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Research Article

Trends of Dust Transport Episodes in Cyprus Using a Classification of Synoptic Types Established with Artificial Neural Networks

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The relationship between dust episodes over Cyprus and specific synoptic patterns has long been considered but also further supported in recent studies by the authors. Having defined a dust episode as a day when the average PM10 measurement exceeds the threshold of 50 mg/(m^3 day), the authors have utilized Artificial Neural Networks and synoptic charts, together with satellite and ground measurements, in order to establish a scheme which links specific synoptic patterns with the appearance of dust transport over Cyprus. In an effort to understand better these complicated synoptic-scale phenomena and their associations with dust transport episodes, the authors attempt in the present paper a followup of the previous tasks with the objective to further investigate dust episodes from the point of view of their time trends. The results have shown a tendency for the synoptic situations favoring dust events to increase in the last decades, whereas, the synoptic situations not favoring such events tend to decrease with time.

1. Introduction

It is common knowledge that dust transport from desert areas is not confined to the regions adjacent to the desert source itself, but dust can be transported extensively, and the final deposition can be thousands of kilometers away from the originating source (see [1]). According to Marelli [2], this natural contribution to Particulate Matter (PM) may range from 5% to 50% in different European countries. The Mediterranean Basin is generally recognized as a major recipient of desert dust originating from the Sahara and Saudi Arabia deserts; several t/km^2 are deposited each year in the Mediterranean Sea [3] profoundly affecting its coastal regions (see [4–15]).

Dust transport can be defined as a three-stage process: initially, dust is lifted and suspended in the atmospheric air, resulting in the occurrence of high level concentrations of dust in desert areas and then transported to great distances from the initial source where it finally settles on the ground. This is a quite complex phenomenon since a large number of factors contribute to its intensity and frequency. Particularly, in countries of the southeastern Mediterranean region which is particularly affected, there is an acute interest in understanding the phenomenon itself as well as the various mechanisms which govern important attributes like the severity, duration, and time trends of dust transportation (see [16]). The present study focuses on the third stage of dust transportation, namely the deposition of desert dust at ground level.

The importance of such a task is undoubted since dust transport episodes affect a number of human activities ranging from public health to ground and air transportation safety and renewable energy efficiency (to name but a few). Restricting the exemplars of dust implications to these three areas, it is worth elaborating that implications of high dust levels to human health include respiratory disorders, eye inflammations, heart disease, and lung cancer (see [17, 18]). A deep understanding of dust events and their associated processes is essential for the application of renewable energy systems that utilize solar radiation (e.g., photovoltaic systems for the generation of electricity). These systems are affected profoundly by dust deposition (wet or dry) which can lead to serious problems, such as system degradation or inefficiency due to frequent cleaning requirements [19]. Also, aviation safety can

be severely affected in some circumstances, as the abrasive effect of dust on aircraft hull and engines can have an accumulating adverse impact (see [20]). Dust events can lead to a considerable reduction of visibility at airports, thus resulting in delays and cancellations (see [21]). Under severe conditions, road transportation can also be affected by reduced visibility [22].

A novel approach has recently been proposed contributing to the diagnosis and prediction of dust events in the eastern Mediterranean. The proposed methodology incorporates the adoption of Artificial Neural Networks (ANN) in order to diagnose and predict atmospheric pollutant levels in the eastern Mediterranean resulting from the transportation of dust from the originating sources located in adjacent regions (see [23]). In that study, synoptic circulation types and surface measurements were employed, along with neural methodologies [24] and satellite measurements. In the present paper, the association between synoptic patterns that was established by using the ANN methodology and dust events is presented. Thus, the first objective of the research is to identify favorable synoptic situations that lead to dust events over Cyprus, in order to justify objectively the long existing empirical knowledge of preference of occurrence of dust events to synoptic types.

