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Paolo Billi [1,2]

MEAN ANNUAL AND MEAN MONTHLY TEMPERATURE VARIATION IN ITALY ACROSS THE LAST CENTURY

Abstract - P. Billi, *Mean annual and mean monthly temperature variation in Italy across the last century.*

Mean annual and mean monthly temperature variation has been analysed using the CRU TS (Climatic Research Unit gridded Time Series) dataset consisting of high-resolution, monthly grid of land-based (excluding Antarctica) observations from 1901 to 2019. A marked temperature increase of 1.8 °C was found since 1901. The increase is not uniform as the time series follow a stepped pattern with distinctive trends across three 39-year intervals. In the 1901-1940 interval a moderate increase is observed. In the 1941-1980 interval, an almost equivalent decreasing trend results. An outstanding result of this study is the impressive increasing trend in the 1981-2019 interval. The steep increase of the last decades is paralleled by the increase of sea water temperature in the seas surrounding Italy. In the 1981-2019 interval, June is the month with the highest increase and summer temperature change seems to drive the annual temperature, with a stronger effect in southern Italy. This last interval is also characterised by well below the average values of the North Atlantic Oscillation. The influence of the NAO variations and the onset of heat waves, associated with the frequent northward shifting of Hadley cell, were considered to explain the high rates of change recorded Italy and especially in the Alps. All data indicate a more substantial temperature increase in the north rather than in the south of Italy over the 1901-2019 interval. This may have severe implications on natural systems and explains the fast retreat of several glaciers observed in the recent decades.

Key words - annual temperature, temperature increase, gridded data, natural systems, Italy

Riassunto - P. Billi, *Variazione delle temperature medie annue e mensili in Italia durante l'ultimo secolo.*

Le variazioni delle temperature medie annuali e mensili nell'arco di tempo che va dal 1901 al 2019 sono state analizzate utilizzando i dati distribuiti ad alta risoluzione, basati su dati misurati a terra (escluso l'Antartide) resi disponibili dal CRU TS (Climatic Research Unit gridded Time Series). Un significativo aumento della temperatura media annuale di 1.8 °C è stato rilevato dal 1901 al 2019. L'andamento di questo aumento, non è però uniforme in quanto la serie temporale può essere scomposta in tre blocchi di 39 anni ciascuno in cui si osservano tendenze nettamente diverse. Nel periodo 1901-1940 si osserva un moderato aumento della temperatura, mentre nell'intervallo 1941-1980 la tendenza è opposta e caratterizzata da un tasso di diminuzione di poco inferiore a quello positivo del periodo precedente. L'ultimo periodo, dal 1981 al 2019, si caratterizza invece per un aumento della temperatura impressionante. Il rapido aumento degli ultimi decenni ha un andamento simile a quello dell'aumento della temperatura dell'acqua dei mari che circondano l'Italia e coincide anche con valori tutti al di sotto della media dell'Oscillazione Nord Atlantica (NAO). Nel periodo di massimo aumento della temperatura in Italia il mese che registra il massimo aumento è giugno e le temperature dell'estate mostrano un andamento simile a quello delle temperature annuali suggerendo un effetto di trascinamento delle prime sulle seconde, con un ruolo leggermente più importante delle temperature estive nel sud Italia. L'influenza delle variazioni della NAO e l'avvento di onde di calore, associate allo spostamento verso nord, sempre più frequente, delle celle di Hadley, sono interpretati come possibili cause principali degli elevati aumenti di temperatura negli ultimi decenni in Italia e specialmente nelle Alpi (3°C negli ultimi 38 anni). I dati indicano un aumento generale della temperatura annuale più marcato nel nord che nel sud Italia nel periodo 1901-2019. Questo può avere serie ripercussioni negative sui sistemi naturali e spiega il preoccupante ritiro dei ghiacciai osservato in Italia negli ultimi decenni.

Parole chiave - temperatura annuale, aumento della temperatura, griglia di dati, sistemi naturali, Italia

Introduction

Several studies and international agencies (e.g. Brohan *et al.*, 2006; Smith *et al.*, 2008; Hansen *et al.*, 2010) have shown that the global temperature has markedly increased during the last century. Some studies (e.g. van Vliet & Leemans, 2005; NASA, 2021) have calculated a rate of change between 0.15 and 0.2 °C per decade during the last 50 years, which leads to an overall increase of about 2 °C of today global temperature compared to the pre-industrial age. The observed increase in temperature has several negative impacts on natural systems, agriculture, fisheries, aquaculture and human health to such an extent that, in its report on climate change, the European Environment Agency (EEA, 2012) has indicated average temperature as the key variable to monitor climate change and to assess the impact of climate change in Europe. According to EEA (2012), the average air temperature over Europe in the 2002-2010 decade is about 1.3 °C higher than in pre-industrial times.

According to the 2019 report on the climatic indicators of Italy prepared annually by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) (Fioravanti *et al.*, 2020), the year 2018 has been the

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hottest year, with an increase of 1.5 °C with respect to the 1961-1990 reference interval, followed by the second and third hottest years recorded in 2015 and 2019, respectively.

