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Atlantic influence on spring snowfall over the Alps in the past 150 years

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Abstract
Global warming is believed to be responsible for the reduction of snow amount and duration over the Alps. In fact, a rapid shortening of the snowy season has been measured and perceived by ecosystems and society in the past 30 years, despite the large year-to-year variability. This trend is projected to continue during the 21st century in the climate change scenarios with increasing greenhouse gas concentrations. Superimposed on the long-term trend, however, there is a low-frequency variability of snowfall associated with multi-decadal changes in the large-scale circulation. The amplitude of this natural low-frequency variation might be relatively large, determining rapid and substantial changes of snowfall, as recently observed. This is already known for winter snowfall over the Alps in connection with the recent tendency toward the positive phase of the North Atlantic Oscillation. In this study, we show that the low-frequency variability of Alpine spring snowfall in the past 150 years is affected by the Atlantic Multi-decadal Oscillation (AMO), which is a natural periodic fluctuation of Northern Atlantic sea surface temperature. Therefore, the recently observed spring snowfall reduction might be, at least in part, explained by the shift toward a positive AMO phase that happened in the 1990s.

Keywords: low-frequency climate variability, Alpine region, snowfall, Atlantic Multi-decadal Oscillation

1. Introduction

The Alps are often called the 'water towers' of Europe. In fact, they are the most important freshwater supply of continental Europe: the Rhine, Po, Rhone and several tributaries of the Danube originate here. Due to their high elevation, the hydrological cycle of the Alps is largely affected by snow, with important repercussions for the environment and society (Beniston 2012, Barnett *et al* 2005). In fact, snow acts as an insulator of the underlying soil (Clark *et al* 1999), determining the vegetation distribution and phenology (Keller *et al* 2005) and reducing the surface temperature by reflecting solar radiation (Groisman *et al* 1994). In the Alps, snow is present from late autumn to spring at a wide range of altitudes, allowing ski-related tourism (Toeglhofer *et al* 2011) and determining the seasonality of hydropower production through the runoff originating from the spring snowmelt (Hänggi and Weingartner 2012).

In the past, potential factors determining snowfall and snow cover variations have been extensively studied. Temperature variations can alter the partition of solid to liquid precipitation (Scherrer *et al* 2004, Serquet *et al* 2011, Eccel *et al* 2012) and the spring snowmelt timing, determining the length of the snowy season (Laternser and Schneebeli 2003). Therefore, long-term global warming is likely responsible for the observed reduction of snowfall (Serquet *et al* 2011) and for the possible continuation of this trend in the future (Beniston

2012). The potential economic damage to the tourism-related industry could be quite significant (Elsasser and Messerli 2001). Moreover, climate change can alter the seasonality of hydropower generation (Finger *et al* 2012) and hazard related risks (Marty and Blanchet 2012).

Decadal variations in teleconnections considerably complicate the interpretation of the climate change signal (Trenberth *et al* 2007). Therefore, the snowfall trend computed over a few decades can be larger than the effects that might be attributed solely to climate change. This was evidenced in connection with the retreat of glaciers in the tropics (Francou *et al* 2003, Kaser *et al* 2004). In the Alps, the recent rapid warming and the associated circulation change have largely contributed to the general reduction of snowfall amount and snow cover duration observed in the past few decades (Hantel and Hirtl-Wielke 2007, Serquet *et al* 2011). The change of circulation affecting winter snowfall over the Alps is well known. In fact, the recent tendency toward a predominantly positive phase of the North Atlantic Oscillation (NAO; Hurrell 1995) corresponded to high-pressure, warm and dry weather conditions unfavorable to snow over the Alps, which has decreased particularly since the 1980s at elevations below 1500–2000 m (see e.g. Bartolini *et al* 2001, Beniston 1997, Laternser and Schneebeli 2003, Scherrer and Appenzeller 2006, Marty 2008, Durand *et al* 2009, Valt and Cianfarra 2010). On the other hand, the recent reduction of spring snowfall can be explained by the recent warming of the Alps (Scherrer *et al* 2013).