Having performed this, a second objective of this paper is to investigate whether the frequency of appearance of such favorable or unfavorable synoptic patterns exhibits any time tendencies which can subsequently be used to explain the increase with time of dust episodes; this increase has been (qualitatively and subjectively) registered, at least during the last decade, at the weather observing station network maintained by the Meteorological Service of Cyprus.

Section 2 summarizes the methodologies and data used in this study; also, a brief account of the known relationship between dust episodes and prevailing weather conditions is given. The results section (Section 3) is separated into two parts: in the first, the relationship between synoptic patterns and dust events is established (first objective, above), and in the second the trends with respect to time of the synoptic patterns are investigated (second objective, above). Conclusions are presented in Section 4.

2. Methodologies and Data

Michaelides et al. [23] employed digital meteorological charts, satellite data, and surface measurements of dust in order to determine which synoptic circulation types are most likely to produce conditions which favor dust transport episodes over the island of Cyprus. For that study, a number of integral factors were investigated and discussed, namely, the atmospheric conditions leading to dust transportation and the meteorological conditions associated with the phenomenon, along with a presentation of the surface measurements of PM10 (particles that are less than 10 μm in aerodynamic diameter) used for the definition of a dust event. Also, the methodology for using ANN in order to construct a classification of synoptic patterns as well as the identification of those selected types favoring dust transportation was discussed. Furthermore, the exploitation of satellite technology in estimating dust load in the atmosphere (using the Atmospheric Optical Thickness determined by the Moderate Resolution Imaging Spectrometer (MODIS) sensor onboard the Aqua-Terra satellites) was presented. The application of multiple regression in combination with the synoptic classification for the prediction of dust episodes was discussed, as well as a neural network prediction methodology. Finally, an integrated approach for the prediction of dust episodes that makes use of either the multiple regression or the neural approaches was considered.

In the following, a brief outline of the ANN methodology adopted is given. The reader is referred to Michaelides et al. [23, 25] for more details on this methodology, the mathematical formulations, and the results obtained for the synoptic classification.

The neural network architecture used in this research is Kohonen's Self Organizing Maps (SOM) [26, 27]. These networks provide a way of representing multidimensional data in much lower dimensional spaces, usually one or two dimensions. An advantage of the SOM networks over other neural network classification techniques is that the Kohonen technique creates a network that stores information in such a way that any topological relationships within the training set are maintained; for example, even if the Kohonen network associates weather patterns with dust events inaccurately, the error obtained will not be of great amplitude, since the result will be a class with similar characteristics. For a recent review of the advantages in using SOM as a tool in synoptic climatology, the reader is referred to Sheridan and Lee [28]. Also, the work by Tsakovski et al. [29] stresses the importance and usefulness of Kohonen's Self Organizing Maps in reaching such classification goals, as well as their role in decision-making processes.

Kohonen's SOM algorithm in its unsupervised mode was chosen for building the neural network models, because neither the number of output classes nor the desired output is known a priori. This is a typical example where unsupervised learning is more appropriate, since the domain expert will be given the chance to see the results and decide which model gives the best results. The expert's guidance can help to decide the number of output classes that better represent the system [30].

In unsupervised learning, there are no target values, as in the case of other methods of ANN. Given a training set of data, the objective is to discover significant features or regularities in the training data (input data). The neural network attempts to map the input feature vectors onto an array of neurons (usually one- or two-dimensional), thereby, it compresses information while preserving the most important topological and metric relationships of the primary data items on the display. By doing so, the input feature vectors can be clustered into n clusters, where n is less or equal to the number of neurons used. Input vectors are presented sequentially in time without specifying the desired output (see [31, 42]). The two-dimensional rectangular grid architecture of Kohonen's SOM was adopted in the present research.

