ATMOSPHERIC PATTERNS FOR HEAVY PRECIPITATION IN BULGARIA

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Abstract: This paper presents a classification of the atmospheric circulations producing extreme precipitation events in Bulgaria. Heavy precipitation data set from the National Institute of Meteorology and Hydrology, Bulgaria, atmospheric fields of geopotential height at 1000 hPa, at 500 hPa and temperature at 850 hPa of the ECMWF operational analysis are used to determine the atmospheric patterns (AP). Other atmospheric fields such as geopotential height at 850 hPa, at 700 hPa and relative humidity at 700 hPa are also depicted to analyze the AP. Two statistical methods are used to obtain the AP. Principal Component Analysis (PCA) was applied to reduce the number of variables. Then, Cluster Analysis (CA) was performed and four main AP were obtained. For two AP, heavy precipitation is associated with a low-level cyclone. They can occur in all seasons. For the cold season (October to March), the trajectories of the cyclones are represented. Another pattern, which occurs mainly in the warm season (April to September), depicts an upper-level cyclonic disturbance associated with heavy precipitation. The last AP represents a weak cyclonic circulation. Finally, a more detailed nine-cluster classification has been also obtained by adding some regional and seasonal features of the heavy precipitation events.

1. INTRODUCTION

Heavy precipitation is one of the severe weather phenomena, which usually causes serious damages and even fatalities. This is the reason why it is very important to predict heavy precipitation events as accurately as possible. At the same time, it is a really challenging problem, which inspires the meteorological community to make a lot of effort to improve our knowledge about this hazard. Bocheva et al. (2007) present a climatic study of severe storms over Bulgaria produced by synoptic-scale Mediterranean cyclones in winter. They state that although the number of the Mediterranean cyclones has decreased during the last years, the number of those producing high impact weather, such as heavy precipitation, has increased. By applying a self-organizing map nonlinear classification technique and a feed-forward artificial neural network, Cavazos (2000) showed that extreme wintertime precipitation events in the Bulgarian region are associated with strong meridional flow over Central and Eastern Europe coupled to increased winter disturbances in the Central Mediterranean and a tongue of moisture at 700-hPa level from Eastern Mediterranean to the Black Sea. In 2005 Bulgaria was affected by a huge number of heavy precipitation events that caused floods and serious damages in many parts of the country and they were a real test for the meteorologists and the society.

Case studies on these situations were presented by Gospodinov et al. (2006), Hristov and Latinov (2006), and Stoicheva and Latinov (2006).

The main aim of this study is to increase the knowledge about the situations producing heavy precipitation in Bulgaria. This investigation was inspired by the MEDEX project, which is a part of the WMO World Weather Research Programme by its involvement in THORPEX. MEDEX has the main objective to improve the knowledge and forecasting of the cyclones that produce high impact weather in the Mediterranean area (see http://medex.inm.uib.es).

By using a statistically based approach, a classification of the atmospheric patterns associated with heavy precipitation events is presented in this paper. We followed a similar methodology used in Romero et al. (1999) and in Lana et al. (2007).

2. DATA AND METHODOLOGY

We made this study on 121 cases of heavy precipitation events occurred in Bulgaria from June 1998 to May 2004 using the regular measurements from the conventional network of synoptic, climatic and rain gauge stations (Fig.1) of the National Institute of Meteorology and Hydrology, Bulgaria, available also on the MEDEX website (http://medex.inm.uib.es). The precipitation amounts for day D were measured in a 24-hour period from 07:00 UTC of day D to 07:00 UTC of the day D+1.

