature gradient, which seems to be the dominant process for cyclone intensification in their coarsely resolved simulations. Comparing this model result with proxy records shows that during the LIA more severe storms are observed (Björck and Clemmensen, 2004; de Jong et al., 2007; Sabatier et al., 2012; Trouet et al., 2012; Van Vliet-Lanoe et al., 2014; Degeai et al., 2015; Costas et al., 2016).

Since the early attempts to assess past extratropical cyclone behavior in model simulations (e.g., Fischer-Bruns et al., 2005; Raible et al., 2007) the ability to perform millennium-size simulations in high resolution has improved so that today several simulations for the last millennium based on different models are available (Schmidt et al., 2011; Braconnot et al., 2012; Taylor et al., 2012; Otto-Bliesner et al., 2016). Still, most of these simulations have only saved monthly data, which prevent us to analyze extratropical cyclones in these simulations. Recently, a last millennium simulation spanning the period AD 850 to 2099 became available providing 12-h data (Lehner et al., 2015). This enables us to address the following research questions:

- How are cyclone characteristics projected to change in the 21st century?
- How do these changes compare with variability, in particular low-frequency variation, during the last millennium?

The study is structured as follows: Section 2 briefly presents the model and experimental design chosen to generate the last millennium simulation. Further, the cyclone detection and tracking method is introduced and the cyclone characteristics are defined. In Section 3 the last millennium simulation is compared with ERA interim for the period AD 1980 to 2009 to demonstrate the model's ability in simulating cyclone characteristics. Then, the climate change signals of the different characteristics are put into context to the low-frequency variability (Section 4). Finally, the results are summarized and discussed and concluding remarks are presented in Section 5.

2 Model and methods

2.1 Model and experimental design

To investigate the characteristics of extratropical cyclones we use the Community Earth System Model (CESM, 1.0.1 release; Hurrell et al., 2013). It is a state-of-the-art fully-coupled Earth System Model developed by the National Center for Atmospheric Research. CESM relies on the Community Climate System Model (CCSM; Gent et al., 2011) in terms of the model physics, but it contains a carbon cycle module, which is included in its atmosphere, land and ocean components. ~~The CESM is used in the so-called~~ We use the 1° version ~~to simulate the entire last millennium from AD 850 to 2099. The~~ of the model (used in CMIP-class experiments), i.e., the finite volume core of the atmosphere has a uniform horizontal resolution of $1.25° \times 0.9°$ at 26 vertical levels. Compared to the former version of the atmosphere component, important improvements are implemented in the deep convection parameterization by including a dilute plume calculation of convective available potential energy and by introducing the convective momentum transport (Neale et al., 2013). Additionally, the cloud fraction method has been modified to reduce the positive bias of wintertime polar clouds. Further details on the changes in the atmospheric component are presented in Neale et al. (2013).

CESM is used to simulate the entire last millennium from AD 850 to 2099. The initial conditions for this transient simulation are obtained from a 500-yr control simulation for perpetual AD 850 conditions, which was run into a quasi-equilibrium state (no drift of the global mean temperature in the upper part of the ocean). The transient external forcing follows the Paleo Model Intercomparison Project 3 (PMIP3) protocols (Schmidt et al., 2011) and the Coupled Model Intercomparison Project 5 (Taylor et al., 2012). It consists of TSI, volcanic and anthropogenic aerosols, land use change, and greenhouse gases (GHGs; Fig. 1). Note that the TSI deviates from the PMIP3 protocol in that the amplitude between the Maunder Minimum (1640-1715) and today is doubled. Further, the model has enabled the carbon cycle module. To extend the simulation beyond AD 2005 the RCP8.5 is applied, which corresponds to a radiative forcing of approximately 8.5 W m^{-2} by 2100. Further details on the simulation are summarized in Lehner et al. (2015).

~~The~~ To save storage the analysis is based on 12-h instantaneous output~~, a resolution~~. This resolution is sufficient to derive characteristics of extratropical cyclones. For example, Blender and Schubert (2000) showed that the number of cyclones based on 12-h output is only reduced by 14 % compared to the number obtained from 6-h output. Furthermore, all pressure level simulated data used in the analysis are interpolated using the 3-dimensional field in sigma pressure coordinates, in particular geopotential height at 1000 and 500 hPa. The analysis focuses on the North Atlantic region in winter (December to February, DJF).

2.2 Cyclone detection, tracking, and characteristics

The cyclone analysis is based on a modified Lagrangian cyclone detection and tracking scheme first developed by Blender et al. (1997). The method is applied to the 1000-hPa geopotential height field and consists of two steps: (i) cyclone detection and (ii) tracking:

(i) A low pressure system is identified as a minimum in the geopotential height at 1000 hPa in a neighborhood of eight grid points and its intensity (in gpm/1000 km) defined as the mean gradient between the local geopotential height minimum and its neighboring grid points within an area of 1000 km distance to the minimum. To neglect weak or unrealistic minima, a minimum threshold value of this intensity measure is set to 20 gpm/1000 km and the radius of a cyclone must exceed 100 km. Further, cyclone centers identified in high topography (above 1000 m a.s.l.) are excluded.

(ii) To connect identified pressure minima a next neighborhood search is applied within a search radius of 1000 km. To further prevent erroneous detection of cyclones, two additional thresholds are used: the cyclone has a minimum lifetime of 24 hours, and the intensity (defined above) needs to exceed 30 gpm/1000 km once in its lifetime. More details on the cyclone detection algorithm are provided in Blender et al. (1997), Raible and Blender (2004) and Raible (2007). Furthermore, an intercomparison of different cyclone detection and tracking methods showed that the method used in this study is within the range of other methods (Raible et al., 2008; Neu et al., 2013). In particular, the agreement between the methods increases when focusing on extreme cyclones (Neu et al., 2013; Lionello et al., 2016; Grieger et al., 2018).

The Lagrangian cyclone detection and tracking method provides a variety of extratropical cyclone characteristics. Besides the number of time steps when a cyclone is present (or cumulative cyclone presence), intensity measures for wind are deduced, i.e., the central sea level pressure and the cyclone depth. The latter is the difference between the central geopotential height and the surrounding mean geopotential height in distance of the radius of the cyclone (defined below). The 90th percentile of central pressure and cyclone depth of all cyclones within a season is used to define extremeness of windrelated measures. Note that cyclone depth and wind are connected via the geostrophic approximation in the free atmosphere of the mid-latitudes.

The radius is estimated by a Gaussian radius-depth method based on Schneidereit et al. (2010) to estimate the geometric structure of the cyclones. Thereby, the geopotential height surface in the neighborhood of a cyclone minimum is approximated by a Gaussian, which is fitted by a least squares method. The standard deviation of the Gaussian is then an estimation of the cyclone radius, another characteristic of extratropical cyclones.

Further, the area of the cyclone defined by this radius is used to quantify the amount of precipitation, related to this cyclone. The precipitation is integrated over this area for each time step of the cyclone and defines the cyclone-specific precipitation. To focus on extreme cyclone-specific precipitation, the 90th percentile of cyclone-related precipitation estimated within the season is used as an index of extremeness. A similar approach is selected to deduce cyclone-related temperature, though for this index we are interested in the mean of the season and not in the 90th percentile.