Lo Vecchio & Nanni (1995) used the data of 27 meteo-stations, 14 of which located in northern Italy, to investigate the variation of air temperature over Italy in the interval between the mid-1860s to the late 1970s and found an increasing trend all over the country, with a steeper trend in the south. These authors considered only five stations located in southern Italy. The same data was used by Maugeri & Nanni (1998) and by Brunetti *et al.* (2000 a). Maugeri & Nanni (1998) confirmed the findings of Lo Vecchio & Nanni (1995), though they observed a clearer increasing trend across the 1867-1967 interval for mean temperature at both annual and seasonal timescale. Brunetti *et al.* (2000 a) also highlighted a warming of the Italian climate over the 1866-1995 interval, with a more pronounced increasing trend in southern Italy, as already reported by Lo Vecchio & Nanni (1995).

Toreti & Desiato (2008) used the data of 49 stations but investigated a shorter interval, from 1961 to 2004, and found an initial decrease followed by a marked increase. According to their analysis the change point is indicated in 1981.

In a very comprehensive study, using several climatic indices, Fioravanti *et al.* (2016) demonstrated a substantial increase of extreme daily temperature in Italy across the 1960-2011 interval. These authors used the data provided by ISPRA through the SCIA (www.scia.isprambiente.it), i.e. the "National System for the Collection, Elaboration and Diffusion of Climatological Data" (Desiato *et al.*, 2007, 2011). Several other studies dealt with temperature variations at regional scale (e.g. Viola *et al.*, 2014; D'Oria *et al.*, 2017; Scorzini & Leopardi, 2019) or slightly larger portions of the country (e.g. Aruffo & Di Carlo, 2019).

From this brief review of the literature about the variability of air temperature in Italy, it is evident that previous studies (see Scorzini & Leopardi, 2019, for a comprehensive list) were based on time series which covered different intervals, a few of them included gaps and data missing, were not up-to-date or based on a non-uniform distribution of the meteo-stations, whereas the most of them dealt with precipitation rather than temperature changes and, with the exception of few papers (e.g. Bruntti *et. al.*, 2000a; Brunetti *et al.*, 2000 b; Colombo *et al.*, 2007, Toreti & Desiato, 2008; Toreti *et al.*, 2009) that were focussed on the entire territory of Italy, presented investigations at regional scale. Though the previous studies were highly valuable and substantially contributed to the understanding of temperature change in Italy, the above-mentioned shortcomings suggested to use more homogeneous data to carry out an up-to-date investigation on mean annual and mean monthly temperature variations during the last twelve decades. Most of previous studies highlighted a general trend in temperature, but the extent of the time series and the areas investigated are not homogeneous. For these reasons, gridded data were used to investigate the characteristics of mean annual and mean monthly temperature trends in Italy across a large time interval between 1901 and 2019. Moreover, since previous studies (e.g., Vicente-Serrano & Trigo, 2011) demonstrated the influence of the North Atlantic Oscillation (NAO) on temperature in Europe, especially in winter in northern Europe, NAO data were used to analyse the effect of NAO on temperature variability in Italy as well. Fewer studies investigated the effect of NAO on the Mediterranean climate, whereas Italy, given its intermediate position between northern European and southern Mediterranean dominated atmospheric dynamics (Scorzini & Leopardi, 2019) may present peculiar responses that deserve to be investigated.

Study area

The climate of Italy varies from north to south and from west to east. Such a variability is controlled by the peninsular shape of the country, which deeply stretches into the Mediterranean Sea, and by the location of long, uninterrupted mountain ranges. The seas that enclose the peninsula with different water masses and depths have a substantial influence on its climate, so as the mountain chains that mitigate the effects of the north-western fronts and the north-eastern cold currents. These effects are reflected by the distribution of the Koeppen climates across the country (Fig. 1).

The lower temperatures are recorded in the Alps (the lowest temperature ever of -49.6 °C was measured at Busa Nord di Fradusta in the south-eastern Alps at an elevation of 2607 m asl on February 10, 2013) where thick snow accumulations increase from 120 cm in the west to 400 cm in the east. Heavy snowfall events may also occur in the Apennines and especially in its southern portion when very cold air coming from Scandinavia flows over the much warmer water of the Adriatic Sea (365 cm in 24 hours in December 1961 at Rocaccaramanico, 878 m asl on the Maiella massif, north-eastern side of the southern Apennines). In the south, hot air masses coming from northern Africa result in very high temperatures, especially in the summer. On August 11, 2021, the highest temperature ever recorded in Italy and Europe of 48.8 °C was measured near the town of Siracusa in Sicily. Similar high temperatures in the 46-48 °C range were measured mainly in other parts of Sicily, but also in Sardinia and in Puglia tableland (Foggia) (Cadeddu & Meo, 2007).

