DEVELOPMENT OF A SYSTEM FOR MONITORING AND FORECASTING DROUGHT EVENTS OVER TUSCANY REGION

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EXTENDED ABSTRACT

Drought is a recurrent feature of climate and can affect areas with different climate regimes and human activities. Its impacts depend on the duration, intensity and extent of precipitation deficiency and water demand for several purposes. Due to the complexity of this phenomenon, it is crucial to analyze both current conditions and evolution of a drought event in order to provide accurate, timely and affordable support for policy setting and impacts management.

In this perspective the LaMMA Consortium of Tuscany Region and the IBIMET-CNR Institute are developing a comprehensive operational system for quasi-real time drought monitoring and medium-long time forecasts in Tuscany region (Central Italy), with the aim to deliver periodical, geo-referenced information about areas affected by an increasing reduction of available water resources.

The monitoring part of this system consists of a coupled rainfall-based and satellite-derived set of indices suitable for our region and selected taking into account data availability. This system allows the assessment of vegetation moisture and temperature conditions at different spatio-temporal scales. An analysis of vegetation performances related to temperature and moisture stress is made throughout the Normalized Difference Vegetation Index (NDVI) profiles anomalies and the Vegetation Health Index (VHI), derived from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) products, available since 2000 and updated each 16 days. These indices are selected in order to enhance the climate-based Standardized Precipitation Index (SPI) and Effective Drought Index (EDI), which provide multiple time scale drought occurrence and duration. In this paper a multi-temporal NDVI profile of deciduous Tuscan forests is used as monitoring example of seasonal growth variations related to extreme climate events.

For the forecasting part of the system the SPI, elaborated from a daily E-OBS (Ensamble Observational) gridded data set over the whole Europe, provides the basis for seasonal outlooks of drought evolution. Forecasts of the next 1-3 months follow a physically-based statistical approach based on an “adaptive multi-regressive method” that takes into account potential predictors among a list of physical atmospheric indices and Sea Surface Temperature (SST) anomalies. Information about current condition related to the last 16 days available is delivered on the LaMMA Consortium web site and uploaded on an Open Source WebGIS platform. Finally, monthly bulletins furnish a more detailed description of drought evolution throughout an analysis of the indices in the last 30 days and a forecast of the next 1-3 months. This comprehensive monitoring and forecasting system, can become a timely and stand-alone multi-purpose environment to share information potentially useful to final users for managing drought-related emergencies as crop yields losses, forest fires and water resources reduction.

Keywords: Drought monitoring, seasonal forecasts, operational system, MODIS data, NDVI profile, VHI, SPI, EDI, monthly bulletins, WebGIS.
1. INTRODUCTION

The last two years showed the vulnerability to drought of the central Italy and in particular Tuscany region, registering one of the longest dry periods since 1960. Over 12 months of lack of precipitation cost to Tuscan agriculture and environment over 300 billions Euro of losses in crop productions and forest fires (local administration estimates). Water supplies for industrial and civil uses were also affected by a drastic decrease in surface and ground water availability.

With respect to other extreme climatic events, drought is a creeping and more complex phenomenon (Tannehill, 1947), characterized by a slow and often long lasting evolution; its onset is generally difficult to define, its intensity and spatial extension are extremely variable and the impacts that produces on the environment can arise later and persist even after its end (Vincente-Serrano et al., 2012).

Redmond (2002) defined drought as a condition of insufficient water to meet needs. Because water requirements are extremely variable in space and time, many drought indices exist, based on climatic parameters and sectors affected (Heim et al., 2002; Quiring et al., 2003; Vincente-Serrano et al., 2012), but neither of them alone is effective to detect and describe this kind of event. On the contrary, as other studies have demonstrated (Jayaraman et al., 1997; Brown et al., 2008; Jain et al., 2010), a comprehensive framework including a climate-based and satellite-derived monitoring and a seasonal weather forecast is the most reliable way to identify drought occurrence and trends and to deliver timely information for impacts reduction.

