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ORIGINAL ARTICLE

Sensitivity of typical Mediterranean crops to past and future evolution of seasonal temperature and precipitation in Apulia

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Abstract The region of Apulia, which is located in the south-east tip of the Italian Peninsula, has a typical Mediterranean climate with mild winters and hot-dry summers. Agriculture, an important sector of its economy, is potentially threatened by future climate change. This study describes the evolution of seasonal temperature and precipitation from the recent past to the next decades and estimates future potential impacts of climate change on three main agricultural products: wine, wheat and olives. Analysis is based on instrumental data, on an ensemble of climate projections and on a linear regression model linking these three agricultural products to seasonal values of temperature and precipitation. In Apulia, precipitation and temperature time series show trends toward warmer and marginally drier conditions during the whole analyzed (1951–2005) period: 0.18 °C/decade in mean annual minimum temperature and −14.9 mm/decade in the annual total precipitation. Temperature trends have been progressively increasing and rates of change have become noticeably more intense during the last 25 years of the twentieth century. Model simulations are consistent with observed trends for the period 1951–2000 and show a large acceleration of the warming rate in the period 2001–2050 with respect to the period 1951–2000. Further, in the period 2001–2050, simulations show a decrease in precipitation, which was not present in the previous 50 years. Wine production, wheat and olive harvest records show large inter-annual variability with statistically significant links to seasonal temperature and precipitation, whose strength, however, strongly depends on the considered variables. Linear regression analysis shows that seasonal temperature and precipitation variability explains a small, but not negligible, fraction of the inter-annual variability of these crops (40, 18, 9 % for wine, olives and wheat, respectively). Results (which consider no adaptation of crops and no fertilization effect of CO_2) suggest that evolution of these seasonal climate variables in the first half of the twenty-first century could decrease all considered variables. The most affected is wine production (−20 ÷ −26 %). The effect is relevant also on harvested olives (−8 ÷ −19 %) and negligible on harvested wheat (−4 ÷ −1 %).

Keywords Climate change · Seasonal temperature · Seasonal precipitation · Impacts · Agriculture · Olives · Grapewine · Wheat · Wine

Introduction

A progressively increasing bulk of scientific literature shows that the whole Mediterranean region is likely to be

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critically affected by climate change in the twenty-first century. Model simulations project a large warming, with a maximum in the summer season (e.g. Giorgi and Lionello 2008; Sanchez-Gomez et al. 2009; Gualdi et al. 2011). Summer temperature in the 2071–2100 period with respect to the 1961–2000 period for the A1B scenario is projected to increase 3–4 °C over the sea and to grow further to 4–5 °C in some inland areas. Model projections agree also on a pronounced decrease in precipitation, percent-wise largest in the warm season, when the average reduction is in the range 25–30 %, with some areas in the north-east and the south showing values larger than 50 %. The reduction in precipitation is smallest in winter, varying from no change in the northern Mediterranean to a 40 % reduction in the south. This situation is also reported by IPCC-WG1 (2007), which stresses the great consistency in model results concerning the risk of warming and drying during the twenty-first century.

This study focuses on Apulia (Italian: Puglia), a region in southeast Italy, which is bordered by the Adriatic Sea to the east and the Ionian Sea to the south and south-west (Fig. 1). Apulia comprises an area of 19,345 km^2 and has a population of about 4 million. The climate is entirely Mediterranean with mild wet winters and hot-dry summers (the coldest month is January and the warmest is July). Precipitation falls mainly in winter, and it is irregular and scarce in summer (see Figure 1 and 2 in the electronic supplement of this paper).

In the past, most of Apulia was probably covered with Mediterranean scrub composed of evergreen bushes and trees (see Jalut et al. 2009 for a discussion of past vegetation in the lower and upper holocene), but today only 670 km^2 remain wooded (5 % of the entire territory of the region), while agricultural areas cover about 14,700 km^2 (43 % of the region is cultivated with wheat, 32 % with olive groves, 9 % with grapes, 3 % with citrus and 2 % with vegetables). Agriculture is a very important sector for the economy of the region. The share of gross domestic product generated by the agricultural and service sectors in Apulia is above the national average, for example, about €2,300 million in 2006 (sources ISMEA, ISTAT and Por Puglia 2000–2006).

Due to high substrate permeability (vast horizontal strata of limestone rock) and infiltration of rainwater, in Apulia, there are few rivers and a lack of surface water. The scarcity of water is an acute and long-standing problem, and drinking water is transported by aqueducts from nearby regions. At the same time, progressive expansion in irrigation (and consequential increase in productivity) has extended cultivation from herbaceous to tree crops. Nowadays, intensive irrigation is used for table grapes, tree and vegetable crops. Supplemental irrigation is applied for olives and vineyards.

Climate changes are expected to have a great and negative impact on agriculture in the Mediterranean region (Olesen and Bindi 2002). Warmer temperatures will determine faster crop growth, so that the growth period of crops with determinate cycle (i.e. cereals, grapevine, etc.) will be shorter than now with possible strong negative effects on yields. However, it is not possible to draw general conclusions. Faster development of winter crops may diminish the negative effect of future prolonged summer drought periods and heat waves, while crops growing in summer are likely to be severely affected (e.g. Moriondo and Bindi 2007). Therefore, understanding climate change and the characteristics of its impacts at regional scale is of paramount importance for the sustainable management of agriculture in Apulia.

This paper reports the results of a comprehensive study on Apulia which aims at

(a) Identifying present climate trends at regional scale using a reasonably complete (in term of space and time coverage) dataset,
(b) Describing the effect of present variability of seasonal temperature and precipitation on three agricultural products (grapevine, olives and wheat),
(c) Analyzing climate change scenarios at regional scale on the basis of existing model simulations for the first half of the twenty-first century and estimating the sensitivity of grapevine, olives and wheat to future changes of seasonal temperature and precipitation values.

This study is also meant to represent a demonstration that this sort of analysis is feasible with the presently available information and it can provide indications on vulnerabilities and adaptation goals at the spatial scale that is relevant for regional administrations and agencies. Climate analysis is based on instrumental data, which are provided by a regional network and specifically analyzed for this study, and on an ensemble of climate projections provided regional climate models (RCMs) (see section "Climate data"). Impacts on agricultural products are computed with a linear regression model (LRM) build using mostly official statistics of crops (see section "Data" and "Method") and linking agricultural products to seasonal values of temperature and precipitation. LRMs have already proven to be useful for this type of analysis and have been applied with various level of complexity (e.g. Dixon et al. 1994; Supit 1997; Iglesias et al. 2000; Lobell et al. 2005; 2007). However, there are aspects that LRM cannot model, such as the fertilization effect of increased CO_2 concentration, which has been so far too small for