In this letter we focus on spring snowfall, which determines the length of the snowy season. We show that spring snowfall low-frequency (multi-decadal) variability over the Alps is modulated by the Atlantic Multi-decadal Oscillation (AMO; Schlesinger and Ramankutty 1994). In fact, the AMO has been recently identified as one of the main natural drivers of the low-frequency variability of the European climate in spring, summer and autumn (Sutton and Dong 2012) and of the mass balance of Alpine glaciers (Huss *et al* 2010). Similarly, we report the occurrence of synchronous shifts of the AMO phase and spring snowfall amount from a reconstruction dataset and from station observations. In section 2 we describe the data and methods used in the analysis. In section 3 we show the results, while section 4 is devoted to a discussion and our conclusions.

2. Data and methods

We use a snowfall reconstruction dataset (Chimani *et al* 2011) derived from HISTALP, which is one of the best climatic datasets available for the Alpine area (Auer *et al* 2007, Brunetti *et al* 2009). HISTALP is defined for the so-called 'Greater Alpine Region' (2E–20E, 46N–49N) on a regular grid of 5′ spatial resolution (about 10 km). It is based on observed monthly mean temperature and precipitation time-series that were accurately corrected for temporal inhomogeneities due to relocations of the meteorological stations, changes in the surroundings, instrumentation, shelters, etc. Data are available from 1760 to 2008 for temperature and from 1801 to 2003 for precipitation. The

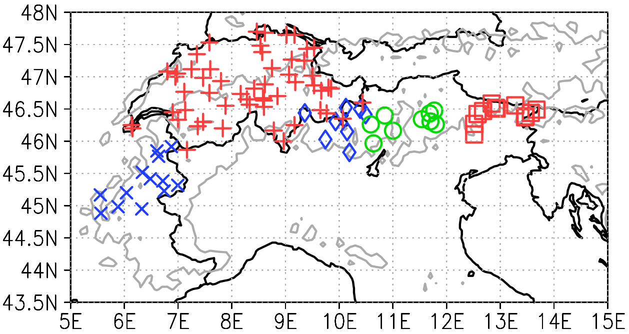

Figure 1. Study region with the station distribution located over the Italian regions of Friuli (red squares), Trentino (green circles) and Lombardia (blue diamonds), and over Switzerland (red crosses) and France (blue crosses). The size of the markers represents approximately the radius of influence of the gridding procedure (see section 2). The gray contour line represents the 1000 m elevation of the orography.

snowfall dataset, based on a statistical relationship between the HISTALP precipitation and temperature and station snowfall observations taken in Austria (Chimani *et al* 2011), is defined from 1801 to 2003. Therefore, it is long enough to allow the low-frequency variability analysis on the multi-decadal time-scales of the signal that we perform in our study.

In order to make more robust our analysis, we compare the HISTALP snowfall data with direct observations collected in different regions of the Alps. These consist of daily measurements of fresh snow computed as the thickness of solid precipitation falling on a tablet that is placed on the snow pack and cleaned after every record. Station data are collected for three Italian administrative regions: Friuli, Trentino and Lombardia, from regional authorities located in the southeastern flank of the Alps (Arpa Friuli, Meteo Trentino and Arpa Lombardia), and for the Swiss and French Alps from MeteoSwiss and MeteoFrance, respectively. Figure 1 shows the station distribution. In some cases, the snow density is measured by collecting and weighing a sample of snow of fixed volume. However, the density observations are sparse and discontinuous in time. Therefore, in order to translate the observations given in depth of fresh snow into the water equivalent, we use a constant average conversion value of 0.067 (±0.009) that we computed over Trentino, where we had the most frequent density observations. This procedure is consistent with the fixed snow ratio approximation of 1 cm of fresh snow depth per 1 mm of snowfall water equivalent that is applied in the common practice (e.g. Baxter *et al* 2005). This assumption probably affects the short-term variability of the data and introduces biases far from the region where the conversion value is derived. However, it is reasonably justified in the analysis of the low-frequency variability, as the comparison with HISTALP and station data will show.