The radius is also used to deduce the Eulerian measure of cyclone occurrences, the so-called i.e. the cyclone frequency. For one time step each grid point within the radius of a cyclone is assigned to be occupied by the cyclone. Summing over all time steps for each grid point and dividing by the total number of time steps results in cyclone frequency at each grid point. This measure enables us to identify regions of high and low cyclone occurrence.

All extratropical cyclone characteristics mentioned above are deduced for the North Atlantic region defined as 30° – 70°N and 65°W – 40°E (Fig. 2a).

3 Model evaluation

Before extratropical cyclone characteristics for the last millennium and the future are presented, the model's ability to simulate cyclones is demonstrated for the period CE 1980–2009 for winter (DJF). To compare the simulated cyclones and their characteristics the ERA interim reanalysis data are used (Dee et al., 2011). The ERA interim data are first bi-linearly interpolated to the same resolution as CESM ($1.25° \times 0.9°$). Similar to CESM, 12-h instantaneous output is used in the analysis.

Figure 2 shows the cyclone frequency of the CESM simulation and ERA interim. The main centers of enhanced cyclone occurrence are realistically simulated, i.e., cyclone genesis region over Northern America, the North Atlantic storm track, as well as the Island low pressure region. Still, the CESM tends to simulate more cyclones over the North Atlantic compared to ERA interim. This bias remains even when using the ERA interim data in 0.75° resolution. Some differences are found around Greenland and the Hudson Bay where CESM overestimates the cyclone frequency. The reason for this is partly the fact that geopotential height over orography is extrapolated to 1000 hPa leading to artificial high pressure and thus ~~a tendency to weak low pressure systems~~ to low pressure in the surrounding~~ocean regions. Still, most of the cyclones in the Labrador Sea are cyclones originating from the cyclone genesis area around Newfoundland~~. The biases are slightly reduced for strong cyclones using cyclone depth as a measure. Another caveat is visible over the Mediterranean where CESM slightly underestimates cyclones over the western and central Mediterranean and overestimates cyclone occurrence in the eastern part. Thus, the interpretation of the results over ~~polar regions around Greenland and the Mediterranean~~ these regions requires particular caution.

To further assess the model's ability in extratropical cyclone simulation, distributions of different cyclone characteristics are presented in Fig. 3. We focus on the ~~area North Atlantic~~ North Atlantic (marked in Fig. 2a~~. In total 12369 cyclones are identified~~). Note that the region excludes the main biases around Greenland. The cumulative cyclone presence is 22993 in CESM and ~~7624~~ 15590 in ERA interim. ~~The~~ One reason for this overestimation is that CESM generates more short-lived cyclones (< 48 h) as illustrated by the life time of the cyclones ~~show a similar distribution for CESM and ERA interim~~ (Fig. 3a). ~~CESM shows a slight overestimation of~~ Assessing the short-lived cyclones ~~and underestimates long-lived cyclones (> 48 h). This is a first hint that~~ we find that these cyclones are on average smaller (radius) and weaker (central pressure or cyclone depth measure, not shown). Thus, more weak cyclones are identified in CESM compared to ERA interim~~explaining partly~~ , which partly explains the higher cyclone frequencies (Fig. 2) ~~. The results of the radius confirm this finding as CESM tends to underestimate the radius , still the~~ also in the area of high biases around Greenland. Another difference between CESM and ERA interim is that the radius of the simulated cyclones is reduced, although the general shape of the distribution agrees with ERA interim. Reasons for this reduction could be manifold, e.g., related to the model's formulation of numerical diffusion or the interpolation of ERA interim. The latter was tested in the original 0.75° resolution of ERA interim. As expected we identify a higher cyclone presence and but the median radius is slightly increased (by roughly 5 %) in the original resolution of ERA interim. The wind-sensitive measures show an interesting behavior. Although the shape agrees between CESM and ERA interim, CESM shows more wind intensive cyclones when considering the measure cyclone depth. The central SLP measure shows a similar behavior with lower central SLP for CESM than for ERA interim, but also the cumulative cyclone presence with high central SLP is increased in CESM compared to ERA interim. Again the latter ~~indicates that weak cycloneslead to higher cyclone frequencies (Fig. 2)~~is affected by the fact that CESM simulates more short-lived cyclones, which are weaker on average. The cyclone-related precipitation shows that CESM slightly underestimates precipitation except for extreme precipitation events (> 17 mm/day).

Besides the distributions, the model should also be able to simulate interannual connections between the indices (if they exist). To uncover such connections, the cumulative cyclone presence, median of the cyclone radius and the 90th percentile of cyclone depth, SLP and cyclone-related precipitation in each winter season are estimated and the resulting time series are considered. Table 1 summarizes pairwise correlations for these quantities derived from CESM and ERA interim, respectively. Significant correlations (5 % significance level) are found between the two wind-related intensity measures, extreme cyclone depth and SLP as well as ~~with~~ between the cumulative cyclone presence and these two measures. Most of the significant observed correlations are reproduced by CESM though with slightly lower coefficients. The observed correlation between cumulative cyclone presence and the median radius is not simulated by CESM, while cyclone depth and radius are correlated in CESM but not in the observations.

In summary, CESM is able to realistically simulate cyclones, their extreme characteristics and the connections among different cyclone characteristics. Some of the discrepancies from ERA interim can be traced back to the tendency that CESM overestimates the number of weak cyclones.

4 Results

4.1 Cyclone intensities during the last millennium

To investigate periods of different cyclonic activity, we define moving averaged indices for all cyclone characteristics, i.e., the cumulative cyclone presence, median of the cyclone radius and the 90th percentile of cyclone depth, SLP, and cyclone-related precipitation (definition see Section 2). First, the indices are estimated for each winter season separately and then averaged over 30-year periods. The resulting time series are shown in Fig. 4.

In the years previous to AD 1850, all indices exhibit strong decadal to multi-decadal variability

(Fig. 4). The cumulative cyclone presence shows a clear negative trend after AD 1850 and leaves the preindustrial range around the year 2000. Thus, the CESM projects a lower number of cyclones for the 21st century in the North Atlantic. The geometry illustrated by the median radius of the cyclones remains unaffected by external forcing at a first glance and varies between about 215 to 222 km.

Extreme cyclone depth and central SLP both show a weak trend (positive for cyclone depth and negative for central SLP, but not significant) over the entire time series towards higher wind extremes by the end of the 21st century. They also agree in some of the periods with high intensities, e.g., decades around the years 1300s, 1400s, 1680s, 2060s but around year 2000 extreme SLP indicates its lowest values whereas extreme cyclone depth seems to indicate average years. This difference is a clear indication that it is useful to investigate different intensity measures to conclude on cyclone-related wind extremes. Note that cyclone depth is more related to wind due to the geostrophic approximation compared to SLP, which might be influenced by the background pressure (if more cyclones are detected in the low pressure belt they will have deeper central pressure but not necessarily stronger winds).

Extremes in cyclone-related precipitation clearly react to external forcing. Already before 1850, colder periods (17th century and 19th century), which are partly caused by reduced solar and enhanced volcanic forcing show lower than average 90th percentile cyclone-related precipitation whereas warmer periods are associated with higher than average values. Clearly, the warmest period in the simulation is the 21st century and there a strong and significant positive trend is simulated.