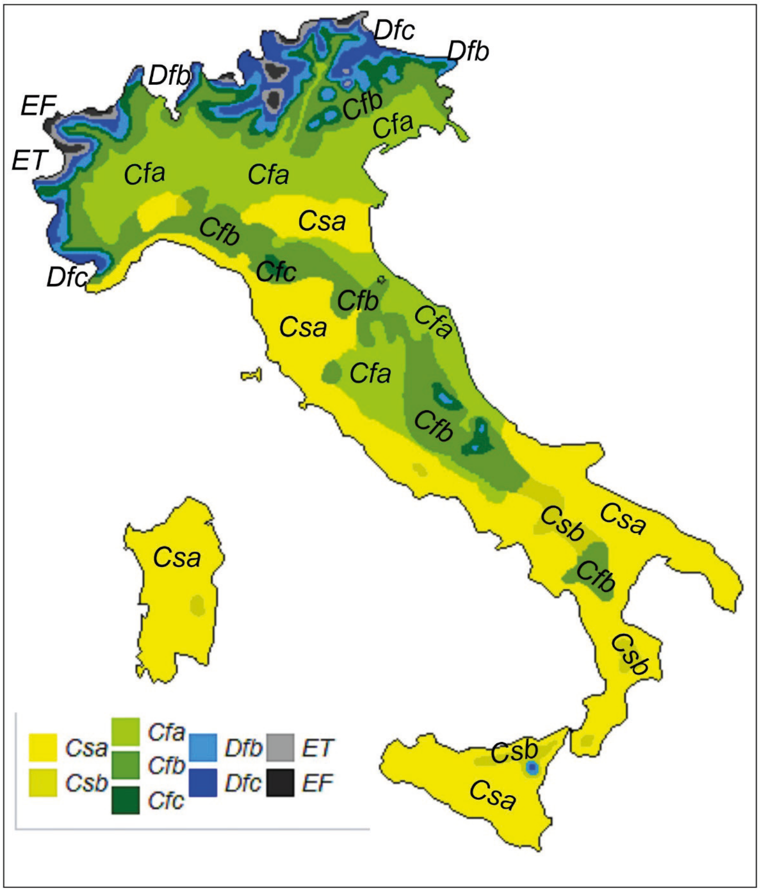

Figure 1. Climate distribution in Italy according to the Koeppen classification. *Csa* = dry hot summer temperate; *Csb* = dry mild summer temperate; *Cfa* = humid hot summer temperate; *Cfb* = humid mild summer temperate; *Cfc* = humid mild summer cold winter; *Dfb* = cold climate with humid winter and mild summer; *Dfc* = cold climate with humid and cold winter; *ET* = tundra climate; *EF* = permanent frost climate.

Data sources

The previous investigations on mean temperature variation in Italy were based on meteo-stations data collected by the National Hydrographic Service since the early 1920s (e.g. Ufficio Idrografico e Mareografico, 1996) and in the latest decades by the regional hydro-climatological departments (e.g. ARPAE, 2020). Though ground instrument data are a crucial resource to investigate climate parameters variability at regional scale, for this general study on the mean monthly and annual temperature variability over the whole Italian country, gridded data were used. Mean monthly temperature data were obtained from the CRU TS Version 4.04 Google Earth Interface (https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.04/ge/?_ga=2.226845332.80016410.1631874272-804770725.1631874270) (Harris *et al*., 2020). The CRU TS (Climatic Research Unit gridded Time Series) dataset provides a high-resolution, monthly grid of land-based (excluding Antarctica) observations from 1901 to 2019 and consists of ten observed and derived variables, including mean temperature. According to Harris *et al.* (2020), in the dataset there are no missing values and the series of individual stations were normalised using their 1961-1990 observations, then gridded to a 0.5° regular grid. For more detailed information about the time series homogenization, data validation and gap filling procedures, also see Harris *et al.* (2013). The CRU TS datasets are based on quality-controlled data files provided by several international organizations including WMO, NOAA, MCDW (Monthly Climatic Data for the World) summaries, etc.

For this study, mean monthly data spanning the 1901-2019 interval were downloaded from all the cells covering the Italian territory. Italy is covered by 193 cells of 0.5° size. The mean monthly temperature data of each cell for a given year was averaged to obtain the mean annul temperature for that year. Mean annual and mean monthly temperature time series were then constructed and plotted into bivariate diagrams to investigate the occurrence of trends.

According to several authors (e.g. Hurrel, 1996; Vicente-Serrano & Trigo, 2011; Iles & Hegerl, 2017) the North Atlantic Oscillation (NAO) has an important influence on the climate of the Mediterranean Region. The NAO is defined as the pressure difference between the Icelandic low and the Azores high. The variability of the pressure difference between these two poles influences the westerlies flow, which oscillates between northern and southern directions, with important implications on the thermal exchange and the climate of Europe and the North Atlantic (Trigo *et al*., 2002; Brandimarte *et al*., 2011).

Monthly mean NAO index normalized data since January 1900 were downloaded from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA, 2023).

The significance of the trends of the parameters considered were tested for significance using the Mann-Kendall test.

