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Spatial and temporal analysis of dry spells in Greece

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With 8 Figures

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Summary

A spatio-temporal analysis of the dry spells that occur in the Greek area is carried out for an extended period of 40 years (1958–1997). The dry spells can be defined as a number of consecutive days with no rain. The number of days defines the length of the dry spells. The longest spells are identified in central (Cyclades) and the south-east Aegean Sea whereas dry spells with the minimum length are shown over the north-west of the Greek area that reflects the significance of the latitude and the topography. Negative Binomial Distribution and Markov Chains of second order have been used to fit the duration of the dry spells of different lengths. The study of the seasonal and annual distribution of the frequency of occurrence of dry spells revealed that the dry spells in Greece depict a seasonal character, while medium and long sequences are associated with the duration and hazards of drought.

1. Introduction

Drought is a complex phenomenon, which is often associated with persistence of dry days. The meteorological definition of drought is based on the knowledge of the physical process, which can give the explanation of the immediate meteorological causes of drought.

Analyses of monthly precipitation data have certain advantages. At the same time, they also have some disadvantages because they cannot detect the driest or wettest period within a month. In fact, there are periods of 10 days in a month, when the probability of rain is lower or greater than the probability of the other two 10-days periods of month. In general, the analysis of monthly rainfall totals has the limitation of not detecting the temporal structure of the rainfall in a high-time resolution. In this respect, many scientists choose to study the drought phenomenon by using the length of dry spells (Kutiel, 1985; Conesa and Martin-Vide, 1993; Douguédroit, 1980).

The spells of dry days can reveal significant changes in the structure of drought. The definition of dry spells, which is based on the number of days without precipitation, has been widely used. Analysis of dry spells could be done employing different rainfall threshold values for a dry day, such as more than or equal to 0.1 mm, 1.0 mm, 10 mm, etc (Kutiel, 1985; Kutiel and Maheras, 1992). Many stochastic procedures have been used as methods to describe the expected frequency of dry spells. Among the most frequently ones are the Markov Chains of different orders (Martin-Vide and Gomez, 1999; Berger and Goossens, 1983; Gomez Navarro, 1996; Conesa and Martin-Vide, 1993; Douguédroit, 1980). In addition to the previous method, Douguédroit (1987, 1991) and Galloy et al. (1982) used the Negative Binomial model for the treatment of dry spells.

2. Methodology – data

A dry spell is defined as a sequence of consecutive dry days with precipitation equal or less than (a) mm. It can be said that a dry spell begins and ends the day after and the day before a daily rainfall amount > (a) mm, respectively. The rainfall thresholds, which have been chosen here are 0.1 mm and 1.0 mm. The purpose of using these two different threshold values was to check if they could influence the relative variation of the dry spells distribution. According to Douguédroit (1987), each dry spell is counted to the month that contains its first day. On the other hand, Dauphiné (1975) counted dry spells to the month that contains the longest sequence of consisting days without rain. However, for Greece, where dry spells frequently contain more than three months it seems inconvenient to use Dauphiné's definition.

In order to evaluate the kind of dry spells distribution two models were used, the Negative Binomial model and the Second order Markov Chains (2^{nd} MC). Both models allow to calculate the probability that a dry spell lasts exactly n days, with $n = 1, 2, \ldots, 30$.

According to the Second order Markov Chains, the probability that a dry spell will last exactly n days is given (Wilks, 1995) through the following analytical expression:

$$Qn = p_{100} \cdot (p_{000})^{n-2} \cdot p_{001}$$
$$Qn = p_{101}$$

where

p_{100} is the probability of a dry day following a dry day when the day before is a rainy one,
p_{000} is the probability of a dry day after two consequently dry days and
p_{001} is the probability of a rainy day after two dry days.

On the other hand, for the negative binomial model the probability that a dry spell occurs can also be defined (Wilks, 1995):

$$p_n = \frac{1}{(1+d)h/d} \frac{(h/d)_{n-1}}{(n-1)} \frac{d^{n-1}}{1+d}$$

where

n is the number of dry spells
$h = (\bar{x} - 1)$, h is the mean value (x) of the length of a dry spell after the first day.

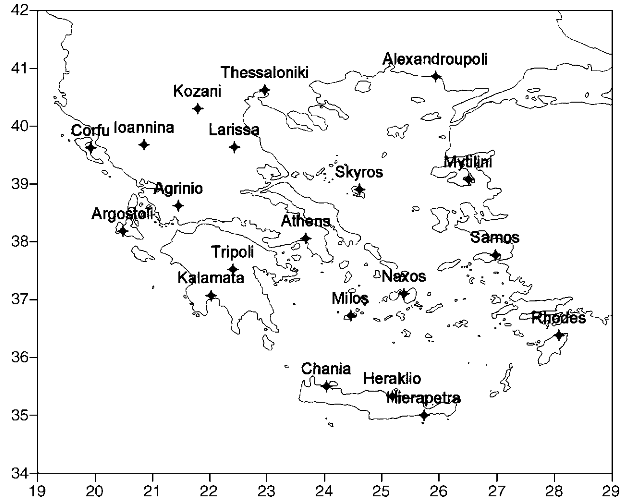

Fig. 1. The locations of the 20 Greek meteorological stations

$d = (\sigma^2/h) - 1$, d is the limit of the ratio of the probability that a spell lasts more than n days to the probability that it lasts n days.

Therefore, d/h is related to the nature of the persistence of drought. The following cases exist:

If $h < d$ then $d/h > 1$ the persistence increases;
If $h > d$ then $d/h < 1$ the persistence decreases, and finally
If $h = d$ then $d/h = 1$ the persistence is constant.

In order to study the spatial distribution of dry spells in Greece, daily precipitation data from 20 stations distributed evenly over Greece (Fig. 1) were used. They cover a 40-year period from January 1958 to December 1997. The dry spells were divided into smaller sub-periods in order to provide a more reasonable distribution. The subperiods are as follows:

Sort sequences: 1–10 days
Medium sequences: 11–20 days
Long sequences: 21–30 days
Very long sequences: >30 days

The following analyses were pursued on an annual and seasonal basis. Then, in order to evaluate the fit of the results of the two models, the X^2-test was used, at the significance level of 0.05.

3. Very long sequences

Extremely long dry spells with a 0.1 mm threshold are found all over Greece during 1958–1997. The distribution of the maximum lengths of the dry spells with thresholds 0.1 mm is shown