Some of the new results presented here confirm earlier studies with coarser resolved coupled climate models, e.g., the decrease of cyclone time steps from the preindustrial to the future climate state (e.g., Raible et al., 2007). Still, there are also differences. Raible et al. (2007) suggested a decrease in wind-related intensity from the Maunder Minimum to the present day climate state and attributed this decrease to generally reduced baroclinicity. This is in contrast to the new simulation where no clear sign of an intensification or weakening is found. ~~A major difference between the two analyses is~~ One reason for this mismatch is that the resolution of the model ~~(in this study around 1°, in Raible et al. (2007)~~ in Raible et al. (2007) was around 4°~~). Given the~~, which led to a general underestimation of cyclone occurrences. Furthermore, the CESM simulation shows high internal variability, as illustrated by the decadal to multi-decadal variations of the two wind-related indices, ~~the~~ so that different processes responsible for extreme cyclones (like baroclinicity in the lower and upper troposphere, low-level meridional temperature gradient, and/or diabatic processes) may interplay differently~~in the new simulation. At least~~. Besides improvements in the atmospheric component (Neale et al., 2013) diabatic processes are better resolved in the used CESM compared to ~~the earlier study~~CCSM3 used in Raible et al. (2007).

4.2 Natural forcing impact on cyclone characteristics

So far there is no clear sign that natural external forcing (volcanoes and solar variations) has a strong influence on cyclone characteristics whereas at least cyclone-related precipitation shows a strong trend during the period of strong anthropogenic forcing. To disentangle natural and anthropogenic forcing impacts we first focus on the potential volcanic and solar influence during the period 850-1850 CE.

To illustrate the volcanic forcing impact the superposed epoch analysis is applied to the extratropical cyclone characteristics. The 10 strongest volcanic eruptions, according to optical depth anomaly, over the period 850-1850 CE are composed and time series of the different cyclone characteristics are presented as deseasonalized monthly anomalies from the 5 years preceding an eruption (similar to Lehner et al. (2015)). Note that the 10 strongest eruptions all have a tropical origin. None of the cyclone characteristics show a volcanic forcing influence (therefore not shown). In particular, wind-related and precipitation-related extremes show no reaction after strong volcanic eruptions although the North Atlantic Oscillation tends to be in its positive phase (Ortega et al., 2015), which has been suggested to be related to wind intense extratropical cyclones (Pinto et al., 2009). The missing volcanic forcing impact on precipitation-related extremes seems to be unexpected as global mean precipitation shows a clear reduction after strong volcanic eruptions (e.g., Frölicher et al., 2011; Muthers et al., 2014; Lehner et al., 2015). Thus, the results suggest that extremes in both wind and precipitation seems to be decoupled from the mean behavior.

A potential connection between cyclone characteristics and solar variations is investigated by correlating the 30-yr running mean time series (Fig. 4) with the solar forcing (Fig. 1) over the period 850-1850 CE. The analysis with all cyclone characteristics shows that none of the characteristics have a significant correlation with the solar forcing (the highest correlation coefficient is 0.19 between solar forcing and extreme central pressure). We also tested lag correlations of up to $\pm$ 30 years, but again the correlations were not significant at the 5 % level. To assess a potential connection to the 11-yr cycle of the solar forcing we performed a cross wavelet analysis (Grinsted et al., 2004; Casty et al., 2011) using the time series of the cyclone characteristics in yearly resolution. Again no robust connection is identified in the 11-yr band (therefore not shown). Thus, a linear connection of mean and extreme cyclone characteristics to solar forcing is not found in the pre-industrial period of this simulation.

4.3 Low-frequency variations of extreme cyclone characteristics during the last millennium

In the following we will focus on the analysis of the two extreme cyclone characteristics for the period 850-1850 CE: 90th percentile of cyclone depth and of cyclone-related precipitation over the North Atlantic region. To obtain information on the low-frequency of extreme cyclone characteristics, 30-years running averaged periods are investigated in more detail.

Correlation patterns between extreme cyclone depth with different variables like, 2-m temperatures, 500-hPa geopotential height, cyclone frequency and mean precipitation show distinct significant (5 % level) patterns in the North Atlantic and over Europe (Fig. 5). Low-frequency variations of extreme cyclone depth correlate negatively with 2-m temperatures around Greenland and positively over Northern and Eastern Europe (Fig. 5a). This correlation is consistent with the correlation found between extreme cyclone depth and 500-hPa geopotential height (Fig. 5b)~~which resemble a NAO-like structure, but slightly~~. The pattern agrees with some aspects of the canonical pattern of the North Atlantic Oscillation (NAO), but is shifted to the north-east, in particular the center located over the Mediterranean Sea. The center north of Iceland of this pattern is baroclinic, as the corresponding centers of the correlation patterns with the 1000-hPa geopotential height are shifted to the east resulting in a westward tilt with height (not shown). The negative correlations of the 2-m temperature around Greenland go hand in hand with negative correlations between extreme cyclone depth and the sea surface temperature (SST, not shown). ~~This reduction is~~ These negative correlations are present over the entire North Atlantic basin, even if the southern part of the Atlantic does not show a statistically significant ~~change~~correlation. Furthermore, these negative correlations co-occur with positive correlations ~~with~~ between extreme cyclone depth and sea ice around Iceland (not shown). Additionally, an increase in extreme cyclone depth is related to reduced cyclone frequency over Europe and to a reduction of cyclone-related precipitation around Greenland and an increase in ~~both measures around~~ cyclone-related precipitation around the British Islands to Scandinavia (Fig. 5c,d). Thus, the negative geopotential height anomaly (enhanced low pressure system in the mid of the atmosphere) steers the track of cyclones towards Scandinavia where the cyclone frequency correlates positively with extreme cyclone depth. Furthermore, the correlation pattern of extreme cyclone depth with 2-m temperature show that ~~under increased extreme cyclone depth~~ Scandinavia is located in a region with an enhanced low-level horizontal temperature gradient, and thus a strong baroclinicity when extreme cyclone depth is enhanced.

Another important region where low-frequency variations of extreme cyclone depth show significant ~~correlation~~ correlations with other variables is southern Europe. Under high cyclone depth index conditions, it is a region of ~~minimized~~ reduced low-level meridional temperature gradient~~, as in the north it is relatively warm, while the south, i.e. Africa, is characterized by relatively cold temperatures~~. Such changes in the temperature field strongly reduce the ~~baroclinic zone, which finally leads to a reduction in~~ low-level baroclinicity. Thus, cyclone frequency over central Europe and ~~to a reduction in~~ cyclone-related precipitation over southern Europe are reduced when cyclone depth index is enhanced (Fig. 5c,d, respectively).

Compared to the extreme cyclone depth, which shows distinct and statistically significant correlations, extreme cyclone-related precipitation reveals less clear results. ~~Although an atmospheric wave train can be identified in the correlation pattern of~~ The correlation pattern between extreme cyclone-related precipitation and the 500-hPa ~~geopotential height field, it shows no statistical significance~~

over the North Atlantic region and 1000-hPa geopotential height fields show no statistical significant pattern (therefore not shown). Although not significant, we find similar patterns in the 1000-hPa geopotential height, indicating that extreme cyclone-related precipitation may be related to barotropic pressure structures. Furthermore, the The 2-m temperature reveals a slightly significant positive correlation along the European Atlantic coast (Fig. 6a). Thus, enhanced extreme cyclone-related precipitation is related to a warmer coastal line, which leads to increased moisture availability in winter, and thus finally influences the precipitation especially over Iceland, Scandinavia and the Barents Sea (Fig. 6b).

