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Atmosphere-cryosphere interactions at 21 ka BP in the European Alps

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Abstract. Evidence that during the Last Glacial Maximum (LGM) glaciers extended well into the piedmont planes is still identifiable in the alpine foreland as a system of well-preserved moraines. Glaciers are strongly affected by temperature and precipitation and therefore they are excellent indicators of climate change. Here we use a regional climate model (RCM) to investigate the physical processes sustaining the glacier extent during the LGM. We find a predominance of convection during summer and increased southwesterly stratiform precipitation over the southern Alps compared to pre-industrial conditions. This precipitation pattern, along with lower temperatures, determined summer snowfall extending to low elevations with a consequent substantial drop of the equilibrium line altitude (ELA) consistent with the estimated LGM glacier extent. Our RCM based estimates of the ELA at the LGM yield excellent consistency with Alpine glacier reconstructions, further demonstrating the great potential of this technique for use in paleoclimate studies.

1 Introduction

The Last Glacial Maximum (LGM) was a period of maximum global ice volume (Hughes et al., 2013) during the last glacial cycle (0 to 150 ka BP; Lisiecki and Stern, 2016), and it extended approximately from 26.5 to 19 ka BP (Clark et al., 2009). It is conventionally defined by a minimum in global sea-level (Peltier and Fairbanks, 2006; Lambeck et al., 2014) and a maximum in marine oxygen isotope records (Mix et al., 2001). However, although the LGM is considered a global event, there is evidence (Hughes et al., 2013; Clark et al., 2009; Monegato et al., 2017) that it did not occur synchronously worldwide, with mountain glaciers and ice sheets reaching their maximum extent at different times and being out-of-phase with respect to the signal of marine isotope records (Hughes et al., 2013).

The European Alps have been widely affected by the LGM glacier advance. The Alps' ice-stream network, icefields (Kelly, et al., 2004; Ivy-Ochs et al., 2022) and piedmont lobes (Salcher et al., 2010; Monegato et al., 2007; Preusser et al., 2011) released on the ground a large set of well-preserved moraines and landforms testifying major advances at 26.5 to 23 ka BP (Monegato et al., 2007; Wirsig et al., 2016). The size of the glacier piedmont lobes was different across sectors and not always corresponding to large accumulation areas (Ivy-Ochs et al., 2022). The largest glaciers were located to the north (Rhone, Rhine, Isar-Loisach, Inn and Salzach), whereas piedmont lobes were smaller to the south, with only few of them exceeding 250 km2 (Ivrea, Verbano, Lario, Garda and Tagliamento). In fact, they remained confined into the valleys in the southwestern and eastern Alpine sectors (Durance and Drau were respectively the largest trunk glaciers). The LGM Alpine glaciers started their collapse not synchronously from 20 to 18 ka BP with still-stand phases and short re-advances (Monegato et al., 2017; Wirsig et al., 2016; Ivy-Ochs et al., 2004; Fontana et al., 2014; Ravazzi et al., 2014).

At the LGM, atmospheric and environmental conditions were drastically different from today. The mean sea level dropped by about 120 m (Clark et al., 2009; Lambeck et al., 2014; Yokoyama et al., 2000) as a consequence of the sustained growth of ice sheets and mountain glaciers, and this lead to the exposure of lands that were previously submerged. A typical example is the North Adriatic region, which was characterized by a transition from the semiarid Adriatic alluvial Plain to wide braided proglacial rivers in the Alpine piedmont area (Peresani et al., 2021). Global temperature at the LGM was 3 to 6 °C lower than in pre-industrial conditions (Annan and Hargreaves, 2013), although a large discrepancy still exists between model simulations and proxy data (Jost et al., 2005; Kageyama, et al., 2006; Ramstein et al., 2007).

At the LGM, air-masses followed different patterns compared to today, thereby modifying global and regional precipitation regimes. In particular, most model simulations (Laîné et al., 2009; Merz et al., 2015; Pinto and Ludwig, 2020; Strandberg et al., 2011) and proxy records (Monegato et al., 2017; Luetscher et al., 2015) show evidence of a southward shift of the Atlantic storm track caused by the expansion of the North American Ice Sheet (NAIS). Laîné et al. (2009) noted a thinning of the storm track in the north-western Atlantic associated with an intensified baroclinicity between the Azores Islands and Iberian Peninsula. This lead to a wetter climate in southwestern Europe and drier conditions North of the Alps. The differential insolation and temperature between the subtropical regions and the mid to high-latitudes, together with a semi-permanent blocking high over the Fennoscandian ice sheet, determined a marked latitudinal pressure gradient likely responsible for Rossby-wave breaking west of the Alps (Luetscher et al., 2015; Florineth and Schlüchter, 2000). This in turn induced a latitudinal flow of moist air from the subtropics towards the Alpine range, where air masses were forced to rise and release abundant precipitation, thus triggering ice build-up on the up-wind slopes (Monegato et al., 2017; Luetscher et al., 2015; Florineth and Schlüchter, 2000). Increased precipitation in the Southern Alps and western Mediterranean may also be ascribed to intense and frequent cyclogenesis in the Gulf of Genoa due to polar air outbreaks over the warm Mediterranean Sea (Kuhlemann et al., 2008).

The atmospheric circulation at the LGM over Europe has been widely studied. However, a large uncertainty still exists about the main mechanisms sustaining the expansion of Alpine glaciers during the LGM. The analysis of speleothems sampled in different caves across the Alps suggests that the LGM glacier expansion was predominantly fed by precipitation occurring between spring and autumn (Luetscher et al., 2015). Conversely, recent research (Spötl et al., 2021) relating cryogenic cave carbonates formation with precipitation and permafrost suggests that the LGM glacier advance in the Alps was determined by intense snowfalls during autumn and early winter. One of the major challenges in paleoclimatic reconstruction (from both models and proxies) is thus to reduce the uncertainties in estimated LGM precipitation patterns, especially at small spatial

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scales in areas of complex orography (Kirtman et al., 2013). This challenge can be addressed with the use of regional climate models (RCMs), which allow one to carry out simulations at resolutions of a few tens of km, or even less (e.g. Giorgi, 2019). Therefore, here we use the regional model RegCM4 (Giorgi et al., 2012) to investigate possible atmosphere-cryosphere interactions leading to the expansion of the LGM glaciers in the European Alps, in particular as related to the seasonality and spatial variability of atmospheric circulations and related precipitation.

A glacier's sensitivity to changes in climate conditions is reflected by the Equilibrium Line Altitude (ELA), i.e. the line separating the accumulation area from the ablation one (Haeberli et al., 2007; Lie et al., 2003; Mcgrath et al., 2017; Zemp et al., 2008). Therefore, changes in ELA are especially powerful indicators of changes in the extension of a glacier. Here, we thus estimate environmental ELA (envELA) of the LGM Alpine glaciers from simulated temperature and precipitation (Žebre et al., 2020; Ohmura and Boettcher, 2018), thereby disregarding the local topographic effects acting on glaciers. Finally, we assess the different contributions to the LGM glacier mass balance, and in particular the concurrent action of low temperatures, reduced snowmelt and evaporation, increased southerly moist air advection towards the Southern Alps, intensified cyclogenesis in the Tyrrhenian region and convection during the warmer months.