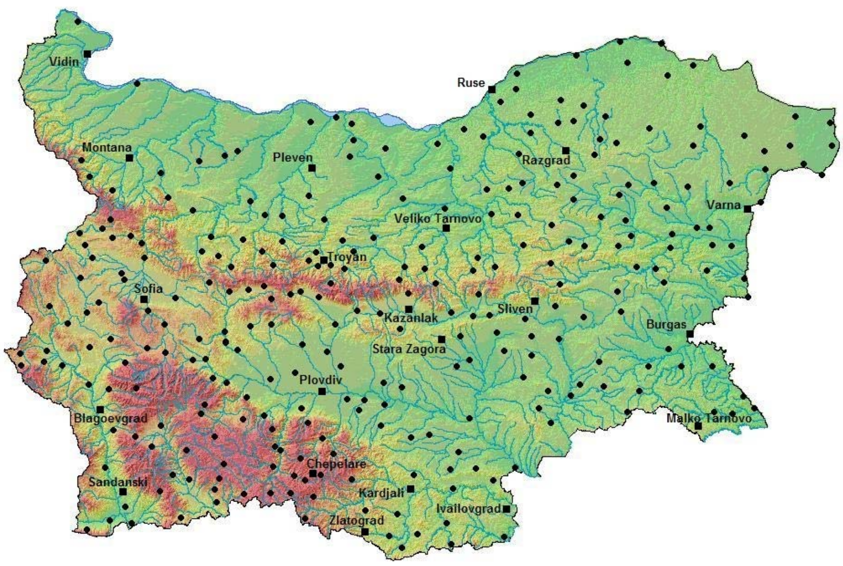

Fig.1. The network of meteorological stations of the National Institute of Meteorology and Hydrology used for selecting heavy precipitation events. The percentile of 60 mm/24h are given in table 1 for the stations marked with squares.

We define the precipitation as "heavy" if its amount is at least 60 mm/24h, so this investigation is intended to include all events with extreme precipitation. The percentile of 60 mm/24h for some stations representative for different regions is given in Table 1.

Table 1. Percentile of 60 mm/24h for some stations indicated on the map.

Station	Percentile of 60 mm/24h
Blagoevgrad	93
Burgas	85
Chepelare	76
Ivailovgrad	75
Kardjali	76
Kazanlak	82
Malko Tarnovo	50
Montana	82
Pleven	78
Plovdiv	86
Razgrad	83
Ruse	79
Sandanski	94
Sliven	92
Sofia	93
Stara Zagora	91
Troyan	76
Varna	79
Veliko Tarnovo	89
Vidin	85
Zlatograd	40

Therefore it could be considered that any precipitation that exceeds 60 mm/24h is potentially dangerous. The same threshold is also chosen in the MEDEX project that this work is related to.

To obtain the atmospheric patterns, we used the operational analysis at 12:00 UTC of the day D from the ECMWF global model (T319), interpolated to 0.5° latitude x 0.5° longitude as the representative for the 24 h interval. The investigated region is from 50° N to 35° N and from 12° E to 34° E. Bulgaria is situated almost in the center of this domain. For each of the 121 heavy precipitation events, we obtained three matrices with the values of geopotential height at 1000 hPa (H1000), geopotential height at 500 hPa (H500) and temperature at 850 hPa (T850) at all the 1395 grid points belonging to the region under study.

To examine the trajectories of the lows, we used one of the MEDEX databases of cyclones.

For reducing the number of variables, a Principal Component Analysis is performed (Wilks, 1995). First we specified a T-mode (day-by-day) of decomposition and prepared a correlation matrix for each parameter (H1000, H500, T850) (Yarnal, 1993). An eigenvector analysis allowed us to determine the principal components as those eigenvectors with the highest eigenvalues of the correlation matrix that, finally, represented 90% of the variance in the data. In this way, we stored 6 components for the geopotential height at 500 hPa, 7 for the geopotential height at 1000 hPa and 7 for the temperature at 850 hPa.

We applied the non-hierarchical K-means clustering method (Anderberg, 1973) to the retained components. The algorithm minimizes the total sum *W* of the squared Euclidean distances between the cases and the centroids of the clusters

$$W=\sum_{i=1}^{k}\sum_{j=1}^{n}(x_j-c_i)^2,$$

where x_j is the j-th case, c_i is the i-th centroid, *n* is the number of all cases (121 in total) and *k* the number of clusters. The method requires the initial determination of the number of clusters *k* as well as the initial cases to start with (the so-called seed points). Obviously, *W* decreases as the number of clusters *k* increases. The appropriate number of clusters could be selected when there is not significant decrease of *W*. In this study, *W* was calculated for all *k* from 2 to 20 by applying two different methods. For the first one, we chose, as the seed points, the first *k* data cases in the data set. Thus we obtained that the appropriate number of classes for a general classification was 5 and for a more detailed one, it was 9. The second method consisted in the generation of an initial partition by dividing all cases equally into *k* clusters and computing the cluster centroids. For this method the criterion gave us 8 groups as an appropriate number of clusters. Thus, we obtained that the criterion we used to select the number of clusters *k* strongly depends on the method of the choice of the seed points as it could be expected when there is not a unique well-defined classification of the data set. To obtain the optimal number of clusters, we varied *k* from 4 to 9 and then we analyzed all the classes and the cases belonging to them. Thus, we semi-empirically chose *k*=4 as the most appropriate number of the classes for the general classification because for *k*=5 one class did not add any significant information from a synoptic point of view. For a more detailed classification, we chose 9 clusters because it gave the maximum useful information about the regional and seasonal aspects of the distribution.