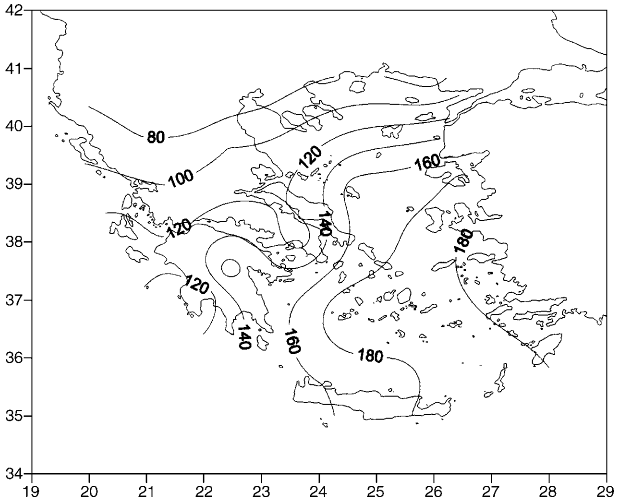

Fig. 2. Maximum length of dry spells with 0.1 mm precipitation threshold

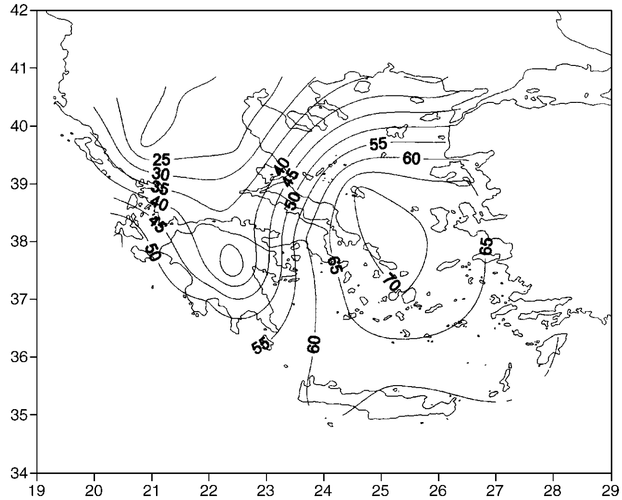

Fig. 3. The annual frequency of very long dry spells

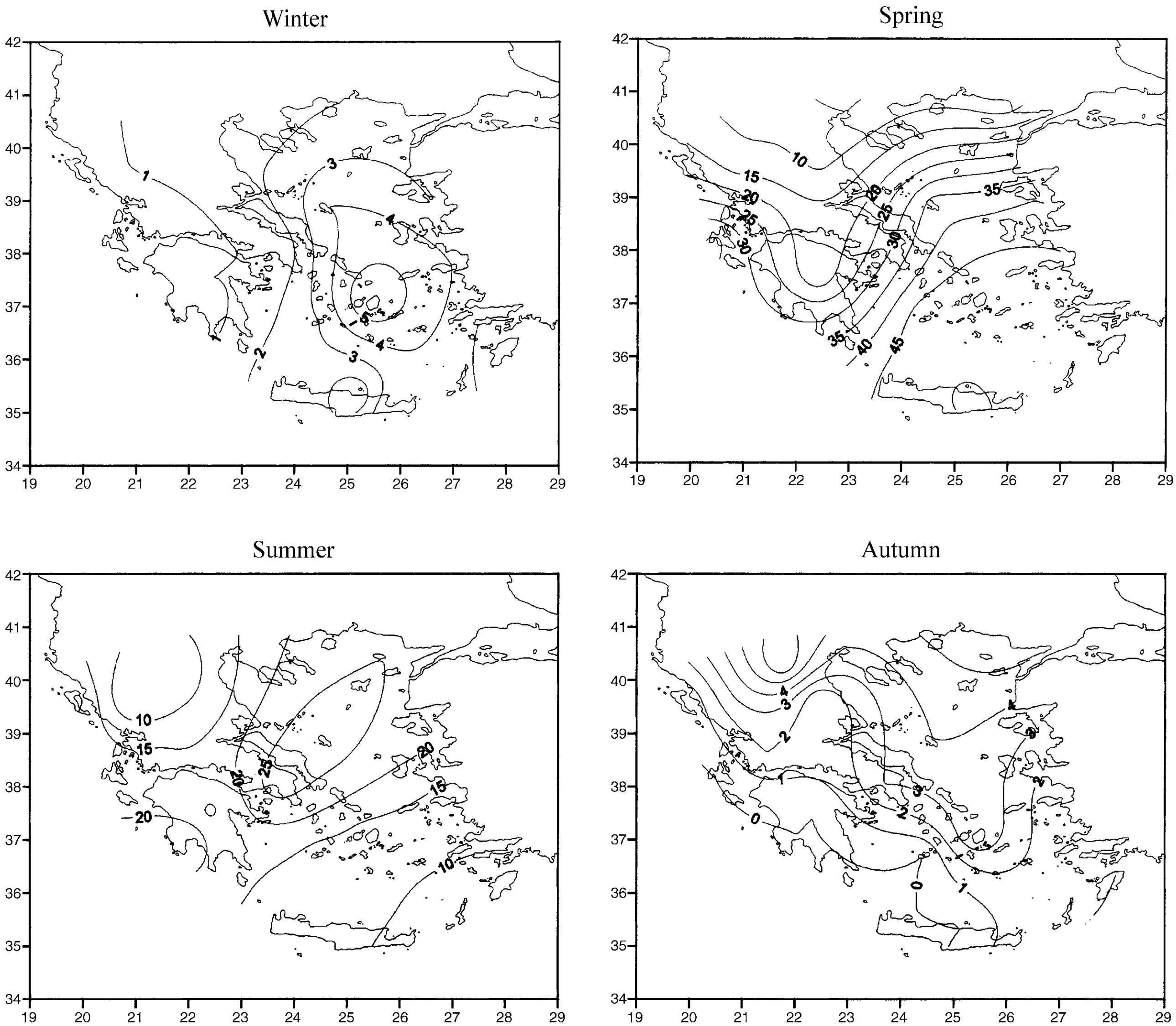

Fig. 4. The seasonal frequency of very long dry spells

in Fig. 2. Most noticeable are the very long dry spells in Cyclades and Rhodes (south-east Aegean Sea). It is indicative that a spell with 180 dry days has been identified in this region. On the contrary, in the continental area of Macedonia, the longest period without appreciable precipitation is about 60–80 days (2–3 months).

Examining very long dry spells, the annual maximum extreme frequency of dry spells was found to be about 70, under a 0.1 mm threshold, which means that during the analysed period there were 70 cases of sequences longer than 30 days. (Fig. 3). The maximum frequency of dry spells occurs in the Central Aegean Sea. The minimum occurs in the northwest of Greece and counts only 20 cases.

The corresponding seasonal results show different distribution (Fig. 4). In winter, the continental region of West Greece, which is considered as a rainy region, counts only 1 case, whereas 5 cases of very long sequences are encountered in the Central Aegean Sea (Cyclades). Spring shows a geographical distribution similar to the annual one. In the south-east Aegean Sea more than 45 dry spells occur, while dry spells of Macedonia do not exceed 5 cases.

In summer, contrary to what is generally expected, extremely long dry spells show lower frequency than those in spring. This happens because many of the long dry spells start at the end of spring so they are counted to it. The general distribution of this season presents high frequency from the North Aegean Sea to the South Ionian Sea, with lower frequency on either side of it. Similarly to winter, autumn shows low frequency of extra long dry spells (maximum is close to 5), and a decrease of the frequency from north to south.

Dry spells with 1.0 mm threshold represent a similar geographical distribution to the ones with 0.1 mm. Of course, the main difference is that dry spells with 1.0 mm threshold are longer and have higher frequency than dry spells with 0.1 mm threshold. Only in the case without any precipitation, the results of both thresholds would be equal.