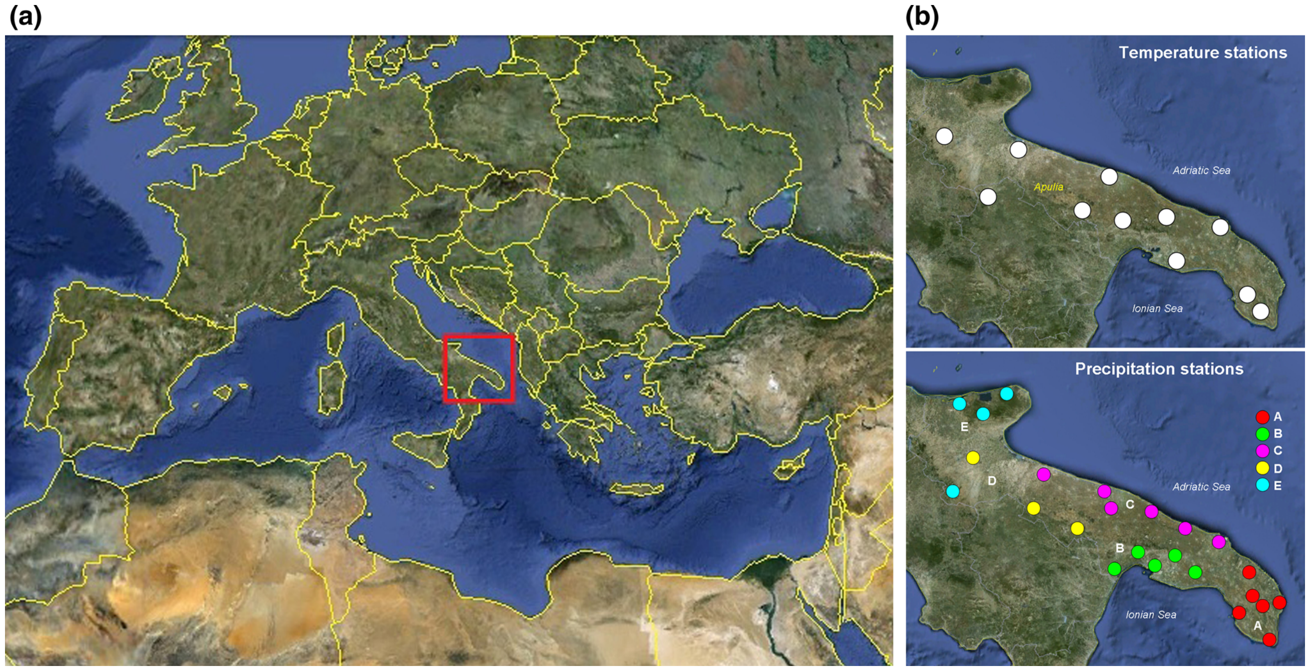

Fig. 1 **a** (*left*) Map showing the location of Apulia in the Mediterranean region. **b** (*right*) spatial distribution of the temperature (*top*) and precipitation (*bottom*) stations used in this study. Precipitation stations have been grouped into 5 areas, labeled "A" to "E" in the map

being included in a LRM (Ewert et al. 2007). Further, adaptation can substantially reduce the effect of climate change impacts (e.g. Reidsma et al. 2009). Finally, the choice of variables reflect those currently used for describing climate change (e.g. Giorgi and Lionello 2008), but do not include statistics on extreme weather events (such as hail, extreme precipitation and floods). Consequently, it is anticipated that this study cannot describe comprehensively the effects of climate change, but only assess those caused directly by changes of mean seasonal temperature and precipitation fields considering the present cultivation practices. In other words, this study aims to identify critical sensitivity of agricultural products to climate change, but not to predict their future quantitative evolution. This approach is consistent with other studies, such as Quiroga and Iglesias (2009), who support the use of simple LRMs, which never provide the level of detail possible with process-based models, but whose results that are meant to assist the risk management and decision-making process by farmers and policy-makers.

The manuscript is structured in a sequence of sections (sections "Present trends of monthly temperature and precipitation in Apulia"–"Future evolution of seasonal temperature and precipitation and its impact on crops") corresponding exactly to goals (a) to (d) and is integrated with two short sections containing a discussion of the results (section "Discussion") and a summary of the main conclusions of the study (section "Conclusion").

Present trends of monthly temperature and precipitation in Apulia

Climate data

The main public climate datasets (E-OBS, Haylock et al. 2008, ECA Project team ECA&D 2012) include very few meteorological stations in Apulia (e.g. only three stations are present in the ECA maps[1]). In order to compensate for this limitation, values of mean monthly daily maximum and minimum temperature, T_{max} and T_{min}, and of total monthly rainfall, RR, for the period 1951–2005 have been extracted from the dataset of the Apulia hydrology agency (SIRP, Servizio Idrografico Regione Puglia). Although this dataset contains a large number of stations (83 for temperature and 133 for precipitation), several time series are not continuous with no metadata documenting interruptions and apparent anomalies. Preliminary standard quality checks (referring to criteria such as those that are listed in Project team ECA&D (2012) and homogeneity tests (Buishand 1982; Craddock 1979; Petit 1979) were carried out to identify suitable stations for climate analysis. As a result of this procedure, only 11 temperature stations were retained, which contained no break points and a sufficient amount of data (Fig. 1). This procedure was less critical for precipitation, for which, 24 stations have been selected. Missing data in these station time series (5 % of the total

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[1] http://eca.knmi.nl/.

for temperature and 3 % for precipitation) were replaced assuming a constant bias (computed separately for each station on the basis of all available data) with respect to the mean of all other available stations.

Analysis and results

The average annual cycles of temperature and precipitation have typical Mediterranean characteristics. Summers are hot and winters are mild (see Figures 1, 2 of the Appendix). In July and August, T_{max} and T_{min} mean values are about 30 and 20 °C, respectively, while in January, they are about 11 and 5 °C (the diurnal temperature range is larger in summer than in winter). Summers are very dry, and precipitation has a maximum in November. The largest winter–summer range occurs in the low elevations of the southernmost tip of Apulia, with more that 100 mm average total precipitation in November and less than 20 mm in July. Summer precipitation in the elevations of the northern area, where the average total of July is about 40 mm (see Figure 2 of the Appendix), is larger than in the rest of the region

Time series for annual T_{max} and T_{min} have been obtained by averaging data of the eleven selected Apulia stations for the period 1951–2005. Linear trends are calculated for the whole period (1951–2005) and for the last 30 years (1976–2005) using the Sen's estimate (Sen 1968) and Mann–Kendal test (Mann 1945) for establishing the statistical confidence level. Figure 2 shows that for the period 1951–2005, mean annual T_{min} has warmed at a rate of about 0.18 °C/decade (significant at the 99.9 % confidence level). In contrast, mean annual T_{max} has not changed significantly. This suggests a progressive narrowing of the daily temperature range. Note that the absence of trend in T_{max} reflects the presence of a cool period in the central part of the record, after which T_{max} has warmed at a very fast rate. Therefore, the trend estimate of T_{max} depends crucially on the time period considered. Warming trends for mean annual T_{max} and T_{min} estimated using the last 30 years of the twentieth century are very high: 0.47 and 0.45 °C/decade, significant at the 99 and 99.9 %, respectively.

Figure 3 shows the rates at which mean monthly values have changed. Two estimates are provided as well, using the whole 55-year-long record and the last 30-year-long period 1976–2005. Figure 3 shows that for the period 1951–2005, warming has affected only T_{min} from May to October, but for the last 30 years of the record, summer T_{max} (June–July–August) has warmed at a rate comparable to that of T_{min} and both have warmed much faster than during the first part of the record, with a peak value of 1.0 °C/decade in August for both variables (see also Figure 3 of the Appendix). However, large negative values are obtained when T_{max} trends in August are computed during the first 25 years of the record. This suggests that these values are strongly affected by multidecadal variability. Figure 3 reports the statistical significance of the trends, which is large from May to August for T_{min} and T_{max} in the period 1975–2006, and for T_{min} for the whole 1951–2005 period as well.