The input vector is connected with each unit of the network through weights whose number is equal to the number of grid points, for the area in study. The training procedure

utilizes competitive learning. When a training example is fed to the network, its Euclidean distance to all weight vectors is computed. The neuron whose weight vector is closest to the input vector (in terms of Euclidean distance) is the winner. The weight vectors of the winner neuron, as well as its neighborhood neurons, are updated in such a way that they become closer to the input pattern. The radius of the neighborhood around the winner unit is relatively large to start with, in order to include all neurons. As the learning process continues, the neighborhood is consecutively shrunk down to the point where only the winner unit is updated [32]. As more input vectors are represented to the network, the size of the neighborhood decreases until it includes only the winning unit or the winning unit and some of its neighbors. Initially, the values of the weights are selected at random.

The number of outputs is not *a priori* determined, but an "optimum" can be adopted by experimentation, in relation to the specific application under study. For several applications, it appears that the optimum number of outputs is around 30, as this exhibits the level of discretization required for the synoptic scale phenomena examined (see [33]).

Local weather forecasters have long identified specific atmospheric circulations as favoring the overall process for dust transportation over the area of eastern Mediterranean. The type of synoptic-scale atmospheric circulation which favors wet or dry dust deposits over the eastern Mediterranean is comprehensively described as one yielding a southerly to south-westerly flow throughout the entire troposphere (see [34]). The first step in the process is the elevation and suspension of dust in the atmosphere which starts with the development of a north African low pressure system, giving rise to a dust storm. This low pressure is primarily initiated in two ways: either by an upper-level trough which occurs on the polar front jet, when it overlies a heat low, or by the presence of a low level frontal system southeast of the Atlas Mountains [35, 36]. Both "initial conditions" are more frequent in late winter and spring (see [37]); indeed, this is the time of the year when dust events are most frequent over the eastern Mediterranean [1]. The second step, the transition of the dust "cloud" from its point of origin to its final destination (which can span a considerable distance), is supported by a south-westerly tropospheric flow. Finally, the third step of dust deposition can occur under dry conditions (gradual sedimentation due to gravity) or under conditions of increased humidity (where dust particles mix with rain droplets and fall on the ground as colored precipitation). Spring and autumn are the two seasonal periods favoring dust episodes, whereas summer appears to be suppressing these events. Dust episodes are also present in winter, although not as much as during spring or fall.

The ability of ANN to group synoptic patterns into seasonally dependent clusters was originally noted by Michaelides et al. [25]. Since the number of distinctive synoptic patterns used in order to classify synoptic patters over any particular geographical region is by no means fixed, it was decided to run a number of experiments and build classification models with different numbers of output nodes (i.e., classes). For the present analysis, 35 output nodes were used. For the construction of the synoptic patterns, data from the National Centers for Environmental Prediction (NCEP) were retrieved. The data consist of the 500 hPa isobaric level values distributed on a $2.5^\circ \times 2.5^\circ$ grid and valid at 1200 UTC of each day. Such data for the 25-year period 1980–2005 were exploited in order to establish the synoptic classification which is based on ANN, as explained above.

A dust transport episode is considered as a day when the average PM10 measurement exceeds the threshold of 50 mg/(m^3 day), (which is the threshold used by Cyprus' Ministry of Labor and Social Insurance). For the needs of this study, ground measurements of PM10 were used, obtained from the Background Representative Station at Ayia Marina Xyliatou in Cyprus (35 02′ 17″N, 33 03′ 28″E), and operated by the Cyprus Ministry of Labor and Social Insurance. The location has been selected because it has negligible local particulate sources, so the pollution levels registered are ascribed, to a large extent, to external sources. The data retrieved for this station cover the three-year period 2003–2005, which consists of the available data provided by the ministry.

Having established a relationship between synoptic patterns and dust events (by using the available data for the three-year period, as explained above), the synoptic classification over the entire 25-year period (1980–2005) was exploited in an attempt to identify trends in those synoptic conditions which favor or not dust transport episodes for this period. For each year, the total of days belonging to each of the 35 classes was counted, and the trends were exposed by using linear regression. This task is performed assuming that the three-year period used for the identification of classes that favor or not dust events is representative enough to establish such a relationship.