4. Dry spells with 0.1 mm threshold

For the annual dry spells with length between 1–10 days the maximum frequency is found in the north-west Greek area with more than 38 cases

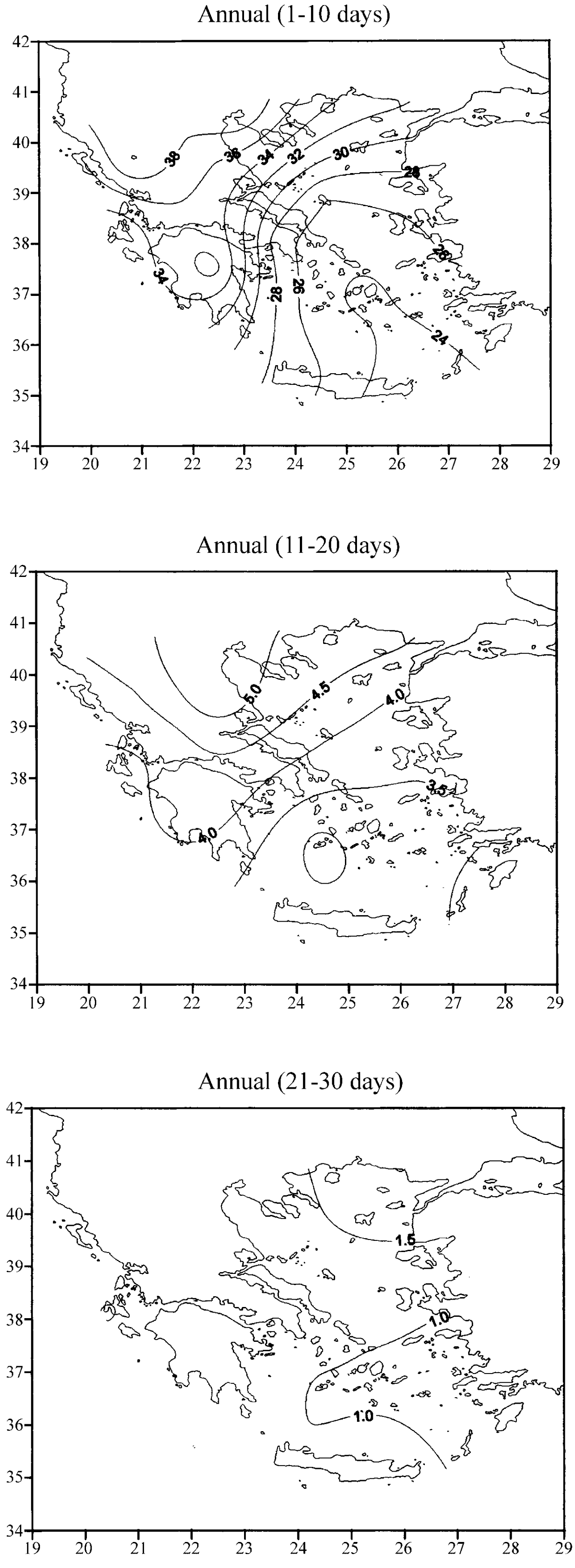

Fig. 5a. The frequency distribution of the mean annual observed dry spell class

(the mean frequency was calculated by dividing the total number of dry spells to the number of years (40)) during the analysed period, while the minimum is in the south-east Greek area (Fig. 5a). A decrease of the frequency values is identified from west to east. For medium sequences (11–20 days) the distribution of the observed data shows patterns similar to the short sequences, but with lower frequency. The maximum frequency of long dry spells is found in the north-east Greek area, providing a representative picture of the great pluviometric variation in Greece. It is noticeable that the whole Greek area presents values equal to 1–2 days, suggesting that long dry spells occur in the whole examined region.

The distribution of isopleths for seasonal dry spells reflects the seasonal character of dry spells for the Greek area (Fig. 5b). In winter, Alexandroupoli records less than 11 cases, while Kalamata and south west Greece more than 13. Isopleths of spring appear to have a similar disposition with the annual one. They show a gradient by a factor of five between Kozani and Ierapetra, accounting for 11 cases in Kozani and only 2 in Ierapetra. The distribution of summer frequency agrees with the previous one, but with smaller values. Six (6) cases of dry spells occur in north Greece, but no case was found in the south-east Greek area, which justifies the driest place of the Greek region. This phenomenon

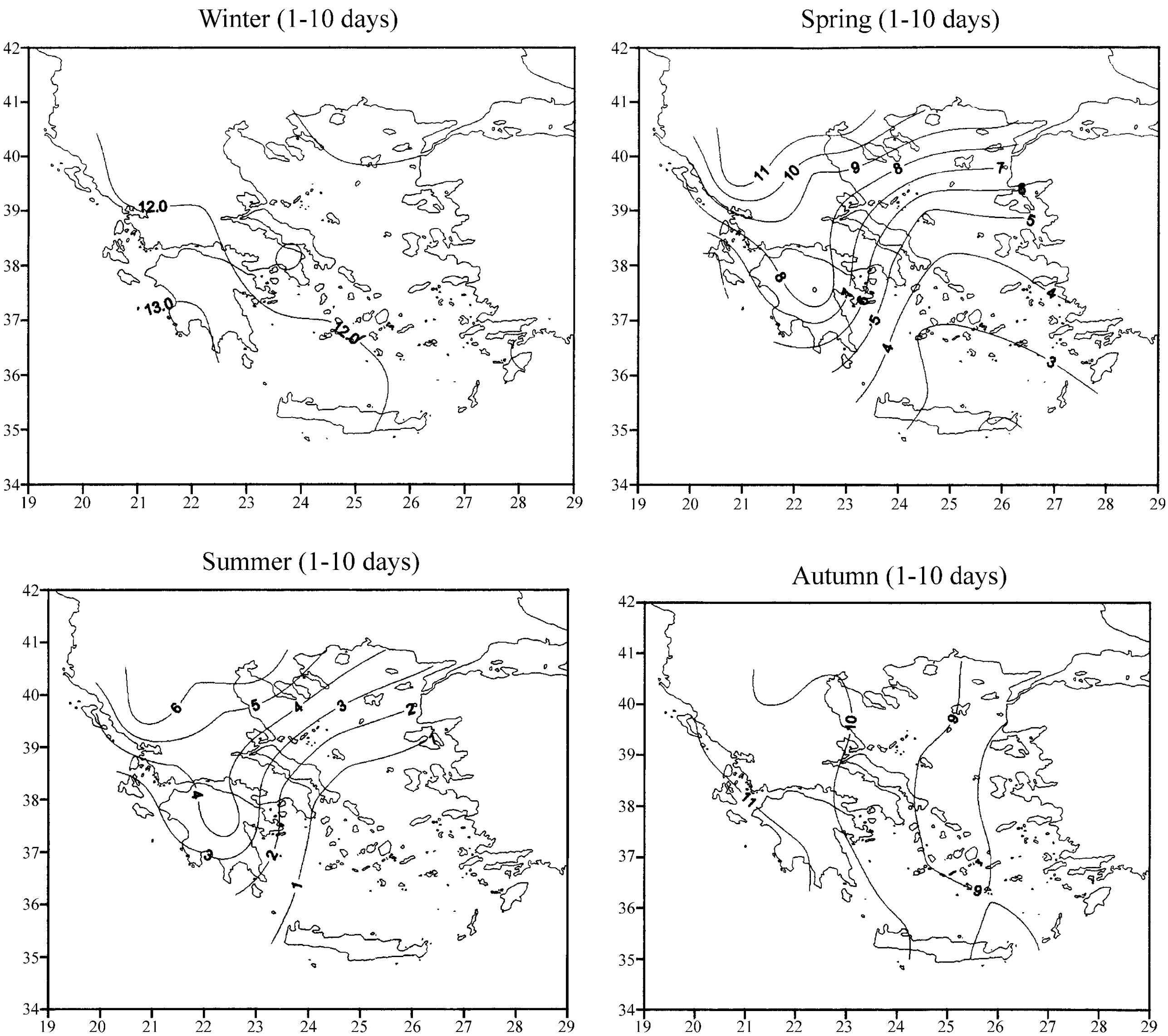

Fig. 5b. The frequency distribution of the 1 to 10 days dry spells class for all seasons