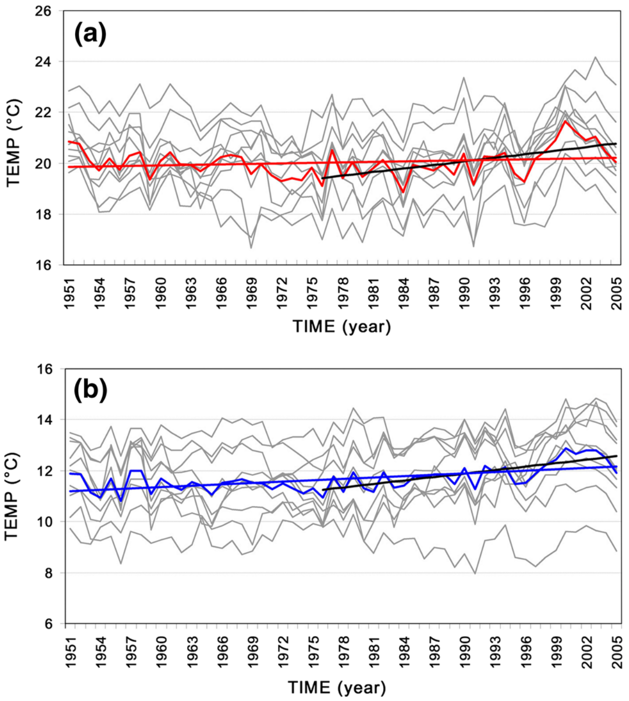


Fig. 2 Annual average T_{max} (**a**) and T_{min} (**b**) for 11 individual Apulia stations (*gray lines*) and the average of the 11 stations in red (T_{max}) and blue (T_{min}). Linear trends are shown for the whole period 1951–2005 and 1976–2005 (*black lines*)

The precipitation stations are grouped into five areas, labeled A–E (Fig. 1b, bottom panel), on the basis of geographic location and climatology. For the period 1951–2005, total annual precipitation (Fig. 4) across Apulia has decreased at a rate of 14.9 mm/decade, which, though it is large in relative terms (it would approximately imply a one-fourth reduction in the mean value in one century), it is not statistically significant. Figure 4 shows that although areas “E” and “A” have systematically higher values than the other areas and inter-annual variations are not identical in the five areas, most high and low precipitation years occur simultaneously. Figure 5 shows that the declining trend in rainfall is concentrated in the months October to January. The maximum decrease (−5 mm/decade) is observed in October. However, no monthly trend is statistically significant, but some of them are very close to reach the 90 % confidence level, so that small changes of the considered period can make them statistically significant (see results in section “Future evolution of seasonal temperature and precipitation and its impact on crops”).

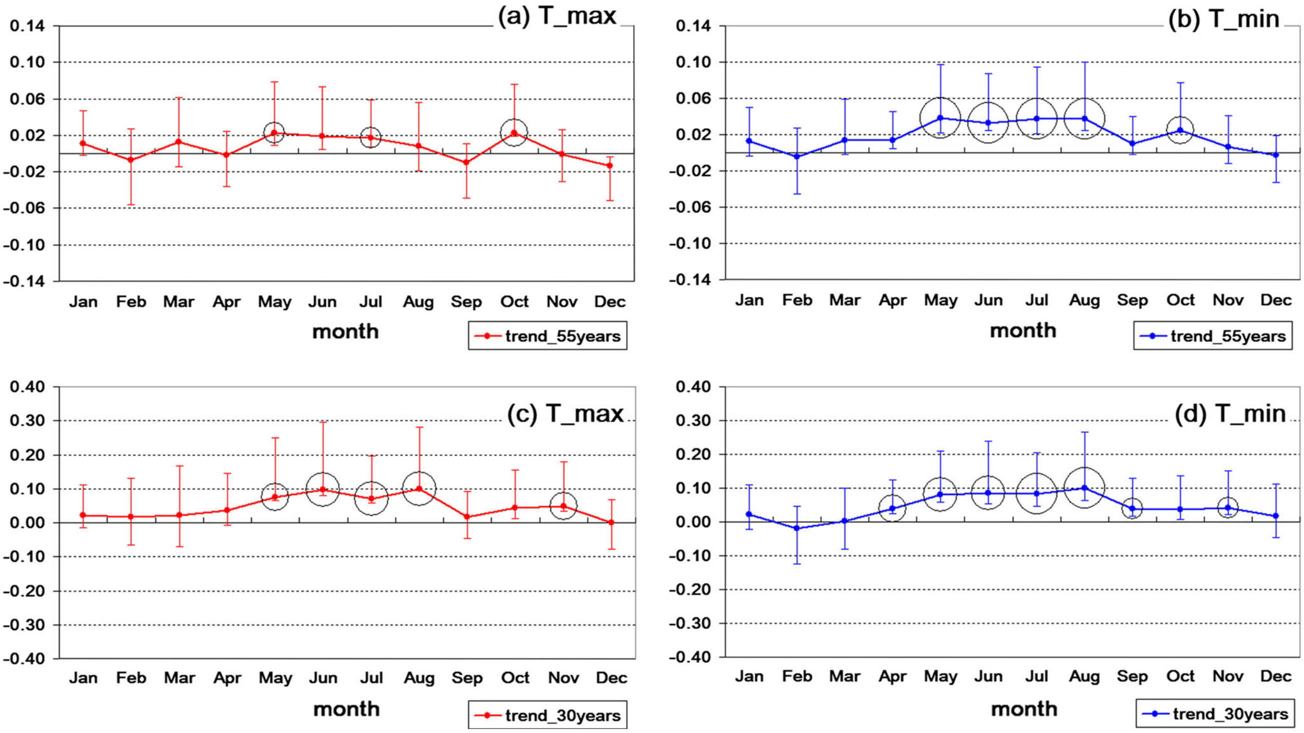
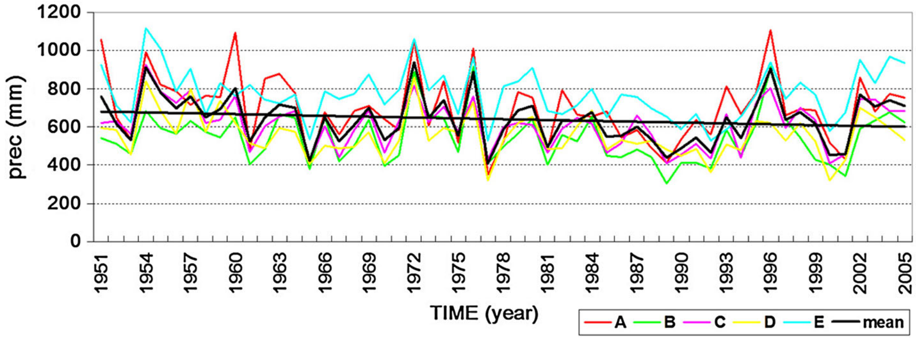


Fig. 3 Trends of monthly mean $T_{\max}$ (**a, c**) and $T_{\min}$ (**b, d**) over Apulia (°C/year). Trends have been computed for the whole period 1951–2005 (**a, b**) and for the period 1976–2005 (**c, d**). *Circles* with increasing size denote trends statistically significant at the 90, 95, 99, 99.9 % levels. *Vertical bars* show the 1–99 percentile uncertainty range

Fig. 4 Total annual rainfall (mm) in Apulia for the period 1951–2005. The *black line* shows the overall regional mean (with its trend), and the *colored lines* correspond to the five areas in Fig. 1b



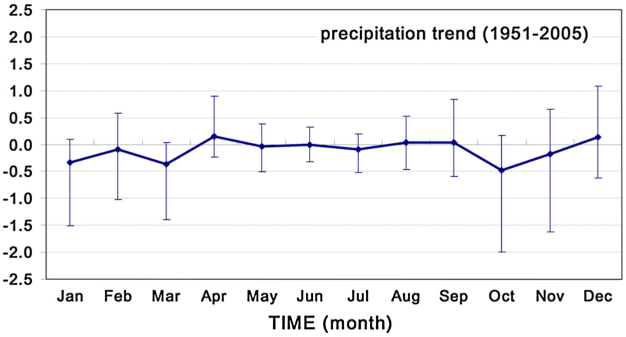


Fig. 5 Trends of monthly rainfall (mm/year) for the whole period 1951–2005. Statistical significance does not reach the 90 % confidence level for any month. *Vertical bars* show the 1–99 percentile uncertainty range as computed by the Mann–Kendall test statistics

Impacts of climate variability on grapevine, olives, wheat

Data

Data for wheat, olives, olive oil, grapes and wine production are available at several databanks for most European countries and regions. Specifically, data for Apulia can be downloaded from ISTAT (Italian Institute of STATistics, http://www.istat.it/), ISMEA (Italian Institute of Services for the agricultural and food market, http://www.ismea.it/) and Eurostat (http://epp.eurostat.ec.europa.eu). Data are estimates based on records collected at sub-regional scale and processed with statistical methods. They include information on products (such as olive oil, must and wine) and crops (total harvest, yield and harvested area). The choice of the variables used in this study (harvested olives, harvested wheat, must and wine production) is driven by the requirement of having at disposal time series sufficiently long to establish a statistical link with climate variables (such as seasonal temperature and precipitation).