In summary, this analysis shows that different circulation and temperature patterns are related to extreme cyclone depth and cyclone-related precipitation. Thus, we can conclude that, on average, cyclones with extreme winds (measured by extreme cyclone depth) are disconnected from cyclones generating extreme precipitation over the period 850-1850 CE. Nevertheless, this might not be true for single isolated events. Note, however, that the analysis focuses on the mean of the North Atlantic to give a broad picture overview. Clearly, spatial variations of the cyclones characteristics within the North Atlantic region cannot be assessed with the analysis presented.

4.4 Anthropogenic forcing impact on cyclone characteristics

Two of the cyclone characteristics (Fig. 4a,e) show strong trends in the 20th and 21st century and thus are influenced by GHG forcing: the cumulative cyclone presence and the cyclone-related precipitation. In contrast, the wind intensity measured by either central pressure or cyclone depth shows no significant trend in the 21st century (Fig. 4c). In the following, we discuss these trends the behavior in the 21st century of the cyclone depth measure and cumulative cyclone presence with respect to trends of temperature, mean precipitation, and cyclone frequency in order to assess potential processes for GHG induced changes in cyclone characteristics. FurtherFor the trend in cyclone-related precipitation, the relevance of thermodynamic processes is investigated by assessing the Clausius-Clapeyron relation.

The temperature trends shown in Fig. 7a are in line with the patterns assessed in IPCC (2013), suggesting a strong warming of the polar areas and the continents and weaker warming of the ocean, in particular due to polar amplification. Additionally, a stronger positive temperature trend is found over land than over ocean due to the difference in heat capacity. In the central North Atlantic shows no significant warming . The former is due to polar amplification, induced by a strong sea ice reduction and the reduced heat capacity of the land surface compared to the oceanis found, again in line with IPCC (2013). The latter is related to changes in the ocean circulation, i.e., a weakening of the AMOC as projected by most of the comprehensive climate models. These different trends lead to a change of the in horizontal surface temperature gradients, the latter one which is a prerequisite for baroclinicity and thus cyclone development and enhancement. In particular, the contrast between the North Atlantic and Scandinavia is enhanced, a feature also found in the correlation pattern of extreme cyclone depth with temperature in the period 850 to 1850 (Fig. 5a). If similar processes worked for decadal variations in the Common Era and the future, we would expect to see a positive trend in extreme cyclone depth, which is not the case in Fig. 4c. Thus, we hypothesize that other processes such as increased static stability (Raible et al., 2010) and the overall decreased low-level meridional temperature gradient – both reducing cyclones and wind-related intensity – compensate for the locally increased baroclinicity near Scandinavia.

~~Precipitation~~ Mean precipitation trends also resemble the results presented in the latest IPCC assessment (IPCC, 2013) showing a negative trend over the Mediterranean and a wetting in high latitudes ~~(Fig. 7b)~~(Fig. 7b; Santos et al., 2016). This is a first hint that cyclones are redistributed in the future as most of the precipitation in winter in the mid-latitudes originate from cyclones. Fig. 7c shows the cyclone frequency trend pattern for the 21st century with significant negative trends mainly over the Mediterranean and partly over the central North Atlantic. This pattern resembles the precipitation trends and illustrates the connection between cyclone occurrence and precipitation. As we find a reduction of 12.5 % in the cumulative cyclone presence over the entire region (Fig. 4a), the reduction over the Mediterranean and the central North Atlantic cannot be compensated by the positive trends found over Scandinavia and the Hudson Bay (note that only a small part of the Hudson Bay is included in the area (Fig. 2) of the indices). Again the signals over the Mediterranean resemble earlier findings obtained with different models (e.g., Lionello and Giorgi, 2007; Raible et al., 2010). In these studies, enhanced static stability together with enhanced stationary wave activity are the main reasons for reduced cyclone activity over the Mediterranean.

The most striking trend of the cyclone characteristics in Fig. 4 is the positive trend of extreme cyclone-related precipitation in the 20th and 21st century, similar to findings of Zappa et al. (2013). The trend pattern of temperature (Fig. 7b) suggests an overall warming, and thus the capability of the air to hold moisture is strongly increased in the 21st century.

To test whether the trend of extreme cyclone-related precipitation is mainly due to thermodynamics, we estimate the regression coefficients β between ~~extreme~~ 90th cyclone-related precipitation and ~~extreme~~ mean cyclone-related temperature for the entire simulation in a 150-yr running window ~~and compare them~~ (similar results are obtained with a 100-yr running window). These regression coefficients are compared with the range given by the Clausius-Clapeyron relation, i.e., a 2-3 % increase in precipitation per 1°C temperature increase (O'Gorman and Schneider, 2009). Note that ~~similar results are obtained with a 100-yr running window.~~ by attributing the two variables 90th percentile of precipitation and temperature to the cyclone we obtain to some extent a regionalized view.

The regression coefficients for the period 1851-2100 show a strong shift to the upper bound of the Clausius-Clapeyron relation (3 % increase in precipitation per 1°C), a level never reached during the

Common Era (Fig. 8). This is in line with recent results of Neelin et al. (2017) who found that the interplay of moisture convergence variance and precipitation loss ~~,~~ increase under global warming. Thus, the result of the 20th and 21st century agrees with other findings that show that extreme precipitation is mainly thermodynamically driven, as it follows the Clausius-Clapeyron relation under global warming (e.g., Pall et al., 2007; O'Gorman and Schneider, 2009; Pendergrass and Gerber, 2016; Neelin et al., 2017). Interestingly, we find that roughly 50 % of the periods in the Common Era show a different behavior where extreme cyclone-related precipitation reacts less to temperature changes than Clausius-Clapeyron relation would predict, as illustrated by regression coefficients below (0.16 mm/day)/°C. Thus, we show that the hypothesized general governance of the Clausius-Clapeyron relation on extreme precipitation (e.g., Pall et al., 2007; O'Gorman and Schneider, 2009) seems to be time dependent. Hints that this is not just a model result are found in proxy records over Europe, e.g. flood occurrences cluster also during rather cold periods in the Common Era (e.g., Czymzik et al., 2010; Wirth et al., 2013; Glur et al., 2013; Amann et al., 2015).

5 Conclusions

Extratropical cyclone characteristics are investigated for the period 850 to 2100 CE in a seamless transient simulation using CESM (version 1) with the focus on the North Atlantic European region and the winter season (DJF).

The evaluation under present day conditions shows that CESM is able to realistically simulate cyclones and their characteristics, though some biases to the reanalysis product ERA interim remain.

Before 1850, the variability of cyclone characteristics is dominated by internal variability showing pronounced low-frequency variations of different cyclone characteristics. The extreme wind-related characteristics show a significant connection to the large scale dynamics on decadal time scales~~, whereas the~~ . This north-eastward displaced NAO-like connection resembles earlier findings for decadal to multi-decadal time scales (Raible et al., 2007; Pinto and Raible , 2012). The index representing cyclone-related precipitation is only weakly related to the background temperatures and large scale dynamics on these time scales. The different cyclone characteristics are not correlated with each other over time, being a first indication that external forcing plays no dominant role in generating these variations. A more detailed analysis of the volcanic and the solar forcing imprint confirms this and thus earlier findings with other coarsely resolved climate models ~~(Fischer-Bruns et al., 2005)~~(Fischer-Bruns et al., 2005; Raible et al., 2007).

