Drought stress patterns in Italy using agro-climatic indicators

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ABSTRACT: This paper examines the drought patterns in Italy for the period from 1961 to 2006. The condition of drought was considered from an agricultural perspective, using the variability in the annual yield of maize as an indication of climate patterns. A procedure is presented where weather datasets, a drought stress index (MCDI: Mediterranean crop drought index) and geo-spatial analysis are used to assess the spatial distribution and the general evolution of drought. The regional perspective presented characterizes the general climatology of Italy and compares the climate to a severe drought that occurred in 2003. This study identifies some areas (such as major islands, the central Tyrrhenian coast and south-eastern zones) where agricultural drought is likely to be a problem. In general, the temporal patterns outlined in this study indicate an increase in drought over Italy. Considering the poor resolution of global output results for regional and sub-regional assessments, the analysis carried out provides background data and a methodology for climatologists, ecologists and others interested in developing bio-climate patterns within large geographical regions.

KEY WORDS: Climate change · Drought · Italy · Mediterranean crop drought index pattern · Geo-spatial analysis · Temporal analysis

1. INTRODUCTION

Ecosystem responses to future climate change and the likely impact of the response of plants to such changes have been widely analysed (Easterling et al. 2000, Füssel & van Minnen 2001, Meir et al. 2006). However, only recently has evidence of the observed effects of climate change on crop production been addressed and reported (Lobell & Asner 2003, Chmielewski et al. 2004, Tao et al. 2006). In this context, drought has received special attention, since it was regarded as having been the most serious climatic risk in the 20th century, responsible for the loss of billions of U.S. dollars (Bruce 1994). Drought is considered to be an extreme climatic event, which varies in severity, duration and magnitude across all continents, causing critical damage to both the natural environment and human lives (e.g. Min et al. 2003, Modarres 2007). Climate models point to a future exacerbation in drought related to an increase in the frequency of severe heat wave episodes (Beniston & Stephenson 2004). However, drought is generally identified by a variety of climate elements, where precipitation plays an important role in natural and managed environments (Tao et al. 2006). For the Mediterranean basin, precipitation is expected to decrease in the future (New et al. 2002), and, if the projections are met, the regional consequences will be severe, owing to the scarcity of water resources in this area, the high demand through human activities, and erosion and desertification processes. However, global climatic models have limitations because of their scale resolution, and the model output patterns of drought may not be consistent for areas with high precipitation variability, such as Mediterranean climate areas (Vicente-Serrano et al. 2004). Heat waves and droughts are common features of Mediterranean/European climate and have a massive, negative impact on growth in ecosystems (Mavromatis 2007). However, rainfall deficiencies in summer and winter can have different hydrological impacts depending on the pre-

ceding levels of storage. Historical droughts were analysed by Thomsen (1993) at selected European stations for the period from 1750 to 1989; results were that both types (summer and winter) can occur, encompass large areas and persist for several years, although dry winter and spring seasons were less frequent during both the 18th and 19th centuries throughout the Mediterranean (Pauling & Paeth 2006, Diodato 2007). More recent paleoclimatic reconstructions for Europe (Masson-Delmotte et al. 2005) indicate that, when climate changes from cooling to warming, the frequency of extremely dry years is doubled. This was also found by Beniston & Stephenson (2004), indicating that extreme drought events are becoming more frequent. In this context, drought is currently an environmental problem afflicting Mediterranean and European ecosystems with ever increasing importance (Conedera et al. 2003). The effect of droughts may be of regional or continental concern, including the decrease of precipitation and soil moisture or the increase of crop yield variability and reduction in suitable areas for traditional cultivations (Olesen & Bindi 2002). In the last decades, yield losses from drought events have significantly increased in Europe, which suggests trends towards both increasing vulnerability in some regions (Lloyd-Hughes & Saunders 2002) and increasing length of dry spells (Klein Tank & Konnen 2003).

The analysis of moisture extremes across Europe (Briffa et al. 1994) showed strong decadal-scale variability in dry-spell frequency. Although drought can be important in a sequence of years with rainfall deficiency, the heat wave and extreme drought that hit Europe in 2003 were driven by an extraordinary extension of the subtropical anticyclone for some months, during which hot, dry air was conveyed northward from the southern Mediterranean (Luterbacher et al. 2004, Rebetez et al. 2006). During this event, temperatures of 35 to 40°C were repeatedly recorded in July and, to a larger extent, in August in many European countries (including Italy), drastically raising evapotranspiration rates. Managing drought continues to be a big issue, in spite of improvements in crop and livestock breeding, irrigation systems, tillage practices, and new or emerging technologies, and it demands more research and development on drought mitigation measures (Wilhite 2000). Case studies recently reported for the Mediterranean area have indeed demonstrated that extended periods of drought stress still continue to result in significant impacts on agricultural production (Perini & Beltrano 2004). In environments with high spatial and temporal variability of precipitation, it is reasonable to expect the same variability in droughts (e.g. Fowler & Kilsby 2002). Peninsular Italy and its islands are particularly suitable for drought and heat wave analysis (Baldi et al. 2006).

The interpretation of drought-induced plant stress is a focus of the present paper. Several indices have been developed over the years that estimate the severity of drought (Loomis & Connor 1992). They basically assume that a large accumulation of heat during a given time frame (e.g. decade, season, month), associated with a large deficiency in rainfall during the same time frame, will result in great plant stress. The Palmer Drought Index (Palmer 1965) was often used to characterize drought in many parts of the world, and its use is interesting because it considers both precipitation and evapotranspiration. However, since it requires a number of somewhat restrictive assumptions (Alley 1984), simpler indices have also been used to characterize potential plant stress (e.g. Gage & Mukerji 1977).