Results

The mean annual temperature (T_{ma}) shows an overall increasing trend (Fig. 2). The pattern however, is not regular since it is characterised by a modest increasing trend during the first four decades, a more marked decreasing trend in the following four decades and a very marked increase in the last four decades. In order to point out the occurrence of three different patterns as evident in Fig. 2, the time series was split into three intervals, 1901-1940, 1941-1980, 1981-2019, and the respective data were plotted in the diagram of Fig. 3.

The T_{ma} trends of the three portions of the time series resulted: positive with a confidence factor of 99.3% for the 1901-1940 interval, negative with a confidence factor of 99.9% in the 1941-1980 interval and positive with a confidence interval of 99.9 %.in the 1981-2019 interval. The mean annual temperature was 13.9, 14.1 and 14.9 °C in the first, second and third interval, respectively, with an overall increase of 1 °C (Table 1). If we consider the first decade and the last decade the temperature increase is even larger from 13.6 to 15.4 °C, i.e. almost two centigrade.

The most impressive result, however, is the steep increase observed since the early 1980s. Such a marked increase is also evident in the plot of the normalized data (Fig. 4). The T_{ma} data were normalised through the Z statistic, whereby:

$$Z = (n-m)/d$$

in which n is the ith datum, m the mean of the series and d its standard deviation.

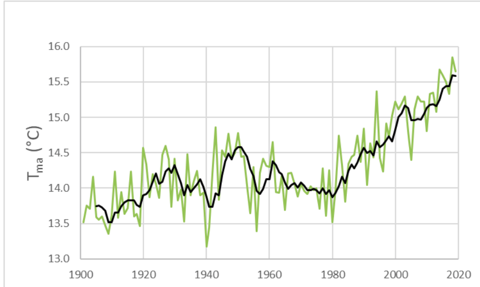

Figure 2. The mean annual temperature variation from 1901 to 2019. The solid black line is the ten-year moving average.

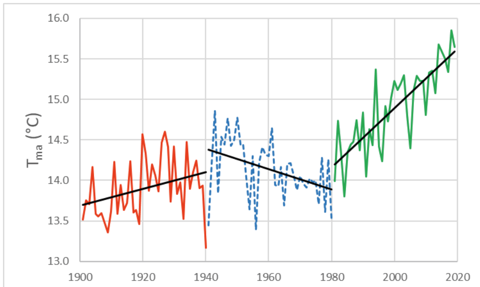

Figure 3. The mean annual temperature time series of Figure 2 split into three intervals: 1901-1940, 1941-1980 and 1981-2019. The black solid lines indicate the trends for the individual time blocks.

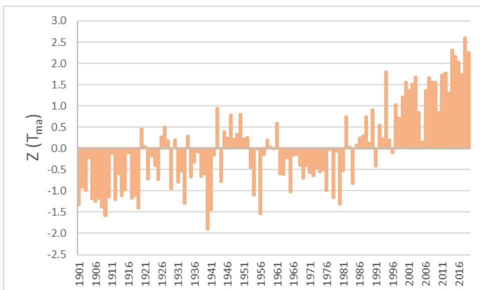

Figure 4. Time series of the normalized mean annual temperature data. Notice the marked increase after 1981.

Table 1. Characteristic values of mean annual, winter (DJFM) and summer (JJA) temperature (T_{ma}) and their rate of change (r_c). All the trends are significant ($p < 0.001$) except for (*).

	T_m (°C)			r_c (°C/a)		
	Annual	**Winter**	**Summer**	**Annual**	**Winter**	**Summer**
1901-1940	13.9	5.75	20.14	0.0103	0.0037*	0.0092*
1941-1980	14.1	5.92	20.34	-0.0128	0.0134	-0.0322
1981-2019	14.9	6.48	21.47	0.0367	0.0309	0.0504

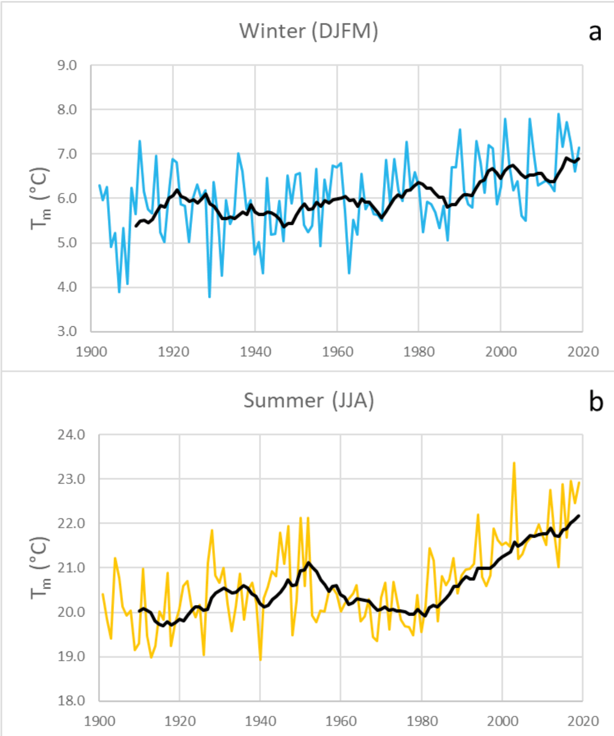

Figure 5. Long term variation of the winter (a) and summer (b) temperatures. The solid black line is the ten-year moving average.