2 Methods

2.1 Experimental Design

In our experiments we use a double nesting approach. The large-scale driving fields are produced by the Max Planck Institute for Meteorology Earth System Model in Paleo Mode (MPI-ESM-P; Stevens et al., 2013), compliant with the PMIP3/CMIP5 protocol (Paleoclimate Modelling Intercomparison Project; Braconnot et al., 2012), for two 20 years time slices extracted from 150 year long simulations at the LGM standard and PI. Then, the International Center for Theoretical Physics Regional Climate Model RegCM4 (Elguindi et al., 2014; Giorgi et al., 2012) is nested into the MPI-ESM-P model with an intermediate 50 km resolution domain which in turn drives a high resolution domain at 12 km grid spacing. The MPI-ESM-P has already been successfully employed in the study of the LGM (e.g. Pinto and Ludwig, 2020), showing an overall behavior in line with other models (Ludwig et al. 2016), while for the RegCM4 this is the first application to paleoclimate studies in the Alpine region. We evaluated both models against observations (CRU; Harris et al., 2013) and reanalysis data (ERA-Interim; Dee et al., 2011) after customising the RegCM4 and providing it with a tailored land-use reconstruction. The RegCM4 orbital parameters and greenhouse gas concentrations were modified to follow LGM and PI conditions.

2.2 Land-use and topography reconstruction

During the LGM, the land surface conditions were quite different from present, and this information needs to be fed into the model, as it may affect the regional climate (Ludwig et al. 2017). These conditions may be reconstructed using available

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proxies and paleoclimate archives. First, we modified the model topography by decreasing sea level by 120 m (Peltier and Fairbanks, 2006) and changed the land sea-mask in order to take into account the corresponding variation of the coastline. Finally, we added a two-dimensional representation of the glaciers based on Ehlers et al. (2011). Concerning vegetation cover, we constructed a high-resolution dataset, based on poxy data (Monegato et al., 2015; Duprat-Oualid et al., 2017), using an association of plant types in each region with altitude and latitude, modulated by a random spatial distribution within each region. Every plant type is characterised by an annual cycle in leaf and steam area index.

2.3 Bias correction

In order to account for model biases revealed by the PI simulation (e.g., a precipitation overestimation over the Alps), we applied a first-order bias correction to precipitation and temperature output data. We first calculated the bias by comparing observations and pre-industrial RegCM4 data for both variables. Then we applied a correction to the RegCM4 PI and LGM temperature and precipitation, assuming that the biases between model and observations are the same in the two time periods. Precipitation is thus corrected by applying a linear scaling approach:

$$P_{corr}=\frac{P_{y,LAPREC}}{P_{y,PI}} * P_{y,RCM}, \quad (1)$$

where $P_{y,LAPREC}$ is annual accumulated precipitation from the LAPrec observation dataset (Auer et al., 2007; Isotta et al., 2014) averaged over the period 1871-1900, $P_{y,PI}$ is annual accumulated precipitation from the pre-industrial RegCM4 simulation averaged over 19 years, and $P_{y,RCM}$ is the simulated annual accumulated precipitation (PI or LGM) that needs to be corrected. Similarly, temperature was corrected as:

$$T_{corr}=T_{m,RCM}+\left(T_{m,PI}-T_{m,HIST}\right), \quad (2)$$

where $T_{m,RCM}$ is the simulated summer monthly mean temperature (PI and LGM) that we want to correct, $T_{m,PI}$ is the summer monthly mean temperature from the pre-industrial RegCM4 simulation averaged over 19 years, and $T_{m,HIST}$ is the summer monthly mean temperature from HISTALP dataset (Auer et al., 2007) averaged over the period 1871–1900.

2.4 Environmental Equilibrium Line Altitude

We calculated the environmental ELA, which represents the regional altitude of zero mass balance determined only by climatic factors (Anderson et al., 2018). The envELA is averaged over the 19 years of the model simulations, since we assume that glaciers are at a steady-state during the simulation time, and use as input the bias corrected precipitation and temperature (Eqs. 1 and 2). The calculation is performed according to the methodology adopted by Žebre (2020) which is based on an empirical equation relating mean summer temperature and accumulated annual precipitation (Ohmura and Boettcher, 2018), as:

$$P_a=5.87 * T_{JJA}^2+230 * T_{JJA}+966 \quad (3)$$

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The equation is solved for T_{JJA}, the mean summer air temperature of the 19 simulated years, using P_a, the RegCM accumulated annual precipitation averaged over the 19 years. Then the envELA is calculated for every grid-cell, as:

$$envELA = DEM - \left[\left(T_{JJA} - T_{RCM} \right) * \frac{100}{0.65} \right] \quad (4)$$

where the elevation-induced difference between the local temperature, $T_{JJA,}$ and the RegCM4 temperature, T_{RCM}, is computed by applying an environmental lapse rate of 0.65°C/100m. Finally, the resulting elevation difference is subtracted from the model topography (DEM) in order to obtain the environmental equilibrium line altitude, envELA. This method has already been validated for the Alpine region by Žebre (2020).

2.5 Circulation Weather Type

RegCM4 produces wind components, which are then used to calculate the total shear vorticity (Z) and the resultant flow (F). These values are then applied to the circulation weather type (CWT) method of Jenkinson and Collins (1977) with the aim of quantifying the occurrence of cyclonic events in the Tyrrhenian region. When the resultant flow is smaller than the total shear vorticity and the total shear vorticity is positive there are cyclonic conditions, when it is negative there are anticyclonic conditions.

3 Results

3.1 Domain of study

High-resolution RegCM4 simulations (~12 km, see methods) are performed over a domain that extends between 4 and 20 °E and from 38.5 to 50 °N, including the Alpine and Balkan Mountain ranges in their full extent, along with the north-central Apennines. However, our focus is on the greater Alpine region, where bias correction is applied to temperature and precipitation data produced by RegCM4 (Eqs. 1, 2) based on two observational datasets covering this area.

3.2 The large-scale framework: the MPI-ESM-P simulation

The MPI-ESM-P global model, run by the Max Planck Institute, is used to drive our RegCM4 simulations (see methods). This model (not shown in figure) correctly reproduces the large-scale conditions during the LGM in terms of jet-stream position and strength, temperature and precipitation anomalies (Ludwig et al., 2016). The LGM European climate simulated by the MPI-ESM-P is on average 9 °C colder and overall drier than at PI time over our broad region of interest, particularly over central and northern Europe (−30 %). The southern flank of the Alps, however, is somewhat wetter than, or with similar precipitation levels as, at PI time. The main upper troposphere circulations over the area of interest are westerly and north-westerly, both at the LGM and PI. The LGM-minus-PI anomaly in the MPI-ESM-P model highlights a southward shift of the Atlantic jet stream, which at the LGM generated strong winds in the Mediterranean region. In agreement with Ludwig et al.

(2016), the Scandinavian Ice Sheet at the LGM generated a semi-permanent high-pressure system responsible for blocking and deflecting the westerly air masses around the southern margin of the Ice Sheet.