We analyze these datasets separately for each region, as they may reflect different measuring and processing practices, durations of the covered period, and different climates. Most of the time-series end in 2012. The longest Italian records start in 1973 in Friuli, in 1981 in Lombardia and in 1982 in Trentino. In these cases we select the stations covering 30 years or more, with less than 25% missing data and missing seasons, in order to cover the last AMO transition and to validate the interannual variability of the HISTALP data. This leaves us 12 stations for Friuli, 10 for Trentino and 8 for Lombardia.

In our analysis, we will focus specifically on the spring season. Therefore, time-series of spring snowfall are computed and used to detect and characterize the climate variability signal. For the snowfall station data obtained from the southern flank of the Alps (Friuli, Lombardia and Trentino) the seasonal average are defined as the mean of the March and April values, because in most cases no observations are taken in May. For Switzerland and France, much longer station datasets, defined for the entire spring (March, April and May, MAM), are available and, for these cases, we consider only stations with more than 50 years of data. With this choice, we have 55 station records (the longest from 1877 to 2012) for Switzerland and 13 station records (the longest from 1954 to 2012) for France, which are used to validate the snowfall multi-decadal variability detected in the HISTALP dataset.

Furthermore, in order to fill the gaps in the observed seasonal time-series due to the missing values in the station data, we use a method based on the correlations with the closest stations established by Eischeid *et al* (1995) and extensively used in data homogenization and reconstruction (Eccel *et al* 2012). Finally, in order to allow a consistent comparison between the station data and the HISTALP data set, the former are gridded over the same HISTALP mesh, using the gridding technique discussed in Cressman (1959), then spatial averages are computed for the considered regions. It is worth noting that a sensitivity test has shown that the results are only marginally affected by small changes of the length of the radius used for the re-gridding.

In order to discuss the relationship between the AMO phases and the climate of the Alps, we use the Enfield *et al* (2001) spring AMO index. It consists of linearly detrended time-series of monthly mean North Atlantic sea surface temperature (SST) averaged from 0 to 70N. This index is computed using the Kaplan *et al* (1998) SST analysis from 1856 to the present.

We quantify the relative importance of the climatic shifts due to the AMO phase changes in terms of the potential impact on ecosystems and of the perception by society, computing the statistical significance of the differences with respect the actual interannual variability, without any time-smoothing or trend removal.

The statistical significance of the results is assessed with a non-parametric statistical test at 95% threshold, using a bootstrap method for correlations and the Mann–Whitney method for anomalies.

Furthermore, we also check the consistency of the results for precipitation and temperature with the 20th Century Reanalysis provided by the NOAA/OAR/ESRL PSD (Compo *et al* 2011; www.esrl.noaa.gov/psd/), which is defined from 1871 to 2010, but with a much lower resolution (about 2°) than HISTALP. Unfortunately, the snowfall product is not included. However, this dataset allows an investigation of the dynamical and physical mechanisms through which the AMO modulated the climate of central Western Europe and the Alps.

3. Results

As a first step, we analyze the variability of spring snowfall during the past 30 years. This period covers the last AMO transition that occurred in the mid-1990s (Enfield *et al* 2001, Sutton and Dong 2012). Figure 2 shows the comparison of the March and April (MA) mean snowfall time-series averaged over the three regions in the southeastern Alps (top panel) and of the spring (MAM) averages computed over Switzerland and France (central panel) from the HISTALP reconstruction and from the direct observations. In general, we note a good consistency between the two sources. The HISTALP reconstruction appears to overestimate the snowfall with respect to the direct observations, especially in France and Switzerland. This might be due to the constant value that we use to convert fresh snow depths into the snowfall water equivalent that we assumed for the entire Alpine region, as anticipated in the previous section. However, HISTALP captures some of the essential features of the observed snowfall interannual variability. Correlation coefficients computed between the observations and the reconstructed annual values over all the overlapping periods are 0.60 for Friuli, 0.78 for Trentino, 0.84 for Lombardia, 0.53 for Switzerland and 0.50 for France. All of them are statistically significant, at least at the 95% threshold level. The relatively low correlation coefficients found for Switzerland and France might be due to the statistical relationship used to derive HISTALP snowfall from precipitation and temperature. This relationship is in fact based on rather scattered data (Chimani *et al* 2011), thus its robustness might be problematic in certain areas and for relatively high-frequency (interannual) fluctuations. However, in this work our main focus is on the low-frequency (decadal and longer) variations, for which the statistical validity of Chimani's relation appears to hold. In this respect, we obtain better agreements between the observed and HISTALP datasets. In particular, most of the time-series suggest the presence of a statistically significant shift toward a moderate snowy regime that corresponds to the AMO phase change. In Trentino and Lombardia, the shifts are statistically significant at the 95% threshold level only in the observations, but not in HISTALP.