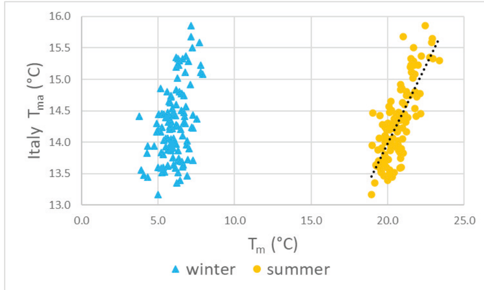

Figure 6. Correlation between the winter and summer temperatures with the mean annual temperature.

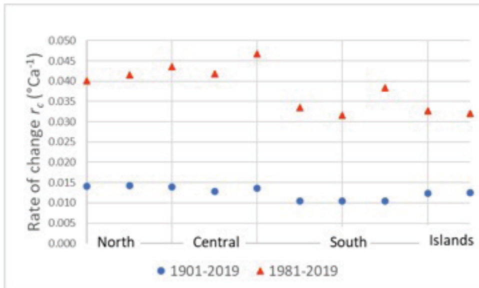

Figure 7. Variation of the mean annual temperature increase in the long term and in the recent decades.

The jump in temperature during the last four decades is also confirmed by the highest rate of change (r_c) recorded in the last four decades interval by the winter (December, January, February and March) and summer (June, July and August) data subsets (Table 1). Notwithstanding this result, the diagrams of winter and summer temperature variability show a rather different pattern (Fig. 5 a and b). Though both winter and summer temperatures show an increasing trend, the pattern of the summer data is more similar to that of the annual data of Fig. 2. The summer temperature, in fact, shows a decreasing trend during the 1941-1980 interval and a steep increase in the last decades (Fig. 5 b). The summer temperature controls 61% of the annual temperature variability, whereas there is no significant influence of the winter data (Fig. 6). This result confirms that the jump of annual temperature in Italy since the 1980s is mainly driven by the summer temperature.

In the 1901-2019 interval, the mean annual temperature rate of change is higher in northern Italy and tends to decrease southwards (Fig. 7). In the last four decades, characterised by a steep increase in temperature across the whole country, the pattern is similar, but with more marked increasing rates in northern-central Italy in winter, whereas the rate of change in the summer temperature is higher in the south and lower in the north in the 1981-2019 interval (Table 2). The highest increasing rates recorded for the summer temperatures lead to an increase of 1.65, 1.77 and 2.00 °C for the north, centre and south, respectively in the 1981-2019 interval.

Table 2. Rate of mean temperature change (r_c) in northern, central and southern Italy in the 1901-2019 and 1981-2019 intervals.

	Rate of change r_c (°C/a)		
1901-2019	North	Central	South*
Winter	0.0128	0.0116	0.0087
Summer	0.0166	0.0143	0.0182
1981-2019	North	Centre	South*
Winter	0.0351	0.0389	0.0267**
Summer	0.0424	0.0455	0.0528

(*) South also includes the islands of Sicily and Sardinia. All the trends are significant with a confidence factor of 99.90%, except (**) whose confidence factor is 98.30%.

The rate of temperature change varies widely among months and between the whole study interval (1901-2019) and the last four decades (1981-2019) (Fig. 8). In the twelve decades interval, the month with the highest rate of change is July (+1.92 °C in 118 years), where-

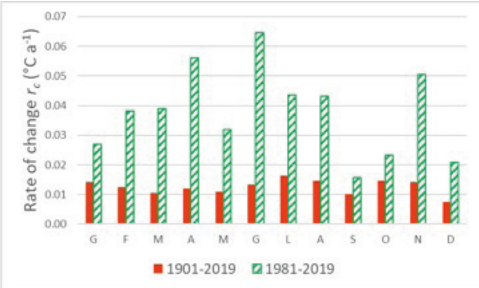

Figure 8. Monthly increasing rates in the long term and in the recent decades.

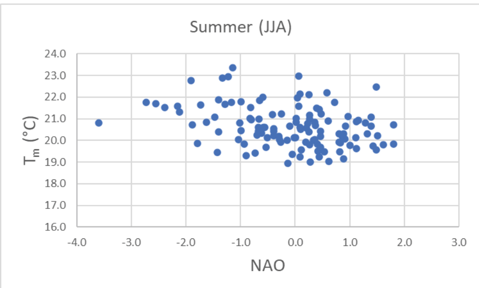

Figure 9. Correlogram of the summer NAO and the summer temperature. The correlation is weak and non-significant.