3. RESULTS

As it has been detailed in the previous paragraph, finally, four main atmospheric patterns related to the presence of heavy precipitation in Bulgaria were obtained. Figure 2, 3 and 4 show the mean fields of some meteorological variables for each AP. Table 2 shows the monthly distribution and Table 4 presents some precipitation values of the cases of different patterns. AP1 is characterized by a cyclonic circulation and relatively cold air at upper levels over Bulgaria. Mean field at ground suggests easterly airflow bringing moisture from the Black Sea. This type of situations occurs mainly in the warm season (April-September) (90% of the cases), especially in summer.

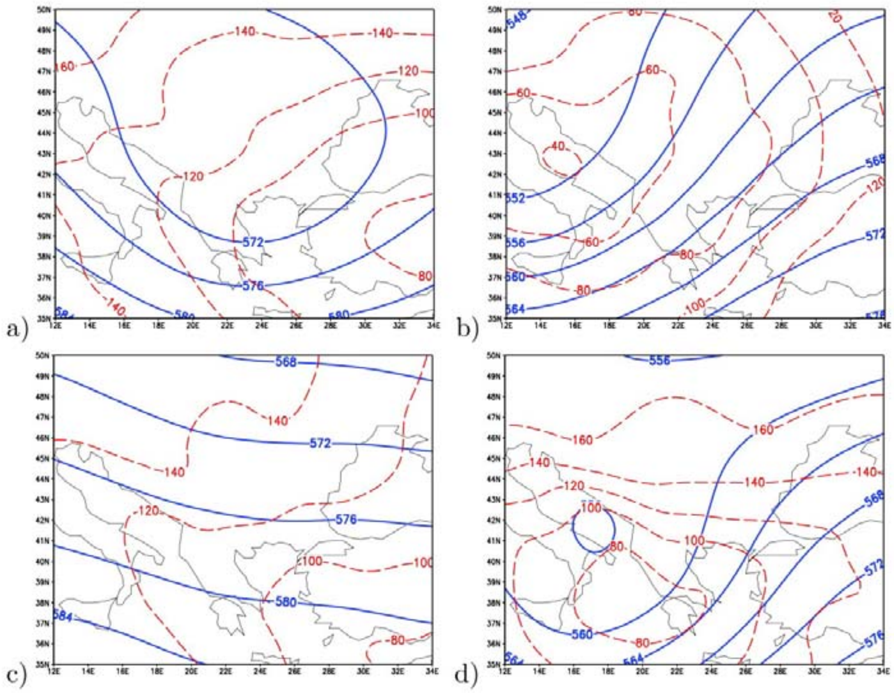

Fig. 2. Geopotential height at 1000 hPa (dashed lines, gpm) and geopotential height at 500 hPa (solid lines, gpdam) for a) AP1, b) AP2, c) AP3 and d) AP4.

