Identification of extreme weather phenomena in near real-time

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Abstract
This paper describes an operational system for defining weather phenomena and indices, as well as, identifying and documenting extreme weather conditions based on the hydrometeorological observations from meteorological stations. The results are published directly on the website of the Hydrological Observatory of Athens. Different techniques are implied in real time in order to identify and exclude data errors from further processing. Extreme weather phenomena, such as extreme heat, frost, intense and heavy rainfall and extreme windy conditions, are currently monitored. Moreover, bioclimatic indicators measuring the felt air temperature (heat index and wind chill) by combining more than one meteorological variable are calculated. The system provides the flexibility to define weather phenomena and indices and to apply the identification algorithm to time series stored in the hydrometeorological database.

***Keywords**: extreme weather phenomena, extreme events, hydrological extremes, monitoring system, hydrometeorological data.*

1 INTRODUCTION

Daily weather prediction systems clearly attract the interest of the public, since much of our everyday life and schedules depends on their outcomes. In contrast to this, real-time weather monitoring systems and weather reports attract a much smaller share of the public interest[1]. Nevertheless, these services provide valuable information for all, hydrometeorological experts and common people alike, who are often particularly interested in extreme events in past and current weather conditions.
Extreme weather phenomena are not universally defined. Most temperature related definitions such as heat waves or extreme cold conditions refer to observed daily average and/or minima/maxima e.g. (1). Definitions of phenomena related to precipitation, measure the intensity, the duration of an event and the rainfall accumulated over time e.g. (2). Hydrologists are particularly interested in the frequency extreme rainfall events occur assigning a return period to a rainfall amount according to probability distributions e.g. (3) and (4) or creating in combination with their intensity and duration IDF-curves for a specific region (5). Water managers are also interested for water resources management purposes including the optimum operation of reservoir for multiple purposes (18).
Some evaluations adopt a single, absolute threshold which distinguishes extreme values from the rest. This is simple to understand and is useful for indices measuring events of a fixed intensity. Other definitions are based on relative thresholds, referring to a predefined percentile of all observed values from a specific period. These thresholds ensure that extreme events are selected based on their low occurrence frequency/rarity rather than on their intensity (6). Even in studies with common methodology for setting the threshold, the definitions may differ in a number of

[1] Personal communication with K. Lagouvardos on Jan. 2013 regarding the visits of meteo.gr, a weather monitoring and forecasting service of the National Observatory of Athens.

aspects such as the degree of intensity or rarity which defines an extreme event, the minimum duration of an event or the temporal and spatial aggregation methodology.
Given the variety of weather parameters and definitions of extreme phenomena, a flexible system for the identification and documentation of extreme events out of historical data has been developed. It is capable to operate in a near real-time environment and can be adapted to a wide range of extreme weather definitions. Its methodology is described in the following section. The application of the system in the campus of the National Technical University of Athens (NTUA) and the related service provided through the website of the Hydrological Observatory of Athens (HOA) are described in the subsequent sections.

2 METHODOLOGY

2.1 Definition of extreme phenomena

The system implies a methodology, which is generic and to a great extent parameterized. Although it has been used on hydrometeorological data to document extreme weather phenomena, it may as well be applied to any type of time series, providing users the flexibility to identify extremes with almost arbitrary characteristics. An extreme phenomenon or index is identified based on criteria which apply either alternatively or in combination (upon selection of the user). Each criterion is characterized by the following:

- One or more *time series* recording measurements from specific parameters.
- A *threshold* that defines an upper or a lower limit.
- A *time period* for which the threshold refers to. Based on the same period the peak value of the event is calculated.
- A *method* for identifying an extreme event. Currently the following methods have been implemented: a) The moving average of the measured parameter values over the specified time period must lie below/above the threshold. This method usually applies to parameters measuring temperature and wind speed for the documentation of extreme warm, cold and windy conditions. b) The sum of all values within the specified period must be below/above the threshold. Typical example for the application of this method is the documentation of heavy rainfall. c) All values within the specified period must be below/above the threshold. This method applies to document frost conditions. d) Other methods apply for the calculation of specific indices from one or more variables, such as wind chill and heat index (see section 3). For these indices the moving average of the calculated value over the specified time period is compared with the given threshold.