Several approaches have been developed to evaluate the spatial and temporal patterns of drought-stress conditions (see Gathara et al. 2002 for a synthesis), from remote-sensed data (Ghosh 1997) to surface data (Hisdal et al. 2001, Wilhelmi et al. 2002), or from both types of data (Vogt et al. 2000). However, none of these methods is consistent and reliable (Fowler & Kilsby 2002). The conversion of remote sensing data into useful information for drought detection and monitoring requires a good understanding of the physics of the measurements as well as sophisticated analysis tools (Vogt et al. 2000). Conversely, surface climatic measurements are readily usable, but their limited spatial density poses difficulties in the interpretation of results. To overcome this problem we studied the spatial variability and temporal patterns of drought across Italy, using a long-term database of agricultural production and weather records, and an indicator of agricultural drought stress. Maps of the drought indicator, integrated with crop yield and vegetation greenness, were generated for Italy using the inverse weighed distance interpolator (driven by an explorative geostatistical analysis). The analysis was performed using maize *Zea mais* L.—a crop that was well fitted to the Mediterranean region and central to the Italian economy—to gather information on water stress situations. For drought characterization, annual grain yield of maize was chosen, as it is a singular representation of the culmination of diverse biophysical processes.

The present paper is structured into 4 sections. In Section 2, we present the study area, the database, and the methods for temporal and spatial analyses. In Section 3, the temporal and spatial drought patterns are shown and long-term climate dynamics are investigated. Possible consequences on crop productivity of drought patterns at regional levels are also discussed. Finally, remarks are made concerning the bearing of the findings on a wider interpretation of drought phenomena and the need for future studies.

2. STUDY AREA AND METHODS

2.1. Study area

Italy is centrally located in the Mediterranean basin and comprises an area of about ~301 000 km² between 36 and 47° N (Fig. 1). For the purpose of this study, a subregional classification was adopted between northern (~44 to 47° N), central (~41 to 44° N) and southern (~36 to 41° N) Italy. The yearly mean air temperature is ~13°C (from about 8°C in the north to 16°C in the south), and the mean annual rainfall values are between <500 and ~1500 mm, roughly decreasing from north to south, but following complex spatial and temporal patterns. The area is, in fact, characterized by a heterogeneous mix of geographic systems (peninsular shape, Alps chain in the north, Apennines chain all along the peninsula). Such heterogeneity affects mesoscale circulation and generates greatly varying precipitation (Meneguzzo et al. 1996) and evapotranspiration (Diodato & Bellocchi 2007) patterns at all spatial and temporal scales. In summer, long periods of bright sun can be associated with hemispheric circulation from the south (i.e. sub-tropical anticyclones), often interrupted by atmospheric instability with showers and thunderstorms.

Weather has an important impact on Italian agricultural activity, which plays an essential role in the ecology and economy of the country. Domestic crop production comprises a significant proportion of the national food supply and by-products, as well as a component of the nation's export marketing strategy. The role of weather as a cause of the variability of crop production at local and national scales is therefore a subject of concern. Variability in the annual yield of crops (especially for non-irrigated cultivations) is a useful indicator of regional climate patterns because plant growth and biomass accumulation have been found to depend primarily on weather (e.g. Gage 2003). The Italian climate is usually defined as mild-temperate, although in recent years the climate has often deviated from this type towards either an excess of rainy months or more arid seasons. In the period from May to September, rainfall amounts are generally slight, with long periods of drought stress in mid- and late-summer, when the maximum temperatures frequently exceed 30°C. As a consequence, the soil moisture reserve declines. Water storage is the most limiting factor for crop yields, causing varying levels of crop stress, contingent on the developmental stage of the plant. An example of this was the extraordinary heat wave that occurred in 2003 throughout Europe, which was associated with deficit soil moisture and extreme drought stress. In particular, for the period from May to August 2003, the temperature anomaly registered throughout Europe was considerably above normal (1961 to 1990) values of 2 to 4°C (www.ncdc.noaa.gov/oa/climate/research/2003/ann/global.html).

2.2. Database description

A database of annual maize grain yields and climate data (monthly values of precipitation and minimum and maximum temperatures, then aggregated on monthly basis) was compiled from public web sources supplied, respectively, by ISTAT (www.istat.it) and the system SCIA (www.scia.sinanet.apat.it) of the APAT (Italian National Agency for Environmental Protection, www.apat.gov.it). The SCIA database is based on information from different weather networks: Italian Air Force Meteorological Service (www.meteoam.it), UCEA-BDAN (www.ucea.it) and other local networks. SCIA weather data were available for individual weather stations from 1961 to 2006. The climate datasets were downloaded from primitive data points not uniformly distributed in time and space. For this reason, a minimum number of stations (81), common to a long-term climate dataset — 1961 to 1990 (baseline) — and next to this period for individual years, were taken for this study (Fig. 1). For analyses on a yearly basis, since 1961, a homogeneous dataset was only available on a ~1 × 1° grid, supplied by the Goddard Institute for Space Studies (www.giss.nasa.gov). Weather data from other recent years were used for a more complete temporal analysis in 2 test areas: the Lombardy region (northern Italy) and Benevento province (southern Italy).