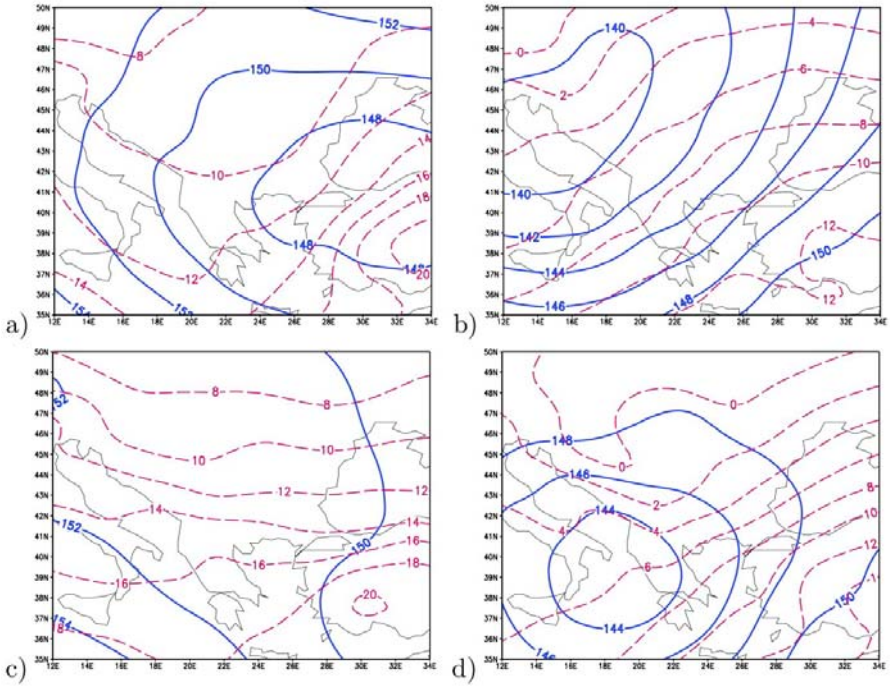

Fig. 3. Geopotential height at 850 hPa (solid lines, gpdam) and temperature at 850 hPa (dashed lines, ºC) for a) AP1, b) AP2, c) AP3 and d) AP4.

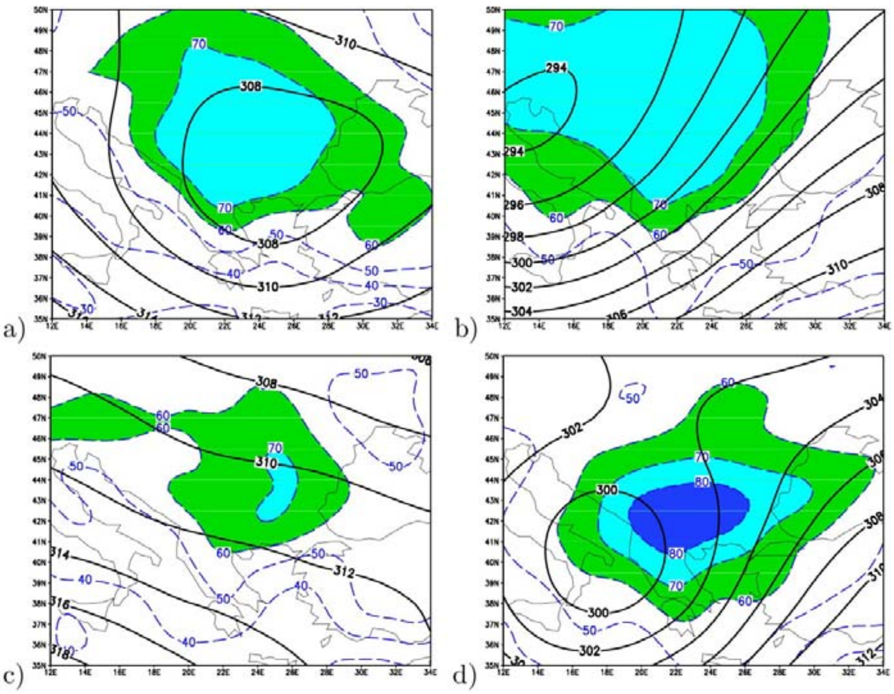

Fig. 4. Geopotential height at 700 hPa (solid lines, gpdam) and relative humidity at 700 hPa (shaded above 60%) for a) AP1, b) AP2, c) AP3 and d) AP4.

Table 2. Monthly distribution of the heavy precipitation events from June 1998 to May 2004 in the case of 4 atmospheric patterns.

AP	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*total*
AP1	0	0	0	2	3	5	8	2	8	2	1	0	31
AP2	4	4	0	2	1	1	3	2	3	3	3	6	32
AP3	0	1	0	0	3	6	8	6	1	3	0	1	29
AP4	2	1	2	2	0	0	5	1	3	3	3	7	29
total	6	6	2	6	7	12	24	11	15	11	7	14	121

Table 4. The median P_{median}, mean P_{mean}, maximum precipitation P_{max} and the relative number of cases with precipitation grater than 100 mm/24h for AP.

AP	*P_{median}, mm*	*P_{mean}, mm*	*P_{max}, mm*	*P 100 mm/24 h, %*
AP1	77.0	85.6	186.5	23
AP2	75.3	80.7	160.0	22
AP3	71.4	78.3	158.0	14
AP4	75.0	82.9	176.0	28

Cyclonic circulation, the cold air at upper levels and the moist low-level flow increase the convective instability and force the convection. Other features such as thermal lows, convergence lines and moisture favour the convection. Heavy precipitation affects mostly the central and eastern parts of Bulgaria. AP1 is the pattern with the highest values of the mean and median of the distribution and with the largest precipitation amount of 186.5 mm recorded on 4th of September 1999 (Table 4).