3.3 RegCM4.7: Atmospheric circulation

The LGM high-resolution RegCM4 simulation shows the presence of a NE-SW pressure gradient, with a maximum in the north-eastern sector of the domain and a minimum over the Tyrrhenian and the Mediterranean Sea, particularly evident in the coldest months (Fig. 1). A similar pattern is shown by the annual temperature anomaly, with lower values northeast of the Alps and higher values over the Tyrrhenian region (Fig. 2). The largest temperature anomaly between the LGM and PI occurs in winter (−8.30 °C on average), especially northeast of the Alps and in the northern Adriatic. During winter, the monthly mean anomaly is smaller in the Alpine region than in the rest of the domain, while during summer the anomaly is larger over the Alps. All these findings indicate a strong influence of the Siberian high on the climate of the Alps and the Adriatic basin.

The 700 hPa winds (Fig. 1) indicate that in the LGM during winter the Tyrrhenian region is characterised by advection of cold air descending the Italian peninsula from the northwest, while during the warmer months the air masses coming from the northwest are deflected eastward over the Tyrrhenian Sea. This often generates a cyclonic circulation pver the Gulf of Genoa which occasionally leads to a north-easterly flow. Generally, south of the Alps the circulation is stronger at the LGM than at PI, while north of the Alps it is weaker.

Compared to the PI time, the simulated LGM conditions are colder, with a lower average temperature of ~6.6°C (Fig. 2) and annual precipitation reduced by ~16.4% (Fig. 3) over the Alps. Despite the overall drier conditions characterizing the LGM, we find some relatively wetter areas in the southeastern Alps, the Dinaric Range, the Ticino region, and the northern Apennines (Fig. 3). The RegCM4 simulations thus highlight the important role played by the Alpine orography, which determines two distinct climate regimes north and south of the Alps. At the LGM, Central Europe is 20 to 40 % drier than at PI, while the southern Alpine flanks present some wetter areas (up to 20%) during the LGM.

The use of RegCM4 allows us to distinguish between convective and stratiform precipitation. The former dominates during the warmer months, over the sea and at the lowest elevations, but shows a marked reduction in the LGM due to the lower temperatures. For example, in central Europe and over the Alps convective precipitation in the LGM is reduced by about 50% compared to the PI. Conversely, stratiform precipitation deriving from larger scale circulations presents positive anomalies in the LGM compared to PI almost everywhere and year-round. In the Alpine region during the PI, convection is always dominant, while at the LGM it dominates only during summer. The yearly maximum of stratiform precipitation over the Alps corresponds to the maximum of total precipitation, which occurs in September. Application of a circulation weather type approach (CWT; Jenkinson and Collison, 1977) over the Italian peninsula shows increased LGM cyclonic activity compared to the PI in all seasons.

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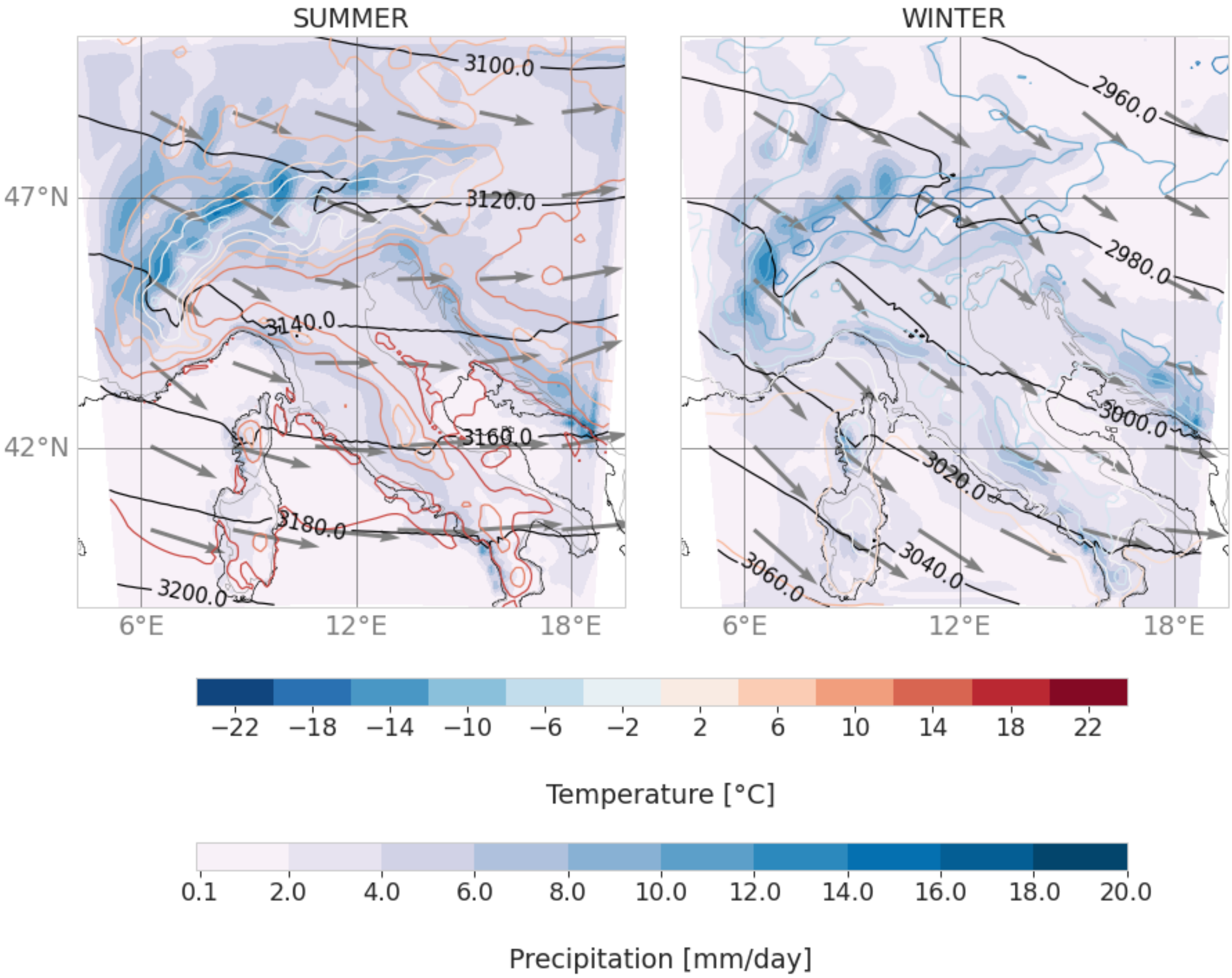

Figure 1: LGM mean summer and mean winter synoptic conditions. LGM 700 hPa average wind field (arrows), temperature (blue to red lines), precipitation (blue scale) and 700 hPa geopotential (black lines). Temperature and precipitation are not bias-corrected. These data represent the average summer and winter situation.

We then analyzed wind direction and associated precipitation for four Alpine piedmont glaciers: the Rhine and Inn-Salzach-Traun glaciers in the northern Alps, and the Dora Baltea and Tagliamento glaciers in the southern Alps (Fig. 4). We used daily data from 19 simulated years in order to calculate the frequency and intensity of precipitation associated with given wind directions. The two glaciers north of the Alps are mainly interested by precipitation brought by north-westerly and westerly air masses. At the LGM, north-westerly winds dominate, especially in summer, while at the PI, westerlies occur more frequently. At the LGM, more events are low intensity (darkest blue in Fig. 4), as northerly and north-westerly (dry) winds reach the northern rim of the Alps. In the southern Alps, the Dora Baltea and Tagliamento glaciers present quite different precipitation and wind patterns. The Dora Baltea glacier is affected mainly by winds from the northwest and

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southwest, however, the events from the west and northwest are often dry, while the most intense precipitation comes from the southwest and southeast.