The length of the time series is the basic reason for preferring must and wine production to grapevine harvest and yield, though the latter are likely more directly linked to climate. In fact, must and wine (values in thousands of hl) data are available for the period since 1980, while data on harvested grapes and yield are available only since 1996. In any case, inter-annual variability is identical for harvest and yield (the correlation of the respective time series is 0.99), which are very strongly linked to must and wine production (correlation is larger than 0.90), suggesting that relation to climate is similar for all these variables. Market choices and import/export of grapes from/to other regions may explain the marginal differences in inter-annual variability among time series.

Wheat has the longest available time series among the variables considered in this study. For both harvest and yield, which are strongly linked (correlation between the two time series is 0.96), data are available since 1975. Harvested wheat (thousands of tons) is the variable used in this study. Separate records for durum wheat are available since 1995 and show that its percentage fluctuates in the range 98–99 % of total wheat production in Apulia. Therefore, harvest values are in practice representative only of durum wheat production.

Harvested olives (thousands of tons) are available in public databanks only after 1996. The time series has been extended to the period 1983–1991 using published data (De Gennaro 1996). This extension allows to base the analysis on a total of 20 values from 1983 to 2005 (there are no data in the period 1993–1995). As for the previous crops, harvest and yield have an identical inter-annual variability. Harvested olives appear more suitable than values of oil production for this study. First, they should be more directly linked to climate than the latter, which, further, can be affected by import of olives from other regions and possibly altered by misreporting aiming at taking advantage of EU policies in support of olive oil production. However, time series of harvested olives and olive yield are strongly correlated with oil production in Apulia (correlation is 0.94 for both), suggesting that the results of climate analysis do not depend on this choice.

Methods

Must and wine production, harvested wheat and harvested olives have been correlated with seasonal values of T_m ($T_m = (T_{max} + T_{min})/2$) and RR (winter: December–January–February, spring: March–April–May, summer: June–July–August, autumn: September–October–November). The idea is to identify which seasonal variables are actually relevant for each crop and use only variables that are significantly correlated (at the 90 % confidence level) in a simple LRM:

$$y = a + \sum_{i=1}^{N_c} b_i x_i$$

where a is the intercept, b_i *is* the model coefficients, y is the predictand (in turn must and wine production, harvested wheat and harvested olives) and the sum considers only the N_c climate variables x_i (predictors) that are significantly correlated with y. In order to avoid the well-known problem of inflated variance, the LRM does not use T_{max} and T_{min} of the same season, which are highly correlated variables, but uses their mean T_m. Therefore, the candidates for the predictors are seasonal (winter, spring, summer and autumn) T_m and RR, but, in practice, only a small subset is used, depending on correlation with the predictand (see Table 1). A longer time series could presumably allow identifying a larger number of predictors and include in this study a model validation as well.

The relevance of each predictor is estimated by the coefficient of determination R^2, estimated for each individual predictor, and by the adjusted coefficient of determination R^2_{adj}, estimated for the whole LRM. Both coefficients vary from 0 to 1 and are a measure of the fraction of variance of the predictand that is explained by the LRM (see Steel and Torrie 1960 and Theil 1961). When a new predictor is added to the LRM, R^2 necessarily increases, while R^2_{adj} increases only if R^2 is improved more than would be expected by chance. Therefore, R^2_{adj} can be used to decide whether it is worth including a predictor in the LRM.

Table 1 Correlation between seasonal values of the three variables used in this study with mean temperature T_m and precipitation RR

	T_m (winter)	T_m (spring)	T_m (summer)	T_m (autumn)	RR (winter)	RR (spring)	RR (summer)	RR (autumn)
Wine	−0.38*	−0.45**	−0.65**	−0.22	0.01	0.21	0.01	−0.25
Olives	−0.37* (−0.16)	−0.11 (−0.26)	0.03 (0.24)	0.02 (0.22)	0.08 (0.36)	0.01 (0.43*)	0.37* (−0.15)	0.12 (0.22)
Wheat	−0.12	−0.08	0.12	0.12	0.26	0.35*	0.00	0.06

Values are denoted with '*' and '**' for 90 and 95 % statistical significance level. For olives, values between brackets refer to the previous calendar year

Table 2 LRM coefficients, intercept, coefficient of determination R^2 and adjusted overall R^2

	Parameters of selected LRM ± SE					
	Wine (10^3 hl)		Olives (10^3 tons)		Wheat (10^3 tons)	
Intercept	46,400 ± 8,800		620 ± 270		700 ± 110	
	Coefficient	R^2	Coefficient	R^2	Coefficient	R^2
T_m summer (°C)	−1,520 ± 360	0.42****				
T_m winter (°C)			−109 ± 95	0.13*		
RR spring (mm)			2.9 ± 1.8	0.18*	1.52 ± 0.77	0.12*
RR summer (mm)			2.3 ± 1.9	0.14*		
Overall R^2_{adj}	0.40****		0.20*		0.09*	

Only seasonal values of mean temperature T_m and precipitation RR with statistically significant correlation at the 90 % confidence level and used in the LRM are reported in this table. For olives, "RR spring" refers to the previous calendar year. Units of coefficients: for T_m versus wine 10^3 hl/°C, versus olive oil and wheat 10^3 tons/°C, for RR versus olives and wheat 10^3 tons/mm). R^2 and R^2_{adj} values are denoted with '*', '**', '***' and '****' for 90, 95, 99 and 99.9 % significance level, respectively

Results

Table 1 shows the correlation coefficients for must and wine production, harvested wheat, harvested olives and for each seasonal T_m or RR value. Table 2 shows for the three selected predictands, the LRM parameters (intercept a and coefficients b_i), R^2 and R^2_{adj}.

Only wine, among the considered variables, presents a relevant correlation with climate, specifically with temperature (Table 1). Quantity of wine is strongly linked with summer T_m and, to a lesser extent, with spring T_m. Figure 6a and b shows that years with warm summers and springs are characterized with lower than average production. However, spring T_m is significantly correlated with summer T_m ($\rho = 0.41$). Winter T_m (Fig. 6c) is negatively correlated with wine production as well, but only at the 90 % confidence value. Finally, there is weak positive correlation with spring RR (Fig. 6d), which does not reach the 90 % significance level. The LRM on the basis of summer T_m alone is able to explain 42 % of the inter-annual variability of the amount of wine produced ($R^2_{adj} = 0.40$). The extension of the LRM to include spring and winter beside summer T_m is very modest. Adding only one of them, the LRM gives $R^2_{adj} = 0.42$ in both cases, and this value does not increase if all three variables are used. Therefore, the LRM is based on summer T_m alone (Fig. 7a). This is conservative approach that eventually underestimates the effect of climate variability on wine production, but avoids problems related to the use of cross-correlated predictors. In general, the relation of wine production (and quality) with temperature is spatially variable. The negative relation in Apulia between quantity and T_m temperature is likely associated with crossing a high-temperature threshold in a relatively hot region such as southern Italy (see Jones et al. 2005, for a comprehensive discussion). Supplemental irrigation may prevent the identification of the effect of precipitation variability on wine production.