AP2 includes situations with a cyclone situated over the Adriatic Sea. A deep trough extends from north far to the coasts of North Africa. Cold air has already penetrated over the Central Mediterranean and there is a well-defined frontal zone over the Balkans. This pattern is more frequent during the cold season (October-March) (63% of the cases) although it can also occur in summer when convection develops. Heavy precipitation is typical for the southwestern part of Bulgaria and especially for Rodopa mountain area, which is affected by heavy precipitation in 72% of the cases.

AP3 occurs mainly in the warm season (83% of the cases) especially in summer. Average fields show almost zonal airflow with weak through at 500 hPa and a frontal zone over the Balkans. At these situations, the thermal low situated over the Anatolian peninsula extends to northwest when a cold front is passing through the Balkans. It is the weakest precipitation pattern as it could be seen in Table 4. Heavy precipitation could be associated with the passage of the cold front and with the convective cyclogenesis. Figure 5 shows the dominant trajectories of the lows.

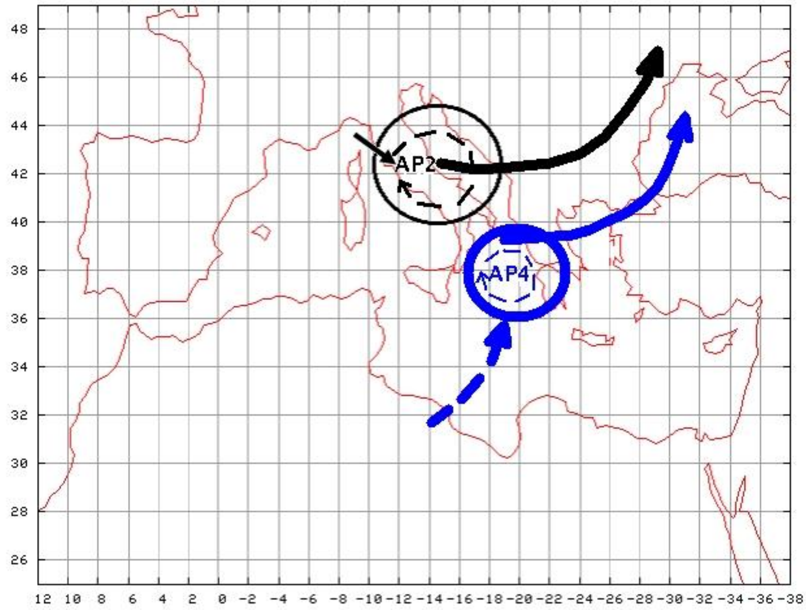

Fig. 5. Trajectories of the cyclones from AP2 and AP4. Circles show regions with maximum density of cyclones. Dotted arrows in the circles represent quasi-stationary cyclones. Arrow from the gulf of Genoa represents Genoa cyclones. Dashed arrow represents the cyclones of the origin in North Africa.

instability during the warm season. These situations need a more detailed analysis in the mesoscale to explain the heavy precipitation events.

AP4 shows a deep low pressure to the southwest of Bulgaria over the Ionian Sea. At these situations, we observe southerly upper-level airflow and a frontal zone over Bulgaria. Mean map of the relative humidity at 700 hPa clearly marks an area with high values (above 80%) over Bulgaria. This pattern is more common from September to April (79% of the cases). Heavy precipitation is more probable in South Bulgaria. AP4 is the atmospheric pattern with the largest number of cases with precipitation amounts greater than 100 mm/24 h (Table 4).

AP2 and AP4 clearly suggest that a great number of the heavy rain events are associated with low-level cyclones over the Mediterranean. They are more typical in the cold season when the Mediterranean Sea is a center of

For AP2, cyclones are developing over the Adriatic Sea. Most of them have trajectories over Bulgaria or very close preferably to the northwest through Serbia and the others are quasi-stationary and are dying out over the Central Mediterranean. Some of these cyclones originate in the gulf of Genoa, and they evolve as the well-known Genoa cyclones (Buzzi and Tibaldi, 1978). AP4 contains situations with quasi-stationary or slowly moving cyclones over the Ionian Sea or Greece and Aegean Sea. Some of these cyclones have their origin in North Africa and are known as so called North-West African depressions whose classification and description is presented by N. Prezeracos et al. (1990). AP4 also includes cyclones passing through Greece and the Aegean Sea to the Black Sea moving closely to the Bulgarian coast.

A more detailed classification of the atmospheric patterns consisted of 9 classes is presented as well. It gives additional information about the regional distribution of the heavy precipitation over Bulgaria and about the seasonal distribution of the AP. The mean fields for each pattern are presented in Figure 6, 7 and 8. Table 3 shows the monthly distribution of the different patterns.