In figure 2 (bottom panel) we plot the spring snowfall over Switzerland and France in a longer time frame. In this case, we smooth the annual time-series with an 11 years running average filter in order to emphasize the low-frequency fluctuations. The results show a relatively large overestimation of the HISTALP reconstruction compared to the observed spring snowfall. The correlations computed on the smoothed time-series are larger than for the individual years, reaching 0.68 for Switzerland and 0.87 for France, and they are statistically significant.

In the same picture (figure 2, bottom panel) the spring AMO index is also plotted (black thick line) with a reversed sign (i.e., it has been multiplied by -1) to facilitate the

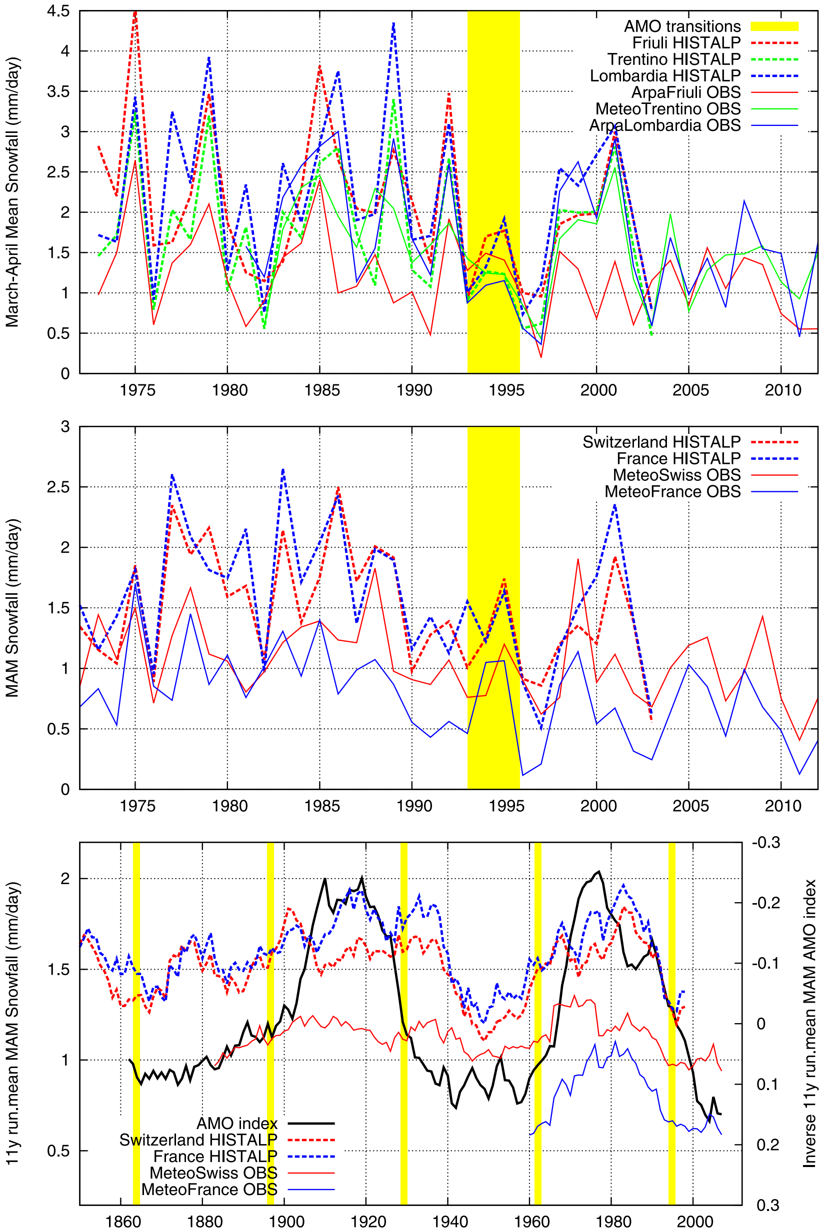

Figure 2. Top panel: time-series of snowfall HISTALP reconstruction (dashed lines) and the direct observations (solid lines) of March and April mean snowfall averaged over Friuli (in red), Trentino (in green) and Lombardia (in blue), in mm of equivalent water per day. Central panel: the same for Switzerland (in red) and France (in blue). Bottom panel: 11 years running mean time-series computed over Switzerland (in red) and the French Alps (in blue). The black line represents the 11 years running mean spring AMO index, of which we plot the inverse to allow an easier comparison with the spring snowfall data. The yellow regions highlight the Atlantic Multi-decadal Oscillation (AMO) transitions from cold to warm periods in the past 150 years, as defined in the text.