For each Italian province, ISTAT supplied average maize yields for 1961 to 1990 and annual yields for 1999 to 2006 (public web source). For 2 test areas
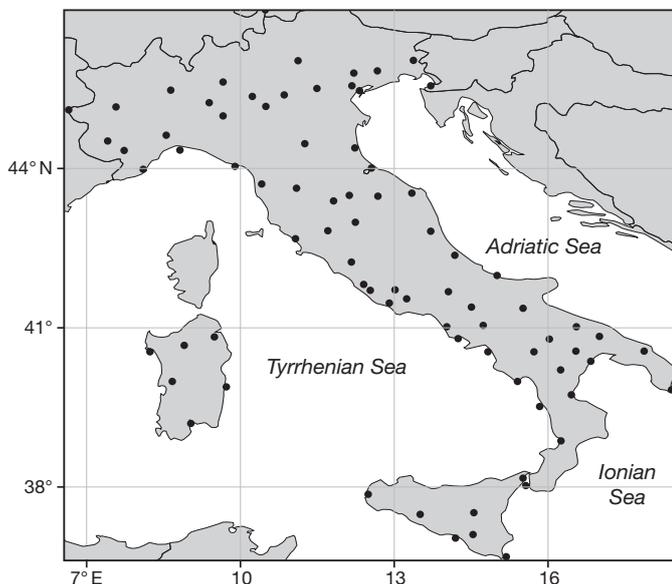

Fig. 1. Distribution of station data points in Italy

(Lombardy region and Benevento province), annual yields were also retrieved for antecedent years (1992 to 1998) from ISTAT bulletins.

2.3. Geo-processing

Climate and maize yield patterns were comparatively assessed, as associated with the measurements taken at the meteorological sites. To scale the climate data to ecological regions, each of the ecological categories (roughly reflected by the administrative provinces) was associated with each of the data points in the Italian domain. Weather and crop data points did not match exactly. Crop data for the provincial territory were centrally placed in each province, and associated to the closest available station. Both climate and yield databases were retrieved from the public web domain to describe average conditions for a 30 yr reference period from 1961 to 1990 (climate baseline) and for individual years (from 1961 to 2000). Both climate and yield datasets were imported by a GIS system (ArcGIS-ESRI, www.esri.com) and processed to generate equal grid-cells of output (pixel size equal to 30 km) for successive manipulation, computation and interpretation. The final map made by geo-processing permits the linkage of crop yield and monthly drought index values to gain knowledge about temporal and spatial characteristics of crop yield and the effects of climate on crop production–regulating patterns.

Satellite-derived maps of an indicator of the state and productivity of vegetation in Italy, FAPAR (fraction of absorbed photosynthetically active radiation), were downloaded (http://fapar.jrc.it) and used to relate the response of drought events to the vegetation patterns.

2.4. Drought assessment using stress indices

Drought was analysed using a crop drought stress index developed for potential use in Mediterranean areas, termed Mediterranean crop drought index (MCDI). This index, derived from temperature and precipitation data, was compared to 2 relatively simple drought stress indices, which, to some extent, share the same type of inputs: Ulanova's index (Gathara et al. 2002) and the heat/precipitation ratio (HPR) (Gage & Mukerji 1977). Both these indices avoid the need for continuous evapotranspiration inputs that are not observed (or difficult to estimate) for a large number of stations over a long period of time.

The Ulanova's index (C_y) is a generic crop drought stress index, formulated as follows:

$$C_y = \frac{0.01 \sum T_{\text{May–June}}}{W_a + \sum p_{\text{May–June}}} \tag{1}$$

where $T_{\text{May–June}}$ (°C) is the sum of mean air temperatures for May and June, $p_{\text{May–June}}$ (mm) is the sum of precipitation for May and June, and W_a (mm) is the usable soil moisture reserve at 1 m depth when the average daily spring air temperature exceeds 5°C (climatological value supplied for each site by Perini et al. 2004).

The HPR, originally developed for interpretation of drought-induced stress in insect populations (Gage & Mukerji 1977) and later applied to maize (Gage 2003), is as follows:

$$\text{HPR} = \frac{\text{MDD}_m}{1 + p_m} \tag{2}$$

where MDD_m is the degree-day accumulation in the month m and p_m (mm) is the precipitation in the month m. High HPR values indicate that heat accumulations are associated with low amounts of precipitation.

Since the response of yield throughout the growing season is dependent on the environmental conditions occurring in the growing month, as well as the conditions occurring in antecedent periods (Wu & Wilhite 2004), C_y and HPR were revised to give the monthly based MCDI such that:

$$\text{MCDI} = \frac{\text{MDD}_m}{0.55 p_{m-1} + p_m + 30} \tag{3}$$

For both Eqs. (2) & (3), degree-day accumulation was calculated following the single triangle method (after Snyder 2002):

$$\text{MDD}_m = n\left[\frac{(T_{\max} - T_L)^2}{24} + (T_{\min} - T_L)\right] \quad \text{if } T_L < T_{\min} \tag{4}$$

$$\text{MDD}_m = n\frac{(T_{\max} - T_L)^2}{24} \qquad \text{if } T_L \geq T_{\min} \tag{5}$$

where $T_{\max}$ and $T_{\min}$ are the monthly mean maximum and minimum air temperatures (°C), respectively; T_L is the threshold temperature, which was set equal to 10°C for maize; and n is the number of days in a month.

Scatterplots and linear fits of data in Fig. 2 show a high degree of correlation ($R^2 = 0.65$) between MCDI and maize yield, while a poor fit was observed with both other indices. The terms of Eq. (3) are therefore a combination of concepts that make MCDI more operational than other indices in the face of the relationship between drought and maize yields.