Although the above framework provides a solid basis for the positive identification of an extreme event and the determination of the starting time, i.e. the moment the observation parameter or index exceeds the given threshold, there is a need for further considerations regarding the extent of the event. For most weather phenomena, if the parameter values temporarily fall back to "normal" this does not necessary signal the end of the event. Only if the values remain at this level for an additional period of time, the event should be considered as terminated. Any subsequent extreme values would then be part of a separate event. This buffer period differs from one phenomenon to another and should also be considered as part of its definition. Therefore, for each phenomenon, an event separation period has been introduced, which is the minimum time period between two distinct, subsequent events. This way a single rainfall event may be stretched to a longer time period including intervals with no rain. In another example, a single heat wave event, defined by high average temperature during the daytime, may last several days although the temperature cools down below the specified threshold during the night.
While an event may last very long, what often interests most and characterizes the event is its magnitude during the peak time (e.g. maximum intensity of a storm). This is a smaller time period

within the identified period of extreme weather conditions in which the event shows its most extreme behavior. The magnitude of an event (the peak value) is calculated from the average values during the peak period of the first criterion defined for this phenomenon.
Figure 1 illustrates in a line chart the main characteristics of an event relevant to the calculation of its boundaries and magnitude, assuming the phenomenon is defined by a single criterion/parameter. The chart shows the moving average of the parameter values, the threshold *S* (here: a minimum), the peak period *Tp*, the magnitude of the event *Avg(Tp)* and the separation period *Ts*.

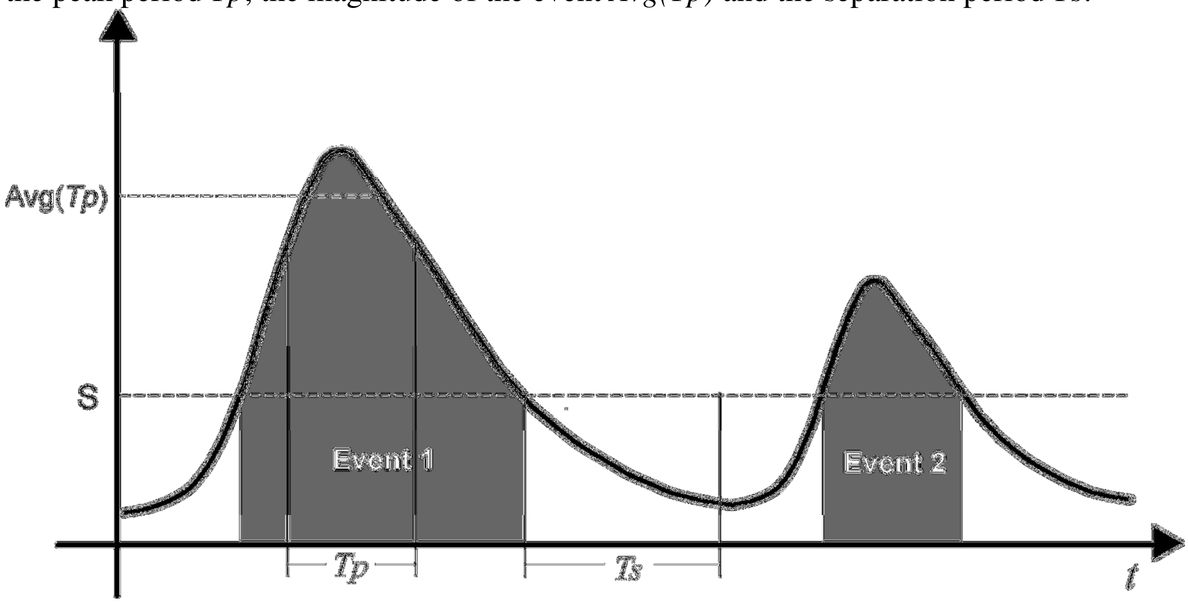

Figure 1: The main characteristics of events relevant to the calculation of their boundaries and magnitude