comparison with the snowfall data. From this time-series we can identify five periods (separated by the yellow stripes in the picture): three of warm/positive AMO (AMO+) and two with cold/negative AMO (AMO−). The three more recent periods are the same as in Sutton and Dong (2012): 1996–2012 (AMO+), 1964–1993 (AMO−) and 1931–1960 (AMO+). The remaining periods are defined analogously as 1899–1928 (AMO−) and 1866–1895 (AMO+), keeping in mind the constraint of having periods that reflect an oscillation of about 65–70 years (Schlesinger and Ramankutty 1994). This definition of the periods is arbitrary to a certain extent. However, sensitivity tests varying the initial and final date in a 5-year range do not produce any significant change of the results.

The curves shown in the picture suggest a relationship between spring snowfall time-series and the AMO phase, with a tendency for relatively intense/moderate snowfall to occur preferably in cold/warm AMO periods. The correlation coefficients between the AMO index and HISTALP snowfall are −0.49 for Switzerland and −0.63 for France (but, importantly, the same correlations obtained from the station data are −0.59 and −0.83 respectively).

The snowfall shifts are statistically significant for every AMO phase transition, suggesting that some relevant amount

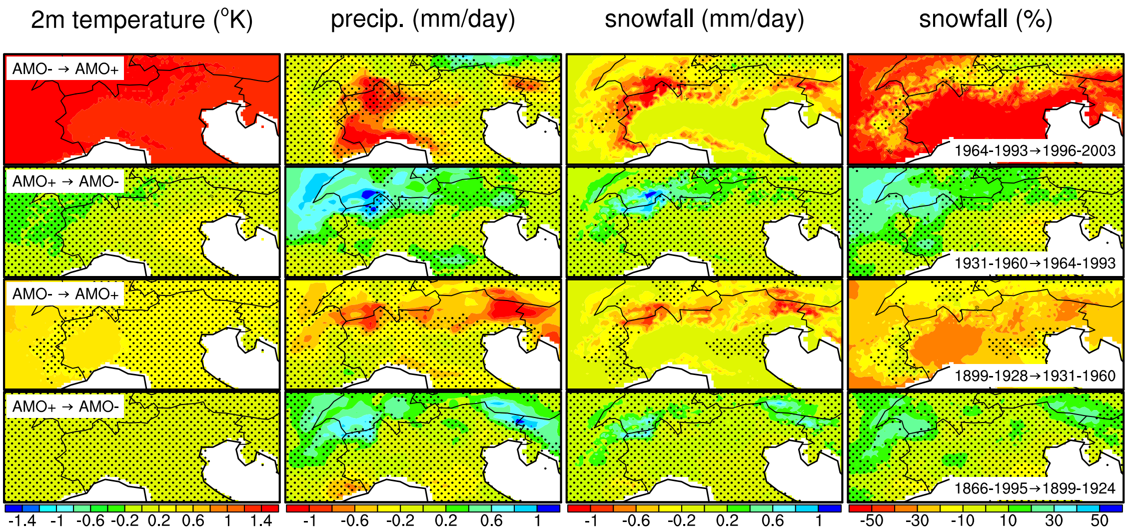

Figure 3. From left to right: differences of HISTALP spring temperature, total precipitation observations and spring snowfall reconstruction (in absolute values and in percentage) due to the four AMO transitions that occurred in the past 150 years. The periods over which we computed the differences are listed in each row of the plot. Shading is applied over areas where the statistical significance of the differences is below the 95% threshold level according to the Mann–Whitney test.