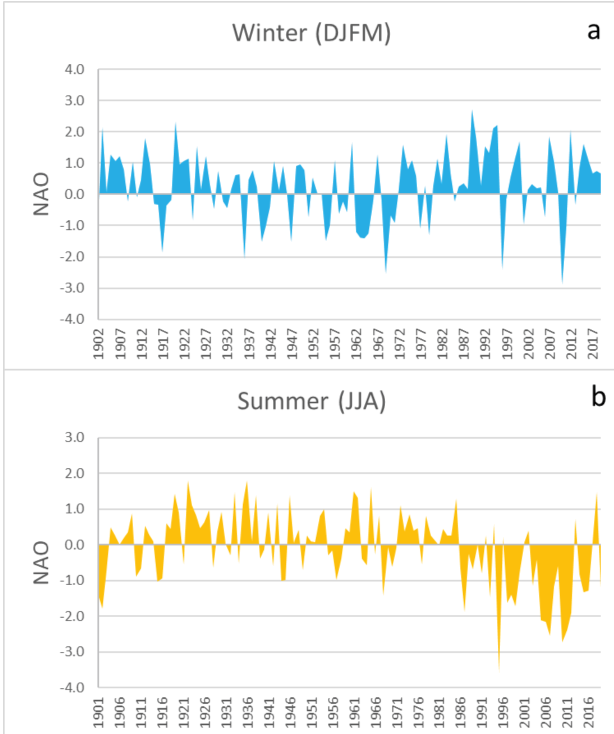

Figure 10. Long term variation of the winter NAO (a) and the summer NAO (b).

as the lowest value is recorded in December (+0.88 °C in 118 years). In the 1981-2019 interval, which experienced a very steep temperature increase, the highest rate of change is observed in June (+2.46 °C in 38 years) and the lowest value is measured in September (+0.59 °C in 38 years).

Several authors (e.g. Hurrel, 1996; Vicente-Serrano & Trigo, 2011; Iles & Hegerl, 2017) investigated the influence of the North Atlantic Oscillation on the climate over Europe, and found that the winter NAO has some control especially on winter temperature. Other authors (e.g. Chronis *et al.*, 2011; Wang *et al.*, 2011; Linderholm & Folland, 2017) also found some influence of the summer NAO on summer temperature.

In this study, no direct correlation was found between winter and summer NAO and winter and summer temperature variations, except for a general, non-significant, inverse correlation between summer NAO and summer temperature (Fig. 9).

The plots of the winter and summer NAO time series (Fig. 10) do not show any clear trend. However, a block of almost negative values of the summer NAO index is evident after the early 1980s., confirming a certain influence of the summer NAO on the marked increase in summer temperatures observed in Italy in the 1981-2019 interval.

Discussion

The gridded data used in this study indicate that, during the last 12 decades, the mean annual air temperature of Italy has been increasing of 1.6-2.1 °C, that is almost twice the increase recorded for the entire planet. This result is in line with Toreti *et al.* (2010) findings. These authors, in fact, measured a temperature increase of 1.5 °C for Italy, using the data of 43 meteo-stations managed by the Italian Air Force Weather Service. The smaller temperature increase found by Toreti *et al.* (2010) depends on the shorter interval (1961-2006) that these authors considered, in which the first decades of the 20th century, characterised by lower mean annual temperatures (Fig. 4), are not included. In a similar work based on meteo-station data, Brunetti *et al.* (2000 a) calculated a mean temperature increase of 0.7 °C, in the 1867-1995 interval. The lower value obtained by Brunetti *et al.* (2000 a) can be attributed to the different period considered by these authors who obviously could not include the whole 1981-2019 interval which is characterised by the highest increase in temperature observed in the last twelve decades.

On the base of the data measured by 143 meteo-stations, Fioravanti & Piervitali (2018) obtained a temperature increase of 1.5 °C across the 1961-2015 interval. This result confirms that of Toreti *et al.* (2010). Yet,

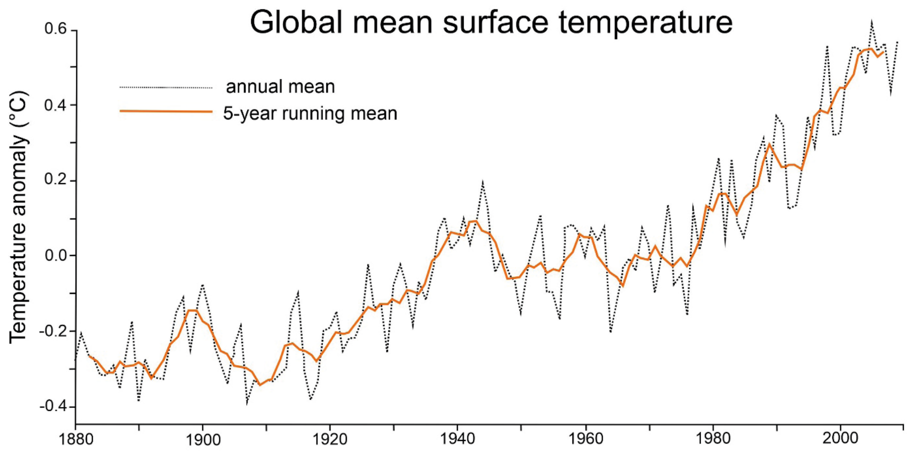

Figure 11. Planetary increase in temperature (modified from NASA, 2021).