2.2 Events identification and analysis

Based on the definitions of extreme weather phenomena, a system has been developed to identify extreme events and analyze their behavior. The procedure includes mainly the following stages as illustrated in Figure 2:
Stage 1 – Data QA. In this initial stage all relevant time series are loaded from the database and undergo certain basic quality checks that ensure a behavior within the expected range. Two basic quality checks apply on all time series to prevent obvious errors caused by instrument malfunction and data transmission: a) Extreme value checks, realized by an upper and a lower limit for every time series. b) Temporal consistency checks calculate the absolute value of the difference between two subsequent records x_i and x_{i+1}. The resulting difference must be smaller or equal a given value e:

$$e \geq | x_i - x_{i+1} | \quad (1)$$

The value of e greatly depends on the variable and the time step of the chosen time series. Records that fail to pass the above tests are automatically excluded from further processing.
Stage 2 – Data aggregation. Loggers of hydrometeorological stations are usually recording parameters measured at smaller time steps than actually needed to identify a weather phenomenon. To measure the overall precipitation that characterizes a heavy rainfall for instance a timeframe of several hours should be considered. Therefore, time series of moving averages and moving sums are created according to the definition of each phenomenon. The resulting aggregated time series are used for further processing.
Stage 3 – Data processing. Some indices are calculated from more than one variable (e.g. wind chill). New time series are calculated for these indices in a time step as specified in the definition of these indices. Values of variables for which the index is undefined are excluded from further

processing. The resulting aggregated time series produced in this stage enhance the already produced datasets from stage 2.