The analysis of olive harvest shows a positive correlation with winter T_m, spring RR of the previous year (approximately 18 months before harvest) and summer RR (all significant at the 90 % level). Phenology of olive trees can explain the favorable effect of cold winter temperatures (Rallo et al. 1994), and their biannual production cycle can explain the presence of a correlation with such large lag. The weak positive correlation with summer precipitation is consistent with the need for irrigation during dry hot summers (e.g. d'Andria and Morelli 2002). Specifically, note that emergency irrigation can reduce effects of dry years on olive oil production. In this case, R^2_{adj} passes from 0.13 using only previous year spring RR to 0.19 including summer RR as well. Including in the LRM winter T_m further increases R^2_{adj} to 0.20. Therefore, in this case, three variables (which are not significantly correlated) are used in the LRM (Fig. 7b).

Wheat harvest (Fig. 7c) has the weakest correlation with seasonal T_m and RR among the considered quantities. No link has been found with temperature variability and correlation with an acceptable confidence level has been found only with spring precipitation (Table 1). This result qualitatively agrees with published literature in similar climate conditions (Quiroga and Iglesias 2009, for Spain), where features such as crop reduction for cereals in dry years were found. The LRM using only spring RR explains about 9 % of the inter-annual harvest variability.

Future evolution of seasonal temperature and precipitation and its impact on crops

Future climate scenarios are provided by the ENSEMBLES European project (Hewitt and Griggs 2004; Hewitt 2005;

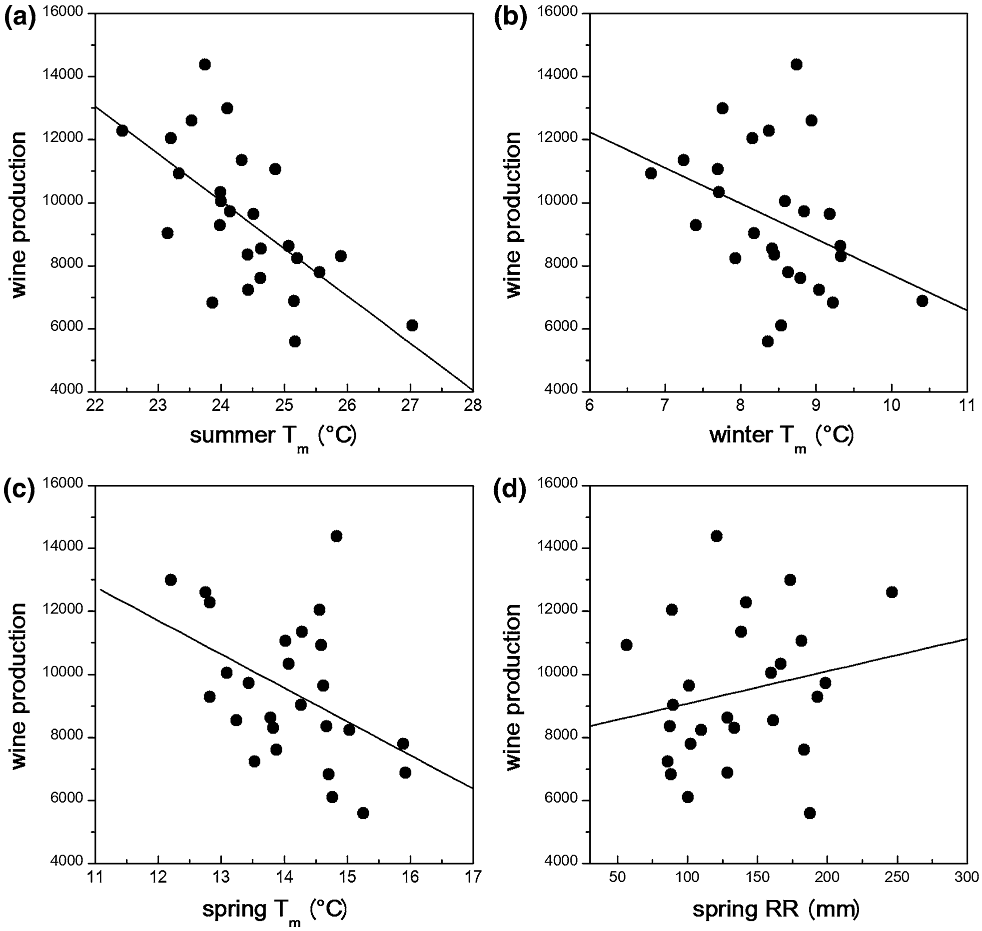


Fig. 6 Linear regression between must and wine production (thousands of hl) and average seasonal temperature T_m (°C) in winter (**a**), spring (**b**) and summer (**c**) and total amount precipitation RR (mm) in spring (**d**) in Apulia for the period 1980–2005. Correlation with seasonal temperatures is significant at a confidence level larger than 90 %. Correlation with spring RR is not significant

http://www.ensembles-eu.org/) and by three simulations carried out during the CIRCE project (Gualdi et al. 2011): the INGV global model with a 80 km resolution, the PROTEUS system of ENEA with a 30 km resolution and the REMO model of MPI with a 25 km resolution. These three simulations have included a two-way coupling with a circulation model of the Mediterranean Sea, which is a unique feature of the CIRCE project. The MPI REMO and ENEA models are RCMs, which were driven by the INGV and by ECHAM5 "non-CIRCE" global models, respectively. The REMO simulation is therefore a dynamical downscaling of the global INGV simulation, and this explains the parallel behavior of their temperature time series (Fig. 8). Seven ENSEMBLES models (the institute that produced the simulations is shown between brackets) are used in this analysis: RegCM (ICTP), RACMO (KNMI), REMO (MPI), RCA (SMHI), which use boundary and initial conditions provided by ECHAM5; CLM (ETHZ), HIRHAM (METNO), PROMES (UCLM), which use boundary and initial conditions provided by HadCM3Q0. The period considered for these simulations is 1951–2050. All simulations adopt the A1B emission scenario for greenhouse gases and aerosol concentrations.

Climate change signal

Figure 8 shows projections for average annual maximum and minimum daily temperature, and total annual precipitation. The gray area represents an estimate of the uncertainty due to the ENSEMBLES models. It is delimited by the maximum and minimum yearly values among the seven ENSEMBLES model simulations considered in this study. The CIRCE model results are very close to the ENSEMBLES mean (red) and are inside the uncertainty range associated with the ENSEMBLES simulations. Figure 8 shows a substantial inter-model agreement. All projections suggest progressively warmer and drier conditions over the next few decades, despite large inter-annual variability. By the mid-twenty-first century, regional temperatures are projected to be more than 2 °C warmer than in the period 1961–1990. Decrease in annual total precipitation (about 100 mm in 100 years) is less clear because of comparatively large inter-annual variability.