of the low-frequency variance of snowfall might be related to the AMO fluctuation. However, we should bear in mind that this is only a portion of the snowfall variability and that other climatic factors, different from the AMO, have an important role in modulating the Alpine snowfall, as it appears evident when considering, for example, the intense snowfall period (about 10 years) that has followed the 1930 transition from a negative to a positive AMO phase.

A more complete picture of the connections between AMO and Alpine snowfall low-frequency fluctuations is obtained from the spatial characteristics of the climate anomalies connected to the AMO shifts. Figure 3 shows the long-term anomalies of temperature (first column), total precipitation (second column) and solid precipitation (third and fourth columns) related to the AMO phase transitions (displayed in the different rows). In each row we list the periods over which we computed the differences. As for temperature (first column), statistically significant changes are found in the shifts toward warm AMO in the 1990s and around 1930 (first and third rows of figure 3, respectively). These transitions correspond to warming of the Alps, more marked on the western side. The largest warming, of about 1.5 °C, is recorded during the last AMO transition. Warm to cold AMO transitions that occurred in the early 1960s and around 1900 are displayed in the second and fourth rows, respectively.

The same analysis conducted for precipitation is shown in the second column of figure 3. With respect to temperature, precipitation is not characterized by a significant long-term trend. Despite the larger spatial variability, the precipitation variations show a relatively similar pattern in every transition. In fact, every AMO−to AMO+ change (both forward and backward in time) is characterized by a reduction of total precipitation up to 1 mm d^{-1} in the western Alps, i.e, over the French and Swiss territory and northwestern Italy. A similar signal is found for the southeastern Alps, in Friuli, Trentino and Lombarda, but with smaller amplitude and not always statistically significant. In particular, the difference in precipitation is less significant in the last AMO transition (top panel), most likely because of the shorter period available to compute the averages.

Snowfall (third and last columns) offers the most consistent picture. In fact, snowfall changes are quite similar for every AMO phase shift. In the cold to warm transition, especially in the last episode, snowfall inherits the statistical significance of the temperature change. In fact, the temperature rise occurring during the cold to warm transitions produces statistically significant snowfall reduction at low altitudes. On the other hand, the snowfall increase, passing from warm to cold AMO periods, is more confined at higher elevations. Again, the most significant and robust changes of spring snowfall due to AMO shifts are in the western Alps, where the associated pattern is characterized by a reduction (increase) of about 1 mm d^{-1} passing from cold to warm (warm to cold) periods, corresponding to 20–30% of the mean spring snowfall. The signal is weaker and less significant going back in time, but always consistent in terms of the spatial pattern.

Sutton and Dong (2012) show that spring precipitation anomalies connected to the AMO in the last two transitions were due to a change of circulation, consisting of a ridge of high mean sea level pressure (MSLP) over central Europe, sandwiched between two troughs (low MSLP) over the northeast Atlantic Ocean and northeastern Europe. Here, we explore this dynamical link and its physical consequences over Western Europe for all the AMO transitions in the past 150 years using the 20th Century Reanalysis. Figure 4 shows the anomalies of temperature, precipitation, MSLP and cloudiness associated with each shift. Results for temperature and precipitation are consistent with HISTALP, particularly in the western Alps, and they confirm the presence of a teleconnection pattern between the North Atlantic basin and the European continent, which, affecting the atmospheric