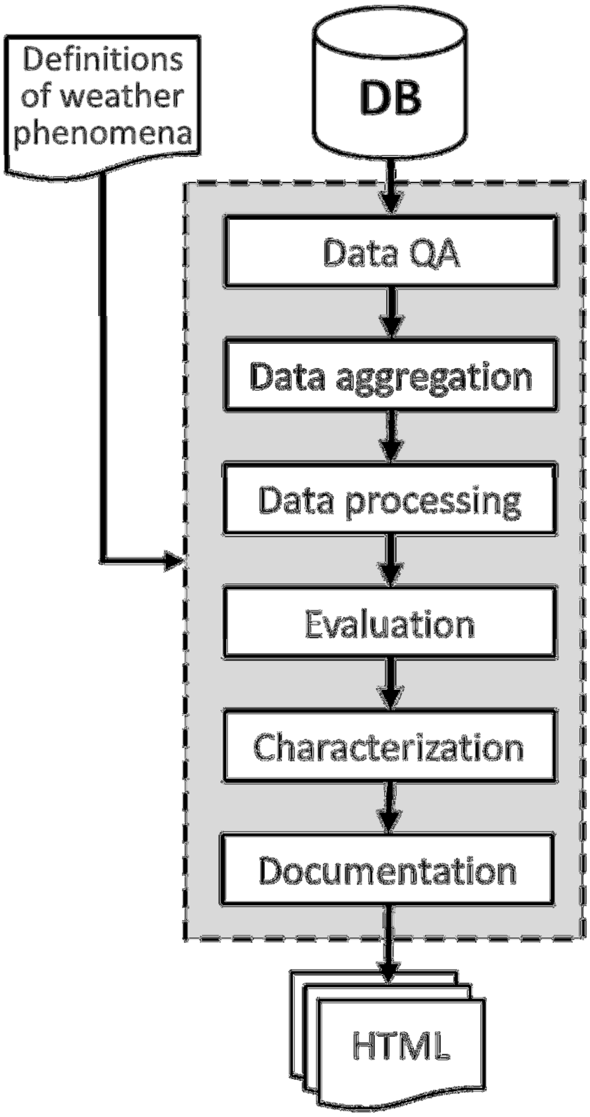

Figure 2: Main procedures of extreme event identification and analysis

Stage 4 – Evaluation. In this stage the aggregated time series are evaluated to identify extreme events. On every time step it is checked whether the criteria for an extreme phenomenon are met. A list of all time periods, defined by the starting time, that meet the criteria of an extreme phenomenon is created.
As an additional measure to increase the reliability of the results, the system may be configured to perform a spatial consistency check of the time series. In such a case a phenomenon is defined by (at least) two criteria, each of which is related to independent from each other sensors measuring the same parameter (e.g. temperature). The first one is the main sensor of the main station and the second the control sensor usually located either in the same or in a nearby station. Only if both criteria are met (here: conjunctive operation) an extreme event is identified. This way outliers caused by malfunction of one instrument, which have not been detected by the initial basic tests, do not lead to false positive identifications of extreme events. Both sensors/stations should be placed in small distance from each other in order to measure at a given time the same impact of the event. The chosen thresholds for the criteria of the control sensor should be less strict than the ones for the main sensor, taking into account factors that may mitigate the extremes observed by the main one e.g the distance between the two sensors and the accuracy of the measurement.
Stage 5 - Characterization. In this stage the system does in parallel the following two activities: a) identifies the boundaries of events separating them from each other based on the event separation period defined for each phenomenon and b) measures the magnitude of the event by identifying its peak period first.
Stage 6 – Documentation. Based on the results of the previous stage the following documents are produced as HTML code in a form suitable to be included in websites: a) Information of the two or three most recent extreme events (peak period values of the main and an additional parameter). b) Detailed information for every identified extreme event. c) Definitions of weather phenomena, the criteria and the time series used.

3 APPLICATION IN THE NTUA CAMPUS AREA

The first telemetric meteorological station in the campus of the NTUA went into operation in 1993 (7). Additional stations operated by the Laboratory of Hydrology and Water Resources of NTUA have been included forming a meteorological telemetric network of monitoring stations in the Greater Athens Area (8). All data collected from these stations as well as additional features for the visualization of data (maps, charts) and advanced applications for a statistical analysis are available in near real-time through the site of the HOA. Both weather stations located in the campus of the NTUA have been used for this application. The main station (9) is located on the NW side of the campus at an altitude of 181m. The second one (control station) (10) is located at an altitude of 219m on the SE side of it at the foot of Mount Hymettus. The distance between the two stations is 950m. In both stations the recording time step is 10 minutes. The data are periodically transmitted to the HOA server for storage in the database and further processing. The main station provides measurements for all parameters, relevant for the identification of weather events and their characteristics. In contrast, the role of the control station is to check whether the values for temperature, wind speed and relative humidity measured by the main station are reliable. Precipitation is measured by both rain gages installed in the main station, the second of which acts as the control sensor. All weather phenomena and indices defined for this study are listed in Table 1 together with the parameters used to determine an extreme event (basic parameters). Additional parameters are measured and documented, completing the picture of the prevailing weather conditions during the event. In case of precipitation, time series are analyzed in two ways to identify: a) intense rainfall events, i.e. those with high precipitation values in the smallest available time step, which is 10 minutes and b) heavy rainfall, observed in a timeframe of 12 hours.

Table 1: Defined weather phenomena and indices, their basic and additional parameters.

Phenomenon/ Index	Basic parameter(s)	Additional parameter
Heat	Temperature	Rel. humidity
Frost	Temperature	Rel. humidity
Intense rainfall	Precipitation	Wind speed
Heavy rainfall	Precipitation	Wind speed
Windy conditions	Wind speed	Temperature
High felt air temperature (Heat index)	Temperature – Rel. humidity	
Low felt air temperature (Wind chill)	Temperature – Wind speed	

The detailed specifications of weather phenomena and indices currently used in the application are shown in Table 2.

