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A review of past changes in extratropical cyclones in the northern hemisphere and what can be learned for the future

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Abstract
Extratropical cyclones, a major phenomenon of the mid-latitude atmospheric dynamics, show strong variability over a range of time scales. Future projections hint at an increase of cyclonic intensity and the associated precipitation, an important fact to be considered when developing future risk assessments. This review presents a first overview of studies which (a) puts the current variability and projected future climate changes of extratropical cyclone characteristics in a long-term perspective, (b) shows connections to natural external forcings, and (c) deepens our understanding of cyclone intensification processes for past climate periods. We summarize the current state of knowledge for two periods in the past—the last millennium and the Last Glacial Maximum (LGM, 21,000 years ago). For these two periods, the sparse information from paleo proxy archives are compared to climate modeling results on global and regional scales. For example, strong changes of the climate mean state, induced by orbital forcing and associated feedbacks, show strong effects on different cyclone characteristics, for example, a southward shift of the storm tracks over the North Atlantic during the LGM. Other findings indicate that dynamic processes could play at least an equally important role as thermodynamic processes for the variations of cyclone-induced precipitation. This is in contrast to the projected future changes in cyclone-related precipitation, which are driven primarily by thermodynamic processes. The review demonstrates how a paleoclimatic view can foster an extended process understanding and be instrumental to better understand future changes in extratropical cyclones and associated characteristics.

This article is categorized under:
- Paleoclimates and Current Trends > Modern Climate Change

KEYWORDS
climate change, extratropical cyclones, internal climate variability, Last Glacial Maximum, Last Millennium

1 | INTRODUCTION

Embedded in the westerlies, extratropical low-pressure systems, also referred to as extratropical cyclones, are important features of the mid-latitudes in both hemispheres. They are the main phenomenon transporting energy from the subtropics to higher latitudes, and play a determinant role in the hydrological cycle. These systems often develop along the polar front, which separates air masses of the mid-latitudes from polar air. They are associated with the occurrence of precipitation and winds as well as changes in temperature and cloudiness. Thus, they are significant for characterizing the weather and regional climatic conditions of the mid-latitudes. In particular, extreme cyclones can cause heavy precipitation, strong gusts, and storm surges, or cold waves after their passage, leading to major societal impacts (Colle, Booth, & Chang, 2015; Dangendorf, Arns, Pinto, Ludwig, & Jensen, 2016; Fink, Brücher, Ermert, Krüger, & Pinto, 2009; Raible, 2007; Schwierz et al., 2010).

Several processes are relevant for generating and intensifying extratropical cyclones. The two most important processes are baroclinicity and latent heat release within cyclones. Baroclinicity is the main driver of extratropical cyclone development (Charney, 1947; James & Hoskins, 1985; Tierney, Posselt, & Booth, 2018). It is influenced by temperature contrasts, such as the equator-to-pole temperature gradient and the land-sea contrast. Thus, different climate states can influence these temperature distributions and, thus, affect extratropical cyclones. For example, future climate change will decrease the meridional temperature gradient near the surface due to polar amplification whereas in the upper troposphere this temperature gradient is increased. The second driver is the latent heat release (Booth, Wang, & Polvani, 2013; Davis, 1992; Grams et al., 2011; Kuo, Shapiro, & Donall, 1991). Again, under warmer or colder conditions latent heat release is intensified or reduced and thus have implications on the strength of extratropical cyclones. Given the two main competing processes, predictions on the behavior of extratropical cyclones in different climate states (past or future) are challenging (Catto et al., 2019).

Nevertheless, a large body of literature exists, which focuses on the analysis of extratropical cyclone variability in recent climatic conditions and future decades, see reviews (Feser et al., 2015; Ulbrich, Leckebusch, & Pinto, 2009). Such studies typically use Eulerian measures like the 500 hPa geopotential height fields filtered to the synoptic scale (2–6 days) (Blackmon, 1976; Hoskins & Valdes, 1990) or Lagrangian methods, such as cyclone detection and tracking methods, to derive statistics of the cyclone characteristics such as regions of occurrence, lifetime, trajectory, track length, peak intensity, intensification rates, associated precipitation, and others (Neu et al., 2013; Raible, Della-Marta, Schwierz, Wernli, & Blender, 2008). These statistics permit a wide characterization of cyclones and their variability and thus of the climate (Grieger, Leckebusch, Raible, Rudeva, & Simmonds, 2018; Reale et al., 2019).

The assessment of recent climatic conditions shows that cyclone characteristics are dominated by decadal variability and connections to modes of variability in both hemispheres (Feser et al., 2015; Grieger et al., 2018; Woollings & Blackburn, 2012; Woollings, Gregory, Pinto, Reyers, & Brayshaw, 2012). Under future climate change, some studies based on models evaluated in the Coupled Model Intercomparison Project (CMIP3 and CMIP5) point to a small increase of cyclones over western Europe (Feser et al., 2015; Ulbrich et al., 2009), which may be associated with a small increase in intensity, particularly in terms of cyclone related precipitation (Raible, Messmer, Lehner, Stocker, & Blender, 2018; Zappa, Hawcroft, Shaffrey, Black, & Brayshaw, 2015). For other areas like the Mediterranean, a more consistent picture is found, that is, a robust and strong decrease of cyclones in winter is projected (Economou, Stephenson, Pinto, Shaffrey, & Zappa, 2015; Lionello, Boldrin, & Giorgi, 2008; Raible, Ziv, Saaroni, & Wild, 2010; Zappa et al., 2015). Still, there are several open questions on how a warmer climate will affect the intensity of cyclones, particularly in terms of the role of latent heat release (Ahmadi-Givi, Craig, & Plant, 2004; Binder, Boettcher, Joos, & Wernli, 2016; Booth et al., 2013; Catto et al., 2019; Shaw et al., 2016). For CMIP6, the patterns of change resemble the ones of CMIP3 and 5, but the magnitude of the change is enhanced due to the larger climate sensitivity of the CMIP6 models (Harvey, Cook, Shaffrey, & Schiemann, 2020).

Clearly, the devastating impact of extratropical cyclones on society was evident long before industrialization has started. Incisive events, like the first and second "Grote Mandränke" (great drowning) in the years 1,362 and 1,634, swept across the British Isles, the Netherlands, northern Germany, and Denmark. These events reshaped the coastline of Germany and formed the North Frisian Islands. The socio-economic impact of these events was enormous, including thousands of deaths, destruction of settlements like the city of Rungholt, and losses of large portions of cultivated land along the coastlines (Arends, 1833). In 1717, another extreme storm was responsible for the so-called "Christmas flooding" which affected the coastline from the Netherlands up to Denmark and caused 12,000 deaths (Jakubowski-Tiessen, 1992; Pfister, 1994). These examples all show the importance to better understand past behavior of extratropical cyclone characteristics and their impacts, in particular of the most extreme events.