The southern Alps at the LGM receive much more precipitation than the northern Alps. The Tagliamento glacier is shielded by the Alpine topography barrier from precipitation coming from the northern and eastern quadrants, while precipitation is supplied by south-westerly winds. This precipitation is more abundant at the LGM than at the PI (Fig. 4 and Fig. S1) and the frequency of intense precipitation is the highest across the domain. At the LGM, precipitation associated with south-westerly air masses is intense throughout the year, which is an important difference compared to the glaciers in the northern rim of the Alps showing only one rainy season (JJA).

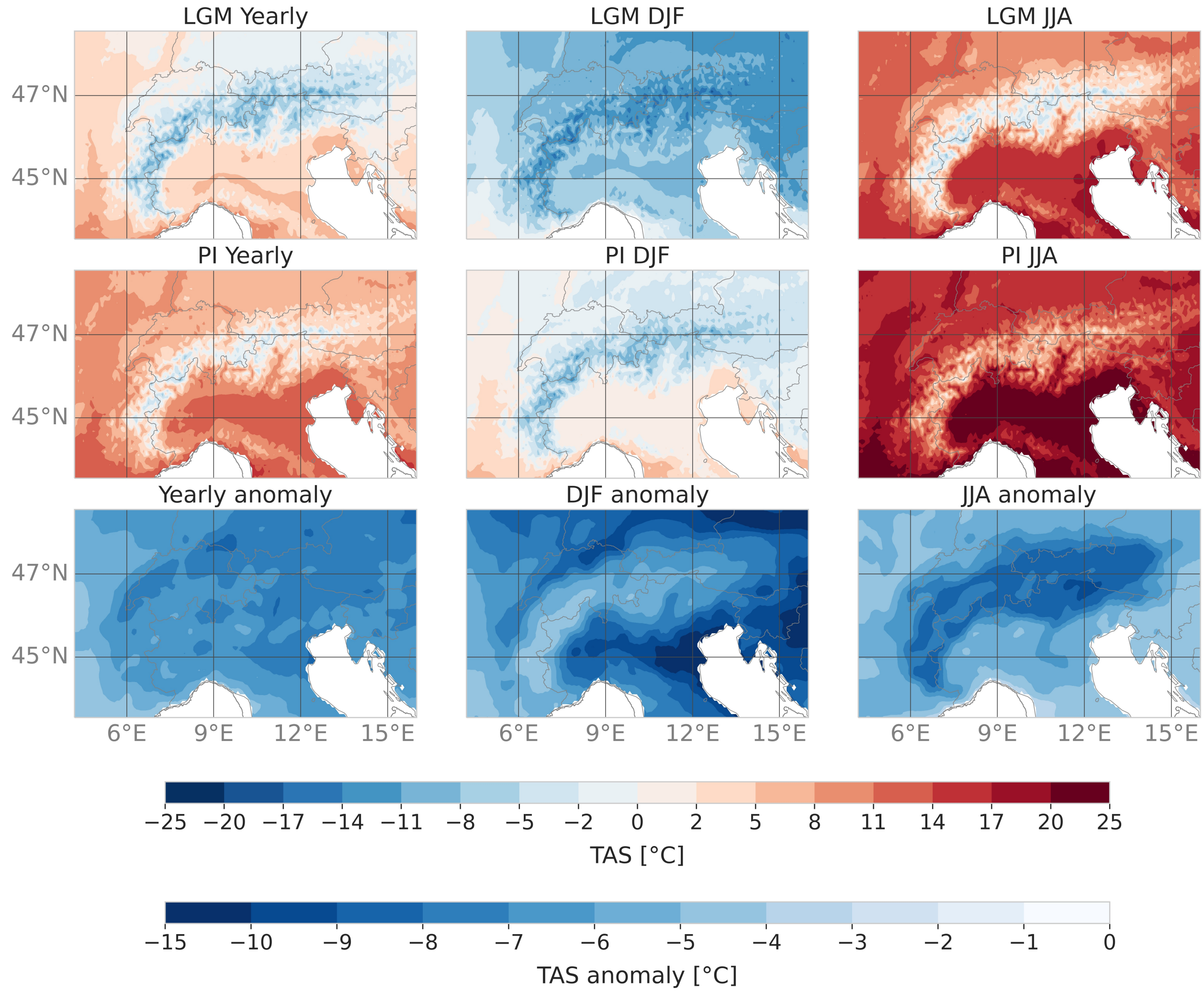

Figure 2: LGM and PI temperature and anomaly. Yearly, winter and summer averaged RegCM4 bias-corrected temperatures data.

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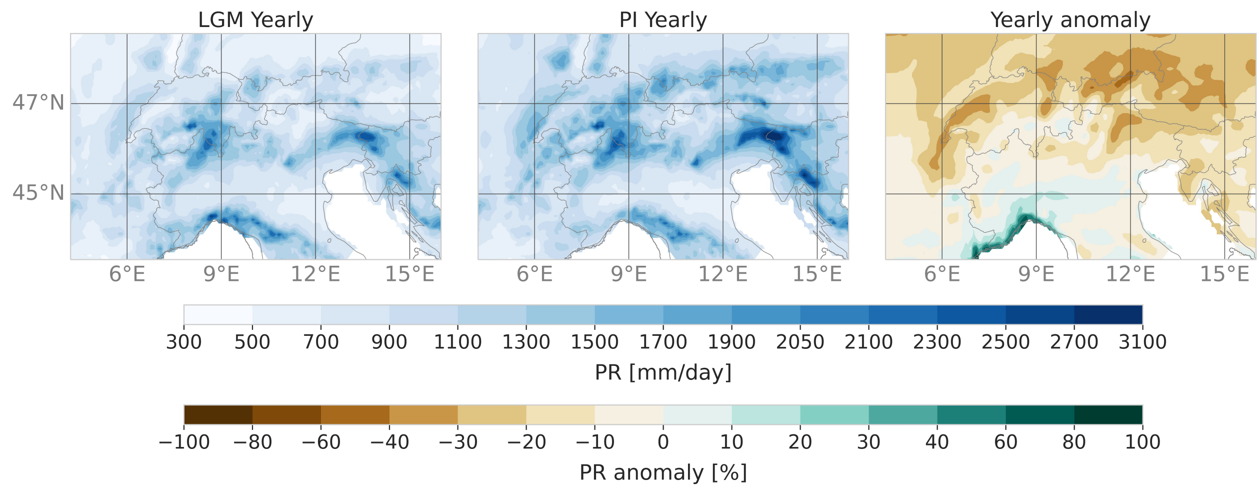

Figure 3: LGM and PI precipitation and anomaly. Yearly averaged RegCM4 bias-corrected precipitation data.