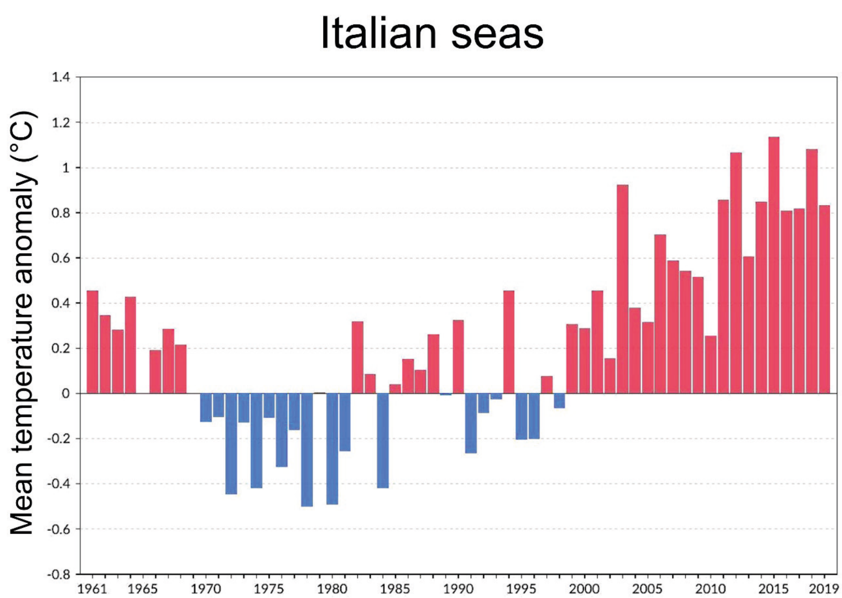

Figure 12. Variation of sea water temperature anomaly recorded for the Italian seas since 1961 (modified from ISPRA, 2021).

the former authors did not consider the first decades of the 20th century, though used a larger number of meteo-stations. The increase in temperature calculated by these authors using meteo-station data is, however, close to that obtained in this study based on gridded data. This confirms that the CRU TS gridded data (Brohan *et al.*, 2006) are a reliable option for trend analysis at least at the scale of Italy.

The mean annual temperature variation within the 1901-2019 interval shows a segmented pattern of the time series in which three main trends are evident for the 1901-1940, 1941-1980 and 1981-2019 intervals, with the latter period characterised by a very steep increase. This temperature jump was already highlighted by other authors (e.g. Toreti & Desiato, 2008; Toreti *et al.*, 2010; Liuzzo *et al.*, 2017; Aruffo & Di Calo, 2019). The stepped pattern of the mean annual temperature observed in Italy parallels that of the global mean surface temperature anomaly produced by international organizations such as the NASA (2021) (Fig. 11), in which different trends and breaking points occur for approximately the same 1901-1940, 1941-1980 and 1981-2019 intervals selected in this study.

The marked change in the air temperature from the moderately negative trend in the 1941-1980 interval to the very marked increase in 1981-2019 almost parallel the water temperature pattern of the seas surrounding Italy, prepared by Fioravanti *et al.* (2020) for ISPRA on the base of NOAA data (Fig. 12) for the 1961-2019 interval. A substantial increase of sea water temperature in the Mediterranean and especially in its western part after the early 1980s is also reported by Skliris *et al.* (2011).

The 1981-2019 interval sees the steepest increase in temperature over Italy and the month with the most pronounced increase is June. Pastor *et al.* (2018) also observed the maximum increase (ca 1.5 °C) of the Mediterranean Sea temperature in June, across a slightly shorter 1982-2016 interval. These authors also emphasise the role of the Mediterranean as a hot-spot for climate change. These results indicate that air and sea water temperatures are likely affected in a similar way by the global warming. Though some heat transfer between sea water and atmosphere should be expected, their mutual influence is not fully understood yet (Della Marta *et al.*, 2009), whereas Chronis *et al.* (2011) found some influence of the summer NAO on the eastern Mediterranean Sea water temperature variations.

The data of this study indicate that the summer temperature is the main driver of the substantial increase in temperature over Italy in the 1981-2019 interval. Several authors (e.g. Hurrel, 1996; Iles & Hegerl, 2017) attribute to summer NAO a small role in affecting temperature. However, the MetOffice (2021) associates colder temperatures and wetter conditions on the Mediterranean region with summer NAO index well above zero and warmer and dryer conditions with summer NAO index well below zero. The 1901-2019 variation of the summer NAO is reported in Fig. 10 b, which shows values of the index below zero in the 1981-2019 intervals, during which a marked increase in summer temperature was observed in this study as well. Though the correlation between summer NAO and summer temperature in Italy is weak, the similarity of their pattern, especially in the 1981-2019 interval is rather apparent. Previous studies (e.g., Folland *et al.*, 2009) were able to demonstrate some control of summer NAO on the summer climate of northern Europe climate, whereas such effect is not so evident in the Mediterranean