Over the past two decades, the scientific community has started to draw their attention also to past variability of extratropical cyclones and processes relevant to their generation and intensification (Wanner et al., 2008). One important motivation to study the past is to test main drivers and mechanisms of variability of extratropical cyclones and the conditions that are conducive to extreme impacts as identified under present day conditions. Moreover, understanding preindustrial and past conditions is essential to define a baseline so that recent changes and future projections can be put into a long-term perspective (Fischer et al., 2018). An important source of information to estimate past climate variability are paleo proxy records obtained from different climate archives, such as ice and sediment cores, tree-rings, speleothems, historical documents, and so on. Most of these archives are only sensitive to temperature and/or precipitation and not to wind or pressure, the last being essential for the characterization of extratropical cyclones. Moreover, only few proxy archives, such as historical documents, deliver climate information at a sub-daily resolution needed to assess extratropical cyclone characteristics. Thus, proxy-based considerations of extratropical cyclone variability are limited to long-term changes at very sparse spatial scales (de Jong, Björck, Björkman, & Clemmensen, 2006; Trouet, Scourse, & Raible, 2012) or indirect measures, that is, pressure indices such as the North Atlantic Oscillation (NAO) (Wanner et al., 2001) which are reconstructed from temperature and/or precipitation proxy records (Ortega et al., 2015; Pinto & Raible, 2012).

Another line of research—climate modeling—aims to close these gaps. Several climate modeling studies on global and regional scales investigated extratropical cyclone characteristics and extremes during the last millennium and the Last Glacial Maximum (LGM, 21,000 years ago) assessing the forcing imprint and the relevance of processes involved in cyclone intensification (Hofer, Raible, Dehnert, & Kuhlemann, 2012; Kageyama et al., 2020; Kageyama, Valdes, Ramstein, Hewitt, & Wyputta, 1999; Kutzbach & Guetter, 1986; Laine et al., 2009; Ludwig, Schaffernicht, Shao, & Pinto, 2016; Pinto & Ludwig, 2020; Raible, Yoshimori, Stocker, & Casty, 2007). Instead of running single climate states with climate models, also idealized simulations on an aquaplanet can help to investigate cyclone characteristics in a changing climate. In such simulations, the global temperature or sea surface temperatures can be gradually changed and the impact on extratropical cyclones observed (Büeler & Pfahl, 2019; Pfahl, O'Gorman, & Singh, 2015; Sinclair, Rantanen, Haapanala, Räisänen, & Järvinen, 2020).

This growing body of insights on past changes of extratropical cyclone characteristics and the fact, that cyclones are one of the key factors in the mid-latitude climates, call for a retrospective view on the current state of knowledge. Due to the availability of proxies, the northern hemisphere, in particular the North Atlantic European sector, is discussed most in the paleoclimate studies when focussing on extratropical cyclones. In the following, we give an overview of how extratropical cyclone variability is analyzed for past periods, that is, an overview of proxy archives and climate modeling. Then, we summarize studies on extratropical cyclones along two periods: the last millennium and the LGM. The selection of these two periods is motivated by the availability of studies to be reviewed and the different climate conditions. The last millennium is closest to the current state and the future, so this period delivers the understanding of the baseline (the unperturbed climate state). The LGM is a period where the climate system was very different. So, this period serves as an example of how drastic changes could be and how processes might change. For each period, we start with a review of the proxy evidence and then report the state of knowledge in paleoclimate modeling. Most of the studies focus on winter, because in the northern hemisphere, extratropical cyclones show a seasonal cycle with a larger number and more intense cyclones compared to summer. The review ends with some conclusions, identification of knowledge gaps, and future perspectives on promising research avenues.

2 | METHODS

In principle, two sources of evidence are available to assess past climate states: (a) climate reconstructions based on proxy archives and (b) climate modeling results on global to regional scales. In this review, we show the advantages of using both proxy records and paleo simulations, as only the synergy of both allows obtaining a broader picture of past variations of extratropical cyclones and involved mechanisms. More precisely, this means that proxy data are essential to validate climate models under altered climate conditions, but modeling results are crucial to obtain spatially inclusive and comprehensive information on sub-daily time scales. Such time scales are mandatory to describe extratropical cyclones. In the following, we introduce both sources of evidence and discuss the advantages and disadvantages of each method.

To show what information is needed from proxy and modeling data to describe changes in extratropical cyclones and their underlying processes, we introduce typical characteristics of extratropical cyclones. Extratropical cyclones and their variability can be characterized by several metrics, focusing on different processes relevant for cyclones (Section 1). On the one hand, filtering pressure fields with a 2.5–6 day bandpass filter is a standard Eulerian technique, which delivers the so-called storm track (Blackmon, 1976). On the other hand, Lagrangian detection and tracking methods identify individual extratropical cyclones in pressure or vorticity fields, focusing either on the mass distribution of cyclones or on their rotation (Neu et al., 2013; Raible et al., 2008). The different foci of each of the methods lead to differences in spatial distribution. For example, vorticity-based methods tend to track cyclones equatorward compared to pressure-based Lagrangian methods, while the Eulerian measure shows a much smoother spatial distribution of the storm track than Lagrangian techniques with their cyclone track density (Neu et al., 2013; Rohrer, Martius, Raible, & Brönnimann, 2020).

Another approach is to characterize extratropical cyclones and their variability using established connections to the mean atmospheric circulation, that is, the position and intensity of the jet stream (Woollings & Blackburn, 2012) or modes of variability. An example for the latter is the NAO, which consists of a pressure distribution with two anticorrelated centers of action over Iceland and the Azores. These centers of action are statistically related to other variables, for example, temperature and precipitation (Hurrell, 1995). For example, an enhanced south to north pressure gradient over the North Atlantic (positive NAO), derived from monthly or seasonal means, is interpreted as enhanced storminess and wetter conditions over central to northern Europe and reduced storminess and drier conditions over southern Europe (Hurrell & VanLoon, 1997). Note that the measure of storminess does not discriminate between wind intensity of storms and the number of storms.

Besides the geographic distribution of storms, other measures are used to characterize extratropical cyclones. The number of cyclones or the number of time steps when a cyclone exists (averaged over a region) are often used to investigate the variability of extratropical cyclones. The latter measure has the advantage of not being influenced by split tracks, which leads to double counts in terms of the number of storms (Raible et al., 2018). The strength of storms is either measured with respect to wind or precipitation. However, note that storms with the strongest winds are not necessarily the same ones which generate extreme precipitation (Raible, 2007). For wind, several measures are used, including, for example, central minimum pressure or maximum vorticity of the cyclone and the cyclone depth (Neu et al., 2013). The latter is defined as pressure difference between the central pressure of a cyclone and the pressure at the radius or outer contour of a cyclone. The radius can further be used to describe the area of a cyclone and to define the precipitation intensity, namely, as the average precipitation over this area, called cyclone-related precipitation (Raible et al., 2018). This is an intensity measure, which is related to the latent heat release within a cyclone.

These different measures and characteristics offer a potential to use climate proxy records to assess past changes (PAGES 2k Consortium et al., 2013), particularly before the 20th century, in times when instrumental measurements were not widely available. Climate proxy records are deduced from proxy archives, such as ice cores, sediment cores, trees, speleothems, historical documents, etc. Within each archive, climate-sensitive records are identified and related to meteorological variables by either physical laws or statistical relationships. For example, trees provide the parameter "late wood density", which can be statistically related to temperature, precipitation, or both depending on the location of the tree. These statistical relationships are deduced in the observational period, that is, the 19th and 20th century and then assumed to be stationary in the past.