Although these extreme events require effective actions, policy makers and water users often show low preparedness when drought occurs, because of the lack of a comprehensive, well-organized, simple and promptly delivered products. In this context it is crucial to provide simple, timely and reliable information on the current conditions and forecasts of the evolution of this extreme climatic event, in order to support management decisions and to reduce impacts.

The aim of this paper is to illustrate the proactive, integrated drought monitoring and seasonal forecasting mechanism that the LaMMA Consortium and the Institute of Biometeorology (IBIMET-CNR) are implementing and adjusting for Tuscany region to fill the temporal gap between the development of a dry period and the response of final users in managing drought-related emergencies, by delivering maps and information in quasi-real time. The paper first introduces the test area (Tuscany) and the data utilised; a section describing the methodology applied follows, together with some preliminary results. The final part of the paper provides a brief discussion and some major conclusions and perspectives.

2. STUDY AREA: TUSCANY REGION

Tuscany (9°-12° East longitude and 42°-44° North latitude) is the widest region in Central Italy. Its topography varies from flat areas near the coast-line and along the principal river valleys, to hilly and mountainous zones towards the Apennines chain. From a climatic viewpoint, Tuscany is influenced by its complex orographic structure and by the direction of the prevalent air flows (from West/North-West). As a result, the climate ranges from typically Mediterranean to temperate warm or cool according to the altitudinal and latitudinal gradients and the distance from the sea (Rapetti and Vittorini, 1995).

The land use is predominantly agricultural where the land is flat, and mixed agricultural and forestry in the hilly and mountainous areas. The most widespread cultivations are olive trees and vineyards; concerning forests, both evergreen and deciduous species are diffused over the hilly and mountainous areas.
3. THE OPERATIONAL CHAIN

The operational chain implemented to calculate drought indices and to deliver final products for drought monitoring and forecasting in Tuscany (Figure 1) is based on semi-automatic procedures. The system components of this chain are briefly illustrated below.

Figure 1. Flow chart of the operational chain of the drought monitoring and forecasting system.

3.1. The monitoring system

The monitoring system is developed integrating state-of-the-art science and technologies and selecting a set of coupled rainfall-based and satellite-derived indices that take into account some important criteria: 1) types of drought; 2) availability and consistency of data; 3) geographical characteristics; 4) time and spatial variability; 5) main final users.

Precipitation, as the first and main parameter pointing out drought occurrence, is used in many indices, such as rainfall anomaly, deciles (Gibbs and Maher, 1967), percent of normal, number of consecutive dry days (Deni & Jemain, 2009), Rainfall Anomaly Index (RAI) (Van Rooy, 1965), Cumulative Precipitation Anomaly (CPA) (Foley, 1957; Keyantash & Dracup, 2002), Standardized Precipitation Index (SPI) (McKee et al., 1993), Effective Drought Index (EDI) (Byun et al., 1999).

For our operational framework we selected in particular the last indices, considering the SPI and EDI better then others (Morid et al., 2006), providing multiple time scale drought occurrence, and detecting its variation and duration. Tuscan meteorological stations with the longest and continuous daily data series, starting from 1960, are selected to calculate the SPI and EDI indices. The SPI allows a multiple time scales (1, 3, 6, 12 and 24 months) tracking of dry/wet spells and a comparison between geographically different locations. On the other hand, the EDI index, calculated with a daily time step, shows a more detailed influence of precipitation on the recovery from an accumulated deficit.
SPI values for 3 months interval are analyzed against 12 months interval in order to avoid misunderstanding on the duration of a long lasting drought interrupted by a temporary normal or wet period, as occurred in Tuscany during the 2012 (Figure 2).

**Figure 2.** Comparison between SPI_3 and SPI_12 for the Livorno meteorological station, from January 2011 to February 2013.

The EDI index is chosen because it is more sensitive to each single rainfall event and is especially effective to spatially recognise the onset of a drought episode (Morid et al., 2006) and to characterize a territory intrinsically prone to dryness.