Future changes are found in two cyclone characteristics~~. As~~ : the cumulative cyclone presence and the extreme cyclone-related precipitation. The extreme cyclone depth measure remains unchanged in the 21st century. Zappa et al. (2013) found a similar increase in precipitation but showed a significant decrease of extreme wind intensity under future climate change using CMIP5 multi-model simulations. A possible explanation for the differing results with respect to extreme cyclone depth is the fact that in this study only one simulation is used~~in this study it~~. Still the agreement in extreme cyclone-related precipitation between this study and Zappa et al. (2013) shows that these changes are pronounced and that we should be able to detect these changes at the beginning to mid of the 21th century, irrespective of the realization of natural variability. The cumulative cyclone presence shows a reduction in the 21st century. This change is already found in studies using coarsely-resolved ensemble simulations with an earlier version of CESM, which compare present day climate with the pre-industrial climate (e.g., Raible et al., 2007). The main decrease of cyclone occurrence is found over the Mediterranean. Using future simulations with another global climate model shows a similar decrease in the Mediterranean ~~(Raible et al., 2010)~~(e.g., Ulbrich et al., 2009; Raible et al., 2010; Zappa et al., 2013). The process driving the reduction of cyclones over the Mediterranean is the increase in stability and changes in the stationary wave production over the region in winter (Raible et al., 2010). The other characteristic, which shows a dramatic increase in the future, is the extreme cyclone-related precipitation. This increase is driven by the temperature increase and the Clausius-Clapeyron relation, i.e. purely thermodynamically driven. This is in line with a recent study of Neelin et al. (2017). Thus, changes in the dynamics seems to be less important for changing precipitation extremes related to winter cyclone activity in the future.

Extending the analysis of the Clausius-Clapeyron relation back in time reveals prolonged periods in the Common Era where extremes do not follow the Clausius-Clapeyron relation. Thus, we hypothesize that in the Common Era both dynamical and thermodynamical processes can be dominant whereas in the last 100 years and the future under RCP8.5 thermodynamical processes govern extreme events in cyclone-related precipitation. This result is important as many proxy-based studies show that during cold periods of the Common Era hydrological extreme events occur more frequently (Czymzik et al., 2010; Wetter, 2012; Wirth et al., 2013; Glur et al., 2013; Amann et al., 2015). For example, Amann et al. (2015) recently showed in lake sediments that flood occurrences are enhanced during the LIA, a period known to be cold in Europe – a behavior, which cannot be explained by the Clausius-Clapeyron relation. As the model simulation in this study also shows periods where the Clausius-Clapeyron relation is unable to explain above-normal extreme cyclone precipitation (14th to 15th century) we hypothesize that these periods were dominated by variability of dynamical processes. Moreover, our simulations show that these variations are mainly driven by internal variability and that no systematic response to external forcing like during the LIA is evident. So based on our results, the proxies ~~(e.g. Czymzik et al., 2010; Wetter, 2012; Wirth et al., 2013; Glur et al., 2013; Amann et al., 2015)~~ (e.g., Czymzik et al., 2010; Wetter, 2012; Wirth et al., 2013; Glur et al., 2013; Amann et al., 2015) might just show natural internal variability and hence there is no clear justification to interpret them in context of the LIA (i.e., volcanoes and solar forcing).

Thus, future work shall concentrate on processes of low-frequency changes in cyclone characteristics and the Clausius-Clapeyron relation, e.g., to the assess the role of atmosphere-ocean-sea ice interaction (e.g., Lehner et al., 2013) ~~. Further, a more regional view on Europe is needed to focus on~~

impacts on land relevant for insurance providersand links to modes of variability (e.g., Pinto and Raible , 2012). For this, a regional analysis of the different cyclone characteristics is necessary, which also takes the spatial variability of the different measures into account.

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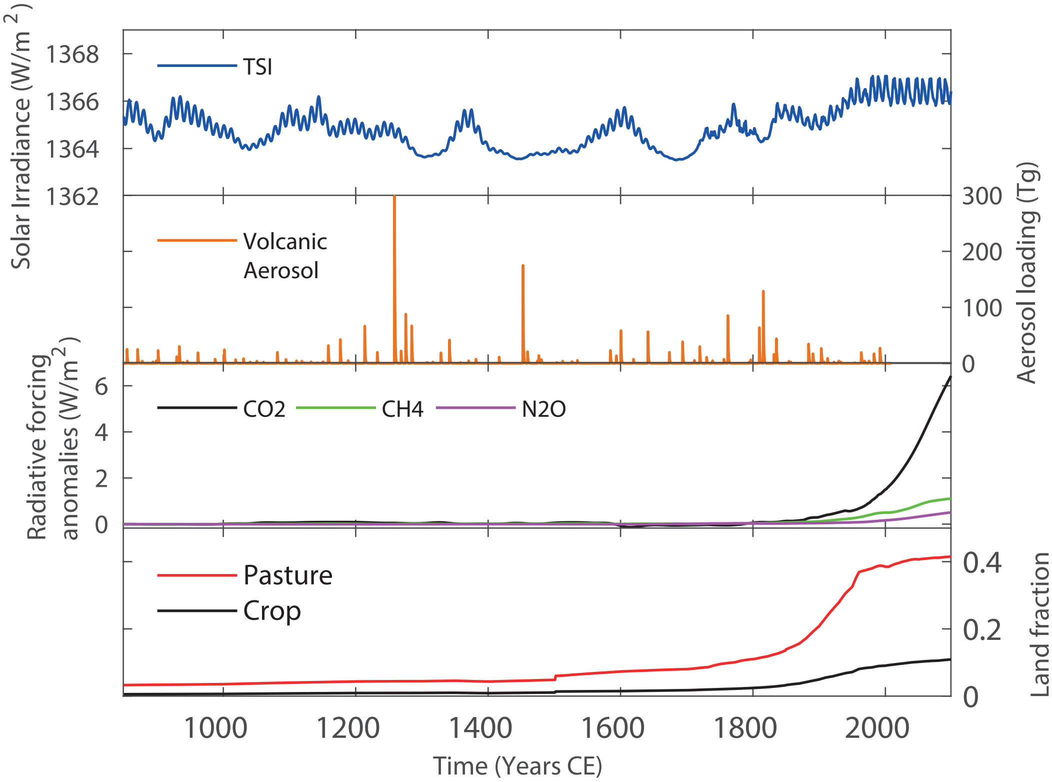

Fig. 1. Forcings used in the last millennium simulation with CESM. From Top to bottom: total solar irradiance (TSI), total volcanic aerosol mass; radiative forcing (calculated according to IPCC, 2001) from the greenhouse gases CO_2, CH_4, and N_2O; and major changes in land cover as fraction of global land area. The figure is adapted from Lehner et al. (2015).

Table 1. Correlation between different cyclone characteristics. The upper right of the table represent CESM correlation, the lower left ERA interim. Bold numbers indicate significant correlation at the 5 % level using a two-side student T test. For this analysis the central SLP time series is multiplied by -1 so that low central pressure corresponds to a high cyclone depth resulting in a positive correlation.