Only a few proxy archives are sensitive to the meteorological variables wind and air pressure, which are essential to elucidate past extratropical cyclone characteristics. Examples for such proxy archives are sediment cores (Buynevich, FitzGerald, & Goble, 2007; Chaumillon et al., 2017; de Jong et al., 2006; Degeai, Devillers, Dezileau, Oueslati, & Bony, 2015; Orme et al., 2016; Raji et al., 2015) and historical documents (Carey, 2012; Pfister et al., 2010), for example, ship log books (Brazdil et al., 2010; Garcia-Herrera et al., 2018; Kuettel et al., 2010; Wheeler & Wilkinson, 2005). To complement the climate proxies, early measurements are also available (Casty et al., 2005; Casty, Raible, Stocker, Wanner, & Luterbacher, 2007). In these archives, the most notable extreme events can be identified, such as storm surges (Degeai et al., 2015; Jakubowski-Tiessen, 1992; Pfister, 1994). Another possibility to assess atmospheric circulation and thus, indirectly extratropical cyclone behavior is a reconstruction of pressure fields (Luterbacher et al., 2002) or pressure-related indices such as the NAO (Ortega et al., 2015). Such reconstruction methods are based on observed statistical relationships between air pressure and other variables (e.g., temperature and precipitation). The application of these methods involves the risk of introducing dependencies and circular statements, that is, using precipitation in pressure reconstructions and then assessing links to precipitation. Moreover, stationary links between the proxies and the large-scale circulation are assumed, which might not necessarily be true for all times (Moore, Renfrew, & Pickart, 2013; Pinto & Raible, 2012; Raible et al., 2006; Raible, Lehner, González-Rouco, & Fernández-Donado, 2014).

Another caveat of most of these proxy records is the sparse spatial coverage and the coarse temporal resolution. Sediment cores have even a centennial resolution, but are an important source for the LGM (Dietrich & Seelos, 2010; Pfahl et al., 2009; Roemer, Lehmkuhl, & Sirocko, 2016). Seasonality also plays an important role in the interpretation of the proxy data. For example, heavy precipitation and flood events are often associated with extratropical cyclones, but summer convective thunderstorms can also play a role for the occurrence of regional warm-season flood events. Several proxy-based studies propose a positive correlation between summer temperature and precipitation over the Mediterranean (Abrantes et al., 2017; Corella et al., 2019) and Europe (Ljungqvist et al., 2016, 2019). Other studies point to a maximum in spring–summer flood occurrence during colder periods of the last millennium in central Europe (Czymzik et al., 2010; Glaser & Stangl, 2004). Thus, one needs to be cautious in particular when interpreting studies focusing on summer precipitation.

Climate modeling is the other source to deepen our understanding of past climate states. So-called models of intermediate complexity are widely used in paleoclimatic studies (Petoukhov et al., 2000; Stocker, Wright, & Mysak, 1992), but they are not useful to assess extratropical cyclone variations due to the highly parameterized atmospheric component (either a simple energy balance model or statistical models). Thus, the Paleoclimate Modeling Intercomparison Project (PMIP) uses state-of-the-art Earth System Models (ESMs) forced with natural and anthropogenic external forcing agents (an example of external forcing is shown for the last millennium in Figure 1a; Schmidt et al., 2012).

The mission of paleoclimate modeling is twofold. First, a comparison between ESM simulations and proxy records (PAGES 2k Consortium et al., 2013; PAGES Hydro2k Consortium et al., 2017; Weitzel et al., 2019) is a way to assess the ability of ESMs to simulate different climate states, increasing the confidence of such models, which are also used for

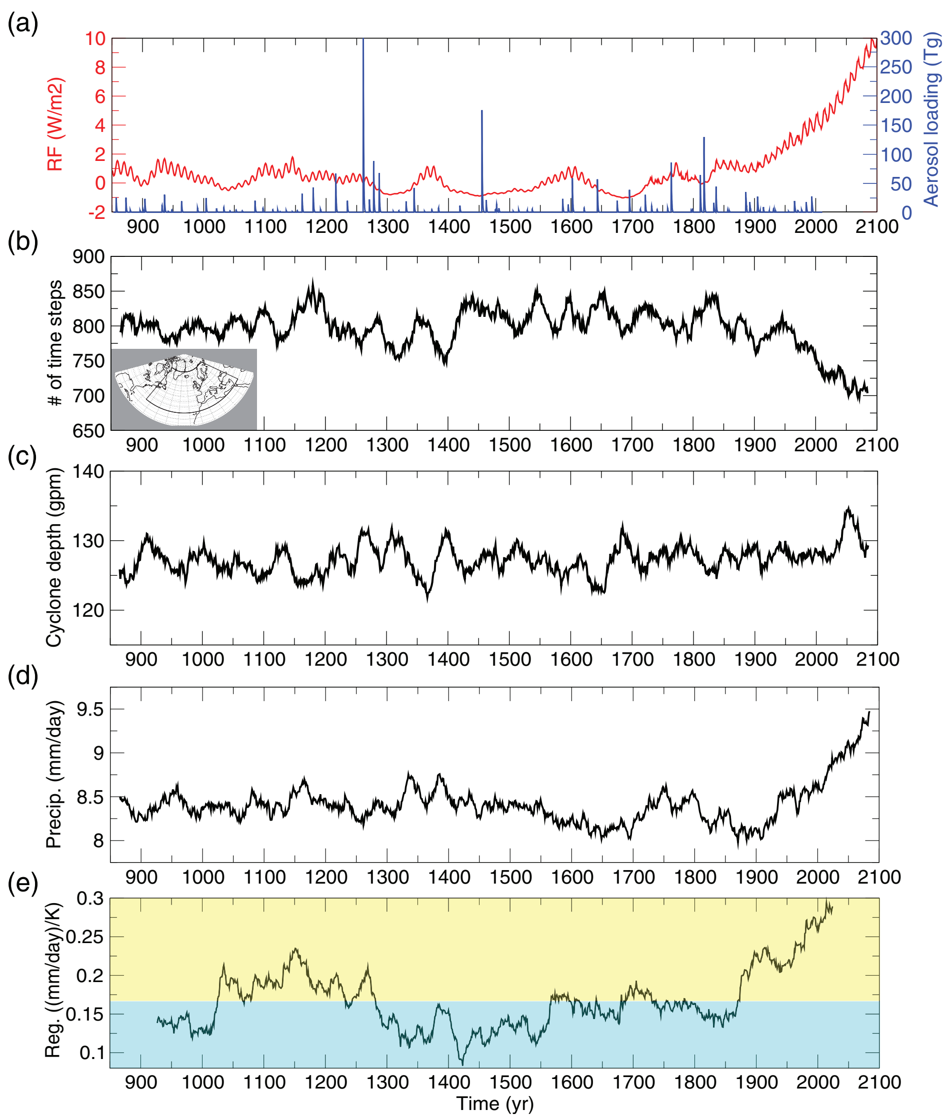

FIGURE 1 (a) External forcing of a PMIP-type simulation for the last millennium (red: sum of the radiative forcing (RF) based on the greenhouse gases CO_2, CH_4, and N_2O as well as solar irradiance; blue: mass of volcanic aerosols). The inset in (b) shows the area in which the following indices are estimated for winter (December–February): (b) number of extratropical cyclone time steps, (c) extreme cyclone depth, (d) extreme cyclone-related precipitation. Note that in (b)–(d) a 30-year running average is applied. (e) Regression coefficients between the cyclone-related temperature and the extreme cyclone-related precipitation estimated in a 150-year running window. The yellow shading in (e) indicates the dominance of thermodynamical processes (Clausius–Clapeyron equation) (O'Gorman & Schneider, 2009). the cyan shading highlights periods where dynamical processes are mainly responsible for the generation of cyclone-related precipitation extremes (Reprinted with permission from Raible et al. (2018))