3. Results

3.1. Synoptic Patterns and Dust Events. In the three-year period 2003–2005, 85 dust deposition events (as defined above) were recorded (out of a total of 1096 days). Figure 1 displays the monthly distribution of these episodes during the three-year period 2003–2005. It is evident from this figure that there is a seasonal preference for dust events to occur.

It has long been realized that there is a strong association between large scale atmospheric circulation patterns and regional meteorological phenomena that are observed at Earth's surface, making synoptic charts a valuable tool for the operational weather forecaster to predict qualitatively occurrences of certain weather phenomena over particular areas (see [33, 38]). One such typical example is the close association between the atmospheric circulation and the onset and maintenance of desert dust transport episodes.

Several techniques for weather type classification can be found in the literature: automatic, objective, and consistent methodologies, each of which being applicable to different circumstances and different problems (e.g., [39–41]). Each method has its strong and weak points. For the present study, a new methodology with the adoption of ANN for the classification of synoptic circulations, as it was originally proposed by Michaelides et al. [25], is utilized. The methodology employs Kohonen's Self Organizing Maps (SOM) architecture

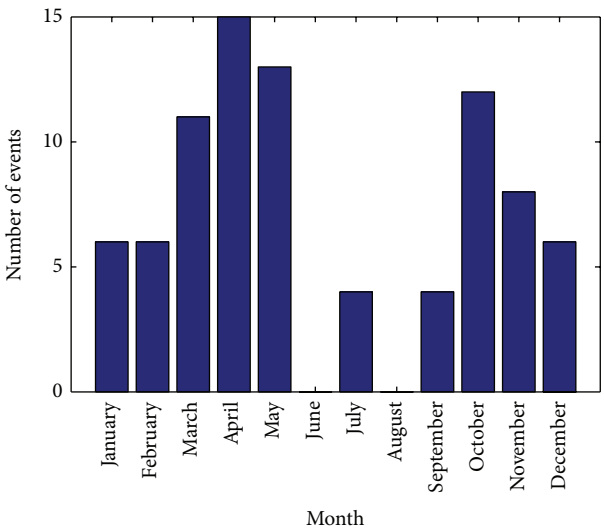


Figure 1: Monthly totals of dust events in the three-year period 2003–2005.

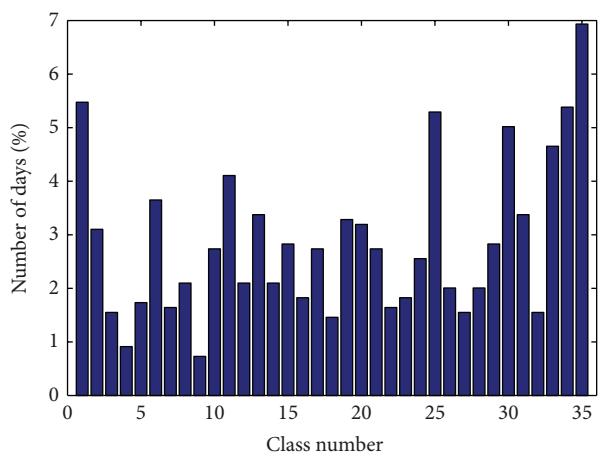


Figure 2: Percentage of days per class, for the 35 classes in the synoptic classification, during 2003–2005.

[27]; this is a neural network method with unsupervised learning (see also [25, 26, 42]) for the classification of distribution of isobaric patterns on 500 hPa charts. The result of this classification is the formulation of 35 synoptic prototypes (classes). Using these results, a correspondence was made between dust events and particular synoptic classes, as explained below.

Figure 2 shows the frequency of appearance of the 35 synoptic patterns for the three-year period 2003–2005, with class 35 being the most frequently encountered, followed by classes 1, 25, and 34.