	Cyclone time steps	Radius	Cyclone depth	SLP	Cyclone rel. Precipitation
cyclone time steps	1	0.21	**-0.42**	**-0.49**	0.11
Radius	**0.42**	1	**0.47**	-0.36	0.07
Cyclone depth	**-0.4**	0.09	1	**0.63**	0.16
SLP	**-0.58**	0.07	**0.81**	1	0.13
Cyclone rel. Precipitation	-0.27	-0.11	0.22	0.15	1

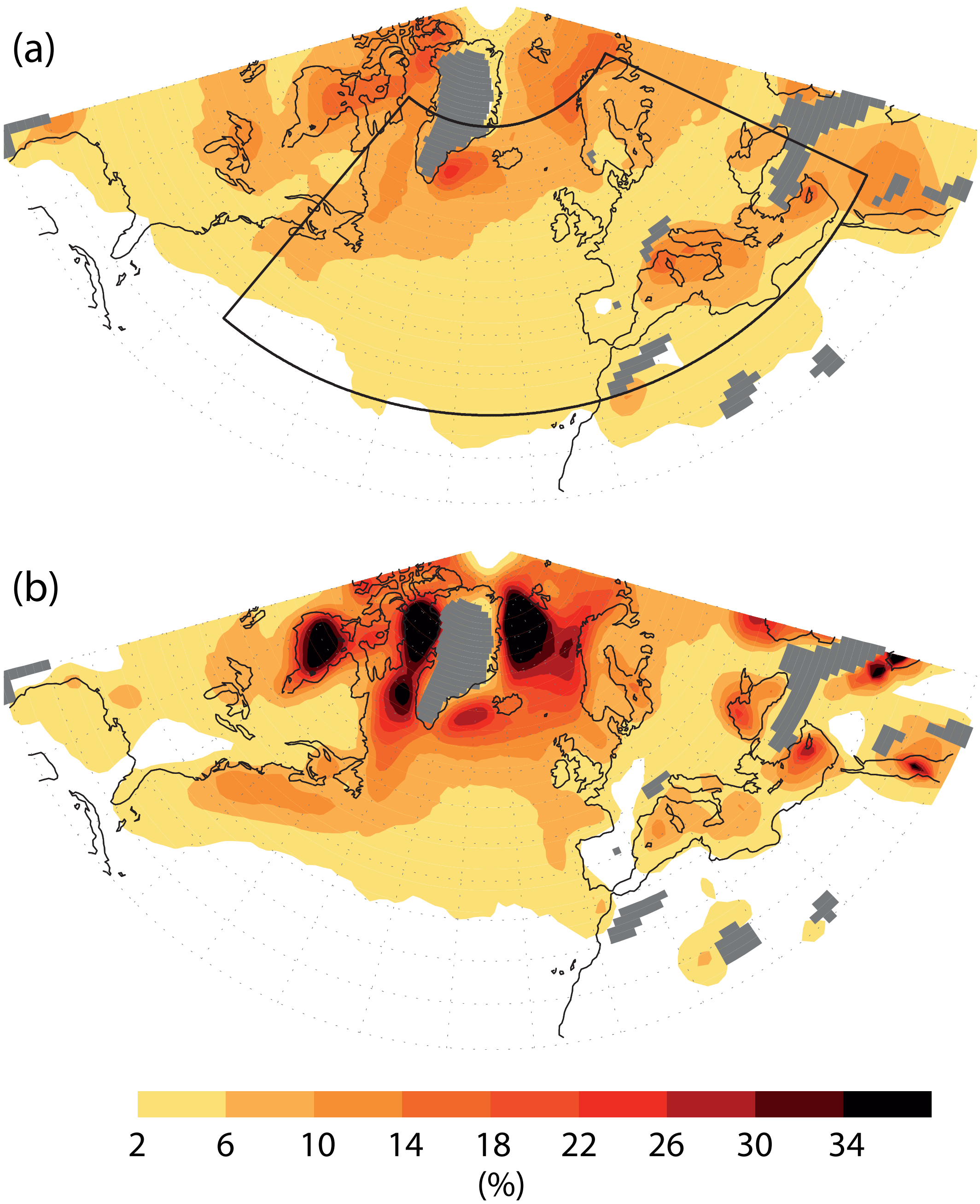

Fig. 2. Cyclone center frequency (% presence per season) for (a) the ERA interim and (b) the CESM simulation for the period AD 1980-2009 in winter (DJF). The bounded domain illustrates the region North Atlantic used to estimate different cyclone characteristics. Grey areas are higher than 1 km above sea level and are excluded from the cyclone detection and tracking method. 10% presence per season means that in 10% of the winter season a cyclone is present at a grid point.

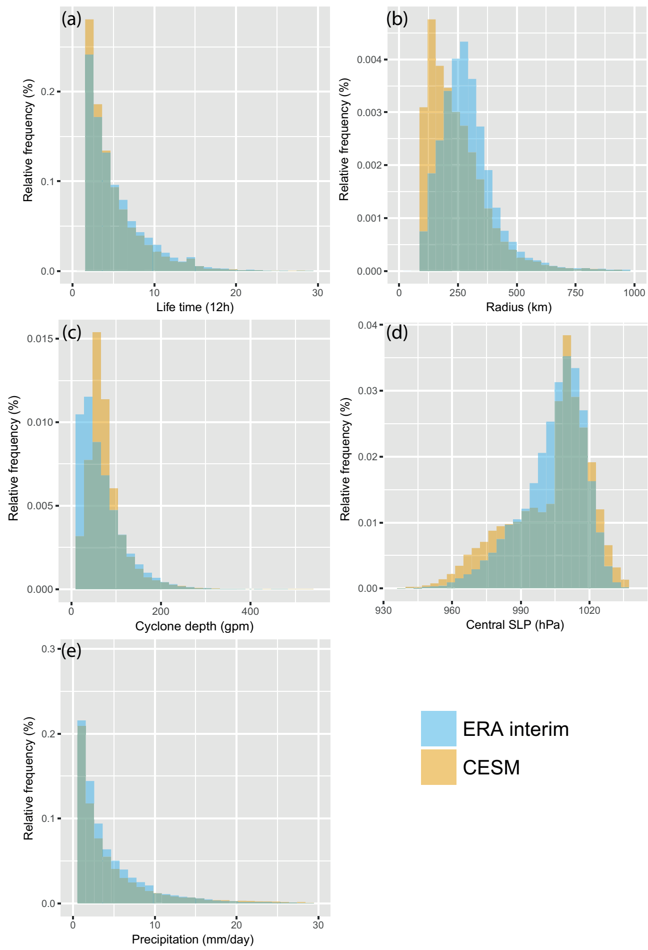

Fig. 3. Histograms of different cyclone characteristics: (a) life time of cyclones, (b) radius of cyclones, and (c) cyclone depth, (d) central SLP and (e) cyclone-related precipitation. The histograms are based on the cyclones detected from 1981-2010, i.e., 7624 cyclones in ERA interim and 12369 in CESM.