future projections (Braconnot et al., 2012). Second, ESMs help to gain process understanding, supporting the interpretation of climate variations recorded by proxies. For example, forcing the model with each external forcing agent separately enables the attribution and detection of external forcing signals (Hegerl, Crowley, Baum, Kim, & Hyde, 2003; Schurer, Tett, & Hegerl, 2014). So far, only few studies focus on the synoptic-scale weather variability (2–6 days), which includes the extratropical cyclones (Fischer-Bruns, von Storch, Gonzalez-Rouco, & Zorita, 2005; Gagen et al., 2016; Raible et al., 2007, 2018; Sousa et al., 2020). A limiting reason is that most of the paleoclimate model simulations are only stored with a monthly resolution, thus undermining studies on shorter time scales (Fernández-Donado et al., 2013; Jungclaus et al., 2017; Kageyama et al., 2018; PAGES 2k Consortium et al., 2013; PAGES Hydro2k Consortium et al., 2017; Schmidt et al., 2012). In general, ESMs with horizontal resolutions of up to 100 km can resolve extratropical cyclone structures and features, but difficulties with representing moist processes and latent heat profiles remain. This has potential impacts on cyclone dynamics, in particular for extreme cyclones. Additionally, comparing proxy reconstructions with ESM results show a substantial misrepresentation of the regional climate response (Harrison et al., 2015). Thus, regional climate models (RCMs) have been recently used in the paleoclimatic perspective (Bromwich et al., 2004; Ludwig et al., 2019; Pinto & Ludwig, 2020; Strandberg, Brandefelt, Kjellstrom, & Smith, 2011) in order to overcome some of the shortcomings of ESMs and/or boundary conditions. The resolution obtained are in the scale of 10–50 km. Currently, convection resolving simulations (<5 km horizontal scale) are performed for small regions like the European Alps (Velasquez, Messmer, & Raible, 2020) and provide additional information on the local scale.

3 | THE LAST MILLENNIUM

The last millennium is assigned to the current interglacial, the holocene. It is characterized by the warm period of the so-called "Medieval Climate Anomaly" (MCA; the 10th to the 13th century) and the transitioning to the colder period of the "Little Ice Age" (LIA; the 14th to the 19th century; Bradley, Wanner, & Diaz, 2016; Mann et al., 2009). This transition is mainly caused by changes in the volcanic forcing (Bronnimann et al., 2019; Schurer et al., 2014) and potentially induced feedbacks between sea ice, ocean, and atmosphere (Lehner, Born, Raible, & Stocker, 2013). The warmer (colder) period is associated with a reduced (enhanced) meridional temperature gradient near the surface and thus reduced (enhanced) low-level baroclinicity and enhanced (reduced) latent heating. Due to the proximity to present day and future climate, the last millennium often serves as testbed for the quantification of natural variability and the assessment of natural external forcing, such as the solar activity (Schurer et al., 2014) and volcanic eruptions (Raible et al., 2016; Robock, 2000). This time period is marked by a comparatively dense and with time increasing network of different climate proxy information, so that several climate reconstructions of temperature and precipitation are available (Emile-Geay et al., 2017; PAGES 2k Consortium et al., 2013). Thus, the last millennium is predestinated to put current and future changes into a long term perspective, also in terms of extratropical cyclone characteristics (Raible et al., 2014, 2018; Sousa et al., 2020). Within PMIP, this period is selected as one of the key periods to be investigated in their past and current assessments (Jungclaus et al., 2017).

As suggested in Section 2, proxy records can be used to provide valuable information on extratropical cyclones. Wind-related characteristics of extratropical cyclones are rather sparse and often indirect sources (like NAO reconstructions) have to be considered for the last millennium. For example, the grainsize distributions of sand, which is transported by winds to sites in southern Sweden, suggest that storm-induced wind activity over Europe was increased during a cold period of the LIA in the 17th century (de Jong et al., 2006). Also, an erosion related proxy record based on sediments in the Gulf of Maine, the region upstream of the North Atlantic storm track, hints to an enhanced storm activity in the past 500 years (Buynevich et al., 2007). Other authors (Trouet et al., 2012) supported this increase in storminess during the LIA using several marine sediment cores in the North Atlantic and a Greenland ice core record (Meeker & Mayewski, 2002). These sediment cores can only give a rough estimate of past changes during the last millennium due to their coarse temporal resolution. Thus, the spatially gridded reconstructions for monthly or seasonal mean air pressure distributions over Europe can add more details. Using reconstructions from proxies sensitive to air pressure only, no clear long-term change in storminess is observed over Europe during the 17th to the 19th century, but variability on decadal to multi-decadal time scales is identified (Barriopedro et al., 2014; Casty et al., 2007; Garcia-Herrera et al., 2018). Gridded pressure reconstructions, based on multi-sensitive proxy records, even suggest a weakening of the pressure gradient over the East Atlantic during the LIA, which is interpreted as a weakening of storminess over Europe (Kuettel et al., 2010; Luterbacher et al., 2002).

Also, different reconstructions of the NAO add to this inconsistent picture, supporting either an increase in storminess, no change, or a weakening over Europe during some phases of the LIA (Appenzeller, Stocker, & Anklin, 1998; Orme et al., 2016; Ortega et al., 2015; Pinto & Raible, 2012; Trouet et al., 2009). For the Mediterranean, two studies show an increase in storm activity during the LIA (Camuffo, Secco, Brimblecombe, & Martin-Vide, 2000; Degeai et al., 2015). As the storm behavior is anti-correlated between central to northern Europe and southern Europe (Hurrell & Vanloon, 1997), these two studies support the concurrent reduced storminess over central to northern Europe. Given these contrasting proxy evidences, it is obvious that no clear conclusion on the origin of periods with higher or lower storm activity with respect to wind over the North Atlantic and Europe can be deduced from the proxy-based studies alone. Moreover, potential links between storminess and natural external forcing depend on the proxy records and reconstructions used.

Another important aspect associated with storms is heavy precipitation and related flooding. For example, in central Europe, extratropical cyclones, particularly Mediterranean cyclones moving to central Europe, play an important role for the occurrence of heavy precipitation and severe river floods (Grams, Binder, Pfahl, Piaget, & Wernli, 2014; Kelemen, Ludwig, Reyers, Ulbrich, & Pinto, 2016; Messmer, Gómez-Navarro, & Raible, 2015; Mudelsee, Börngen, Tetzlaff, & Grünewald, 2004; Rimbu, Czymzik, Ionita, Lohmann, & Brauer, 2016). One needs to keep in mind though that not all floods or heavy precipitation events are induced by extratropical cyclones. Studies using the precipitation or flood behavior of the entire year (Amann, Szidat, & Grosjean, 2015; Wetter, 2017; Wetter et al., 2011) are used here to assess the connection to extratropical cyclones. These authors found that flood occurrences in central Europe during the entire year are enhanced in the rather cold periods of the LIA compared to warm periods. They suggested a negative correlation between temperature and floods although in some cases the season of flood might not be coherent with the season of cold temperatures. Still, as these events occur over long periods of several decades, this seasonality problem is of minor importance. Thus, following the interpretation of Amann et al. (2015), Wetter (2017), and Wetter et al. (2011). This proxy evidence is ostensibly in contrast to the thermodynamic theory which states that a warmer atmosphere can hold more moisture based on the Clausius–Clapeyron equation, and thus stronger (weaker) precipitation extremes are expected under warmer (colder) conditions (Berg, Moseley, & Haerter, 2013; O'Gorman & Schneider, 2009). Again, proxy-based studies show a range of partly contradicting results when assessing linkages between extratropical cyclone and extreme precipitation events.