Figure 3 shows the way in which the 85 dust transport events are distributed among the 35 classes in the synoptic classification adopted above. There appears to be a certain preference of classes associated with these dust events: most prone to dust events is class 1, followed by class 31. For the sake of brevity, representative synoptic situations for these two classes are selectively shown in Figure 4. Figure 4(a) refers to 1200 UTC February 1 2003, and Figure 4(b) at 1200 UTC May 10 2004; in the former, a central Mediterranean upper trough extends well into the north African desert; in the later, the trough axis extends southwards from the Iberian Peninsula. In both cases, typical patterns are identified favoring dust raising and its transfer eastwards with the prevailing southwesterly airflow over the eastern Mediterranean.

Table 1: Categorization of classes according to the association between dust events.

Category	Classes
Classes associated with dust events (ordered in diminishing importance)	1, 31, 11, 15, 20, 23, 6, 7, 10, 32, 16, 17, 35, 13, 14, 26, 2, 8, 18, 19, 22, 24, 29, 30, 33, and 34
Classes with no association to dust events	3, 4, 5, 9, 12, 21, 25, 27, and 28

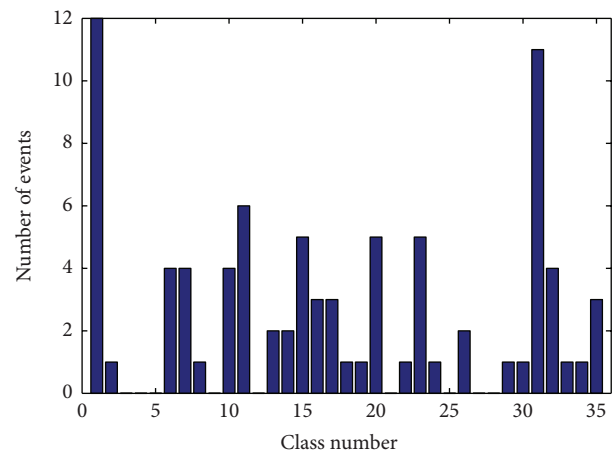


Figure 3: Distribution of dust deposition events per class, for the 35 classes in the synoptic classification, during 2003–2005.

Table 1 summarizes the findings of the above analysis: 26 classes appear to be associated with dust events, whereas 9 classes appear not to be associated with any dust events at all.

3.2. Trends in Synoptic Classes and Dust Deposition Events. Figure 5 shows the frequency of appearance of the synoptic patterns in the classification adopted here, for the 25-year period 1980–2005. Class 35 is again the most frequently encountered, followed by classes 30 and 25.

Figure 6 presents the time evolution of Classes 1, 31 and 11 in the 25-year period considered here; the first two (i.e., classes 1 and 31) exhibit an overall negative trend, while the third (i.e., class 11) exhibits a positive one. These classes were found above to represent the synoptic conditions that mostly favor dust deposition in the 3-year period.

Table 2 summarizes the trends for each of the 35 classes in the classification. It is evident from this table that while