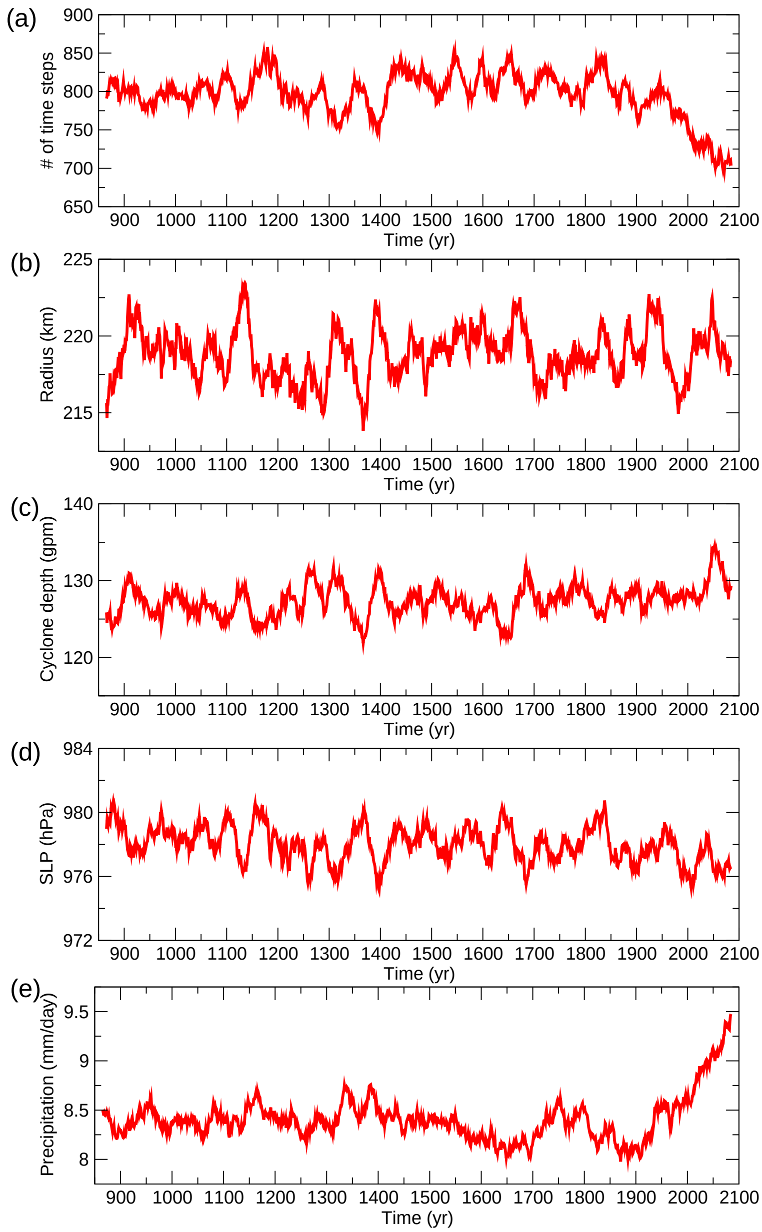

Fig. 4. Long-term time behavior of different cyclone characteristics illustrated by time series averaged with 30-yr running window: (a) cumulative cyclone presence, (b) median radius of the cyclones, and 90th percentile of (c) cyclone depth, (d) central SLP and (e) cyclone-related precipitation.

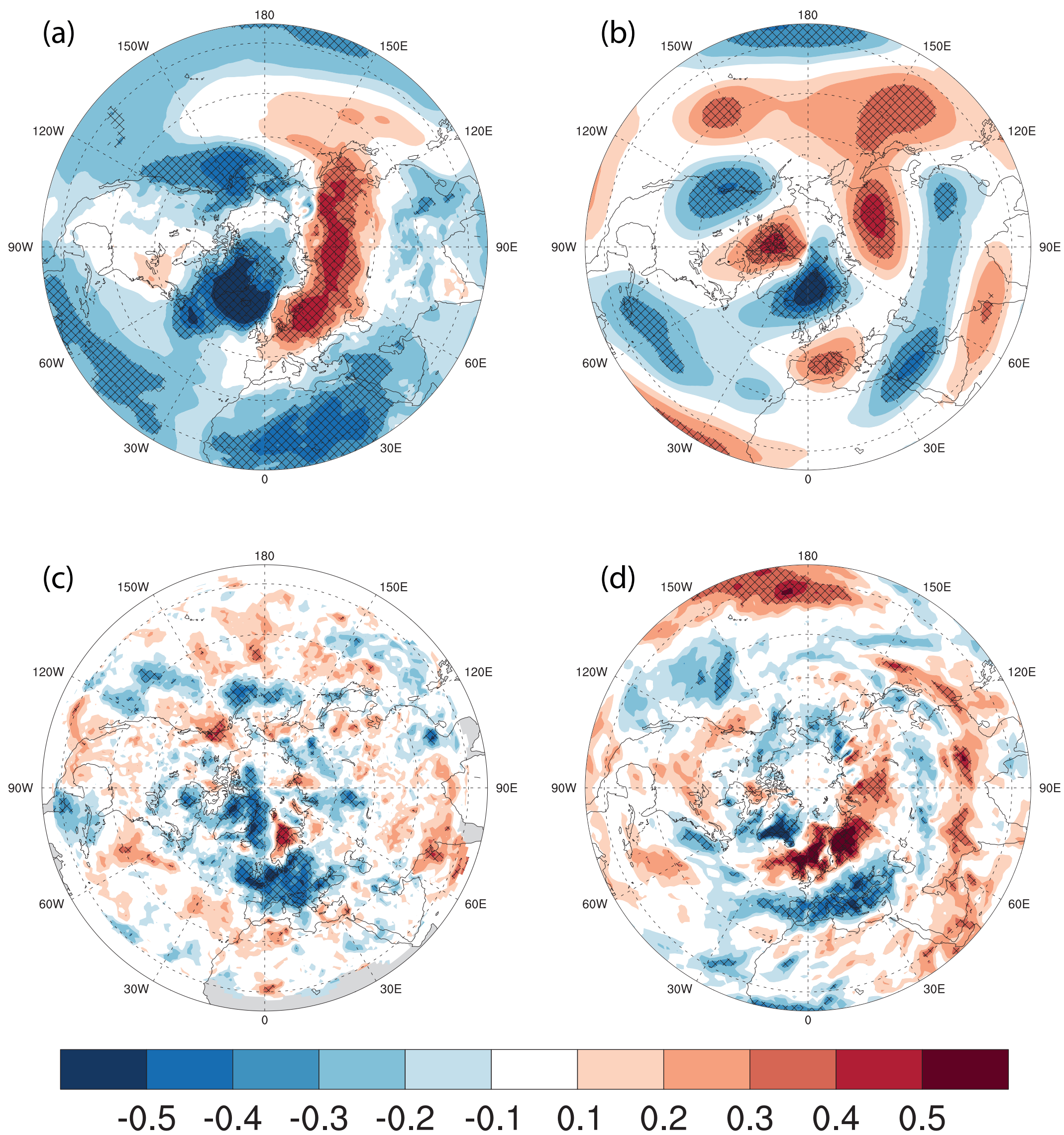

Fig. 5. Correlation between the 30-yr running mean times series of extreme cyclone depth and (a) 2-m temperature, (b) 500-hPa geopotential height, (c) cyclone frequency, and (d) precipitation for the period 850-1850 CE. The 5 % significance level using a student T-test is illustrated with cross-hatching.