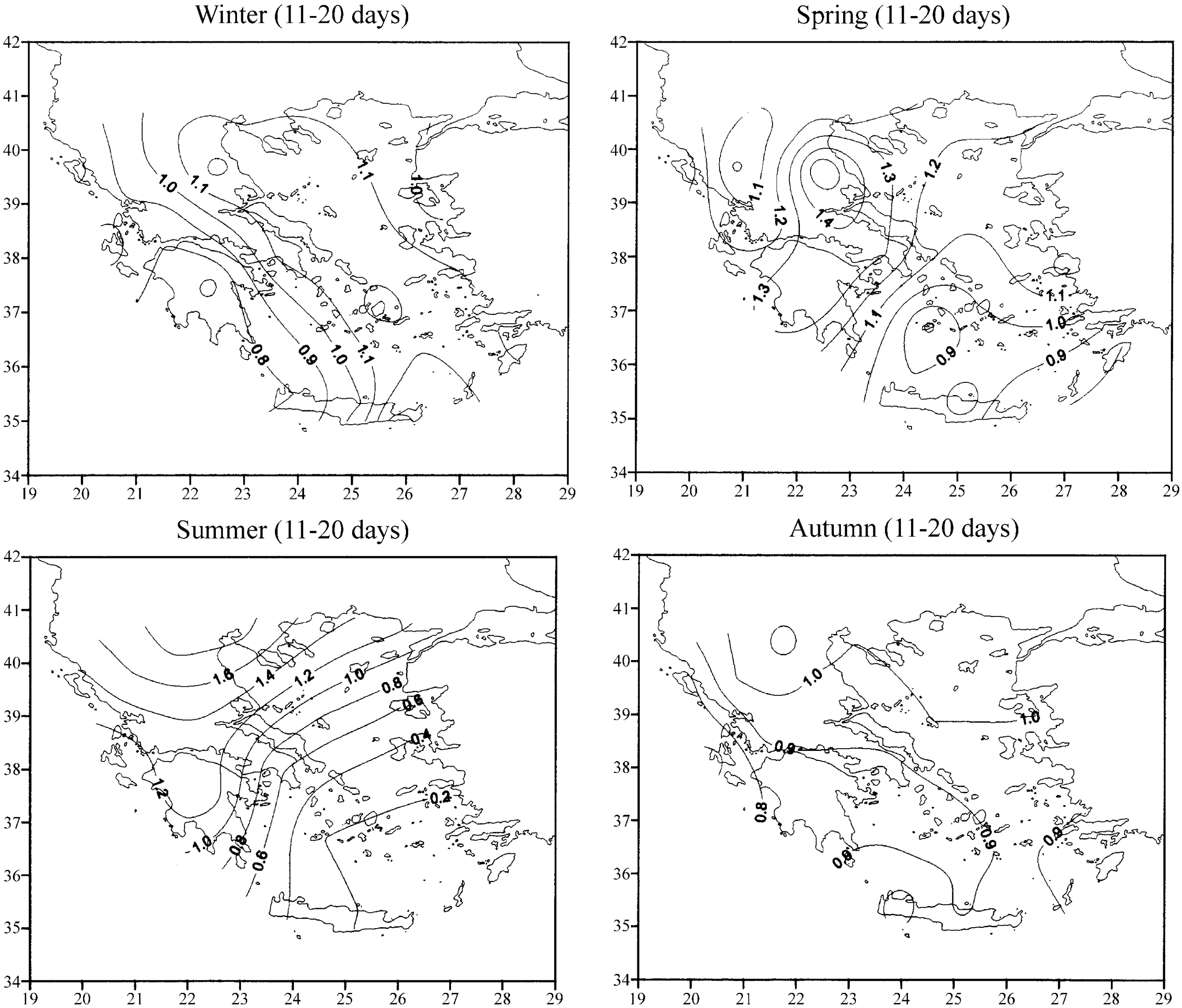

Fig. 5c. The frequency distribution of the 11 to 20 days dry spells class for all seasons

could be explained by the fact that south-east Greece experiences mainly medium and long dry spells during summer. For autumn, the isopleths depict a meridional disposition with frequency decreasing from west to east. West Greek area shows 11 cases with 9 cases over the Aegean Sea.

Dry spells with a length of 11 to 20 days present lower frequency than the previous category (Fig. 5c), varying between zero and two for all seasons. It means that dry spells with length 11–20 days show similar distribution. In winter, the region that shows the highest frequency is the Aegean Sea, while the south-west Greek area shows the lowest one. In spring the distribution pattern changes: Central continental Greece depicts the highest frequency, being surrounded by lower values. The corresponding distribution for summer resembles that of dry spells with 1–10 days. The relatively low frequency in the south-east Aegean Sea as compared to north-east Greece reflects the relative difference in the productive mechanisms of the precipitation. For autumn, the maximum value of the mean frequency, being more than one case is found in the north, while the minimum is in the west Greek area.

The frequency for the last class of dry spells (21–30 days), is very low (Fig. 5d). For winter, a decrease of frequency from north to south is

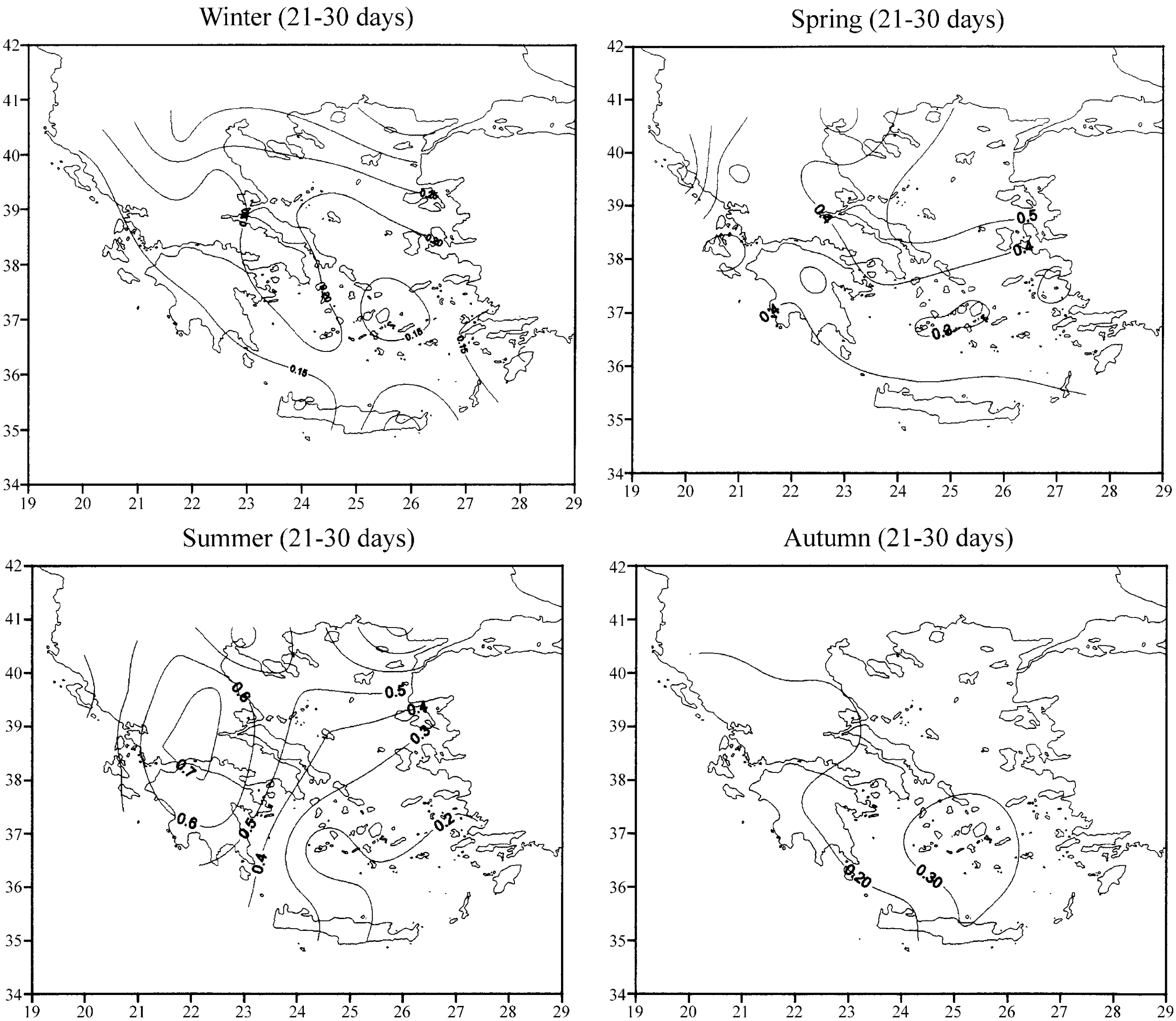

Fig. 5d. The frequency distribution of the 21 to 30 days dry spells class for all seasons