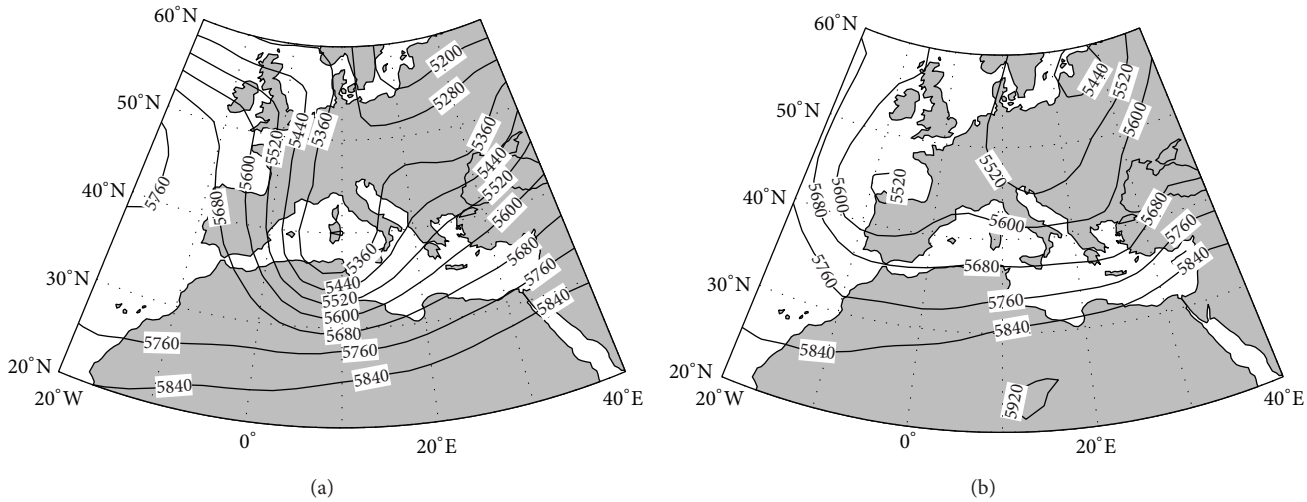


Figure 4: Representative synoptic situations at 500 hPa corresponding to (a) class 1, (b) class 31. Isolines are drawn for every 60 geopotential meters.

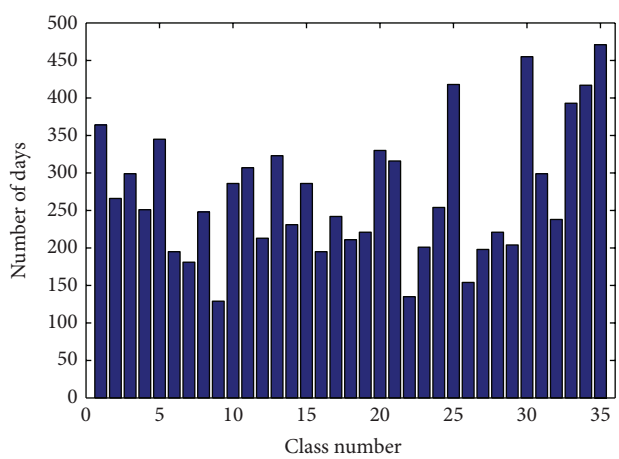


Figure 5: Number of days per class, for the 35 classes in the synoptic classification, during 1980–2005.

for both categories (dust and no dust), an overall prevalence of negative trends was found; this is more notable in the no dust Classes. Indeed, 8 out of the 9 no dust classes exhibit a negative trend; regarding the dust related cases, for 14 out of 26 classes the trend is negative, too. Furthermore, for the latter category, if we consider only the classes that are associated with more than two dust events, then 6 out of 13 classes exhibit negative trends. Bearing the above in mind, we can postulate that there is an increased presence (with time) of Classes that favor the presence of dust; however, this postulation surely needs to be investigated further by involving a larger period than the one used for this research work.