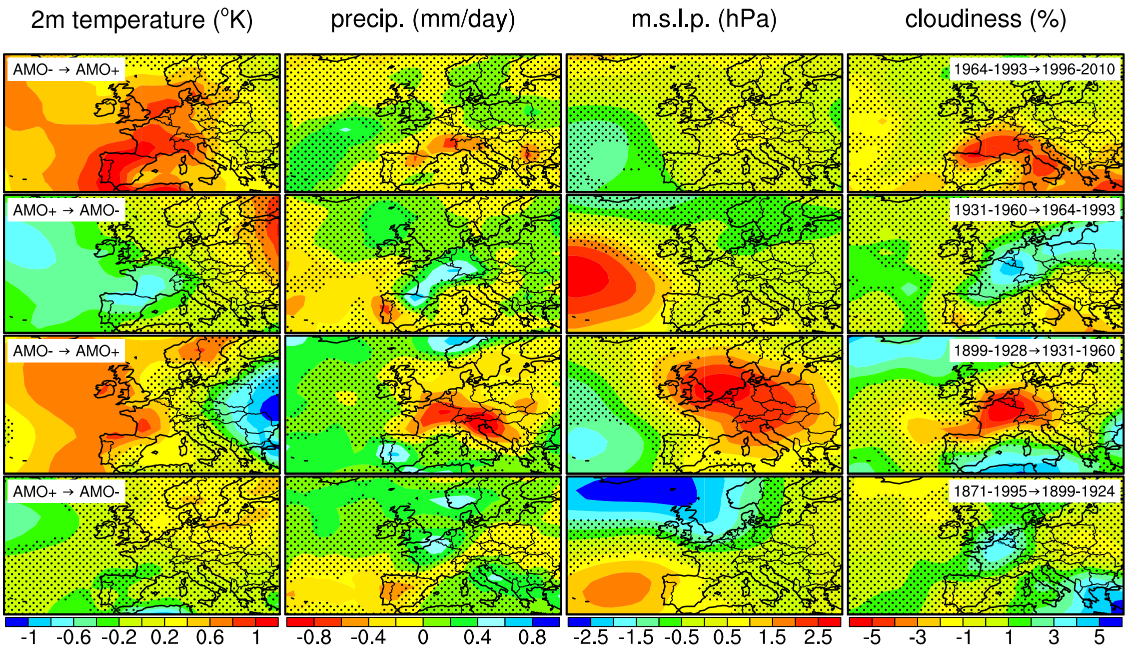

Figure 4. Same as figure 3, but for the 20th Century Reanalysis 2 meters temperature, precipitation, mean sea level pressure and cloudiness, plotted on a larger area (30W–30E, 35N–65N).

circulation, contributes to the low-frequency changes of precipitation. It is worth noting that our results appear to be less significant and stable from the statistical point of view in the case of the oldest transition. Sutton and Dong (2012) attributed the temperature anomalies in Western Europe mainly to advection of Northern Atlantic air. In addition to this effect, we report statistical significant cloudiness anomalies that might explain a portion of the surface temperature variability related to the AMO.

4. Discussion and conclusions

Direct snowfall observations in the western and southeastern Alps show a transition from abundant to reduced spring snowfall regimes in the middle 1990s, corresponding to the last transition toward a warm phase of the Atlantic Multi-decadal Oscillation (AMO). According to the results obtained from the HISTALP snowfall reconstruction and the direct observations in the Swiss and French Alps, there have been two similar pairs of synchronous shifts in the past 150 years, where snowfall regime variations, determined by changes in both total precipitation and near surface temperature, appear to occur concomitantly with changes of the AMO phase. Specifically, we have found that transitions from cold to warm phases of the AMO can produce significant snowfall reductions in wider areas at relatively low elevations of the Alpine region. The signal of snowfall change appears to be more robust in the western Alps, where the AMO transition is accompanied by a spring snowfall reduction as large as 20–30% of the total spring snowfall. According to the 20th Century Reanalysis, precipitation anomalies can be explained by changes of circulation connected to the AMO transitions. In the case of cold to warm AMO transitions, it consists of a high-pressure ridge pattern between two anomalous lows over the northeast Atlantic Ocean and northeastern Europe, in agreement with Sutton and Dong (2012). Temperature anomalies over Western Europe due to advection of Northern Atlantic air are emphasized by the cloudiness anomalies. The teleconnection between spring European climate and the AMO appear to be stronger in the more recent period, at least based on the dataset we used. An interesting follow-up question, the subject of future investigation, concerns the possible influences that anthropogenic climate change might have on this low-frequency teleconnection.

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