2.5. Geo-spatial analysis of drought

An approach that calculates the MCDI values at any unsampled location from the neighbourhood data is the interpolator called the inverse weighted distance (IWD). This method combines the proximity concept with the gradual change of the trend surface. The underlying assumption is that the value of an attribute
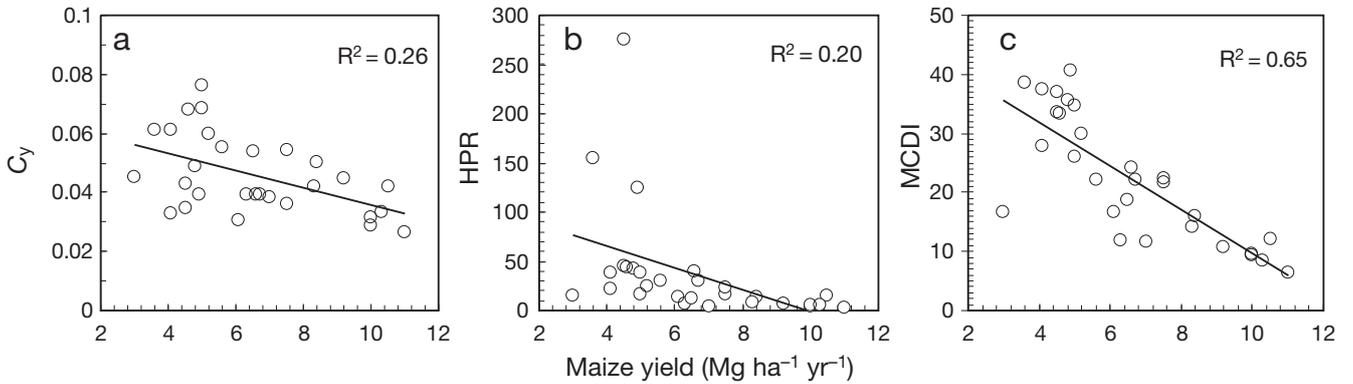
Fig. 2. Relation between drought indices and maize yield in the period from 1999 to 2006 for non-irrigated maize crops in Italy with (a) Ulanova's index (C_Y), (b) the heat precipitation ratio (HPR) and (c) the Mediterranean crop drought index (MCDI). HPR and MCDI were accumulated from May to August

z at some unvisited points is a distance-weighted average of data points occurring within a neighbourhood or a window surrounding the unknown point. The form of the inverse distance weighting estimator, $z^{\star}_{IWD}(s_o)$, is:

$$z^{\star}_{IWD}(s_o) = \frac{\displaystyle\sum_{i=1}^{n(s)} z(s_i) \times d_i^{-w}}{\displaystyle\sum_{i=1}^{n(s)} d_i^{-w}} \qquad (6)$$

where $z(s_i)$ are the station–location data points, d_i are the distances between the station–location combinations s_i and the unknown point s_o, and w is the weight involved in the geospatial interpolator calibration IWD. All computations were carried out by using the Geostatistical and Spatial Analyst modules implemented in ArcGIS-ESRI (Johnston et al. 2001).

3. RESULTS AND DISCUSSION

3.1. Temporal pattern of maize yield

Variability in maize yield over time (1992 to 2006) is shown in Fig. 3 at 2 selected areas of Italy (1 in the north: Lombardy region, Panel (a); 1 in the south: Benevento province, Panel (b). The seasonal MCDI (accumulated from May to August) is also reported for the same period. At both sites, general trends towards increasing or decreasing yields are assumed not to be associated with changes in technology (L. Mariani, University of Milan, pers. comm.). For maize yield in Italy, trends associated with plant breeding can be considered to be no longer effective since the 1990s, with certain stability in both agricultural management and crop genetic basis in the following years (T. Mag-
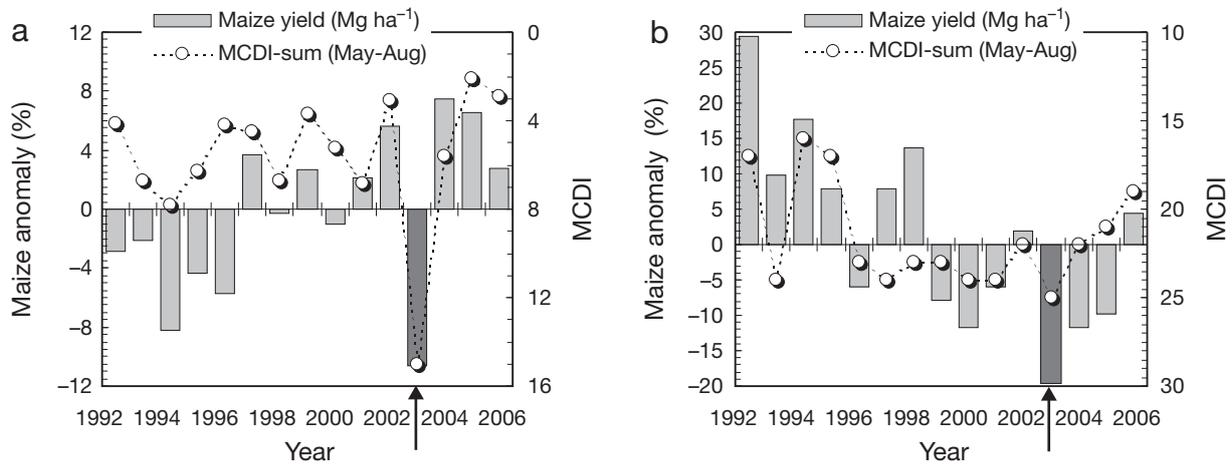

Fig. 3. Temporal patterns of maize yield percent deviation from the mean (1992 to 2006) and the Mediterranean crop drought index (MCDI) during the growing season between May and August from 1992 to 2006, (a) for the Lombardy region, north Italy, and (b) the Benevento province, south Italy. Dark bar denoted by arrow: extreme year (2003)

giore, University of Milan, pers. comm.). This is also in reference to the strict European constraints in the sector of biotechnology (Moberg 2005), whereas genetic engineering has massively expanded worldwide and enhanced the power of modern plant breeding (Thro 2004). Thus, the observed inter-annual variation in maize yields can be considered largely driven by weather factors. Fluctuations in the stress index roughly reflect yield variations. Notably, the extreme drought of 2003 occurred with very high MCDI values and was associated with crop yield depression in both areas (dark grey bars in Fig. 3).

3.2. Temporal pattern of drought during the maize growing season

Temporal analysis of drought was assessed over the 4 decades from 1961 to 2000. To examine the temporal pattern, the MCDI values for May, June, July and August were used. These months were chosen because they encompass times when plant stress may have a considerable impact on plant productivity. The yearly fluctuation of the seasonal MCDI for the relevant months is given in Fig. 4, where the values are contrasted to the season of extreme drought in 2003.