In the recent decades an increased frequency of heat waves has been recorded in the summer over Europe and the Mediterranean (Wang *et al.*, 2011; Hochman *et al.*, 2021). Wang *et al.* (2011) found that the winter (JFM) NAO has some control over the Mediterranean summer temperature, but no correlation was found in this study. The role of the Atlantic dipole on the formation of summer heat waves needs to be further investigated since contradictory results are reported in the literature (e.g. Kueh & Lin, 2018; Li *et al.*, 2020). Several studies (e.g. Watt-Meyer *et al.*, 2019; Grise & Davies, 2020) reported the northward expansion of Hadley cell during the last four decades in response to increasing greenhouse gases emissions. The data of Liu et al (2012) show a clear northward shifting of the Hadley circulation since the early 1980s and the strongest northward trend is recorded in June. The expansion of the Hadley circulation also implies increasingly frequency of the northward shifting of the subtropical dry zone (Hu *et al.*, 2018), i.e. the North African high that in the last decades has been reaching the Italian peninsula, bringing torrid temperatures in June. Furthermore, the observed trend of westward and southward shifting of the Azores High in July (Falarz, 2019) leaves room for the onset of the North African High over Italy, which often occurs in June as showed by Liu *et al.* (2012). The findings of these latter studies confirm the result of this study whereby June is the month with the highest increasing rate in the 1981-2019 interval.

The marked increase in the mean temperature of June observed in northern Italy and particularly in the Alps (about 3 °C in 38 years, the highest monthly rate of change observed across the country) is particularly worrying for the reduction of the alpine glaciers. June, in fact, marks the beginning of the summer and the predominance of clear skies, commonly associated with relatively high temperature also in the mountains, thus expanding the length of the annual glacier melting period.

In this study, no correlation between winter NAO and winter temperature in Italy was found. A similar result was also obtained by Brandimarte *et al.* (2011, their figure 2) for southern Italy. By contrast, a substantial influence of the winter NAO was instead found for norther Europe by several authors (e.g. Trigo *et al.*, 2002; Hurrel *et al.*, 2003; Pokorná & Huth, 2015; Deser *et al.*, 2017; Iles & Heger, 2017). Lopez-Moreno *et al.* (2011) observe a direct relationship between the winter NAO and temperature in the Mediterranean mountains. In this study, the winter temperatures in the Alpine chain and the winter NAO show a direct relationship, but the correlation is very weak and non-significant. The Alps likely act as a barrier for the norther European atmospheric circulation reducing the influence of the NAO. More investigations on the influence of the winter and summer NAO on the climate of Italy are necessary.

Conclusions

The CRU TS, 0.5 degrees gridded data were used to analyse the mean annual and mean monthly air temperature variation in Italy during the 1901-2019 interval. The data indicate a general increasing trend, which is more marked in northern than in southern Italy. In Italy, the increase in mean annual temperature is 1.8 °C, which is almost twice the planet global warming for the same interval. This marked temperature increase, especially in the north, explains important deteriorations and changes in environmental systems such as the substantial retreat of a few glaciers, the marked reduction in annual snowfall days and the natural replacement of high mountain vegetation with species typical of lower elevations.

The variation in mean annual temperature, however, is not constant. It follows a stepped pattern in which three main periods, with different trends, can be identified: 1901-1940, 1941-1980 and 1981-2019. In the 1901-1940 and in the 1941-1980 intervals, a moderate increasing and decreasing trend, respectively, with similar rate of change are evident. They are followed by a very steep increasing trend in the 1981-2019 interval, during which the rate of change is about four times that of the 1901-1940 interval and almost equivalent to the global warming since the 1850-1900.

The steep temperature increase observed in the 1981-2019 interval is mainly driven by the summer temperature whose rate of change is higher in the south with an average increase of 2.00 °C in 38 years.

The data showed a weak influence of both the winter and summer NAO on the stepped temperature pattern recorded in Italy. Unlike several previous studies on the influence of the winter NAO over the climate of Europe, in this study no correlation was found between the winter NAO and the winter temperature of Italy. For the l981-2019 interval, a very general, though weak and non-significant, inverse relationship was obtained. However, in this interval, characterised by a steep increase in temperature, the summer NAO index shows a persistence of well below the average negative values, whereas in the literature a marked increase in the sea water temperature and the influence of the summer NAO on the eastern Mediterranean Sea water temperature variations are reported. Though it was not possible to demonstrate the influence of the NAO on the temperature over Italy, some role of the Atlantic dipole in affecting in a similar way air and sea water temperatures cannot be neglected. Further studies are however needed, especially on the role of the heat waves associated with the northward shifting of the North African high that in the last decades has been reaching the Italian peninsula more and more often, bringing torrid temperatures in June.

In the Alps, the temperatures of June are characterised by the highest increasing rate (about 3.00 °C in the 1981-2019 interval). This condition exacerbates the already existing risk of accelerated glacier melting.

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