4. Concluding Remarks

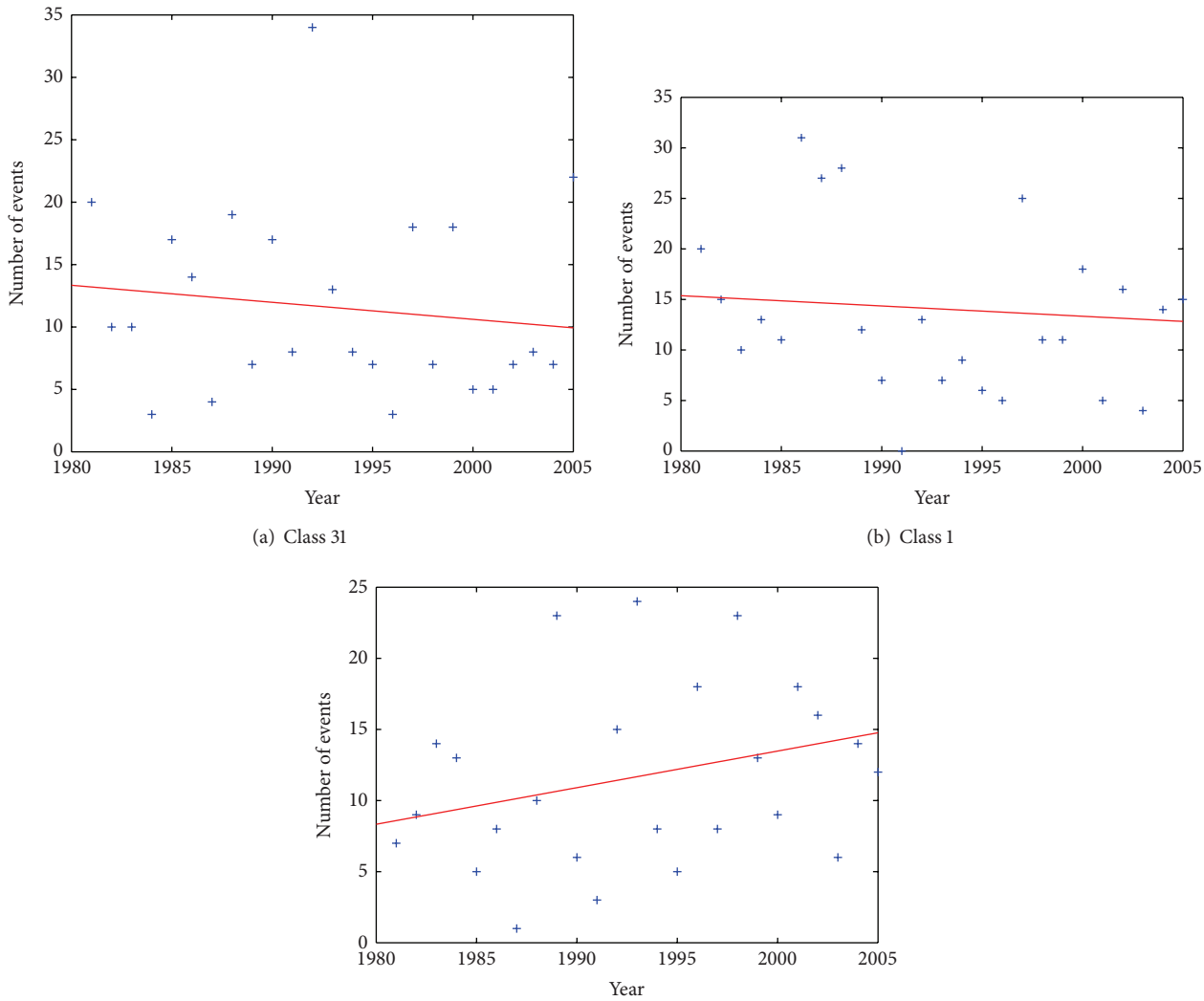
As mentioned in the introduction, local weather forecasters have traditionally identified specific atmospheric circulations as favoring the overall process for dust transportation over the area of eastern Mediterranean. However, such a traditional association of atmospheric circulations and dust events is purely qualitative and subjective. The present research presents an objective methodology which may be applied in establishing an association between the prevailing synoptic circulation and the occurrence of dust events. However, because of the limited time span of the ground dust collection data used, further research is required in order to reach a firm conclusion.

In this respect, an objective classification of synoptic types as they are portrayed by the 500 hPa isobaric analyses was performed. Adopting this classification, an association between dust transportation and prevailing weather conditions in the middle troposphere is established. These results can subsequently be utilized in studying dust transport trends for the island of Cyprus. Despite the fact that the results are site specific and the ANN methodologies used are generally highly data demanding, the methodology has some merit since it allows expanding our knowledge on the phenomenon. Indeed, by utilizing the results of this study, one can achieve some idea of how these synoptic types are associated with dust episodes. The findings can also be used to note the temporal evolution of the synoptic patterns established and also reveal their trends.