evident with the isopleths adopting a quasi-zonal disposition. Isopleths of spring show a relatively different distribution. North-east Greece depicts the highest frequency while the minimum was found in the central Aegean Sea (Cyclades). In summer a complete different distribution occurs, where central continental Greece shows the highest frequency whilst the south Aegean Sea has the lowest. Cyclades are characterised by the highest frequency of dry spells for autumn as opposed to spring, whereas lower frequency values occur in the rest of the country.

In general, the lower the latitude, the greater is the influence of the synoptic subtropical patterns in the middle and upper troposphere, which express themselves in longer droughts, especially during the summer. Thus, during the warm period, the successive passage of fronts or the instability due to cold upper air cause fairly frequent precipitation over northern Greece and especially over Epirus, Macedonia and Thrace (Maheras, 1983). On the other hand, the influence of the subtropical anticyclone in the middle and upper troposphere causes great stability over the south Greek area. The dry spells in northern Greece are relatively short and frequent as compared to southern Greece, where the dry spells are longer but with lower frequency.

5. Comparisons between observed and simulated data

Using the Negative Binomial model and the second order Markov Chains model we calculated the probability for dry spells of length between 1–10 days, 11–20 days and 21–30 days. The adjustments for the two models, have been verified by the χ^2 test, with $v-1$ degrees of freedom

Table 1. Probabilities associated to the χ^2 of annual dry spells. Comparison between the observed and model simulated dry spells: second order Markov Chains and Negative Binomial model. Significance of the fit at the 5% level is indicated by bold numbers

		Year		
		1–10 days	11–20 days	21–30 days
Agrinio	Markov 2nd	0.000	0.000	**0.350**
	Negative binomial	0.000	0.013	**0.177**
Alexandroupoli	Markov 2nd	0.000	0.000	0.037
	Negative binomial	0.049	0.021	0.000
Argostoli	Markov 2nd	0.000	0.000	0.003
	Negative binomial	0.000	0.017	0.001
Athens	Markov 2nd	0.000	0.000	**0.063**
	Negative binomial	0.035	**0.278**	0.041
Chania	Markov 2nd	0.000	0.000	0.001
	Negative binomial	0.000	0.027	**0.321**
Corfu	Markov 2nd	0.000	0.003	0.023
	Negative binomial	0.000	**0.119**	0.000
Heraklio	Markov 2nd	0.000	0.000	0.001
	Negative binomial	0.005	0.018	0.002
Hierapetra	Markov 2nd	0.000	0.000	0.000
	Negative binomial	0.000	0.016	**0.148**
Ioannina	Markov 2nd	0.000	**0.071**	**0.237**
	Negative binomial	0.000	**0.168**	**0.284**
Kalamata	Markov 2nd	0.000	0.000	**0.207**
	Negative binomial	0.000	**0.116**	0.008
Kozani	Markov 2nd	0.000	0.036	**0.201**
	Negative binomial	0.000	**0.068**	0.039
Larissa	Markov 2nd	0.000	0.025	**0.077**
	Negative binomial	0.000	0.041	0.009
Milos	Markov 2nd	0.000	0.000	0.000
	Negative binomial	0.003	0.009	**0.158**
Mytilini	Markov 2nd	0.000	0.000	0.025
	Negative binomial	0.001	0.044	0.006
Naxos	Markov 2nd	0.000	0.000	0.000
	Negative binomial	0.000	**0.358**	**0.392**
Rhodes	Markov 2nd	0.000	0.000	0.000
	Negative binomial	**0.073**	**0.095**	**0.125**
Samos	Markov 2nd	0.000	0.000	0.000
	Negative binomial	0.000	**0.342**	**0.220**
Skyros	Markov 2nd	0.000	0.000	0.002
	Negative binomial	0.002	**0.089**	0.000
Tripoli	Markov 2nd	0.000	0.001	**0.243**
	Negative binomial	0.000	0.046	0.032
Thessaloniki	Markov 2nd	0.001	**0.195**	**0.630**
	Negative binomial	0.001	**0.427**	**0.275**

Table 2. Probabilities associated to the χ^2 of seasonal dry spells. Comparison between the observed and model simulated dry spells: second order Markov Chains and Negative Binomial model. Significance of the fit at the 5% level is indicated by bold number