AP9.1, AP9.3 and AP9.4 look like AP3.

AP9.1 is the rarest pattern, with only 5 events. In the warm season, the heavy precipitation is associated with the convective instability while in the cold season, heavy precipitation occurs along a cold front from north-northeast on the southern edge of the anticyclone. AP9.3 and AP9.4 are very similar. They depict a zonal airflow at upper levels and a well-defined frontal zone over Bulgaria. They occur mainly in the warm season. Heavy precipitation events could be associated with a frontal passage and convective instability along the cold front.

AP9.2 and AP9.5 could be considered as subclasses of AP2. The mean maps place a deep surface cyclone over Italy and a well-defined upper-level through in the Central Mediterranean. AP9.2 is characterized by a warm ridge over Bulgaria. Heavy precipitation is more common in the western and central parts of Bulgaria as it is suggested by the mean field of the relative humidity at 700 hPa. AP9.2 can occur during all seasons. AP9.5 occurs from September to April when low-level cyclones are much deeper as it can be seen on the mean map. The frontal zone is situated over Bulgaria. Heavy precipitation affects mainly the Rodopa mountain area (88% of the cases).

AP9.6 and AP9.8 are very similar to AP1. They are typical for the warm season. AP9.6 places a cyclone at 500 hPa very close to the west of Bulgaria. The mean field at 1000 hPa suggests an

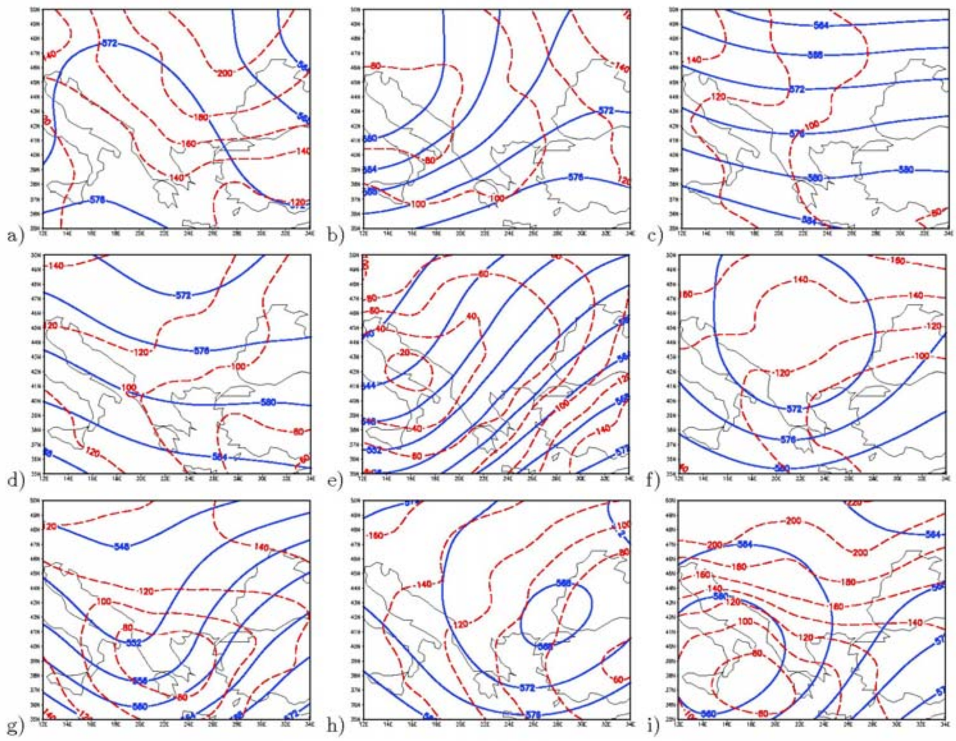

Fig. 6. Geopotential height at 1000 hPa (dashed lines, gpm) and geopotential height at 500 hPa (solid lines, gpdam) for a) AP9.1, b) AP9.2, c) AP9.3, d) AP9.4, e) AP9.5, f) AP9.6, g) AP9.7, h) AP9.8, and i) AP9.9.

easterly airflow and thus penetration of humid air from the Black Sea. The frontal zone is situated over eastern and southern regions. Heavy precipitation