Besides proxy archives, climate modeling is the other valuable method to assess variability of extratropical cyclones during the last millennium. Modeling results can possibly overcome some of the open questions raised by the different proxy studies and help in the interpretation of proxy records.

Concerning wind, a modeling study (Raible, 2007) found an increase in storm intensity, measured as cyclone depth, over the North Atlantic European sector during the mid-17th to the early 18th century compared to present day, resembling the sediment cores in southern Sweden (de Jong et al., 2006). During this period, the NAO was predominantly in its negative phase, as reduced occurrences of cyclones were identified in particular over northern Europe. This finding was recently confirmed by a study performed with a spatially higher resolved ESM (Figure 1b; Raible et al., 2018). Thereby, the aforementioned apparent conflict between some proxy records was resolved. For example, it is possible that during the negative phase of the NAO fewer but more intense extratropical cyclones develop, explaining why proxies recording the NAO (Orme et al., 2016; Trouet et al., 2009) and other proxies recording more directly wind speed (Buynevich et al., 2007; de Jong et al., 2006) can deviate. This finding underpins that focusing only on pressure indices of modes of variability might contribute to misleading interpretations and conclusions when assuming present day relationships (NAO positive phases—higher storminess) to past variability (Lehner, Raible, & Stocker, 2012; Pinto & Raible, 2012; Raible et al., 2014).

Another hypothesis raised by Raible (2007) was that there is a link between external forcing and wind storm intensity, that is, a negative radiative forcing would lead to more intense storms. This hypothesis was not confirmed by a more recent study (Raible et al., 2018). To illustrate this, we show the 90th percentile of the winter cyclone depth time series from 850 to 2100 CE using the historical forcing plus the RCP8.5 scenario for the future (Figure 1c). For the period 850 to 1850 CE, the cyclone depth remains within the range of natural variability, and shows no clear imprint of the external forcing. Other studies focusing on extratropical cyclones over the North Atlantic in summer confirm that internal variability dominates the cyclone intensity (Fischer-Bruns et al., 2005; Gagen et al., 2016). Still, some CMIP models for the recent past and the future show an intensification of extratropical cyclones over parts of the North Atlantic (Feser et al., 2015; Ulbrich et al., 2009). Consequently, the paleoclimate studies show that model uncertainty with respect to wind intensity of extratropical cyclones is still high. This is not astonishing, as several competing processes are relevant in the intensification of cyclones, such as the meridional temperature gradient in the lower and upper troposphere, or latent heat release (Booth et al., 2013; Catto et al., 2019; Charney, 1947; James & Hoskins, 1985; Kuo et al., 1991; Raible et al., 2007; Tierney et al., 2018).

Besides wind, the distribution and intensity of precipitation is often assessed in modeling studies. An interesting measure is the integrated water vapor transport towards Europe, as it is highly related to cyclones, particularly for the more intense cyclones (Eiras-Barca et al., 2018; Sousa et al., 2020). For the pre-industrial period, this measure seems to be dominated by internal climate variability with no clear links to the natural external forcing as the modeling study of Sousa et al. (2020) suggests. However, in the 20th and 21st century (following the RCP8.5 scenario), the authors found a strong increase in integrated water vapor transport, as expected from the Clausius–Clapeyron equation. Interestingly, precipitation and extreme precipitation are reduced over the Iberian Peninsula, although the moisture transport is enhanced, which is traced back to changes in cyclone related weather types and reduced relative humidity (Sousa et al., 2020) and a reduction in cyclone occurrences (Raible et al., 2018). The latter study investigated different extratropical cyclone characteristics in the North Atlantic during winter in more detail, in particular, the relation to precipitation extremes. Thereby, the authors estimated the extreme cyclone-related precipitation (90th percentile in a winter season) by taking the mean precipitation over the area of an extratropical cyclone (Raible et al., 2018; Figure 1d). For the preindustrial period from the MCA to the LIA, no connection to the external forcing is evident, as internal variability apparently dominates (compare Figure 1d with Figure 1a). For the industrial period and a future projection under the RCP8.5 Scenario, the example depicted in Figure 1 shows a strong increase in extreme cyclone-related precipitation, which is related to strong external forcing (Raible et al., 2018). This is in line with future climate projection studies (Hawcroft, Walsh, Hodges, & Zappa, 2018; Pfahl & Sprenger, 2016; Yettella & Kay, 2017; Zappa, Shaffrey, Hodges, Sansom, & Stephenson, 2013; Zhang & Colle, 2017). The main process behind this increase is based on thermodynamics, that is, the Clausius–Clapeyron equation as illustrated by the regression of cyclone related temperature and cyclone-related precipitation (Figure 1e; Raible et al., 2018).

Another interesting period of the simulation is the 14th and 15th century, which brings us back to the apparent contradiction of some proxy evidences (Amann et al., 2015; Wetter et al., 2011) to the thermodynamic theory. The simulation clearly shows periods of enhanced extreme cyclone-related precipitation during these centuries (Figure 1d) within the LIA period. However, the regression analysis indicates that thermodynamics are less important during this period as the regression coefficient leaves the range of the Clausius–Clapeyron equation (yellow shading in Figure 1e). Thus, this study (Raible et al., 2018) shows that other—dynamical—processes (cyan shading in Figure 1e) must be determinant to induce the extreme cyclone-related precipitation during these centuries. This fact shows that a higher number of flooding events during cold climate states (Amann et al., 2015; Czymzik et al., 2010; Wetter, 2017) is indeed possible and does not contradict the theory or future projections, as the key processes involved are different.

4 | THE LAST GLACIAL MAXIMUM

Another period of particular interest in paleoclimate sciences is the LGM (Clark et al., 2009). The LGM is characterized by an insolation similar to the present day. However, the lower greenhouse gas concentrations (EPICA Community Members, 2004) and the presence of large ice sheets in the northern hemisphere led to a global mean temperature that was roughly 5–6.5 °C lower than present day temperatures (Otto-Bliesner et al., 2006). The maximum global land ice volume resulted in a sea-level minimum of 115–130 m below the present sea level (Lambeck, Rouby, Purcell, Sun, & Sambridge, 2014; Peltier & Fairbanks, 2006). Atmospheric dust loadings were substantially higher than present day (Lambert et al., 2008), as vegetation and land-surface have strongly changed (Annan & Hargreaves, 2013; Bartlein et al., 2011; Cleator, Harrison, Nichols, Prentice, & Roulstone, 2020; de Vernal et al., 2006; Shao, Anhaeuser, Ludwig, Schlueter, & Williams, 2018; Waelbroeck et al., 2009). The LGM has been a focal period for PMIP since its inception as the magnitude of the climate response is similar to the one projected for future middle and high emission scenarios (Abe-Ouchi et al., 2015; Kageyama et al., 2017; Otto-Bliesner et al., 2006) and the rather reasonable proxy data coverage.