3.4 Equilibrium Line Altitude

The envELA calculations were performed following the method proposed by Žebre et al. (2021) (Eqs. 3, 4, see methods). At the LGM over the greater Alpine region the average envELA is 1444 m a.s.l. (Fig. 5), while at the PI is 2435 m a.s.l. (Fig. S2), i.e. there is a drop of 991 m in the LGM (Fig. S3). The south-western and north-eastern Alps show the highest envELA values, while the Ticino, south-eastern and the rest of northern Alps present the lowest values both at the LGM (Fig. 5) and PI (Fig. S2). The calculated LGM envELA is between 1000 and 1250 m a.s.l. over the Julian Alps, between 1250 and 1750 m a.s.l. in the Pennine and Graian Alps and between 1500 and 2250 m a.s.l. in the Maritime Alps. In the western Alps, the envELA decreases northward, in central Alps it is lower on the southern rim because of high precipitation in the Ticino region, while in the eastern Alps no significant north-south gradient in envELA is found.

By comparing the envELA with the model topography we can investigate whether the RegCM4 is able to reproduce the correct combination of temperature, precipitation and orography to support the existence of a glacier. At the PI only few grid-cells in the western Alps show an envELA lower than the model topography, while the LGM envELA is lower than the topography over a large section of the Alps, falling within the reconstructed glacier front (Ehlers et al., 2011). Due to the model resolution, the RegCM4 cannot capture the multitude of small glaciers present at the PI but can identify the general glaciated area (the western Alps), while at the LGM the larger glacier extension is better captured by the model.

The RegCM4 simulations also allow us to investigate the different elements affecting the hydrological and glaciological cycles. The lower LGM temperatures lead to longer winters with a consequent more abundant snow amount on the ground lasting until May over most of the Alpine domain. Minimum snow amounts in the Alpine region are reached between August and September, when the first abundant snowfalls end the melting season. Despite the lower temperatures, the LGM snow melting is important due to the large amounts of snow persisting throughout the summer and leading to a permanent snow limit at about 1300 m a.s.l. Above 1500 m a.s.l. melting is inhibited due to < 0 °C temperature. The LGM rate of melting is

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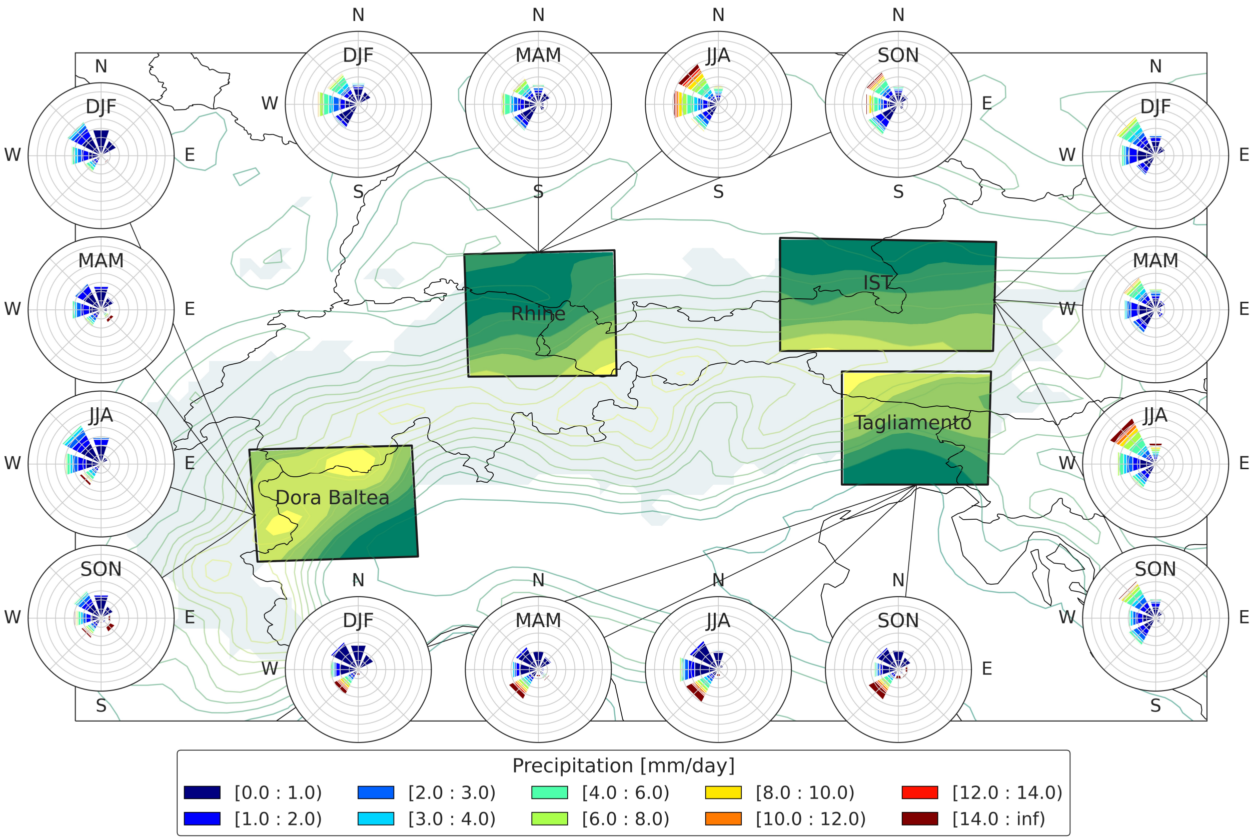
reflected by the runoff values, which are maximum in summer over the Alps and in spring and autumn over the piedmont areas.



230 **Figure 4: LGM wind origins and associated precipitation for four alpine glaciers. Seasonal windroses and precipitation intensity frequency associated to every wind event for Rhine, Inn-Salzach-Traun (IST), Tagliamento and Dora Baltea glaciers. Precipitation is daily cumulated. The shadow in the map is the glacier extension (Ehlers et al., 2011), the color lines as well as the full color in the boxes represent the topography (yellow for higher elevation and green for the lowers) and the black line is the present-day political boundary.**