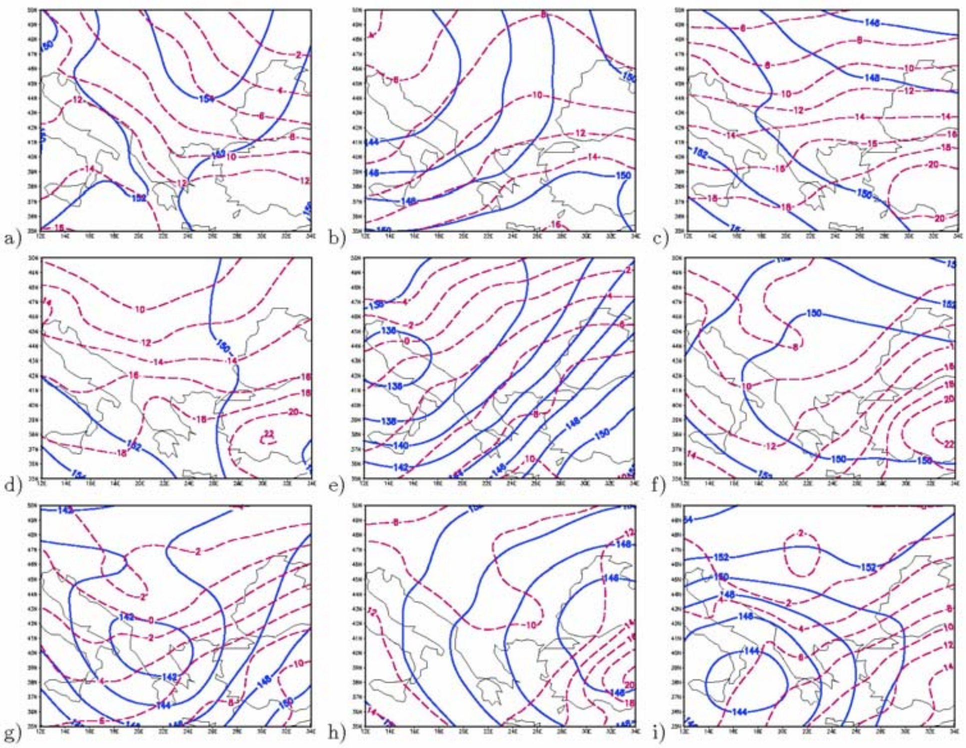

Fig. 7. Geopotential height at 850 hPa (solid lines, gpdam) and temperature at 850 hPa (dashed lines, ºC) for a) AP9.1, b) AP9.2, c) AP9.3, d) AP9.4, e) AP9.5, f) AP9.6, g) AP9.7, h) AP9.8, and i) AP9.9.