The consensus among results of different models and different projects increases confidence in the reliability of these regional climate projections. The similarity of the CIRCE and ENSEMBLES model results shows that the introduction of a dynamically interacting Mediterranean

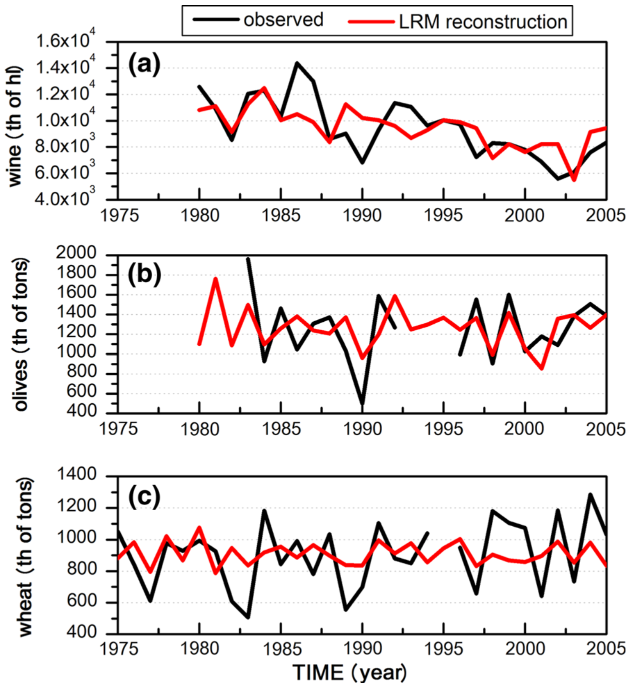


Fig. 7 Observed annual (*black line*) and estimated values (LRM, *red line*) in Apulia for must and wine (**a**, units = 10^3 hl), harvested olives (**b**, units = 10^3 tons), harvested wheat (**c**, units = 10^3 tons)

Sea does not introduce a systematic change in trends with respect to the ENSEMBLES project. However, model results present systematic biases, which cast some doubt on their estimates of the climate change signal (Table 3).

The trends derived from the CIRCE simulations and from the ENSEMBLES simulations are shown in Fig. 9. Trends are computed separately for the two periods 1951–2000 and 2001–2050. Bars in the four panels show trends of average annual temperature, average maximum and minimum daily temperature, and total annual precipitation in Apulia. Colors denote the level of statistical significance of the trends estimated with the Mann–Kendall statistics. Note that observed trends reported in Fig. 9 refer to the 1951–2000 period and are different from those discussed in section "Present trends of monthly temperature and preception in Apulia," which refer to the 1951–2005 period. For precipitation, the different periods imply that trends are statistically significant and larger (−23.9 mm/decade) in Fig. 9 than in Fig. 4.

All model simulations suggest small temperature trends during the second half of the twentieth century, and much larger, significant trends during the first half of the twenty-first century. There is a substantial consistency between the observed model trends in the twentieth century for T_{min} and for RR, while two models show a statistically significant positive trend for T_{max}, which is not present in the observations. However, if trends are computed for the period 1976–2000, when they are stronger, T_{max} trends of models and observations become consistent as well. Model results indicate an acceleration of climate change in the next few decades, which is likely to produce measurable impacts in Apulia. In the period 2001–2050, average annual, and minimum and maximum daily temperatures are projected to increase at similar and very large rates. The means of the three CIRCE models are 0.48, 0.47 and 0.50 °C/decade, respectively, and the means of the ENSEMBLES models are 0.40, 0.39 and 0.45 °C/decade, respectively. Precipitation projections show a general trend toward a reduction, which is about −13.8 and −10.6 mm/decade for the CIRCE and ENSEMBLES means, respectively. The agreement between observed and simulated trends during the second half of the twentieth century increases confidence in the models' capability to reproduce the pace of climate change.

Sensitivity of crops to seasonal changes of temperature and precipitation

The LRM has been used to evaluate the variations production of key crops in Apulia (wine, harvested olives and wheat) caused by the future evolution of seasonal temperature and precipitation. Computations have been carried out using the three CIRCE model simulations and the mean of the ENSEMBLES simulations, as discussed in section "Method." The choice of predictors (including only variables correlated at the 90 % confidence levels and effectively contributing to increase R^2_{adj}) provides a conservative estimate of the effect of climate on crops. Figure 10a shows that the production of wine will be affected in a negative way by the drier and hotter conditions characterizing Apulia in the first half of twenty-first century. Harvested olives will be affected, but less than wine, while the effect on wheat will be small. Table 4 shows the percent change of production for these three crops for the period 2021–2050 with respect to the reference period 2021–2050. Results (which consider no adaptation of crops and no fertilization effect of CO_2) suggest that evolution of these seasonal climate variables in the first half of the twenty-first century will have a negative effect on all considered variables. The most affected is wine production (−20 ÷ −26 %). The effect is relevant also on harvested olives (−8 ÷ −19 %) and negligible on harvested wheat (−4 ÷ −1 %). This last outcome of the LRM is consistent with Ventrella et al. (2012), as they show that durum wheat, sown in winter season, is not particularly sensitive to climate change.

Discussion

Though this analysis provides sensible information, it does not aim at a predictive skill on future evolution of

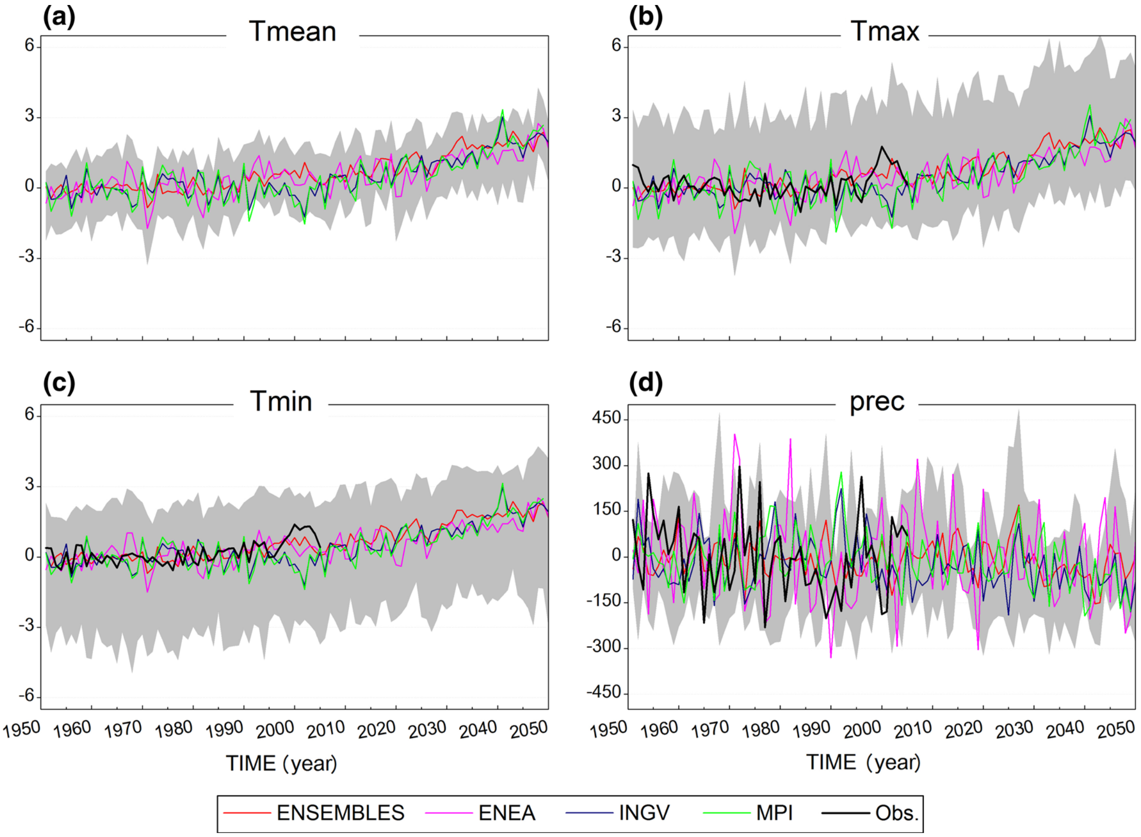


Fig. 8 Time series of annual (**a**) average (**b**) daily maximum (**c**) daily minimum temperature (°C), and (**d**) total annual precipitation (mm) for Apulia. Values are anomalies with respect to the mean baseline period 1961–1990. Lines show the CIRCE climate models: ENEA (*pink*), INGV (*blue*) and MPI (*green*). The *gray area* is delimited by maximum and minimum values produced by the set of models used in the ENSEMBLES project, and the *red line* represents their mean. The *thick black line* shows the time series of the observations (color figure online)