The higher values of MCDI, observed in the second half of the period considered (i.e. 1981 to 2000), are an indication of the climate changes experienced in Italy over the last decades of the 20th century, which led to more severe drought conditions (Fig. 5). For the 1981 to 2000 period, a larger proportion of positive anom-
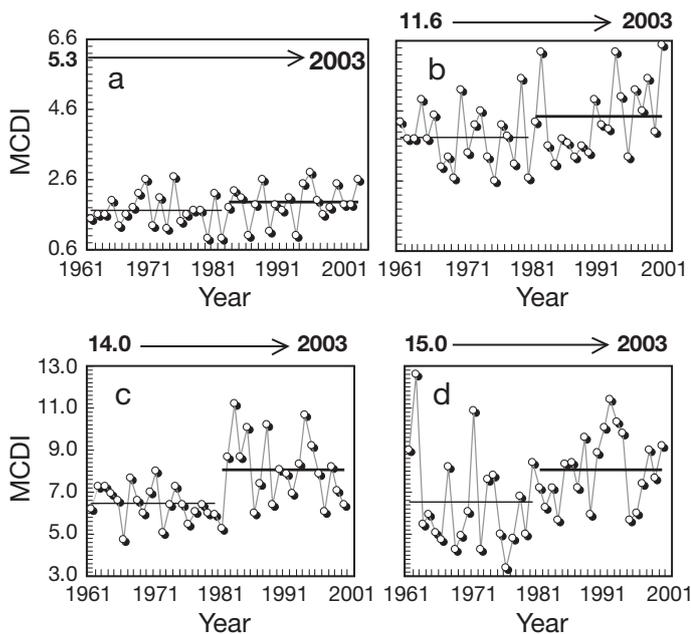

Fig. 4. Fluctuation of MCDI values in Italy from 1961 to 2000 for (a) May, (b) June, (c) July and (d) August. Mean values are reported for periods from 1961 to 1980 (thin bar) and 1981 to 2000 (thick bar). The value computed for the extreme drought in 2003 is also reported
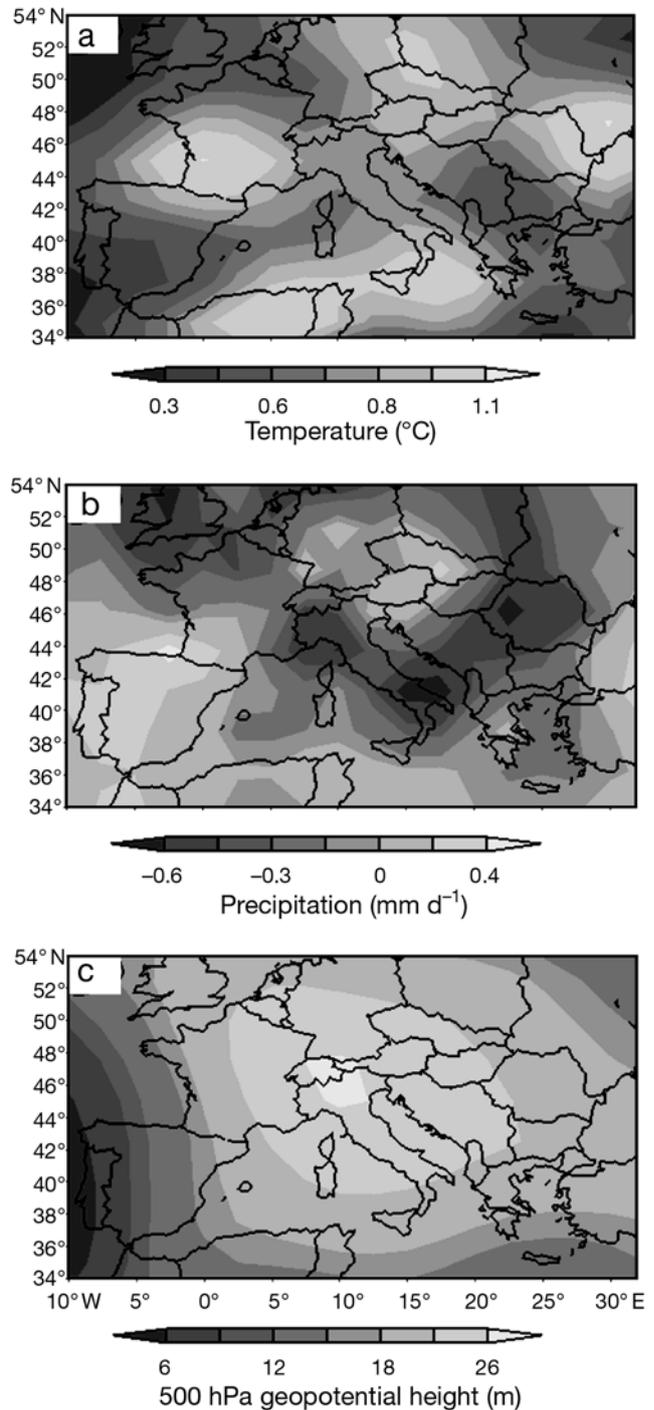

Fig. 5. Seasonal anomalies (mean of May to August: 1981 to 2000 minus 1961 to 1980) of surface (1000 hPa) (a) air temperature (°C) and (b) precipitation (mm d^{-1}), and of (c) geopotential height (m) at 500 hPa, processed by NCEP/NCAR re-analysis (source: www.cdc.noaa.gov)

alies were observed in summer air temperature than during the 2 preceding decades (Fig. 5a), together with extended negative anomalies for precipitation (Fig. 5b). Such patterns (tendency towards air temperature increase and precipitation decrease) are roughly consistent with the geopotential anomaly distribution displayed in Fig. 5c, which shows a positive anomaly of pressure centred in northern Italy, propagating southward along the peninsula. These results are in general agreement with the conclusions obtained for other parts of Europe, where changes in the drought were related to variations in the large-scale circulation features of Europe and the Atlantic Ocean (e.g. Esteban-Parra et al. 1998, for decreases in precipitation over the Mediterranean and in the interior regions of Spain; Xoplaki et al. 2000, for winter dryness in Greece; Tran et al. 2002, for drought in Bulgaria). In particular, stronger westerly flows over the eastern North Atlantic and the rising 500 hPa height (and the sea level pressure) over continental Europe during the last few decades were connected with enhanced atmospheric stabilization and anomalous advection of cold, dry air from northerly directions (Trigo et al. 2006).