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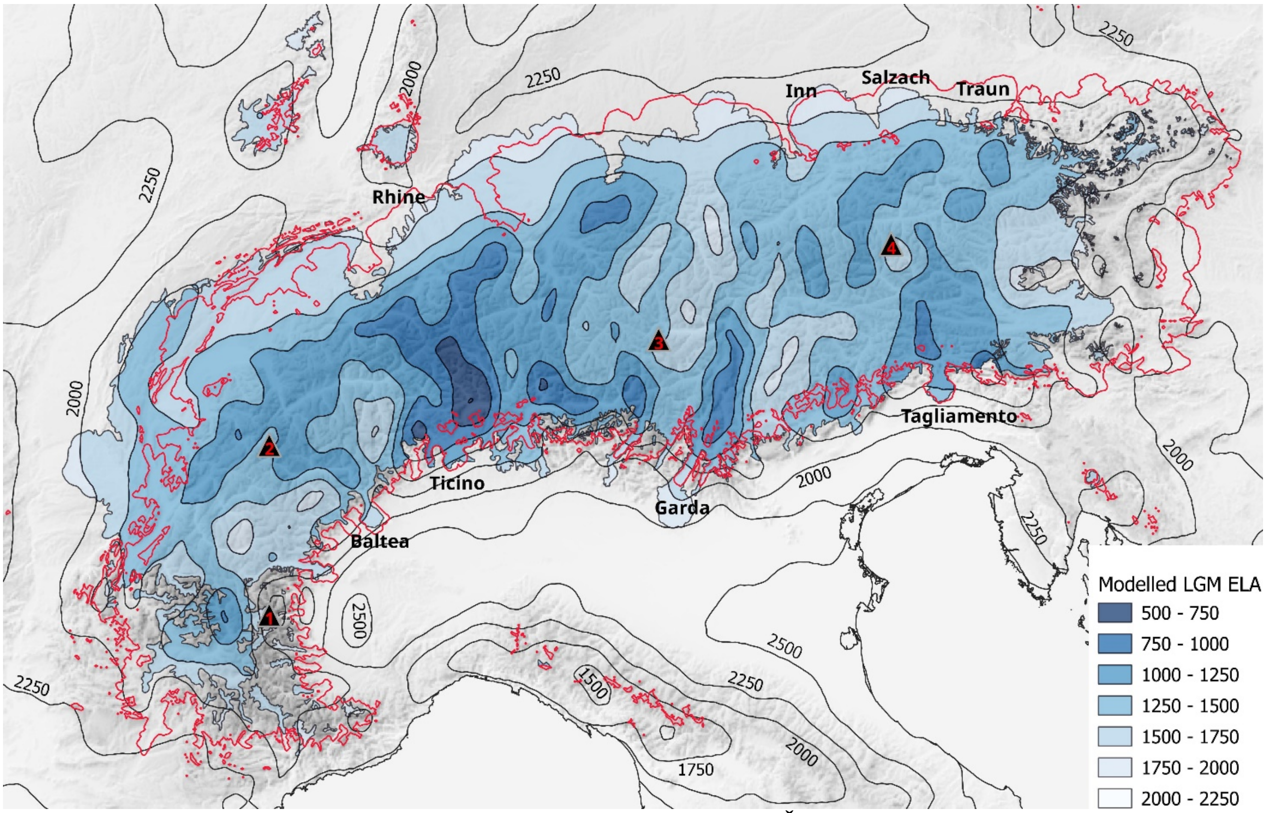

Figure 5: LGM envELA. Env ELA calculated following the method of Žebre et al. (2020), with the extension of the geomorphological reconstruction of the LGM glaciers (Ehlers et al., 2011). The red line is the LGM maximum glacier extent according to Seguinot et al. (2018). The black triangles indicate: 1) Monviso, 2) M. Blanc, 3) Ortler, and 4) Großglockner.

4 Discussion

First, we emphasize that our model resolution is among the highest found in paleoclimate studies (Ludwig et al., 2021), and therefore provides more detailed information about PI and LGM climates compared to the MPI-ESM-P simulation, particularly concerning the effect of complex topography. After a bias correction is applied to the model output using present day observations, the precipitation and temperature patterns for the LGM show good consistency with proxy records (Bartlein et al., 2010; Wu et al., 2007; Duprat-Oualid et al., 2017; Monegato et al., 2015; Sirocko et al., 2016; Tzedakis, 2005; Watts et al., 1996) and other RCM studies (Strandberg et al., 2011, Ludwig et al., 2021; Kageyama et al., 2020; Stadelmeier et al., 2021), indicating that the modeling system we used captured the basic regional climate response during the LGM. In fact, our envELA reconstruction (Fig. 5) compares well with other local estimations for the LGM. Our reconstruction also captures the higher envELA in the eastern and south-western Alps, which has not yet been fully resolved in previous studies. Indeed, in these two sectors, which hosted the Mur, Drava, Durance and Maritime Alps glaciers, a previous reconstruction (Seguinot et al., 2018) based on an ice-flow model forced with present-day climate data modulated by time-dependent temperature from Antarctica ice core records, overestimated the glaciation by tens of kilometers. In

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addition, some underestimation of the glacier extent was found in this previous study over other sectors, such as the Rhône Glacier complex, Jura Mountains, Lyon Lobe, Adda, Garda and Piave (Seguinot et al., 2018) where our envELA shows a drop consistent with the geological reconstructions (Ehlers et al., 2011). Overall, our paleoclimate simulations captured with high detail the zonal and meridional temperature and precipitation gradients.

Another application of an ice-flow model to LGM Alpine glaciers was carried out by Becker et al. (2016) who used a constant climate forcing, and produced simulated glacier extents not consistent with the geological reconstructions of LGM moraine systems in the northern, eastern, and western Alps. This model also captured the meridional shift of the precipitation patterns across the Alps. It is thus evident that the higher resolution information produced by our modeling system can lead to more accurate simulations of glacier cycles and extent. However, we stress that the results would still be limited by uncertainties in the driving large scale climate forcing and by the intrinsic complexity of the glacier dynamics. For example, the ELA distribution is determined by multiple factors that still cannot be entirely disentangled and represented with a model, e.g. avalanches, wind drifts, dust deposition, or debris fraction. As a matter of fact, our method calculates the envELA only from climate fields, which can provide an accurate information considering the whole Alpine chain, but cannot capture effects related to local topo-climatic conditions.

Our LGM simulation refers to 21 ka BP, but individual Alpine glaciers reached their maximum extent and started their retreat at different times in different sectors (Monegato et al., 2017; Seguinot et al., 2018). In particular, radiocarbon and cosmogenic isotope datings (Ivy-Ochs et al., 2022; Kamleitner et al., 2022) show a late retreat (~18 ka) for some glaciers in the southern Alps (Garda and Ticino), for which our calculations indicate a low envELA (Fig. 5), while the Dora Riparia, Dora Baltea, Piave and Tagliamento glaciers started withdrawing earlier. Our results suggest a particularly low envELA (750-1250 m a.s.l.) in the Rhine, Rhone and Ticino valley knot (Fig. 5) where the Rhine and Rhone ice domes are located (8). To the south, the reconstructed glaciers originated from a largely glaciated area (about 5500 km2) including the Verbano and Ossola branches, with contributions from the Rhône glacier in the northern Alps (Kamleitner et al., 2022; Preusser et al., 2011; Scapozza et al., 2014). These glaciers' accumulation basin is asymmetric and characterized by an elevated (>4000 m) Ossola valley and a large but lower elevated Ticino valley network. A low envELA (Fig. 5) is common between the Ossola and Verbano glaciers as well as the Rhône and Rhine glaciers, which formed, to the north, the largest piedmont lobes of the Alps. The northern Alpine glaciers were often characterized by large lobes with respect to the accumulation basins, while in the southern and eastern Alps the piedmont lobes are smaller, but with large basins (Dora Baltea, Ticino, Adda, Adige-Sarca, Drau).

By comparing our results with Seguinot et al. (2018) and Baker et al. (2016), it emerges that the distribution and dimension of Alpine glaciers is determined by a multitude of factors which also regulate the ELA distribution. Thus, it is not straightforward to associate accumulation basin dimension and elevation with the ELA distribution. This can help to understand the discrepancies between palaeoglaciological models and ground-based data. In the Julian and Carnic Alps our envELA calculations indicate values at the LGM of about 1000-1250 m a.s.l. (Fig. 5), which are consistent with reconstructions spanning the range of 1130 to 1300 m a.s.l. (Kuhlemann et al., 2008; Monegato, 2012; Rettig et al., 2021). In

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the Pennine and Graian Alps our estimates are in the range of 1250 to 1750 m a.s.l., with good consistency with the values of 1500 m a.s.l. found by Forno et al. (2010). Our data show a particularly high envELA (2000-2250 m a.s.l.) in the Monviso area, characterized by high elevation (3841 m a.s.l.) but small LGM glaciers. In the Maritime Alps our envELA is between 1500 and 2250 m a.s.l., matches with the range values of 1685 to 1845 m a.s.l. proposed by Federici et al. (2017).