		1–10 days				11–20 days				21–30 days			
		Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Agrinio	Markov 2nd	**0.415**	0.001	**0.205**	0.027	**0.682**	**0.168**	**0.959**	**0.656**	0.027	**0.419**	**0.187**	**0.697**
	Negative binomial	**0.868**	**0.276**	0.001	**0.089**	**0.611**	**0.700**	**0.773**	**0.697**	**0.279**	0.044	0.001	**0.795**
Alexandroupoli	Markov 2nd	**0.066**	0.039	**0.566**	**0.509**	**0.051**	**0.082**	0.038	**0.085**	0.005	0.012	**0.969**	**0.499**
	Negative binomial	**0.268**	**0.126**	0.000	**0.881**	**0.120**	**0.118**	0.043	**0.058**	**0.100**	**0.061**	0.050	**0.207**
Argostoli	Markov 2nd	**0.288**	0.000	0.045	0.014	**0.484**	**0.195**	**0.309**	**0.055**	**0.184**	0.035	**0.130**	0.000
	Negative binomial	**0.104**	0.000	0.000	**0.238**	**0.679**	**0.195**	**0.254**	**0.133**	**0.601**	0.035	0.001	**0.230**
Athens	Markov 2nd	0.023	**0.055**	0.003	0.009	**0.238**	**0.493**	**0.418**	**0.066**	**0.950**	**0.716**	**0.930**	**0.253**
	Negative binomial	**0.318**	0.013	0.000	**0.743**	**0.261**	**0.739**	**0.126**	**0.425**	**0.772**	**0.199**	**0.256**	0.003
Chania	Markov 2nd	**0.407**	0.044	0.006	0.013	0.033	**0.190**	**0.142**	**0.065**	0.004	**0.592**	0.013	**0.974**
	Negative binomial	**0.457**	0.000	0.000	0.004	**0.256**	**0.135**	**0.467**	**0.051**	**0.095**	**0.335**	**0.187**	**0.958**
Corfu	Markov 2nd	**0.569**	0.002	0.013	**0.150**	**0.104**	**0.181**	**0.168**	**0.830**	0.034	0.000	**0.226**	0.040
	Negative binomial	**0.276**	0.000	0.013	0.016	**0.289**	**0.249**	0.044	**0.823**	**0.648**	0.000	0.034	**0.565**
Heraklio	Markov 2nd	**0.108**	**0.069**	0.000	**0.281**	0.026	**0.780**	**0.407**	**0.220**	0.000	**0.441**	0.015	**0.754**
	Negative binomial	**0.102**	0.022	0.000	0.017	**0.204**	**0.454**	**0.436**	**0.352**	**0.079**	**0.127**	0.047	**0.401**
Hierapetra	Markov 2nd	0.023	**0.318**	0.000	**0.131**	**0.109**	**0.895**	**0.289**	**0.094**	**0.454**	**0.895**	0.003	**0.904**
	Negative binomial	0.000	0.000	0.017	**0.643**	**0.249**	**0.301**	**0.781**	**0.158**	**0.874**	**0.560**	**0.086**	**0.511**
Ioannina	Markov 2nd	**0.080**	0.001	**0.541**	0.001	**0.531**	**0.125**	**0.818**	**0.056**	**0.052**	0.000	**0.487**	**0.424**
	Negative binomial	**0.165**	**0.153**	0.008	0.007	**0.578**	**0.195**	**0.856**	**0.189**	**0.195**	**0.133**	0.030	**0.823**
Kalamata	Markov 2nd	**0.467**	0.034	**0.629**	0.024	0.022	**0.289**	**0.971**	**0.559**	0.003	**0.695**	**0.860**	**0.220**
	Negative binomial	**0.599**	0.001	0.000	0.006	**0.121**	**0.461**	**0.829**	**0.553**	**0.204**	**0.285**	0.041	**0.827**
Kozani	Markov 2nd	0.007	0.027	**0.540**	**0.420**	0.043	**0.604**	**0.127**	**0.616**	**0.289**	**0.141**	**0.130**	**0.420**
	Negative binomial	**0.085**	**0.476**	0.000	**0.197**	**0.062**	**0.630**	0.023	**0.811**	**0.442**	**0.565**	0.022	**0.081**
Larissa	Markov 2nd	**0.420**	0.016	0.041	**0.120**	**0.313**	**0.603**	**0.497**	**0.696**	0.017	0.017	**0.111**	**0.925**
	Negative binomial	**0.406**	0.000	0.000	**0.826**	**0.439**	**0.514**	**0.235**	**0.805**	**0.102**	0.009	0.001	**0.839**
Milos	Markov 2nd	**0.481**	0.002	0.000	0.001	**0.508**	**0.098**	0.001	**0.167**	**0.467**	**0.135**	**0.586**	**0.348**
	Negative binomial	0.001	0.020	0.001	**0.497**	**0.349**	**0.064**	**0.797**	**0.440**	**0.759**	**0.108**	**0.858**	**0.146**
Mytilini	Markov 2nd	**0.103**	0.000	0.016	**0.061**	**0.113**	**0.058**	**0.094**	**0.103**	**0.131**	**0.448**	**0.554**	0.038
	Negative binomial	**0.317**	0.000	0.035	**0.521**	**0.161**	**0.290**	**0.588**	**0.132**	**0.296**	0.008	**0.124**	0.009
Naxos	Markov 2nd	0.020	0.009	0.007	0.000	**0.538**	**0.648**	**0.367**	**0.198**	**0.771**	**0.132**	0.001	**0.666**
	Negative binomial	**0.411**	0.001	0.038	**0.106**	**0.496**	**0.219**	**0.713**	**0.600**	**0.775**	**0.728**	**0.054**	**0.227**
Rhodes	Markov 2nd	**0.356**	0.002	0.000	**0.543**	0.009	**0.095**	**0.543**	**0.431**	**0.066**	**0.134**	0.001	**0.573**
	Negative binomial	**0.745**	0.000	0.042	**0.306**	**0.058**	**0.271**	**0.662**	**0.786**	**0.417**	0.028	**0.182**	**0.121**

(*continued*)

Table 2 (*continued*)

		1–10 days				11–20 days				21–30 days			
		Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn
Samos	Markov 2nd	**0.084**	0.002	0.000	0.004	**0.480**	**0.233**	0.031	**0.646**	**0.616**	**0.126**	**0.154**	**0.107**
	Negative binomial	**0.313**	0.003	**0.091**	**0.279**	**0.631**	**0.307**	**0.529**	**0.822**	**0.854**	**0.339**	**0.448**	**0.063**
Skyros	Markov 2nd	**0.242**	0.007	**0.626**	**0.107**	**0.580**	**0.148**	**0.417**	0.045	**0.419**	**0.067**	**0.984**	**0.279**
	Negative binomial	**0.488**	0.004	0.000	**0.064**	**0.587**	**0.168**	**0.445**	**0.085**	**0.411**	0.000	**0.721**	0.029
Tripoli	Markov 2nd	**0.215**	0.007	0.036	**0.293**	**0.068**	**0.722**	**0.150**	**0.772**	0.006	**0.564**	**0.514**	0.001
	Negative binomial	**0.437**	0.022	0.000	**0.366**	**0.094**	**0.807**	**0.084**	**0.675**	**0.233**	**0.244**	0.004	0.034
Thessaloniki	Markov 2nd	**0.151**	**0.143**	**0.741**	**0.668**	**0.200**	**0.367**	**0.472**	**0.528**	0.000	0.014	**0.710**	**0.393**
	Negative binomial	**0.286**	**0.281**	**0.092**	**0.052**	**0.193**	**0.415**	**0.114**	**0.673**	0.005	**0.197**	**0.811**	**0.130**

and a level of significance $\alpha = 0.05$. The variations of the probabilities of occurrence of the dry spells are tested for the three classes of 1–10 days, 11–20 days and 21–30 days (Tables 1–2).

Once the distribution of the frequency of dry spells has been analysed, the differences between mean observed and mean simulated data were calculated. The purpose is to evaluate the closeness between the simulated and the observations. The differences were analysed and plotted. A solid line depicts positive differences and a dotted one the negative ones. The shaded regions in the figures represent the statistically significant model fit.

For annual dry spells with length 1–10 days, the Negative Binomial model overestimates the dry spell frequency. The differences are small and they do not exceed the value 1.2. On the other hand, the Markov Chains of second order model underestimates the simulated frequency in comparison to the observed frequency (Fig. 6). In south-east Greece, the difference between the simulated and observed dry spells is almost 4.5, while in the north continental Greek area the simulated and observed data seem to match. The Negative Binomial model gives an acceptable fit only for one station, whereas the second order Markov Chains model do not fit any of the twenty stations (Fig. 6). For the next class of dry spells (11–20 days), both models overestimate the frequency of dry spells. The Negative Binomial model provides better results than the Markov Chain model (Fig. 6). The long sequences show a completely different picture. The positive differences between observations and Negative Binomial model data present a weak field of isopleths. On the contrary, for the Markov Chain model the isopleths are very tight and the absolute values increase from south-east to north-west and from negative to positive values. The statistically significant regions for both models are indicated in Fig. 6 by the shaded areas.