The yearly percent anomalies of accumulated MCDI from May to August for 1961 to 2000 (Fig. 6a) show a distinct pattern of positive values in the second half of the period of 40 yr investigated. Such a pattern is noteworthy for southern Italy (approaching +40% in 1993), less marked in the centre and almost indiscernible in the north. The soil moisture pattern given for Italy during the same period (Fig. 6b) tends to reflect the MCDI anomalies. Although to a different extent, negative anomalies in soil moisture manifest themselves quite consistently across low latitudes, with attenuation toward the north (to distinctly positive values in the north, close to the Swiss border).

Examination of the MCDI data computed for different latitudinal regions (north, centre and south) also revealed important seasonal patterns (Fig. 7). In Fig. 7a–c, the average MCDI for the time interval from 1961 to 1990 is contrasted with MCDI values in 2003 within each of the regional classifications. For 2003, the MCDI was only less extreme in northern and central Italy in July. However, the co-occurrence in May to August 2003 of above normal values of MCDI within each of the regional classifications investigated demonstrates that extreme drought phenomena occurred in 2003 across all areas of Italy.

3.3. Spatial pattern of MCDI and maize yield

An important step in a geospatial study is the preliminary knowledge of spatial distribution of data, called exploratory data analysis. With exploratory data analysis methods, the properties of a given dataset are investigated prior to taking decisions on the kind of manipulation and computation to be carried out in further analysis (Webster 2001).

Exploratory data analysis was performed in the present study to support scaling up at the sub-regional level. Variogram functions were derived to instruct the ArcGIS-ESRI Geostatistical Analyst on how to gather and use control points during MCDI and yield interpolations with IWD. Weight w (Eq. 6) was estimated for MCDI (1.42) and maize (1.65), corresponding to the lowest values of the mean prediction error and the root mean square prediction error. In the exemplary variogram surfaces of Fig. 8, geometric anisotropy can be seen in a NW–SE direction (dark grey band). Based on the above, an anisotropic neighbourhood of points was used (Fig. 8b), corresponding to the search ellipse
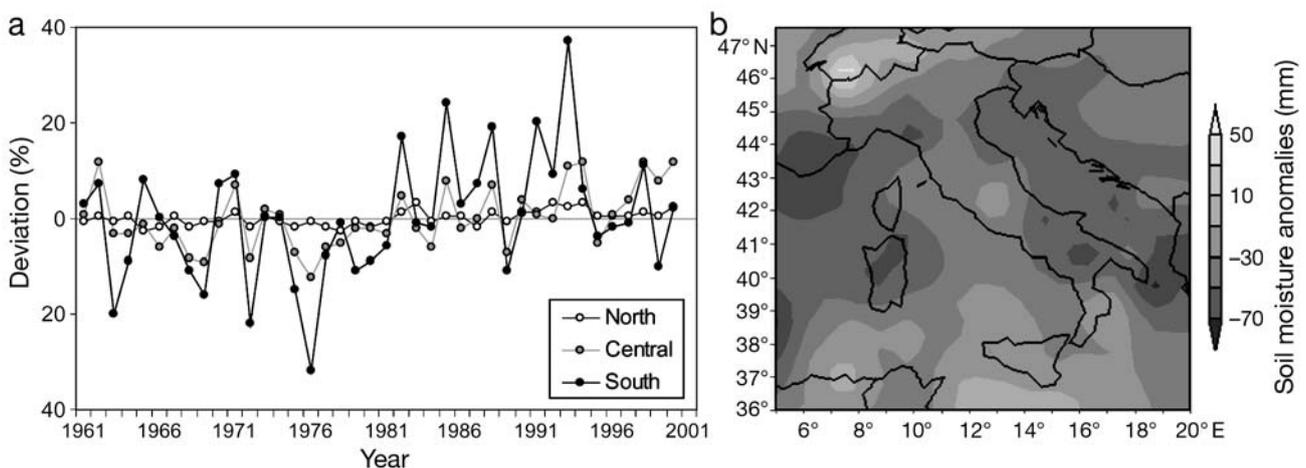