Table 2: Conditions (criteria) for identifying extreme events in the HOA

Phenomenon/index	Conditions/Criteria
Heat	Main sensor: 32.0°C or above on average for at least 24 hours and Control sensor: 31.0°C or above on average for at least 24 hours
Frost	Main sensor: 0.0°C or below for all values within 8 hours and Control sensor: 2.5°C or below for all values within 8 hours
Windy	Main sensor: 7.5m/s or above on average for at least 20 minutes and Control sensor: 6.5m/s or above on average for at least 20 minutes
Storm	Main sensor: 7.0mm or above in total within 10 minutes and Control sensor: 5.0mm or above in total within 10 minutes
Heavy rainfall	Main sensor: 40.0mm or above in total within 12 hours and Control sensor: 35.0mm or above in total within 12 hours
High felt air temperature (heat index)	Main sensor: 36.0 or above on average for at least 20 minutes and Control sensor: 32.0 or above on average for at least 20 minutes
Low felt air temperature (wind chill)	Main sensor: -2.0 or below on average for at least 20 minutes and Control sensor: 0.0 or below on average for at least 20 minutes

The bioclimatic indicators selected for this application require two parameters to be calculated. Wind chill index (WCI) calculates from the air temperature and the wind speed the estimated felt air temperature on exposed skin due to wind The WCI used here has been adopted from the Wind Chill formula introduced by Environment Canada and the U.S. National Weather Service since 2001 ((11) and (12)):

$$\mathrm{WCI} = 13.12 + 0.6215\,\mathrm{T} - 11.37\,V^{0.16} + 0.3965\,\mathrm{T}\,V^{0.16} \tag{2}$$

where T is the air temperature in degrees Celsius (°C), and V is the wind speed in km/h. WCI is defined only for temperatures lower than 10°C and wind speed above 5 km/h. It is expressed in temperature-like units in order to be directly comparable with the air temperature.Correspondingly to the wind chill index for very low temperatures, the heat index (HI) has been created to estimate the human perceived temperature for very high temperatures. The definition of HI shown below has been derived from the formula used by the U.S. National Weather Service ((13) and (14)) in which temperature is expressed in degrees Fahrenheit:

$$\begin{aligned} HI = -8.784694756 + 1.61139411\,\mathrm{T} + 2.338548839\,\mathrm{H} - 0.14611605\,\mathrm{T}\,\mathrm{H} \\ - 0.012308094\,T^2 - 0.016424828\,H^2 + 0.002211732\,T^2\,\mathrm{H} \\ + 0.00072546\,\mathrm{T}\,H^2 - 0.000003582\,T^2\,H^2 \end{aligned} \tag{3}$$

where T is the air temperature in Celsius (°C) and H is the relative humidity measured in %. HI is defined for temperatures above 27°C and relative humidity greater than 40%.
The selected indicators may be useful for revealing short-term trends as opposed to other indicators which are typical for identifying trends on the climatic scale (e.g. De Martonne Aridity Index) (17).

Since there are no universally acceptable thresholds, absolute or relative, which define the here introduced weather phenomena (apart from frost), setting of these thresholds has been influenced mainly by the expected public interest of the resulting selection of events. The documentation of too many, less significant events would distract the attention from the major and important ones. On the other hand, setting too strict limits would risk omitting events that are of public interest. For this reason the web traffic of the HOA website throughout the year 2012 has been examined and compared with the events identified from applying various definitions of weather phenomena. This analysis showed that there is a clear correlation between the number of visits and the occurrence of extreme events of any kind (see Figure 3). Moreover it ensured that the chosen thresholds did not leave any event of major interest out of the selection.