The findings of the research performed can be summarized as follows.

(i) There seems to be a preference of synoptic patterns favoring dust event occurrence over Cyprus; also, it is revealed that there are some other synoptic situations that do not favor such events at all.

(ii) There seems to be a tendency for the synoptic situations favoring dust events to increase with time, whereas, the synoptic situations not favoring such events tend to decrease with time.



(a) Class 31

(b) Class 1

(c) Class 11

Figure 6: The time evolution of classes 31 (a), 1 (b), and 11 (c) in the 25-year period (1980–2005).

The fundamental mechanism behind the initiation and further evolution of a dust episode over the study area is one of synoptic scale; bearing this in mind, the above outcomes of this research can be used to explain the observed increase in dust episodes over the area, as revealed from synoptic observations at weather observing stations in the country (independently recorded from the data used in this study).

Although, as mentioned above, the findings in this study are based on a limited time span of dust ground measurements, the above conclusions are qualitatively justified, using the opinion, knowledge, and experience of operational weather forecasters working in the area for many decades. This qualitative validation of the findings focuses mainly on the justification of the relationship between dust events and specific synoptic situations and the trend for increasing number of dust events over the area over the past decade, as mentioned in the introduction.

The use of an objective methodology for synoptic pattern classification is appropriate. Any subjective classification method can only be used as a first guess approach, as it can assist to identify important favorable patterns but cannot provide an objective quantitative background for an investigation such as the one presented here (see [43]). ANN appears to be appropriate for the purpose as it comprises a nonlinear approach to tackling a very complex and definitely non-linear problem (see [44]).

Plans for further research by the group include the expansion of the ground dust measurements once it becomes available and experimentation with other synoptic classification methodologies (see [41, 45]).

Acknowledgments

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Table 2: Synoptic classes and their trends for the 25-year period 1980–2005. Classes associated with dust events are in bold, whereas classes with no association to dust events are not in bold; positive trends are shown as POS and negative trends as NEG. The R^2 for each class is also shown.

Class	Slope	Trend	R^2
1	**−0.1019**	**NEG**	**0.0083**
2	**−0.0588**	**NEG**	**0.0085**
3	−0.0537	NEG	0.006
4	−0.1255	NEG	0.033
5	−0.3484	NEG	0.148
6	**0.1036**	**POS**	**0.036**
7	**−0.0803**	**NEG**	**0.025**
8	**0.0581**	**POS**	**0.01**
9	−0.0058	NEG	0.001
10	**0.147**	**POS**	**0.052**
11	**0.2574**	**POS**	**0.1**
12	−0.1015	NEG	0.018
13	**−0.0147**	**NEG**	**0.001**
14	**−0.0291**	**NEG**	**0.001**
15	**−0.0472**	**NEG**	**0.004**
16	**−0.0817**	**NEG**	**0.022**
17	**−0.0574**	**NEG**	**0.009**
18	**−0.0229**	**NEG**	**0.002**
19	**0.0131**	**POS**	**0.045**
20	**0.0499**	**POS**	**0.006**
21	−0.0048	NEG	0.001
22	**0.012**	**POS**	**0.001**
23	**0.0961**	**POS**	**0.025**
24	**−0.121**	**NEG**	**0.022**
25	0.0834	POS	0.012
26	**0.0602**	**POS**	**0.021**
27	−0.0048	NEG	0.001
28	−0.1959	NEG	0.092
29	**−0.0178**	**NEG**	**0.001**
30	**0.1084**	**POS**	**0.013**
31	**−0.1364**	**NEG**	**0.02**
32	**0.026**	**POS**	**0.001**
33	**−0.1159**	**NEG**	**0.013**
34	**−0.1338**	**NEG**	**0.002**
35	**0.6376**	**POS**	**0.26**

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