Fig. 6. (a) Percent deviations from the mean (1961 to 2000) of seasonal (from May to August) MCDI, and (b) soil moisture anomalies (mm; mean of May to August: 1981 to 2000 minus 1961 to 1980), processed by NCEP/NCAR re-analysis (source: www.cdc.noaa.gov)
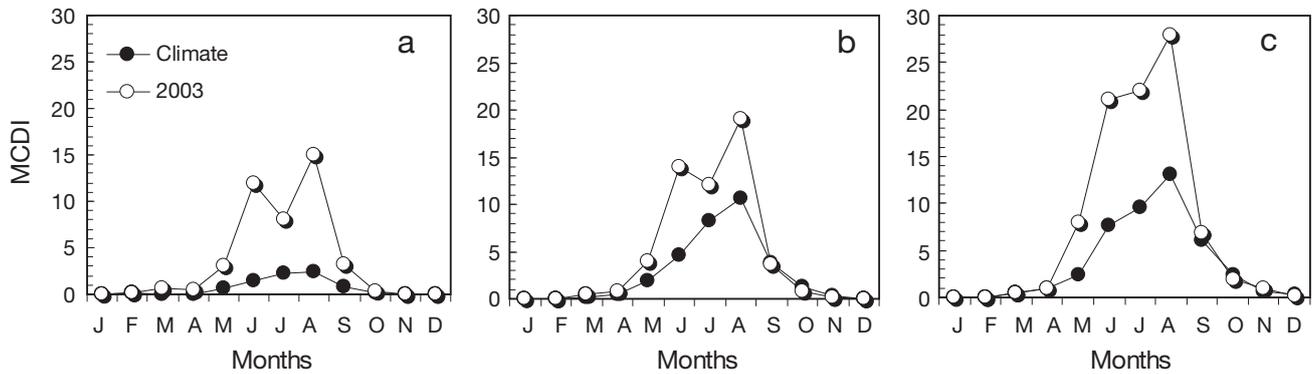
Fig. 7. Monthly regime of MCDI for 1961 to 2000 and 2003 (a to c: north to south)
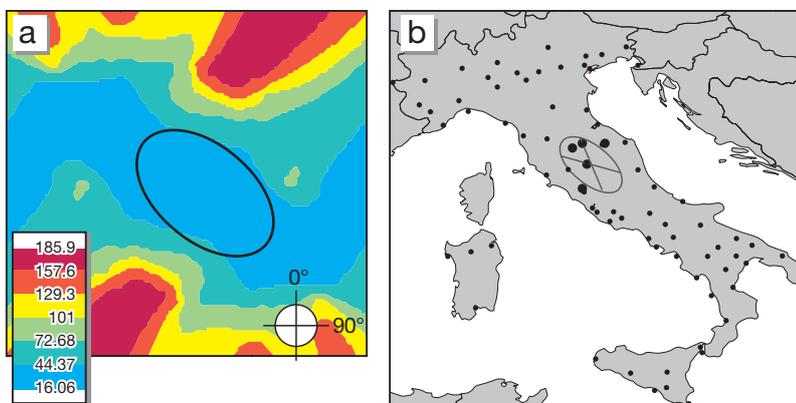

Fig. 8. (a) Variogram surface (MCDI semi-variances) with anisotropic search ellipse and (b) station pattern showing control data points for target site estimation during the interpolation process. Cross through the elipse identifies 4 sectors for station capturing

characterized by the radii of the principal axes (minimum 100 000 and maximum 140 000 m), the angle of the major direction of anisotropy (310°), the number of sectors (4) and the number of data points (2) in each sector.

To characterize the spatial distribution of drought stress throughout the Italian region, surface grid maps of MCDI were developed based on monthly values of MCDI at each location, and 2 maps of cumulative MCDI data from May to August were produced. One of the maps shows the climatic period (Fig. 9a), and one shows the extent of MCDI values for the extreme year 2003 (Fig. 9b). Based on the climatic period, MCDI values >50 occurred only in insular regions (Sardinia and Sicily). However, in 2003, these values occurred in large areas of Italy, with extreme values (i.e. MCDI > 70) over the coasts of Tuscany and Latium (central and high Tyrrhenian), north Apulia (towards the Adriatic coast, ~41 to 42° N latitude) and major islands. These patterns were also reflected in the FAPAR map (Fig. 9c), representing August 2003 (when an increased variation in FAPAR values can be attrib-

uted to the late season senescence of vegetation). A good agreement was thus achieved between areas expected to be agro-climatically drought sensitive and vegetation patterns during this extreme drought-stress event. A drought that occurs over a large region for a relatively short time period (months compared to several years), as was the case with the 2003 drought, can be economically devastating. However, the same event is not necessarily accompanied by ecological catastrophes, as illustrated by the FAPAR image (Fig. 9c).

Under normal drought stress, the agricultural sector is usually the first to be affected because of its dependence on stored soil water, which is rapidly depleted during extended dry periods. Maize is particularly sensitive to summer droughts, and this occurred in a generalized way in Italy over 2003, when this particular climatic anomaly took place. The magnitude of the difference between the 30 yr period (1961 to 1990) and the corresponding 2003 maize yield values is illustrated spatially in Fig. 10. The following equation was used to compute the differences of Fig. 10c:

$$\mathrm{NPD} = \frac{Y_{2003} - Y_{\mathrm{baseline}}}{Y_{\mathrm{baseline}}} 100 \tag{7}$$

where NPD (%) is the normalized percent difference and Y_{2003} and Y_{baseline} (Mg ha^{-1}) are the mean maize yields for year 2003 and the 30 yr period, respectively.