Table 3 Bias in the climate models used in this study with respect to the observed values of annual average maximum temperature (°C), minimum temperature (°C) and total annual precipitation (mm) for Apulia, for the period 1961–1990

1961–1990	ICTP	KNMI	MPI	SMHI	ETHZ	METNO	UCLM	ENEA	INGV	MPI
bias Mod-Obs T_{max}	−2.02	0.40	0.36	−1.51	−0.34	2.82	−2.03	−3.68	−4.13	−0.68
bias Mod-Obs T_{min}	−1.62	1.86	1.71	0.57	0.67	−3.82	0.13	0.41	2.35	−0.57
bias Mod-Obs P_{rec}	−62.70	−265.46	−109.35	−125.77	−70.51	66.15	−72.69	66.73	−159.02	−211.79

agriculture in Apulia, because, as all analog statistical approaches, it has limitations, which are briefly described in this discussion. The adopted model tool (LRM) is rather simple, and this version does not account for very important factors, such as extreme events (e.g. droughts or floods, frost and heat waves), CO_2 fertilization and adaptation.

As it has been mentioned in the introduction, LRMs cannot so far account for CO_2 fertilization (Ewert et al. 2007), which is a very important factor for impacts of climate change on agriculture. Simulations (Ventrella et al. 2012) carried out for the northern part of Apulia show that, for an increase of +2 °C, the positive fertilization effect of increasing CO2 concentration on durum wheat yields was greater than the negative effects due to rising temperature and declining rainfall. Further, positive effects of CO_2 fertilization have been proven by field experiments on grapevine (Moutinho-Pereira et al. 2009), olives (Tognetti et al. 2001) and wheat (Miglietta et al. 1996), showing in this case the essential role of soil nitrogen availability. It is clear that adding CO_2 fertilization is essential for a realistic estimate of the effect of climate change on crops.

Adaptation options, which can be achieved adopting new varieties of the same crops or farming practices (sowing, seeding and harvesting time) and optimizing irrigation management, are not considered, and they could be used for compensating negative effect of climate change or taking advantage from changed conditions. Further,

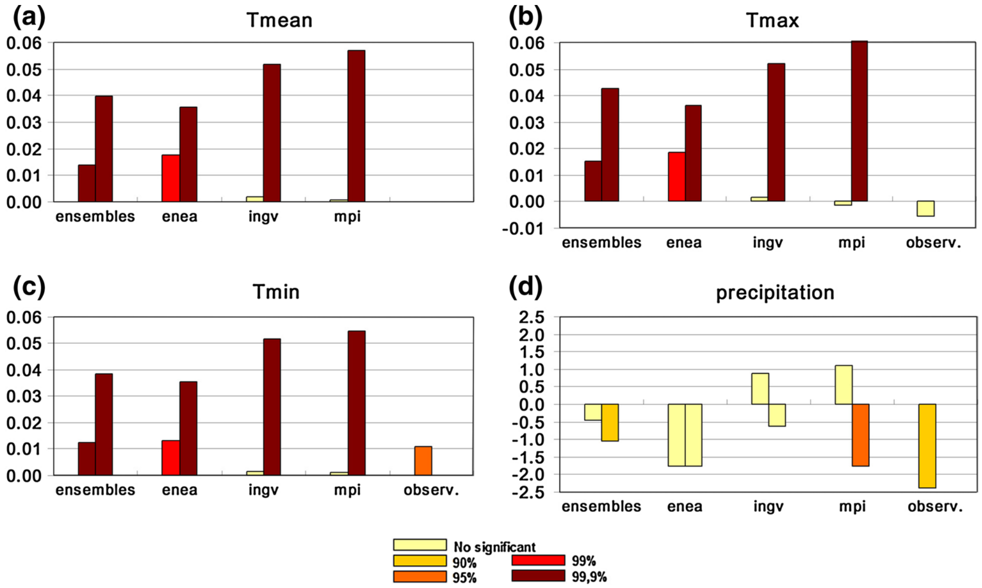


Fig. 9 Trends of annual average temperature (**a**), maximum daily temperature (**b**), minimum daily temperature (**c**; °C/year), and total annual precipitation (**d**; mm/year) for Apulia. Values have been separately computed for the 1951–2000 (*left bar* of each pair) and 2001-2050 (*right bar* in each pair) periods. *Bars* show the CIRCE models and the mean of the ENSEMBLES project simulations (*red*). *Colors* denote the level of statistical significance of trends (not significant, 90, 95, 99 and 99.9 %. The Mann–Kendall test has been used). In panels b, c and d, the single bar on the right shows the observed trend in the period 1951–2000

because of the limited length of the records, the usual validation of the LRM by dividing this short period in two "training" and "validation" parts has not been attempted, and this study has only established the model capability of fitting reasonably well the data. In conclusion, the LRM can correctly show part of the sensitivity of crops to present climate variability, but using its results to estimate the full response of crops to climate change is not correct. A LRM is expected to be realistic only for small deviations from the reference climate conditions, to which it is tuned. It does not include nonlinear dynamics leading to critical thresholds and sudden transition to new environmental conditions.

A small explained inter-annual variance is not a fault only of the simulations in this study. Lobell and Field (2007) show that growing season temperatures and precipitation explain approximately 30 % of year-to-year variations in global average yields for the world's six most widely grown crops. In fact, the literature supports the effectiveness of LRMs (Lobell and Burke 2008). Results of this study for Apulia likely reflect the importance of factors omitted from the analysis. It is relatively easy to speculate on a list of missing climate factors (such as indicators of occurrence of extreme events, number of growing degree days and water availability) and variables that are not part of the climate system, but strongly affect crops (such as year-to-year management changes, changing fertilization, bio-physical and socio-economic factors, pests and diseases and atmospheric pollution), which are difficult to assess and are rarely included in models (see Ewert et al. 2007 for a brief discussion). Other predictors can be chosen in a LRM and eventually lead to better results (Iglesias et al. 2010) than obtained here. The choice of predictors in this study (seasonal T_m and RR) has been driven by the usual choice made by climatologist for describing climate change (e.g. Giorgi and Lionello 2008), and its inadequacy eventually suggests a mismatch between climatologists and agronomists.

The output of LRM depends on the reliability of climate model data and the adopted emission scenario, which are both to some extent debated in the scientific literature. An example is a study, based on statistical downscaling, which suggests a moderate increase in precipitation in Apulia in Summer and Spring (Palatella et al. 2010) in contrast with the results of the RCMs used in this study. However, the considered climate projections for the first half of the twenty-first century show a substantial consensus among models. The models adequately reproduce the observed trend for the period 1951–2000, with the exception of maximum temperature in summer. Note that the recent CIRCE simulations, despite the novelty of including an interactive Mediterranean Sea, confirm the trends of previous uncoupled RCMs. However, most models underestimate precipitation and maximum temperature and overestimate minimum temperature. In some cases, the bias is large and casts some doubt on the capability of the models to reproduce the climate of Apulia.