From an extratropical cyclone point of view, the LGM is interesting as the meridional temperature gradient in the lower troposphere is strongly changed in the mid-latitudes enhancing low-level baroclinity, and mountainous barriers are enlarged, the latter being a major source of atmospheric waves and thus of extratropical cyclones (Brayshaw, Hoskins, & Blackburn, 2009; Dong & Valdes, 1998; Hofer, Raible, Dehnert, & Kuhlemann, 2012; Kageyama et al., 1999; Kutzbach & Guetter, 1986; Laine et al., 2009; Manabe & Broccoli, 1985; Merz, Raible, & Woollings, 2015; Pausata, Li, Wettstein, Kageyama, & Nisancioglu, 2011; Riviere, Berthou, Lapeyre, & Kageyama, 2018). Thus, the LGM is an ideal case study to deepen our process understanding relevant for extratropical cyclones and their associated impacts, such as wind or precipitation extremes (Kageyama et al., 1999; Ludwig, Pinto, Raible, & Shao, 2017; Merz et al., 2015; Pinto & Ludwig, 2020; Raible & Blender, 2004).

Proxy evidence on LGM climatic conditions is available from ice cores, which are restricted to polar areas, speleothems, as well as sediment cores of the ocean, lakes, and land. For the mid-latitudes, the major source for climate information are pollen-based reconstructions of temperature and precipitation (Bartlein et al., 2011; Cleator et al., 2020), multi-proxy reconstructions of the sea surface temperature (Waelbroeck et al., 2009), and loess-paleosol sequences (Lehmkuhl, Zens, Krauss, Schulte, & Kels, 2016; Markovic et al., 2015; Vandenberghe & Nugteren, 2001). Overall, the proxy reconstructions show a substantial cooling of the mid-latitudes, reaching a reduction by 7–8 °C in the northern hemisphere.

Unfortunately, climate proxies that can be directly linked to wind or air pressure and thus to extratropical cyclones have not yet been found for this period. Thus, only a few indirect evidences exist, for example, the major loess deposits found in a belt around 40° to 60°N across Europe (Antoine et al., 2009, 2013; Obreht et al., 2019; Ujvari et al., 2017). These deposits in central and eastern Europe were generated by large fluvioglacial source areas and frequent dust storms triggered by strong winds from either western or eastern direction (Figure 2). Along with the southwestern Atlantic coastal regions, dune fields on the Iberian Peninsula and southwestern France hint to strong westerlies (Figure 2) (Costas, Naughton, Goble, & Renssen, 2016). In North America, loess deposits suggest surface winds with a strong western component (Conroy, Karamperidou, Grimley, & Guenthner, 2019). Another hint for wind, in particular wind direction, stems from varved sediments extracted from maars in Germany (Dietrich & Seelos, 2010; Pfahl et al., 2009; Roemer et al., 2016) and from loess-paleosol sequences from the northern Harz foreland in Germany (Krauss et al., 2016). These authors were able to show that easterly winds dominated during the LGM for these regions.

The strong reduction in temperature during the LGM is accompanied by a general drying (Bartlein et al., 2011; Cleator et al., 2020). On the regional scale, different proxies often show some disagreement. For example, proxies from lacustrine sediments and pollen on the Iberian Peninsula suggest either an increase of moisture during the LGM (Moreno, Gonzalez-Samperiz, Morellon, Valero-Garces, & Fletcher, 2012) or a decrease (Figure 2; Bartlein et al., 2011; Cleator et al., 2020). Part of this mismatch might originate from differences in the seasonal information contained in these proxy records and the fact that they usually are all interpreted as yearly signals. Regarding southern Europe, reconstructions of the Alpine ice cap suggest that the buildup of the ice cover was related to precipitation by a dominant southerly atmospheric circulation during the LGM (Figure 2; Florineth & Schluchter, 2000; Schluechter, Florineth, & Schluechter, 1998). This hypothesis is confirmed by speleothem proxy records (Luetscher et al., 2015). Thus, the available proxy records and reconstructions do provide a few puzzle pieces of the climate state during the LGM. A

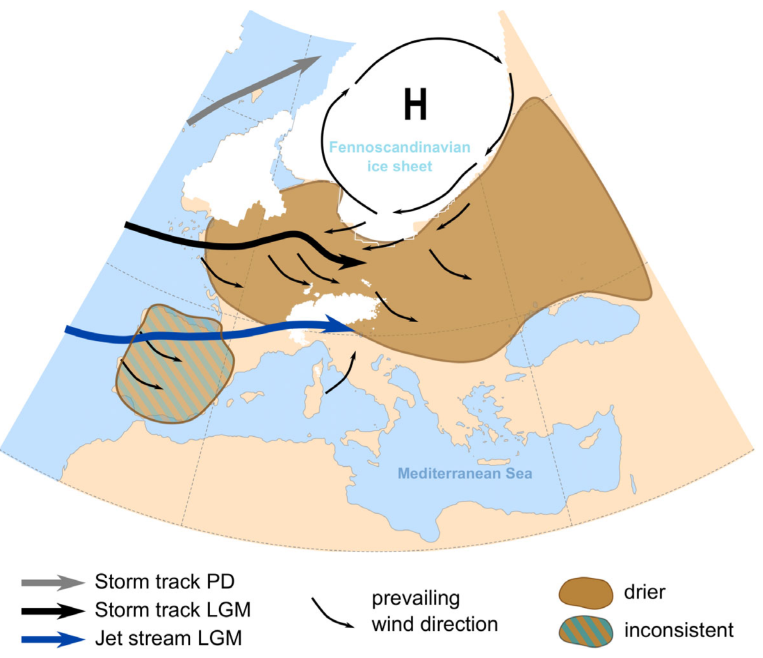

FIGURE 2 Schematic of the storm track, atmospheric circulation relevant for extratropical cyclones, and hydrological implications of extratropical cyclones comparing present day (PD) conditions with the LGM reconstructed based on proxy evidence. A clear specification of the season is not possible, as some proxies such as pollen data (which illustrate the hydrological impact) are more related to the growing season and other such as loess deposits (illustrating wind) are not attributable to a specific season

reconstruction of the dominant circulation patterns based on various proxy records is illustrated with the schematic of Figure 2. However, given the sparse spatial coverage and in particular the inability to resolve the synoptic time scales, conclusions on the behavior of extratropical cyclones and the atmospheric circulation are difficult.