The fitting between simulated and observed data is better on a seasonal basis than on an annual basis. In winter, the Negative Binomial model presents significant results for almost the whole Greek area and all the classes of dry spells (Fig. 7a). The Markov Chain model gives less significant results than the previous one and for a smaller area. Specifically, for sort sequences

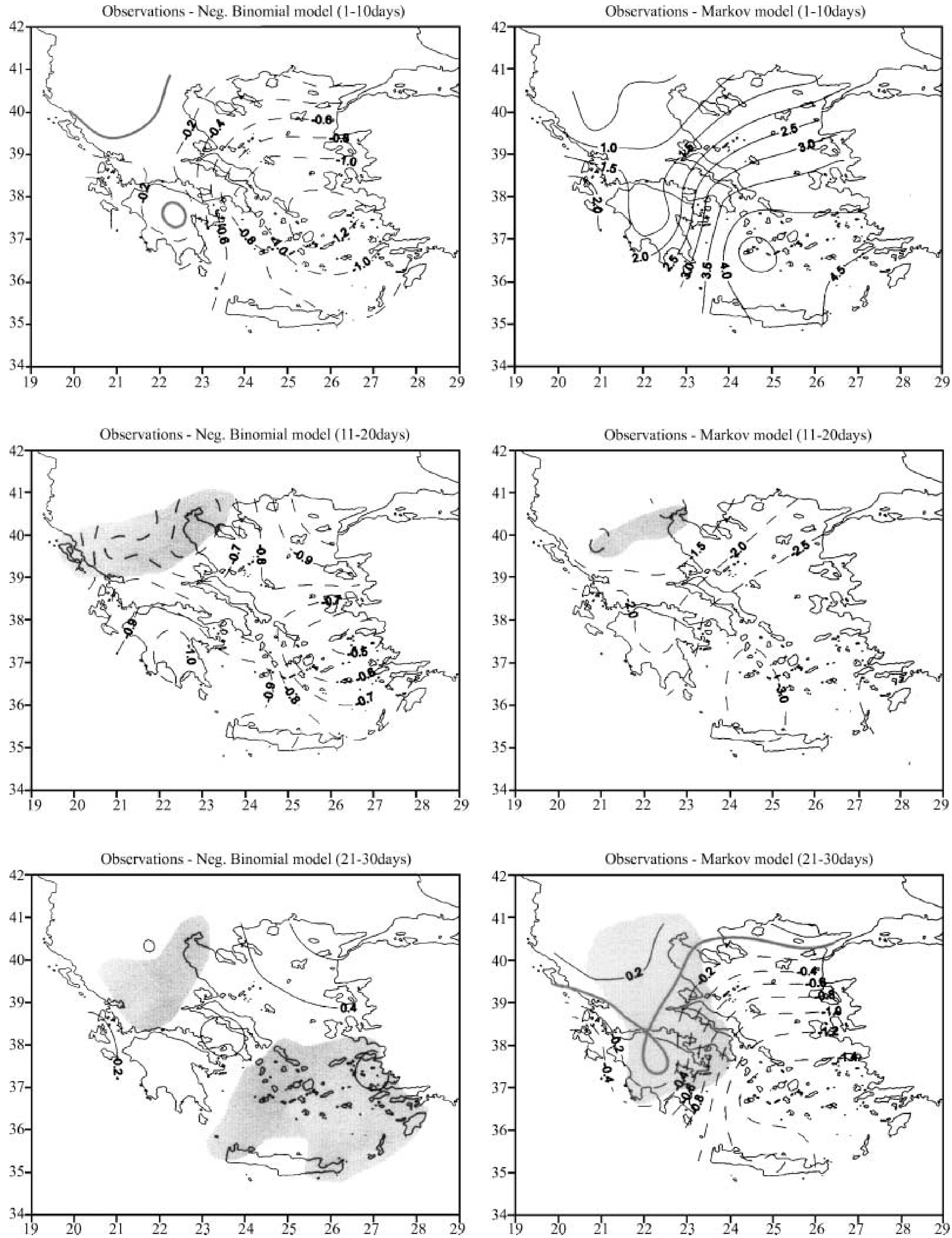

Fig. 6. The geographical distribution of the frequency differences between observed and simulated data for yearly dry spells. The shaded regions represent statistically significant model fit

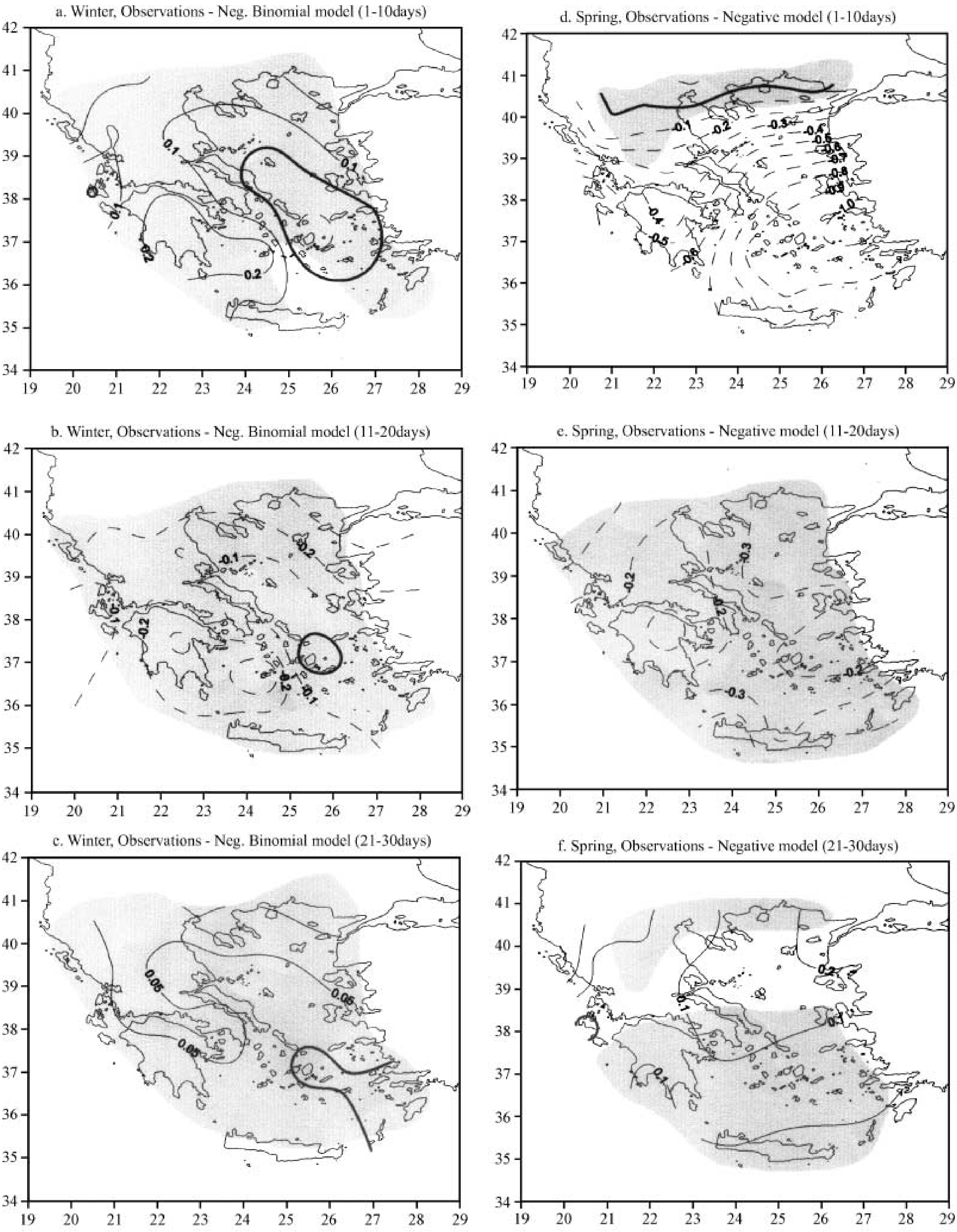

Fig. 7. The geographical distribution of the frequency differences between observed and simulated data for winter and spring dry spells. The shaded regions represent the statistically significant model fit