The envELA estimates for the PI (Fig. S2) can be compared with different studies of the Little Ice Age (LIA). For example, Colucci (2016) placed the ELA in the Julian Alps at 2275 m a.s.l. for the Canin glacier and at 2486 m a.s.l. for the Triglav glacier, while our results yield lower values of 1750-2000 m a.s.l. The ELA in the Ecrins group and Maritime Alps has been estimated at 3000-3100 m a.s.l. and 2841-2818 m a.s.l. respectively (Federici et al., 2017; Cossart et al., 2012), in agreement with our results of 2750-3000 m a.s.l.. Our estimate for the envELA in the Livigno mountains is in the range of 2500-2750 m a.s.l., while Scotti et al. (2017) place it at 2015-2850 m a.s.l. It is important to stress that the envELA calculated here is based on temperature and precipitation only and is completely independent of the local physiography of the glacier's site, while the reconstructions take into account local geomorphological evidence and are site-dependent. This may at least partially explain the differences between our estimates and the reconstructed ones. Discrepancies with field reconstructions could also depend on dust, cloud cover and more in general on radiation-related fields, which are not taken into account in this work.

The decrease in envELA at the LGM compared to PI averaged over the Alpine region is 991 m, which is close to the values of 996 and 1000-1200 m suggested by Federici et al. (2017) and Ivy-Ochs et al. (2006), respectively. The western and eastern Alps (east of about 13°E) show smaller envELA decreases, mostly lower than 1000 m, while in the central Alps (western of 13°E) the decrease ranges between 1040 and 1126 m. This longitudinal gradient is in agreement with values provided by Federici et al (2017) and Ivy-Ochs (2006). In particular, paleo reconstructions show that in the southern Alps there was a substantial decrease of envELA over the Tagliamento glaciers and in the Ticino region. Differently from Višnjević et al. (2020), in the central Alps we find a north-south ELA gradient, with the ELA increasing from south to north, while in the eastern Alps there is almost no gradient, and in the western Alps the ELA decreases from west to east. This result may be explained by the seasonality of precipitations in the different sectors (Fig. 4) driven by the annual shifting of the Polar front.

At the LGM the Alps essentially separated the dry and cold central Europe from the milder and relatively wetter southern alpine region (Figs. 2, 3). The RegCM4 simulations suggest that the reduced precipitation in the northern Alps during the LGM was caused by lower temperatures inhibiting convection and by the southward displacement of the North Atlantic storm track, the main source of moisture for Europe. In this area we also find reduced westerly winds as well as increased north-northeasterly winds, which are eventually caused by the anticyclonic circulation triggered by the Scandinavian Ice Sheet and are also responsible for enhanced dust storm activity and loess deposition (Schaffernicht et al., 2020).

The southern portion of European region is characterized by increased wind activity particularly over the Mediterranean areas, with meridional flows during winter and zonal flows during summer (Fig. 1). These average patterns possibly reflect the influence of seasonal variations of the polar front position. Winters show dominant northwesterly winds driven by enhanced meridional geostrophic circulation due to the marked temperature and sea level pressure gradients between the

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northern and southern parts of the domain at the LGM. Conversely, the warmer months are characterized by a more frequent cyclonic circulation over the Gulf of Genoa, which leads to northeasterly winds.

When cold polar air crossing the western Alps reaches the warmer Tyrrhenian Sea, the thermal contrast destabilizes the lower troposphere, leading to the development of lee-side cyclonic circulations and convective phenomena (Kuhlemann et al., 2008) along a storm track extending in the eastern-northeastern direction. Our LGM RegCM4 simulations, indeed, show high precipitation rates from May to September on the up-wind side of the circulations with respect to the Mediterranean jet in the Apennines, Balkans, and southern Alps. These regions, despite their low latitude, low elevation, and southern exposure, during the LGM hosted several glaciers. In particular, the Tagliamento glacier (Fig. 5) received heavy precipitation from the southwest, at higher rates during the warmer months. In addition, also during the colder months, lee-side cyclones in the Tyrrhenian Sea led to heavy precipitation in the southern alpine slopes (Fig. 6). In the southern Alps at the LGM stratiform precipitation originated from a cyclonic circulation prevailing during the coldest months and at the highest elevations, while in summer, convection was more frequent, often in the form of snowfall. This type of precipitation plays a critical role in preserving the glacier from summer melting and lowering the ELA.

The mechanism suggested by our simulations is that at the LGM a well-defined southerly displacement of the westerlies led to a colder and drier central Europe and a relatively wetter southern European region. The envELA over the Alps was substantially lowered, with values increasing from south to north over the central Alps. Such a pattern is sustained by increased summer snowfall often reaching low elevations and feeding the alpine glaciers. In the southern Alpine region, summer precipitation was mainly of convective origin, while during the rest of the year stratiform precipitation prevailed, often originating from a cyclonic circulation that developed over the Tyrrhenian Sea. In the northern Alps, precipitation was modest and occurred mainly in summer when the polar front moved northward and some limited convection occurred.

Wind direction and associated precipitation (Fig. 4) suggest that a change of the moisture reservoirs position between summer and winter at the LGM (Fig. 6) likely drove the precipitation patterns in the northern and southern alpine regions and consequently controlled the glacier dynamics (Fig. 5). In the southern Alps the humidity was provided mainly by the Mediterranean Sea which, being relatively warm and ice-free also in winter acted as a moisture reservoir all year round. The path followed by moist air masses leading to precipitation in the northern Alps were largely dependent on the sea-ice extension in the North Atlantic Ocean. During summer, the North Atlantic was almost ice-free (black dashed lines in Fig. 4; Rhines and Huybers, 2014), representing the source of moisture for central Europe. Conversely, during winter the North Atlantic sea ice extended towards Europe with a large lobe (Fig. 6; Rhines and Huybers, 2014), reducing the area of moisture reservoir and causing the moist air masses to reach Europe from a southern position. In this framework, the southern Alpine glaciers were fed throughout the year by Mediterranean moisture forced northward by the low-pressure system centered over the Gulf of Genoa (Fig. 6).