As for the last millennium, modeling studies help filling in the gaps of spatial coverage and temporal resolution during the LGM. Here, we summarize the general picture that emerges from various modeling studies for the circulation patterns in the North Atlantic storm track region for the LGM (depicted with the schematic of Figure 3). Early studies in the 1980s assessed the influence of the major ice sheets in the northern hemisphere, the Laurentide ice sheet (LIS) and Fennoscandinavian ice sheet (FSIS) on the general atmospheric circulation (Broccoli & Manabe, 1987; Kutzbach & Guetter, 1986; Manabe & Broccoli, 1985). In these modeling studies, the northern hemisphere winter circulation shows an amplified flow pattern resulting in enhanced westerlies near the LIS and the FSIS (Broccoli & Manabe, 1987; Manabe & Broccoli, 1985) and a splitting of the jet stream in the vicinity of the LIS (Figure 3; Kutzbach & Guetter, 1986). Later, these findings were supported with ESM simulations obtained in several PMIPs, which showed a southward-displaced, more intense, and less variable North Atlantic jet stream than under current climatic conditions (Dong & Valdes, 1998; Hofer, Raible, Dehnert, & Kuhlemann, 2012; Lofverstrom, Caballero, Nilsson, & Kleman, 2014; Lofverstrom, Caballero, Nilsson, & Messori, 2016; Unterman, Crowley, Hodges, Kim, & Erickson, 2011; N. Wang, Jiang, & Lang, 2018). These changes have a direct impact on the storm tracks, which experience a south-easterly shift in the North Atlantic and to a lesser extent in the North Pacific compared to the position of the storm tracks under present day conditions (Hofer, Raible, Dehnert, & Kuhlemann, 2012; Kageyama et al., 1999; Ludwig et al., 2016; Yanase & Abe-Ouchi, 2010). This shift results in an increase in cyclonic weather types over Europe (Figure 3; Hofer, Raible, Merz, Dehnert, & Kuhlemann, 2012; Ludwig et al., 2016). However, easterly winds were more dominant than present day over central Europe (Ludwig et al., 2016), which is consistent with dust modeling and proxy data for the region (Dietrich & Seelos, 2010; Krauss et al., 2016; Roemer et al., 2016; Schaffernicht, Ludwig, & Shao, 2020). The easterly winds are induced by the semi-permanent anticyclone over the FSIS and the further southward moving cyclones, which feature easterly winds at their north-facing side (Figure 3). Using a set of sensitivity experiments where the height of LIS was modified, the authors provided evidence that the stationary wave activity is enhanced southeast of the LIS (Merz et al., 2015). This behavior was confirmed in other studies with different GCMs (Lofverstrom, 2020; Riviere, Laine, Lapeyre, Salas-Melia, & Kageyama, 2010; Roberts, Li, & Valdes, 2019; N. Wang et al., 2018).

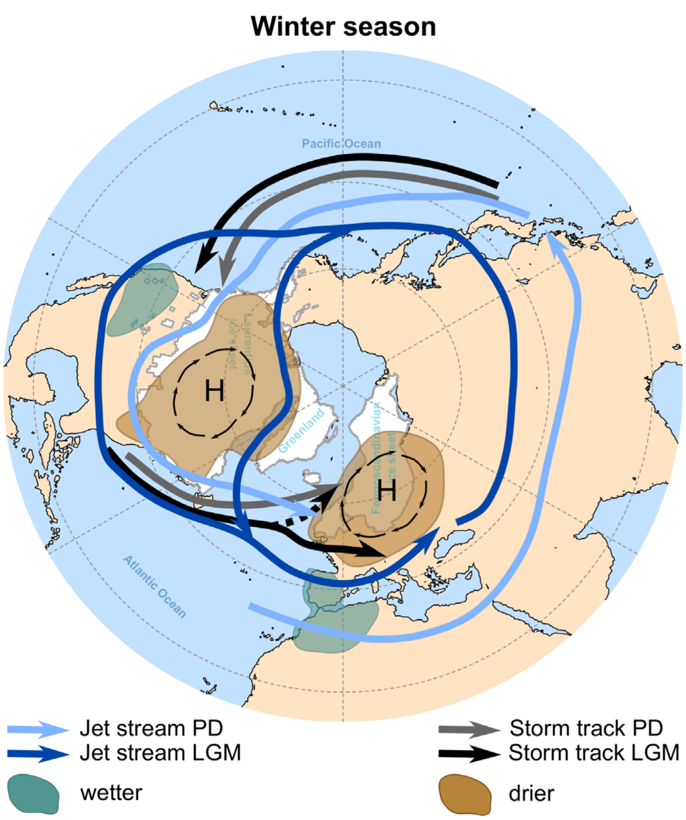

FIGURE 3 Schematic of the storm tracks, atmospheric circulation relevant for extratropical cyclones, and hydrological implications of extratropical cyclones comparing present day (PD) with the LGM based on model evidence. The compilation is based on several modeling studies using different models (as mentioned in the text). We only include features where models agree on. The dashed arrow between Iceland and Scandinavia is only based on limited model evidence. Note that we focus on the winter, where extratropical cyclones are mostly pronounced, and, thus, most of the studies focus on

Besides changes in the land-sea contrast, due to the presence of massive ice shields, this stationary wave activity is another source for baroclinic disturbances, which are essential for the generation of cyclones. Thus, the genesis region of extratropical cyclones in the North Atlantic, which is off the coast of the Carolinas up to south of Newfoundland under present day conditions, is displaced southwards (Merz et al., 2015). The authors also suggested that the storm track intensified over the North Atlantic. In particular, the extratropical cyclones release part of their energy back to the mean flow at the end of the storm track over southern Europe, resulting in an intensified jet over the Mediterranean (Figure 3). This is in line with other LGM simulations, which showed an enhanced baroclinic path of the Lorenz energy cycle over the North Atlantic for this period (Murakami, Ohgaito, & Abe-Ouchi, 2011). Another modeling study found that cyclogenesis was generally enhanced during the LGM, particularly south of Newfoundland and Greenland and over central Europe (Pinto & Ludwig, 2020). Other modeling studies disagree with the intensification of extratropical cyclones in the North Atlantic, exhibiting a reduced storm track despite the enhanced baroclinicity in the North Atlantic (Donohoe & Battisti, 2009; Kageyama & Valdes, 2000; Li & Battisti, 2008; Lofverstrom et al., 2016). A possible reason discussed in the literature (Riviere et al., 2018) for this apparent contradiction is that the mean meridional temperature gradient and the eddy heat fluxes are less well aligned for LGM than for the pre-industrial conditions. Other reasons may be that the storminess depends on the parameterizations used in the model or on differences in sea surface temperatures (Dong & Valdes, 1998; Donohoe & Battisti, 2009). Thus, most of the simulations of the LGM generally agree in the southward shift of the jet and a corresponding modulation of the storm track in the northern hemisphere as illustrated by the schematic (Figure 3). However, an increase in model uncertainty is obvious when considering the extratropical cyclone wind intensity. This finding is also true in the last millennium.

Given the changes of the atmospheric circulation and the storm tracks, a strong change of the precipitation pattern can be expected during the LGM compared to present day. In general, the proxy records suggest dryer conditions in the boreal mid-latitudes (Bartlein et al., 2011; Cleator et al., 2020). This general behavior is well captured by all LGM simulations, as the mechanism is based on the Clausius–Clapeyron equation, that is, the simulated cooler conditions lead to a dryer atmosphere and thus less precipitation. Still, the regional climate changes, such as the increased precipitation associated with changes in the jet streams, are poorly captured by the GCMs (Kageyama et al., 2020). Moreover, the different proxies show contrasting evidence for some regions, for example, for the Iberian Peninsula (Bartlein et al., 2011; Moreno et al., 2012). A detailed multi-model analysis of the relationship between extratropical cyclones and precipitation over the Mediterranean shows that winter precipitation is increased over the Iberian Peninsula and Morocco during the LGM compared to preindustrial conditions (Figure 3; Beghin et al., 2016). This is in contrast to summer, where precipitation is mainly driven by local processes (convection), explaining the range of various signals identified in different paleoclimate archives (Figure 2; Bartlein et al., 2011; Moreno et al., 2012). Similar results are found based on regional climate modeling over Iberia, where the simulated ombrotypes for LGM conditions point to more humid conditions in winter and more arid conditions in summer as compared with preindustrial conditions (Ludwig, Shao, Kehl, & Weniger, 2018). The increase in winter precipitation is in line with earlier studies (Hofer, Raible, Dehnert, & Kuhlemann, 2012; Hofer, Raible, Merz, et al., 2012; Merz et al., 2015), which were able to link this increase in rainfall to a shift and intensification of the storm track as well as the associated changes in the weather types. 40% of the precipitation change can be explained by changes in the occurrences of the cyclone related weather types (Hofer, Raible, Merz, et al., 2012). This example shows that not only thermodynamics (general drying) but also dynamical changes are very important to understand regional to local changes in climate during the LGM.