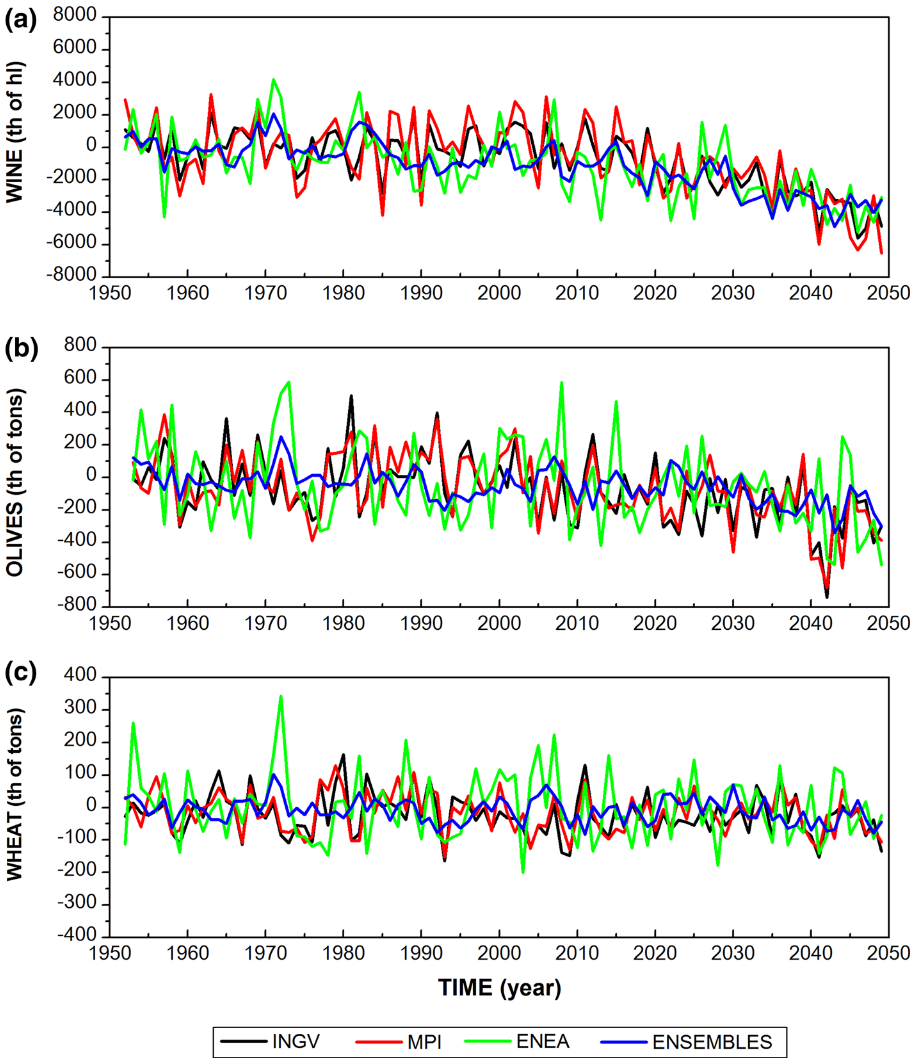


Fig. 10 Crop yield: wine (**a**, in thousand hl), harvested olives (**b**) and wheat (**c**, in thousand tons), simulated by the MLR model using climate data from three different CIRCE models for the period 1951–2049; ENEA (*green*), INGV (*violet*), MPI (*red*). In all panels, values are anomalies with respect to the 1961–1990 mean

Table 4 Percent variation of wine, olive oil and wheat production between the period 2021–2050 and 1961–1990

	INGV (%)	MPI (%)	ENEA (%)	ENSEMBLES (%)
Must and wine	−20	−24	−20	−26
Olives	−19	−17	−8	−8
Wheat	−4	−3	−1	−2

Negative values denote that future production will be lower. The first three columns are based on the results of the CIRCE project models, the fourth column on the mean of the ENSEMBLES project models

It is also important to keep in mind that changes of total production are not linearly related to changes of economic value, as, especially for wine, quality can have a completely different behavior and year with low production can result in high-quality wine with large economic value. Further, worth of growing specific crops is not related to climate change only in Apulia. Climate change in other regions can change international markets in such a way that innovative agriculture practices in Apulia may be needed in order to match competition or take advantage of new opportunities.

In spite of these important limitations, this study shows that climate evolution in the next decade has the potential for triggering changes in agriculture of Apulia. While a simple LRM will never provide the details needed for specific decisions, the interpretation of its results by farmers and policy-makers provides useful information for future risks to be accounted in the decision-making process. Evidence of regional impacts is therefore clear, although, unaccounted factors, the strongly nonlinear character of social-economic dynamics and the potential for adaptation action prevent a deterministic assessment of climate change on the regional economy and society of Apulia.

Conclusions

The SIRP (Servizio Idrografico Regione Puglia) network stations have been used for analyzing monthly temperature and precipitation evolution in Apulia during the period 1951–2005. Although the network contains 83 stations for temperature and 133 for precipitation, only 11 and 24, respectively, were considered on the basis of standard quality control tests and of sufficiently regular availability of data in time. Time series analysis of the Apulia meteorological stations shows trends toward warmer and drier conditions during the second half of the twentieth century. Further work is required on the analysis of daily values and the characterization of weather extremes, such as extreme precipitation, dry periods and heat waves.

Mean annual $T_{\min}$ has warmed at about 0.18 °C/decade. Its increase has been particularly large during the warm season with maximum rates from May to August, when values are about 0.3 °C/decade. The evolution of $T_{\max}$ presents a minimum in the mid-70s, which implies that, considering the whole 55-year period, there is no significant warming trend for the mean annual $T_{\max}$, and even some cooling at monthly scale in December. However, rates of temperature change have become noticeably more intense during the last decades of the century, when mean annual $T_{\min}$ has been increasing at a very high rate (0.45 °C/decade, in the period 1976–2005) and also $T_{\max}$ has also increased significantly at a rate of +0.47 °C/decade, with a faster rate of increase during the summer (+1.0 °C/decade for both $T_{\min}$ and $T_{\max}$).

The detected decline in total annual RR is statistically significant and equal to −23.9 mm/year for the period 1951–2000, but smaller (−14.9 mm/year) and not significant for the slightly longer period 1951–2005. The reduction is larger in the period October–January, but not statistically significant for individual months. However, if sustained for longer time, this decrease could have critical effects on water resources of Apulia, which has a permanent water budget deficit, already imports water from nearby regions and overexploits aquifers.

Climate model projections (the results of the European projects ENSEMBLES and CIRCE have been considered) suggest warmer and drier conditions over the next few decades. During the second half of the twenty-first century, average annual, minimum and maximum daily temperatures are projected to significantly increase with rates in the range from 0.35 to 0.6 °C/decade and precipitation to decrease at a rate larger than 10 mm/decade.

The records of wine production, wheat and olive harvest (three main agricultural products in Apulia) show large inter-annual variability, which, obviously, is strongly affected by many factors outside the climate system, but, however, presents a statistically significant link to seasonal temperature and precipitation. On this statistical basis, a simple LRM has been constructed, showing that these seasonal climate variables explain a significant proportion of inter-annual variability (40, 18 and 9 % for wine, harvested olives and wheat, respectively). An LRM, using the seasonal data of the three CIRCE model simulations and the mean of the ENSEMBLES simulations, has been used to evaluate the effects of seasonal temperature and precipitation evolution on the production of wine, harvested olives and wheat. Its results suggest that wine production (−20 ÷ −26 %) and harvested olives production (−8 ÷ −19 %) could be impacted in a negative way by the drier and hotter conditions characterizing Apulia in the first half of the twenty-first century, while wheat harvest (−4 ÷ −1 %) will be only marginally affected.

This study does not actually aim at having a predictive skill on future crops, because it is based on a highly simplified LRM, which does not account for important factors such as crop adaptation, extreme events, CO_2 fertilization and societal dynamics. However, it confirms that products such as wine and olive harvest are sensitive to climate change in the next decades, which will likely be sufficiently large to have important impacts on regional agriculture in Apulia.

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