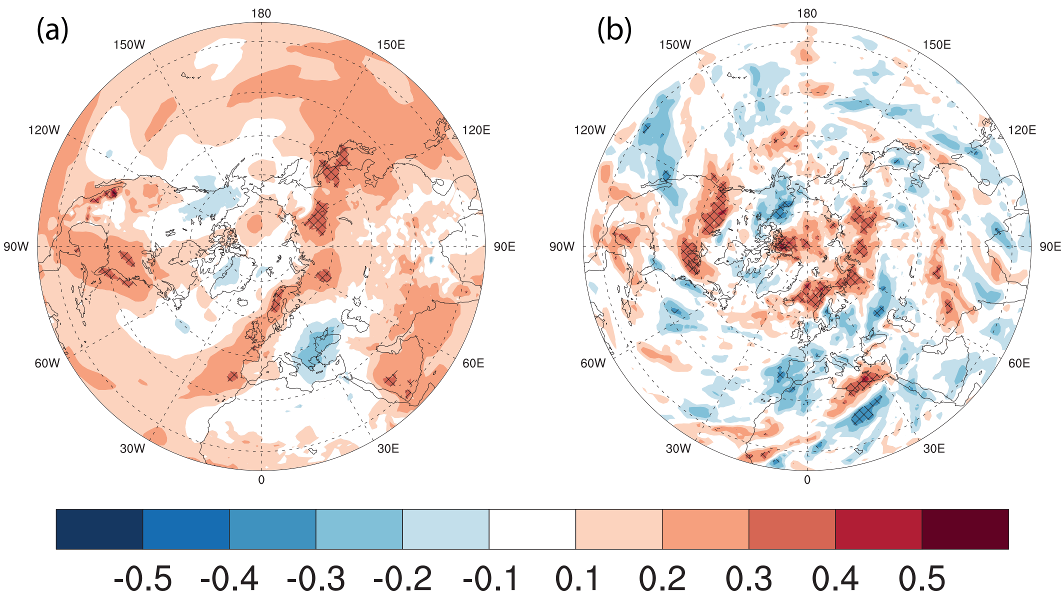

Fig. 6. Correlation between the 30-yr running mean times series of extreme cyclone-related precipitation and (a) 2-m temperature and (b) precipitation for the period 850-1850 CE. The 5 % significance level using a student T-test is illustrated with cross-hatching.

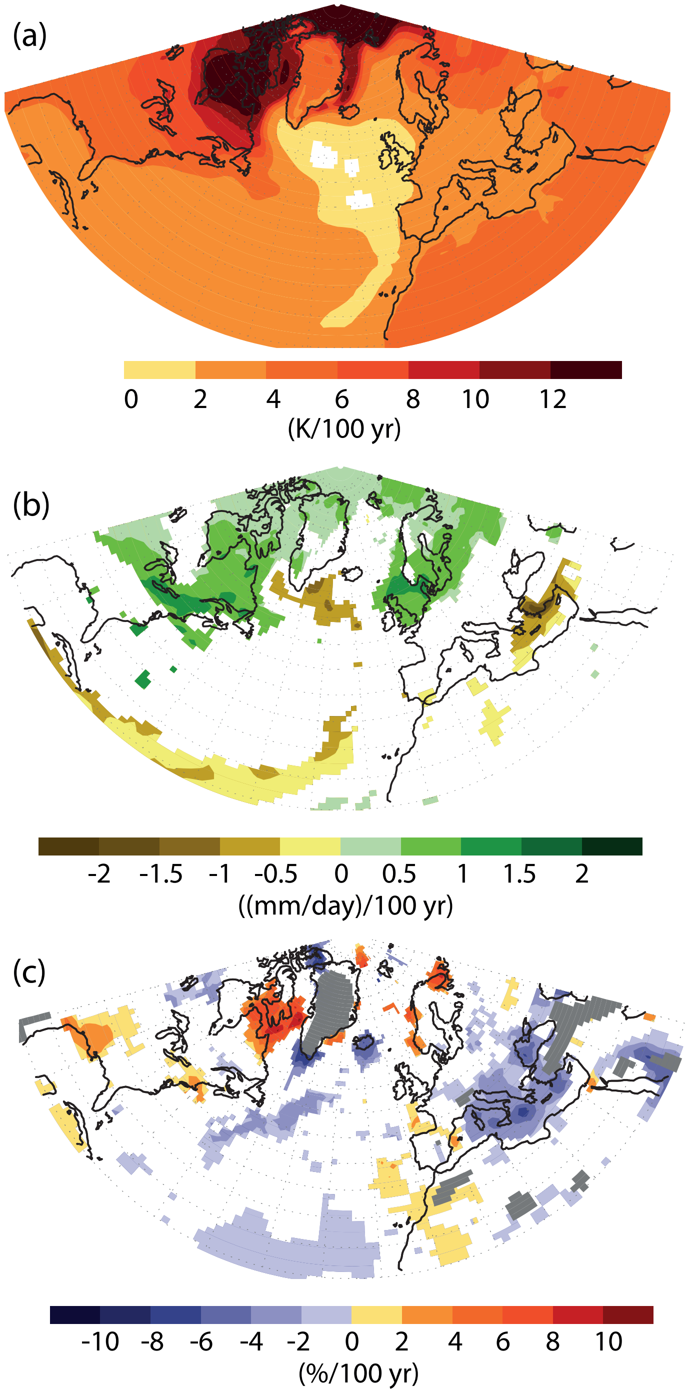

Fig. 7. Trends from 2005 to 2100 for (a) 2-m temperature, (b) precipitation, and (c) cyclone frequency. Only significant trends at the 5 % significance level using a student T-test are shaded. Grey areas in (c) are excluded from the cyclone detection and tracking method (1000 m a.s.l.).

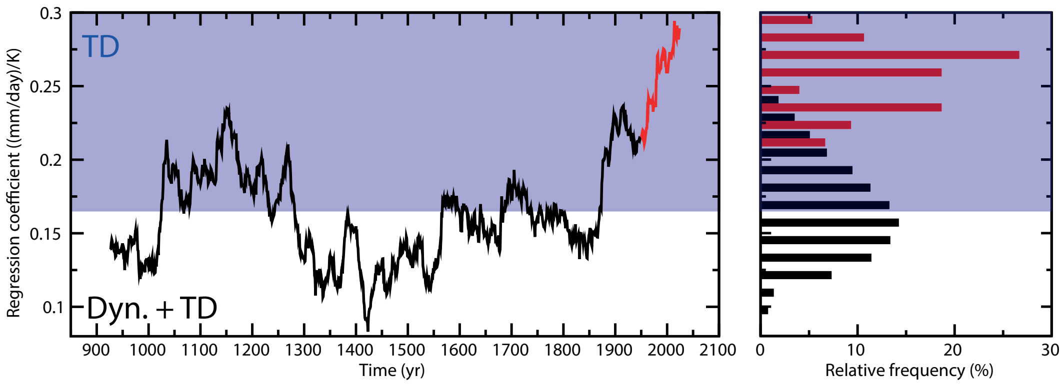

Fig. 8. Time series of regression coefficient estimated between mean cyclone-related temperature and 90th percentile of cyclone-related precipitation for 150-yr window running through the entire period 850 to 2100: Common Era (black) and era influenced by RPC8.5 (red). The right panel shows the histogram of the regression coefficients for the two periods (bin width 0.01). All periods within the blue shading follow the Clausius-Clapeyron relation, named thermodynamic (TD) (O'Gorman and Schneider, 2009). In the white area, dynamics (Dyn.) and thermodynamics are relevant.