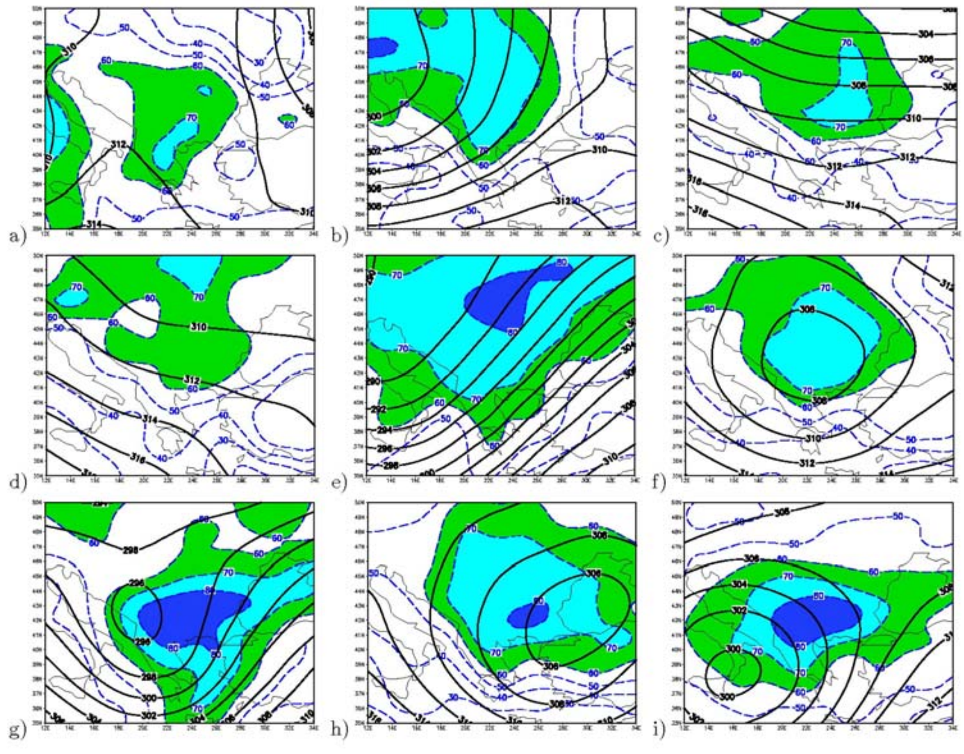

Fig. 8. Geopotential height at 700 hPa (solid lines, gpdam) and relative humidity at 700 hPa (shaded above 60%) for a) AP9.1, b) AP9.2, c) AP9.3, d) AP9.4, e) AP9.5, f) AP9.6, g) AP9.7, h) AP9.8, and i) AP9.9.

affects mostly eastern part of the country and Rodopa mountain area and therefore could be associated with the frontal zone over these regions. At AP9.8, the weather systems are displaced to the east in comparison with AP9.6. The cold air has already penetrated over Bulgaria, which increases the convective instability during the warm season. Heavy precipitation affects mainly the eastern and northern parts of Bulgaria and could be associated with the convective instability in a cold air mass.

AP9.7 and AP9.9 correspond to AP4. AP9.7 is typical for the cold season. It places a deep cyclone over Greece and a trough at upper levels situated slightly to the west. The frontal zone could be observed over Bulgaria and Greece. There is a well-marked area of high values of the relative humidity at 700 hPa over Bulgaria. High precipitation affects mainly the southern parts of Bulgaria, especially Rodopa mountain area (at 92% of the cases). AP9.9 is characterized by a deep cyclone over the Ionian Sea and a high-pressure system to the north-northeast keeping the continuous flow of moist air from the Black Sea. The frontal zone is situated over Bulgaria and Greece. This AP is more frequent from September to March. Heavy precipitation again affects mainly the southern parts of Bulgaria.

Table 3. Monthly distribution of the heavy precipitation events from June 1998 to May 2004 in the case of 9 atmospheric patterns.

AP	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*	*Dec*	*total*
AP9.1	0	0	0	0	1	2	0	0	0	1	0	1	5
AP9.2	0	1	0	1	0	2	3	2	0	1	2	2	14
AP9.3	0	1	0	0	2	1	4	3	2	1	0	0	14
AP9.4	0	0	0	0	1	3	4	2	0	0	0	0	10
AP9.5	4	3	0	1	0	0	0	0	3	1	0	5	17
AP9.6	0	0	0	2	1	2	9	1	7	2	0	0	24
AP9.7	1	0	1	1	0	0	0	0	0	3	4	2	12
AP9.8	0	0	0	1	2	2	2	1	1	1	0	0	10
AP9.9	1	1	1	0	0	0	2	2	2	1	1	4	15
total	6	6	2	6	7	12	24	11	15	11	7	14	121

CONCLUSIONS AND REMARKS

Heavy rain events registered in Bulgaria from June 1998 to May 2004 have been classified into 4 distinct atmospheric patterns. Each atmospheric pattern has been accurately described, as well as their seasonal distribution and the regions most affected by heavy rain. Although each AP is obtained averaging the atmospheric fields of many cases, and therefore real situations could differ significantly from the analyzed AP they belong to, a general description of the most important mechanisms involved into heavy precipitation could be performed.

Two atmospheric patterns, AP2 and AP4, show the presence of well-developed low-level Mediterranean cyclones to the west or to the south of Bulgaria. In AP1 the presence of the cyclone at upper levels suggests that heavy precipitation events are caused by the convective instability. Finally, AP3 does not display well-defined cyclonic circulation. This suggests that heavy precipitation is associated with small-scale processes such as mesoscale convection and convergence lines, which cannot be resolved in the large scale. Hence more detailed analysis is necessary to explain the mechanisms for these extreme wet events.

For more detailed description, nine-class classification has been also performed. It gives additional information on the regional and seasonal distribution of the heavy precipitation events.

This study gains knowledge of the heavy rain events in the Mediterranean and therefore it can be considered to be a direct contribution to the scientific investigations in MEDEX. The classification is much more valuable because of the high threshold for precipitation and hence it presents really extreme wet events in Bulgaria.

This study could also be of special interest to the Bulgarian forecasters. The atmospheric patterns presented in the paper can help operational forecasters treat extreme precipitation events.

The investigation period in this work is short because of the availability of the analyses in MEDEX database and the results have to be used with care.

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