Still, the substantial misrepresentation of regional climate response in PMIP ESMs compared to proxy reconstructions during the LGM is regarded as a general challenge (Harrison et al., 2015). This calls for regional paleoclimate model simulations (Bromwich et al., 2004; Ludwig et al., 2019; Pinto & Ludwig, 2020; Strandberg et al., 2011) to overcome some of the shortcomings of ESMs and/or boundary conditions. One potential source of uncertainty is the fact that PMIP3 ESMs tend to simulate a too warm North Atlantic ocean (T. Wang, Liu, & Huang, 2013). This has certainly an impact on extratropical cyclones and their precipitation. Applying a regional model (Ludwig et al., 2017) and additionally correcting the sea surface temperatures with reconstructions (Waelbroeck et al., 2009) shows that the ESM simulated positive precipitation anomaly during the LGM over the Iberian Peninsula can be reversed with the RCM that better reproduces the dryer conditions suggested by pollen data (Bartlein et al., 2011). Again, the improvements are due to slight changes in the occurrences of weather types and thermodynamic aspects, showing the importance of both dynamical and thermodynamic changes (Ludwig et al., 2017).

Given the range of responses between proxy records and models, a final conclusion cannot yet be drawn for the local to regional changes of cyclone induced precipitation for the LGM as the example of the Mediterranean shows.

Nevertheless, one lesson from this overview is clear: while purely thermodynamic considerations are powerful, they need to be accompanied by detailed dynamical analysis to help in the interpretation of proxy records.

5 | CONCLUSION

This review article presents an overview of published studies which analyzed and assessed past changes in extratropical cyclones and associated impacts. Many arguments were provided on how the paleoclimatic view on a complex meteorological phenomenon—like extratropical cyclones—can lead to new insights, deeper process understanding, and implications for recent and future climate conditions. Given the availability of studies, the focus was set to the northern hemisphere (mainly the North Atlantic European sector) and the winter season for two key periods in the past: the last millennium and the LGM.

The review attempts to highlight the strength of using both proxy records and paleo simulations as a synergistic tool to better retrace extratropical cyclones' relationship with climatic conditions. Proxy records already give some hints about the behavior of cyclones in different time periods. Since the spatial and temporal coverage of proxies is not sufficient to explicitly examine extratropical cyclones, climate modeling plays a decisive role in quantifying extratropical cyclone characteristics. Such simulations further help to identify underlying processes and understand the variability of extratropical cyclones in the past. The review also shows that comparing proxy records with modeling result (PAGES 2k Consortium et al., 2013; PAGES Hydro2k Consortium et al., 2017; Weitzel et al., 2019) is essential not only in generating new knowledge, but also to disclose and constrain model uncertainties, which is also key for future predictions (Harrison et al., 2015). Besides, the past serves as testbed for climate models (Braconnot et al., 2012; Hargreaves, Annan, Ohgaito, Paul, & Abe-Ouchi, 2013; Kageyama et al., 2020), and several examples presented in this review show how we can learn directly from paleoclimate studies (Fischer et al., 2018; Raible et al., 2018; Sousa et al., 2020). The review also shows that new proxy evidence is needed to better constrain past variations in extratropical cyclones, for example, the link between deuterium and cold advection in extratropical cyclones has been recently identified (Aemisegger, 2018). This result is promising as several archives such as ice cores and trees offer the possibility to quantify deuterium ratios.

One rather recent development in the paleoclimate community is the use of regional climate models, which have the ability to build a bridge between the local character of proxy data and the rather coarsely resolved global models (Ludwig et al., 2017, 2018, 2019). Still, further studies are needed, notably at the regional scale, to gain confidence in the modeling and our understanding of the paleoclimatic conditions (Cleator et al., 2020; Harrison et al., 2015; Ludwig et al., 2019). Additionally, other scientific fields can benefit in particular from regionalization, for example, glaciologists or hydrologists strongly depend on the accuracy of precipitation (Felder et al., 2018; Seguinot, Khroulev, Rogozhina, Stroeven, & Zhang, 2014).

One knowledge gap is the rather small range of climate states assessed in this review, namely, the last millennium and the LGM. During the past 3.5 million years, the Earth also experienced climatic conditions warmer than during the pre-industrial Holocene (Fischer et al., 2018). Comparing these states to future climate change studies can contribute to better understand why the total number of cyclones decreases progressively with enhanced CO_2 forcing whereas cyclone intensity over the North Atlantic peaks under $2 \times CO_2$ forcing (Catto, Shaffrey, & Hodges, 2011). Indeed, the fine balance between reduced baroclinicity and additional latent heat release with increasing CO_2 concentrations is hard to quantify and is still the subject of active research (Catto et al., 2019), where also paleoclimate studies can contribute to. Another open issue in climate modeling is that during different climate states the ratio between snow and rainfall may change (Bintanja, 2018; Feng & Hu, 2007), which affects the precipitation related impact of extratropical cyclones such as the seasonality of floods.

Another knowledge gap is the limited regional scope, as the largest part of the available studies focus on the Euro-Atlantic region. Much more effort should be given to other regions, particularly in the southern hemisphere (Ceppi, Hwang, Frierson, & Hartmann, 2012; Fyfe & Saenko, 2006; Solomon & Polvani, 2016; Xia, von Storch, Feser, & Wu, 2016). This is possible, as new CMIP6/PMIP4 simulations (Kageyama et al., 2020) will largely enhance the availability of daily and sub-daily data for analysis, thus enabling a more explicit analysis of extratropical cyclones, its variability, and future climate change. Further, this enables a better assessment of different views on the jet stream position, intensity, and variability, and also of storm tracks and in particular cyclone genesis and lysis regions over the North Atlantic during the LGM (Lofverstrom et al., 2016; Merz et al., 2015; Riviere et al., 2018). Additionally, a larger number of global simulations with daily or sub-daily output also increases the possibilities for applications of regional climate models. Such high-resolution simulations will permit a better analysis not only of cyclone numbers but also of cyclone structure and intensity (Pinto & Ludwig, 2020). Moreover, the computation of small ensembles of regional climate model simulations will enable a much more appropriate estimation of uncertainties at the regional scale. This should be particularly helpful for the comparison to the proxies, their representativeness in terms of seasonality towards better-informed proxy-based climate reconstructions at the regional scale.

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CONFLICT OF INTEREST

The authors have declared no conflicts of interest for this article.

AUTHOR CONTRIBUTIONS

Christoph Raible: Conceptualization; writing-original draft. **Joaquim Pinto:** Conceptualization; writing-original draft. **Patrick Ludwig:** Conceptualization; visualization; writing-original draft. **Martina Messmer:** Conceptualization; visualization; writing-original draft.

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