The contrast between the 30 yr period and 2003 was less marked in areas such as northern Italy, the central Adriatic coast and Sicily, as a result of massive irrigation to ameliorate summer water stresses. In these areas, yields in 2003 were comparable to years when moisture was adequate for normal maize production (Fig. 10c).
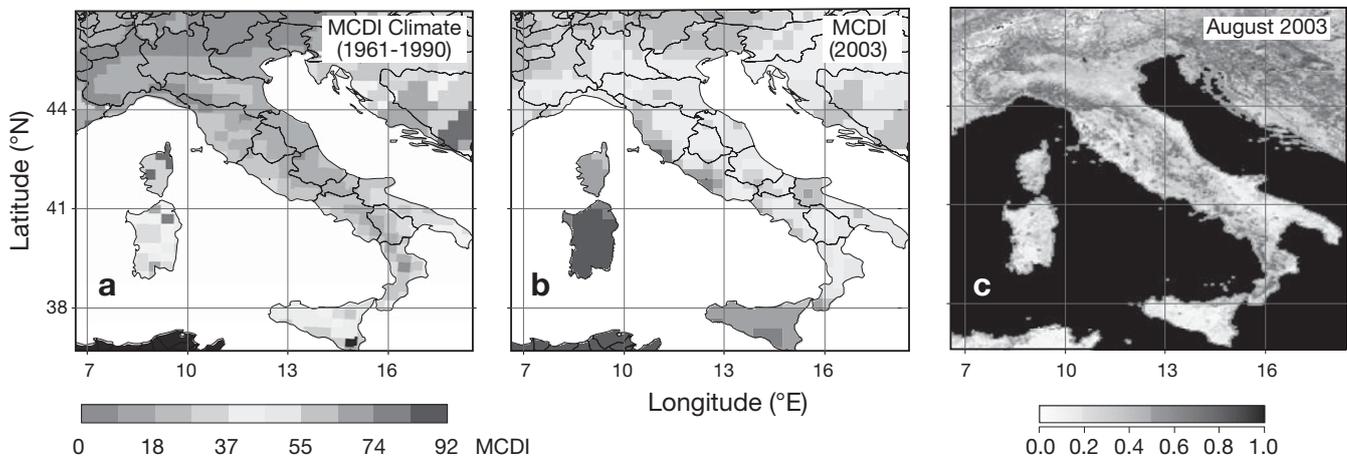
Fig. 9. (a) Spatial patterns of the summer (May to August) MCDI for the 1961 to 1990 climatic period and (b) for the extreme drought in 2003, and (c) the FAPAR (fraction of absorbed photosynthetically active radiation, available at http://fapar.jrc.it) pattern in August 2003
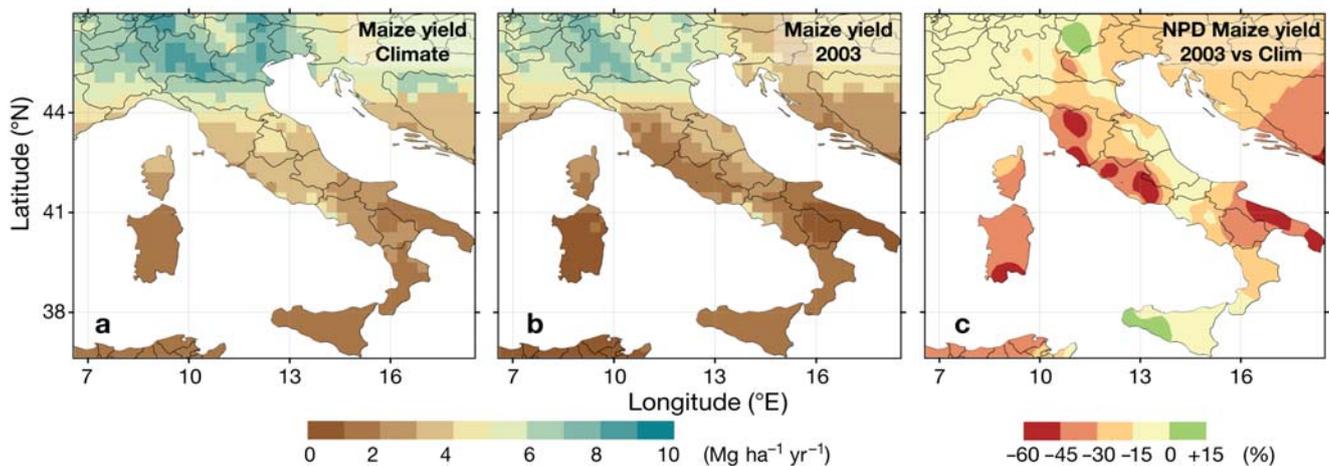

Fig. 10. Spatial patterns of (a) the average long-term (1961 to 1990) maize yield, (b) the maize yield in 2003, and (c) the maize yield by normalized percent difference (NPD) of 2003 versus long-term maize yield

4. CONCLUSIONS

While simulation studies are frequently published about the effects of projected future climate change on crop yields, there are relatively few studies on the impacts of the observed climate change that has already begun affecting crop production. Quantitative reconstruction of the impacts of climate change on organisms and ecosystems represents an important and challenging line of enquiry. Agricultural systems are particularly sensitive to climate changes, and historical crop yields provide an interesting proxy documentation of close interaction between environment and climate trends. The present study offers an evaluation of a newly proposed drought stress index (MCDI), which was used to quantitatively assess the

distribution of drought conditions over Italy in relation to maize grain yield. The indicator proved useful in interpreting the impact of climatic changes that have occurred in Italy in the last decades of the 20th century.

For maize in Italy, it is known that the use of irrigation mitigates drought stress. This use has been (and, due to the effects of climate change, will likely continue to be) massive in certain areas of the country, with significant ecological costs (and subsequent economic costs) from depleting aquifer resources (water being a limited resource that needs to be allocated to different components of the ecosystem). Such costs, not evaluated in this study, have implications especially in situations where drought phenomena turn into a more complex climatic condition. This is a scenerio suggested by Schär et al. (2004), who have, in recent

decades, found a pronounced increase in the year-to-year variability of the European climate in summer. Such an increase in variability might explain the unusual European summer in 2003 and may strongly affect the incidence of extreme events in the future. Furthermore, when an increasing frequency of intense rainfall events is accompanied by a clustering of dry periods, this may also represent a potentially dangerous combination for soil erosion (Sauerborn et al. 1999).

The identification of climate boundaries (areas with homogeneous climate) of drought scenarios at regional or sub-regional scales (as in this study) is important for understanding the climatic features and their potential impact on local agro-ecosystems. The results gained from the present study encourage the use of coupled GIS and geospatial techniques to develop finer interpolation surfaces or probability maps of the drought stress index. Because of the spatial and temporal variability and multiple impacts of drought, there is a need to improve the tools and data available for mapping and monitoring this phenomenon at a variety of scales.

LITERATURE CITED

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