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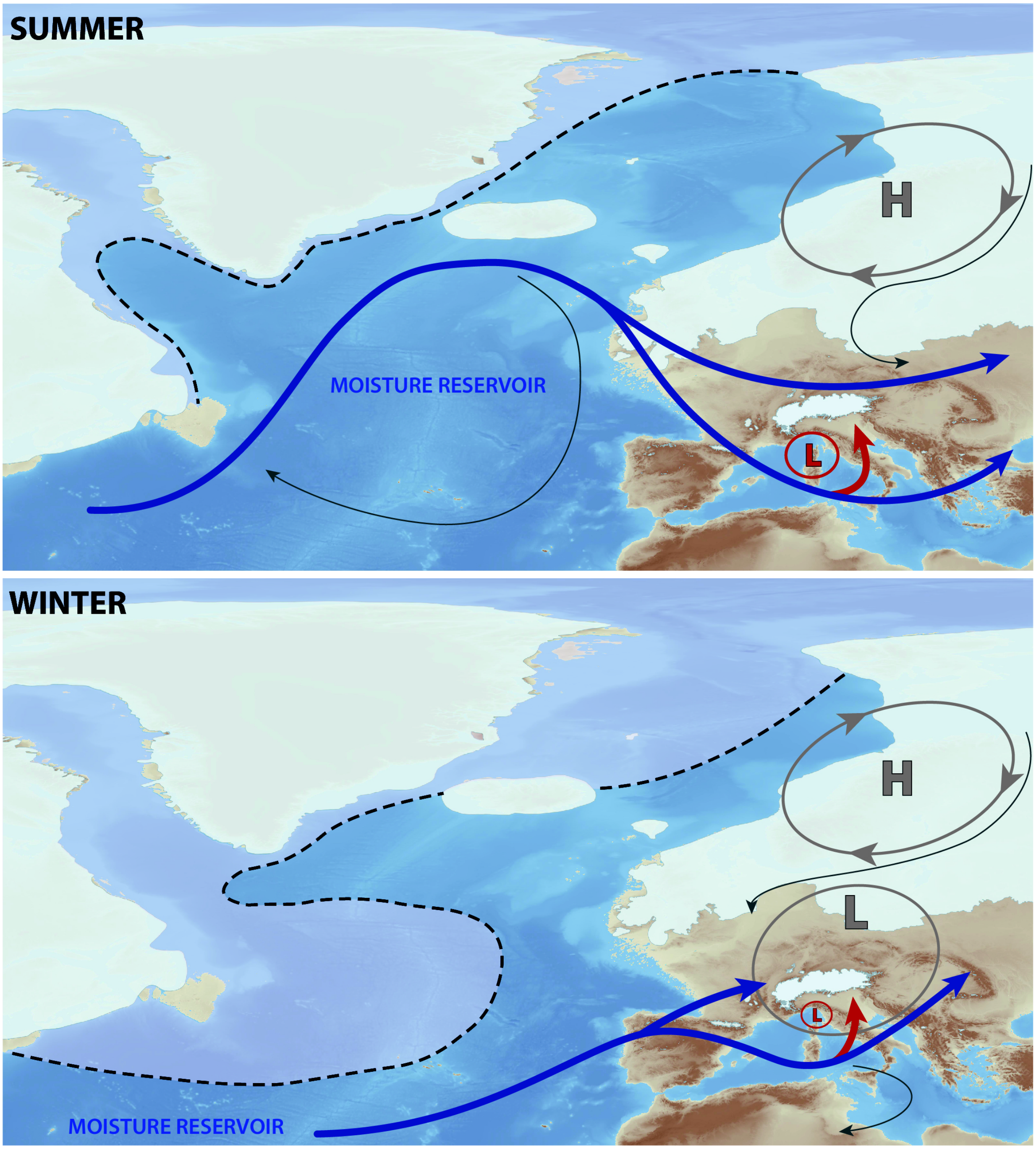

Figure 6: Conceptual model of the air masses yielding precipitation in the Alps at the LGM. In white glaciers and ice sheets; the black line marks the 50% sea ice concentration extension (Rhines and Huybers, 2014); H and L stand for high-pressure and low-pressure system; blue and red arrows represent the air masses leading precipitation on the Alps; gray lines represent other air masses not leading precipitation on the Alps. Blue and gray arrows are extrapolated from the mean winter and summer MPI-ESM 850 hPa winds; while the red symbols show the elements that emerged from the RegCM4 simulations.

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In summary, the Genoa low and the relatively warm Mediterranean temperatures were responsible for frequent and intense precipitation events over the southern Alps, while the northern Alpine glaciers were subject to weaker and more sparse precipitation with a predominance of perturbations from the north-west in summer and the west in winter (as driven by the sea ice extent). These circulation patterns can explain the large piedmont glaciers extending in the southern Alpine foreland and the reconstructed envELA gradient across the Alps (Fig. 4).

Finally, our model can explain some discrepancies between previous LGM Alpine glacier reconstructions and proxy data (e.g., Seguinot et al., 2018; Baker et al., 2016; Jouvet et al., 2017), and provides new detailed information of the LGM and LIA envELA for the whole Alpine region which can explain the different behavior of the Alpine glaciers in light of the morphology of their accumulation basins. An important step forward of our work is that, instead of forcing our model with present-day climate variables scaled for the LGM conditions, we simulated the LGM atmospheric circulation and climate using a high-resolution RCM nested into a paleoclimate Earth System Model and used the simulated climate variables to calculate the envELA. This has provided fine scale physically based paleoclimatic fields which allowed us to capture many regional and local aspects of Alpine glacier reconstructions. Our results thus further demonstrate the great potential for the use of simulated high resolution paleoclimate data in the study of the past cryosphere.

5 Conclusions

With this work, we disentangle the contributions of the atmospheric circulation components and thermodynamic conditions leading to the Alpine glacier advance during the LGM, using a modeling approach. We highlight that the resolution of our model simulations is among the highest found in paleoclimate studies and this allows us to obtain much higher spatial detail compared to previous work dealing with this issue.

We simulated pre-industrial and LGM climate and atmospheric circulation over the Alps using a multiple nesting approach, based on a chain of three climate model simulations with increasing resolution (MPI-ESM-P Earth system model, 50km resolution regional model RegCM4, and 12km resolution RegCM4). The high-resolution RegCM4 output data were then used to calculate the environmental Equilibrium Line Altitude (ELA) over the Alpine region, providing new detailed and physically-based information on the Alpine glacier extent at the LGM and at pre-industrial coditions . Our reconstruction matches with geomorphological evidence and resolves for the first time some shortcomings that occurred in previous LGM glacier reconstructions based on ice-flow dynamics. Our method is based only on simulated temperature and precipitation and is independent of local characteristics of the glacier site (dust, avalanches),

In agreemtn with available literature, our results show much drier and colder LGM conditions (−6.6 °C on average) than today over the Alpine region. Differences in precipitation regimes across the Alps were caused by the southward displacement of the North Atlantic storm track, temperature differences controlling convective phenomena, and frequent and persistent occurrence of cyclones and anticyclones. In particular, in the northern Alps, precipitation was sparse and weak, as the Atlantic storm track was located south of the Alps and was subject only to a small seasonal variability caused by the

Atlantic sea-ice extension. Conversely, the southern Alpine region received frequent and abundant precipitation due to the interplay of the Genoa low with the relatively warm Mediterranean Sea and convective phenomena. These, in particular, led to summer snowfall at low elevations, preserving the glaciers and lowering the ELA. These results emphasize the great potential of modeled high-resolution paleoclimate data in the study of the past cryosphere.

Data availability

All the data needed to evaluate the conclusions in the paper are available with the DOI: 10.5281/zenodo.6340847.

Author contributions:

Conceptualization: RRC, FG
Methodology: CDG, RRC, FG
Investigation: CDG
Visualization: CDG
Supervision: RRC, FG
Writing—original draft: CDG, RRC, FG
Writing—review & editing: CDG, RRC, GM, MŽ, FG

Competing interests

The authors declare that they have no competing interests.

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