The second group of indices, focused on a vegetation health monitoring, represents an indirect drought responsive way to analyze the phenomenon, and satellite-derived indices are widely used due to their spatiotemporal characteristics of full ground cover and quasi-continuous time observations. We propose an analysis of vegetation performances, useful for agricultural and forests drought monitoring, related to temperature and moisture stress throughout a combination of remote sensing indices based on Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST).

Terra MODIS (Moderate Resolution Imaging Spectroradiometer) 8-day smoothed LST images with 1 km resolution (MOD11A2, collection v005) are used, instead of the brightness temperature from which derives, to calculate the Temperature Condition Index (TCI) (Kogan, 1995)

\[
TCI_i = \left(\frac{LST_{i} - LST_{\text{min}}}{LST_{\text{max}} - LST_{\text{min}}}\right) \times 100
\]

where \(LST_i\), \(LST_{\text{min}}\) and \(LST_{\text{max}}\) are the last smoothed 8-days LST and their multiyear absolute minimum and maximum, respectively. TCI values provide information of vegetation stress linked to high temperature.

On the other hand, the Vegetation Condition Index (VCI) (Kogan, 1995), based on Terra MODIS 16-day smoothed NDVI products with 250m resolution (MOD13Q1, collection v005), indicates vegetation dynamics reflecting moisture conditions.

\[
VCI_i = \left(\frac{NDVI_i - NDVI_{\text{min}}}{NDVI_{\text{max}} - NDVI_{\text{min}}}\right) \times 100
\]

where \(NDVI_i\), \(NDVI_{\text{min}}\) and \(NDVI_{\text{max}}\) are the last smoothed 16-days NDVI and their multiyear absolute minimum and maximum, respectively.
MODIS LST and NDVI images are downloaded from the NASA website (ftp://e4ftl01.cr.usgs.gov/MOLT/) from 2000 to the present time. NDVI images, moreover, were corrected for residual atmospheric disturbances, as described in Maselli et al. (2009). The TCI grids are averaged to 16 days and downscaled from 1km to 250 m to be combined with the VCI grids in order to originate the comprehensive Vegetation Health Index (VHI) (Kogan, 1995), available from 2000 and updated each 16 days during Spring-Summer seasons.

\[ \text{VHI} = a \times \text{VCI} + b \times \text{TCI} \]

where \(a\) and \(b\) are coefficients quantifying the VCI and TCI contribution in the combined condition. For our work we allocate the same weight both to the temperature and moisture parameters.

These indices, selected also to enhance climate-based SPI and EDI, constitute the core of the monitoring system during the growing season, when problems due to the cloud cover are reduced.

To deliver more specific information about severity of water deficit, its extent and impacts on vegetation and crop types, we select and extract from VHI maps values corresponding to main forest classes and principal woody cultivations of Tuscany, using a detailed land cover produced by the LaMMA Consortium (LaMMA-Regione Toscana, in press).

We also analyze multi-temporal NDVI profiles of Tuscan forest types to monitor variations in the growing season due to prolonged drought conditions or heat waves. In this paper we present, as example of this study, results obtained on a 3x3 pixels window corresponding to a Turkey oak forest of central Tuscany. NDVI profiles extracted for 2007 and 2012 are compared to the NDVI mean profile (from 2000 to 2012). On 2012 the NDVI values of Spring-Summer period, always below the average curve, reflect, with some months of lag, the exceptional drought occurred from 2011 and 2012 (Figure 3a). On the contrary, the response of vegetation to the 2006-2007 heat wave is represented by an earlier onset of the growing season (Figure 3b). This type of analysis can be also applied to NDVI crops profiles, in order to give a support for the definition of the growing season dynamics and possible yields reductions due to droughts.

3a. 3b.

**Figures 3a and 3b.** Turkey oak NDVI profiles: 2012 values vs mean values (3a) and 2007 values vs mean values (3b).

### 3.2. The forecasting system

The 3 months SPI is used for seasonal forecasts that try to predict, in a statistical framework, the spatial and temporal distribution of weather anomalies few months into the future.