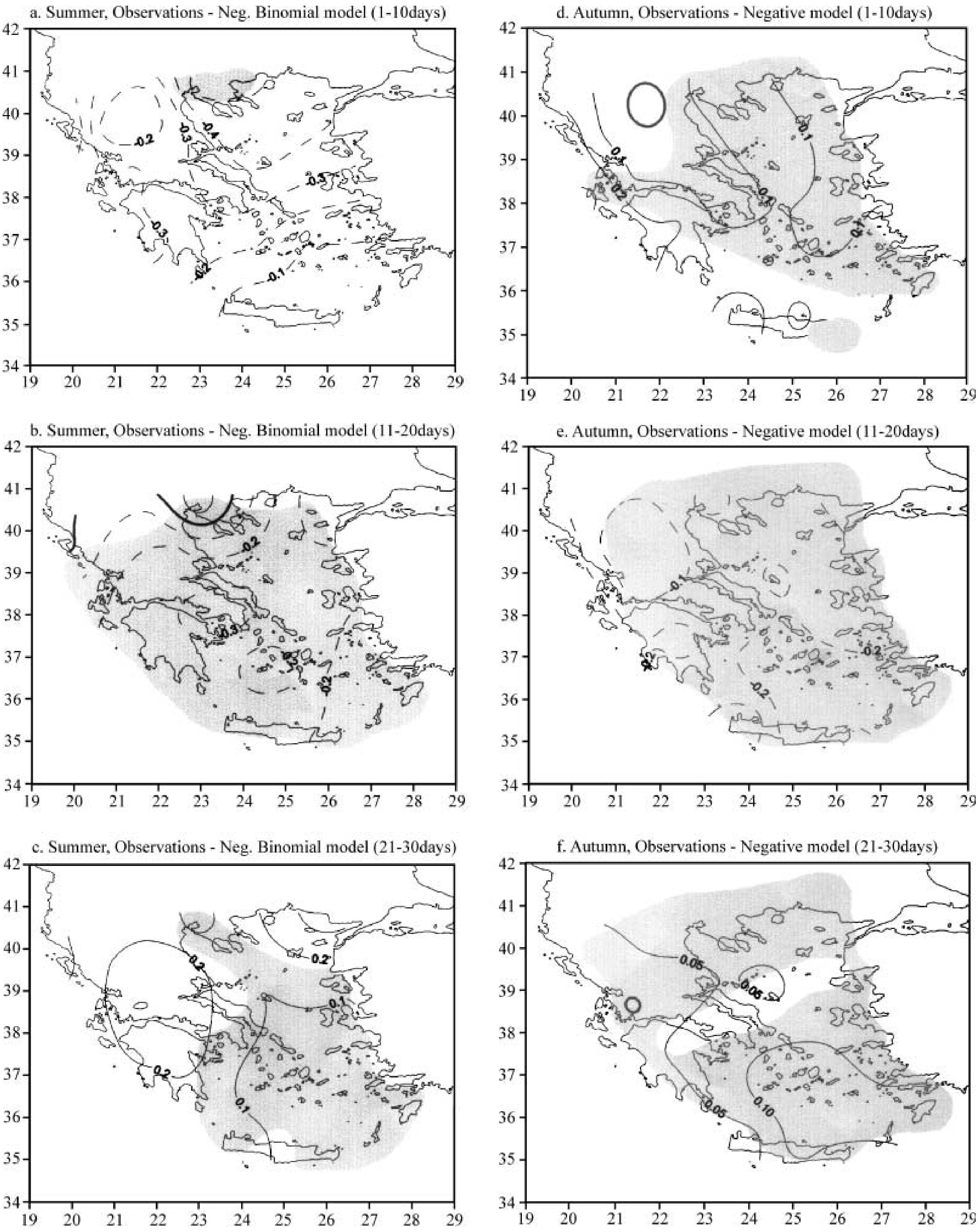

Fig. 8. The geographical distribution of the frequency differences between observed and simulated data for summer and autumn dry spells. The shaded regions represent the statistically significant model fit

the simulated data of Negative Binomial model fit quite well the observed data along the Aegean Sea, with positive differences in the rest of the country. An underestimation of the Markov Chains model is observed in northern Greece while in Crete an overestimation was found (not shown). The isopleths of the dry spells of 11–20 days length show an inverse pattern. Differences between observations and Negative Binomial model data are negative everywhere, except Cyclades (Fig. 7b). The differences between observations and simulated Markov Chains model data are negative in the north and central Greek region while they are positive in Crete and the south-east Aegean Sea (not shown). Finally, for the long sequences, the simulated data have been underestimated from both models whilst the differences are very small.

The patterns of spring dry spells with short duration (1–10 days) differ from those in winter. The Negative Binomial model provides significant results only for northern Greece, while the simulated dry spells have been overestimated almost for the whole Greek area (Fig. 7d). In contrast, the Markov Chains model presents positives differences for almost entire Greece except of the north-west part (not shown). The isopleths of medium sequences present variability between -0.2 and -0.5. In this class, both models give significant result for all stations (Fig. 7e). Finally, in the class of 21–30 dry days, the Negative Binomial model gives better results than the Markov Chains model. Although the differences are very small, significance is reached only in northern and southern Greece for the Negative Binomial model. The Markov Chains model underestimates values for northern Greece though, negative values appear over southern Greece (not shown). Their variability ranges between -0.4 and 0.2.

The corresponding classes in summer represent an invariable picture. For the short dry spells, the Negative Binomial model overestimates whereas the Markov Chains model presents an opposite pattern (Fig. 8a). The Markov Chains model shows more significance than Negative Binomial model (not shown). For the class of 11–20 dry days, the fit is good for both models (Fig. 8b) with slightly better results for the Markov Chains model. For the last class (21 to 30 days), the Negative Binomial model shows a pattern opposite to the 11 to 20 days class with the central and southern Aegean Sea presenting significant results. On the contrary, the Markov Chains model shows a similar pattern for both dry spells classes (not shown).

Finally, for autumn both models underestimate the dry spells with short duration. The differences between observed data and Negative Binomial model simulations vary from 0.0–0.3 (Fig. 8d). On the other hand, the differences for Markov Chains model increase from west to east, and vary from 0.0 to 0.5 (not shown). The opposite pattern is depicted by the 11 to 20 days dry spells, since the differences are all negative but the agreement between observed and simulated data is good for both models. For the last class of 21 to 30 days dry spells, the simulated data from both models agree well with the observations, resulting in very small differences for entire Greece, with a significant fit for both models nearly everywhere.

6. Conclusions

Dry spells in Greece vary strongly with season. This can be described well by two stochastic models. The application of these models on an annual basis does not provide a statistically significant fit because they could not detect the particularity of droughts in Greece.

After the division of dry spells into short, medium, long and very long sequences, the two adopted models (Negative Binomial and Markov Chains model) can in parts explain the distribution of dry spells well. However, dry spells with length of 1 to 10 days, not only present high differences between simulated and observed data, but also show no statistically significant fit for most of the stations. On the contrary, longer dry spells (11–20 days) can be evaluated by both models. Observing the small differences between simulated and observed data, it can be claimed that the results are satisfactory. The results for even longer dry spells (21–30 days) are not as significant as for the medium class, but they can still be considered good.

Cyclades and the south-east Aegean Sea show the longest dry spells both for dry spells with a 0.1 mm or 1.0 mm precipitation threshold. The shortest dry spells are found in the northwest of the Greek area. Generally, the lower the latitude, the greater is the influence of the subtropical patterns in Greece, especially in summer. The predominance of the subtropical anticyclone in the middle and upper layers of troposphere during the warm period causes great atmospheric stability over southern Greece, which expresses itself in very long droughts with hazardous dry spells, which may last over 6 months (180 days).

In general, dry spells of 11 to 20 and 21 to 30 days characterise the duration and the intensity of drought. The Negative Binomial model gives acceptable estimations for these on a seasonal basis, whereas the second order Markov Chains model gives acceptable results only for the medium long sequence. Therefore, we conclude that drought in Greece can be described by a Negative Binomial model.

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