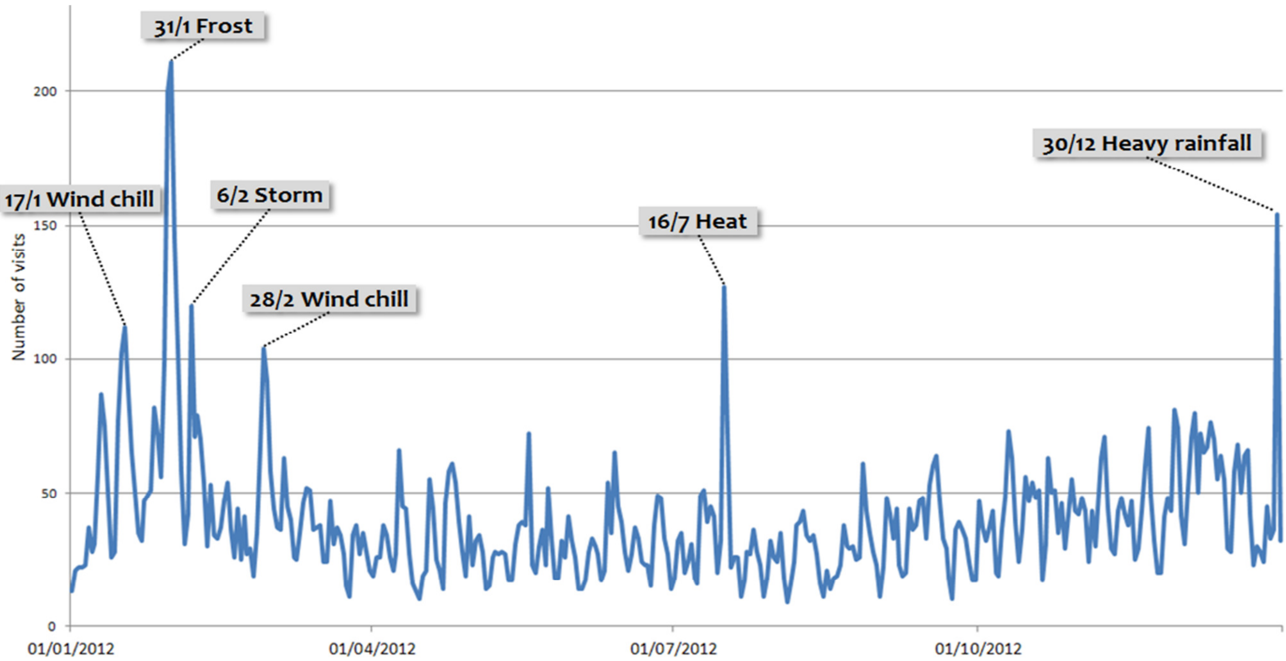

Figure 3: Visits to the website of HOA (hoa.ntua.gr) compared to major weather events in 2012.

Figure 4 shows the section of the homepage of HOA that is regularly updated with the two most recent extreme events. The lack of universally acceptable definitions for extreme weather phenomena and the possible misinterpretation by the broad public that could provoke the use of the word "extreme" in the website of HOA, has led to the adoption of the more general term "weather highlights".

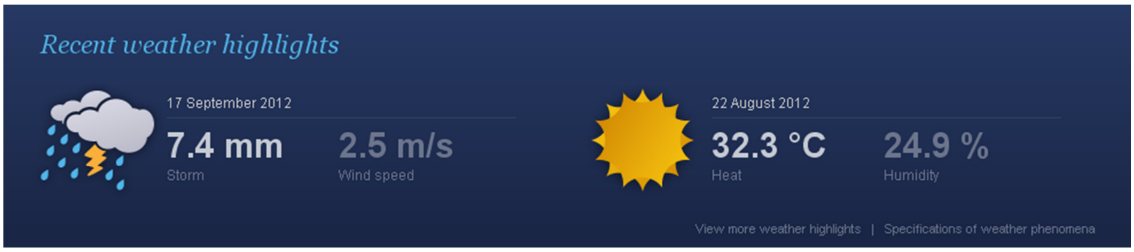

Figure 4: Weather highlights section on the homepage of HOA.

4 CONCLUSUIONS

In this research a fully operational system has been developed in order to define weather phenomena and indices, as well as to identify extreme weather conditions based on the hydrometeorological observations. Different techniques are implied for the suppression of the errors for further processing. An extreme phenomenon or index is identified based on criteria, which applied either alternatively or in combination by the user. Each criterion takes into account the time series for specific parameter, the upper or a lower limit, the time period for which the threshold refers to and the methodology for identifying an extreme event. The phenomena or indices which are considered in real time are the heat, frost, intense rainfall, heavy rainfall, windy conditions etc. are published directly to the Hydrological Observatory of Athens.

Acknowledgements

The software developed for this study uses routines from openmeteo.org (15), an open-source project for the development of free hydrological and meteorological software and the collection and

distribution of free hydrological and meteorological data. The database of HOA is powered by Enhydris (16), the hydrometeorological database of openmeteo.org.

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