Forecasts follow a physically-based statistical approach focused on an “adaptive multi-regressive method” that takes into account potential predictors among a list of physical
atmospheric indices and Sea Surface Temperature (SST) anomalies (Pasqui et al., 2009). To obtain a spatiotemporal homogeneity of the SPI, the analysis is carried out using daily E-OBS (Ensemble Observational) gridded precipitation dataset from the ECA&D (European Climate Assessment & Dataset) project (Haylock et al., 2008), covering the period from 1950 to December 2012, with a spatial resolution of 0.5 degrees lat-lon grid (http://eca.knmi.nl) and focused over Mediterranean Basin. Figure 4 shows an example of forecast of the 3 months SPI for March 2013.

Figure 4. Example of 3 months SPI forecasting for March 2013.

3.3. Products dissemination

Indices analysis and final products must be easily delivered to ensure to end users an useful, effective and timely information for their final needs; Internet is the best way to disseminate drought monitoring and forecasting alerts. For this purpose we deliver information at different time steps.
- During the growing season vegetation conditions of the previous 16 days are updated on a specific page of the Consortium web site, with a lag of about 1 week, especially analyzing the NDVI profiles and VHI index.
- On-line monthly bulletins (http://issuu.com/consorziolamma), on the other hand, furnish a more detailed description of drought evolution throughout a coupled analysis of satellite and climate-based drought indices during the previous 30 days, with particular attention on forest types and main tree crops, and a forecast of the SPI index for the next months.
- To share maps of drought indices with decision-makers and other stakeholders a general purpose framework composed by a WebGIS application (http://www.lamma.rete.toscana.it/webgis-siccit%C3%A0) and developed using PHP/Ajax technologies has been customized (Rocchi et al. 2010).

The customized Graphical User Interface (GUI) supplies advanced queries and specific analysis and grid-based extraction functions using PostGIS 1.5 and MapServer libraries. The Web-oriented architecture proposed, as well as the GUI, are based on open source solutions and OGC standards, in order to guarantee the web application sustainability.
and spatial data interoperability and future implementation of advanced, customized geospatial functions. This WebGIS infrastructure proposed is able to collect, visualize and integrate several types of datasets (shape and raster formats), stored in a PostgreSQL database, at different spatial and time scales (Figure 5).

![WebGIS application and drought Indicators.](image)

**Figure 5.** WebGIS application and drought Indicators.

### 4. CONCLUSIONS AND FUTURE PERSPECTIVES

In the last years drought events have become more frequent, affecting most of Tuscany region. Environmental and economic drought-related impacts have highlighted the lack of timely information and the need to implement a more integrated and coordinated web-based monitoring and forecasting system.

The comprehensive framework developed by the LaMMA Consortium for Tuscany region can represent a quasi-real time and user-friendly web access multi-purpose operational service for final users, potentially able to give “easy to read” information useful for managing drought-related emergencies as crop yields losses, forest fires and water resources reduction.

In fact, the monitoring and forecasting systems, included in the “Drought Observatory” section of the LaMMA Consortium website (http://www.lamma.rete.toscana.it/siccita%CC%80-situazione-corrente), are operative for the whole year and assess and follow the evolution in time and space of a drought event through the integration of data from different sources (climate-based and vegetation indices) on monthly to bi-weekly basis and furnish information on the response of vegetation to drought conditions, even in terms of start/end of season and variations in productivity, tracking the growing season trend of different forests and even crop types.

As future perspectives we are starting to implement the monitoring system with an evapotranspiration index from a biogeochemical model in order to integrate a simplified prototype of water balance into our framework. Moreover the possibility of integrating maps of drought indices with maps and information of different biophysical parameters, as soil moisture, water table levels and forest net productivity (NEE-Net Ecosystem exchange) or other environmental indicators, as
desertification, CO₂ emissions, etc. coming from other public or private archives and regional/local databases, becomes strategic for an improvement of risk management, providing information for more proactive responses that could be made even at local or community level. In fact a future step will be the implementation of a participatory web platform that will allow stakeholders, (as farmers, local water authorities and regional administrations), uploading georeferenced information (comments, photos, data) related to local impacts due to drought occurrence.

REFERENCES