INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **30**: 1014–1025 (2010)
Published online 19 May 2009 in Wiley InterScience
(www.interscience.wiley.com) DOI: 10.1002/joc.1912

Links between the rainfall regime in Israel and location and intensity of Cyprus lows

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ABSTRACT: The interannual variations and the spatial distribution of rainfall in the Mediterranean and semi-arid regions of Israel are analysed with respect to variations in the occurrence of the typical synoptic systems of the Eastern Mediterranean. The synoptic analysis is based on a daily, semi-objective synoptic classification (Alpert *et al*., 2004a). The study covers the months November–March, in which 90% of the annual rainfall is obtained, mostly resulting from Cyprus lows. The interannual variations of the rainfall are well explained by the synoptic types, and the occurrences of Cyprus lows are highly correlated with the rainfall. It was found that the daily and seasonal rainfall are highly dependent on the depth of the cyclone. Moreover, deep lows are more effective for the mountainous regions, due both to the enhanced orographic effect and to the fact that stronger winds, associated with deep lows, are more efficient in transporting rain-producing clouds from the Mediterranean Sea inland. The location of the cyclone determines the spatial distribution of the rain it produces over Israel. The cyclones located east of Cyprus were found productive mainly for the southern parts of the study region, while those located to the west and north of Israel were found productive for the north of the country. The high sensitivity of the rainfall to the location of the surface cyclones emphasizes the major role that lower level moisture transport plays in rain formation. Copyright © 2009 Royal Meteorological Society

KEY WORDS synoptic classification; rainfall; interannual variations; Cyprus low; Eastern Mediterranean; Israel

Received 21 August 2008; Revised 7 January 2009; Accepted 8 March 2009

1. Introduction

The southern part of the eastern coast of the Mediterranean is located at the border between Mediterranean and arid climatic regimes. The rainfall in that region is concentrated in the winter season, as is common for Mediterranean climates, and results mainly from passages of extratropical cyclones over the Eastern Mediterranean (EM) (Sharon and Kutiel, 1986; Alpert *et al*., 1990; Ziv *et al*., 2006). These cyclones are named Cyprus lows since most of them tend to pass, intensify or even develop over the cyclogenetic region of Cyprus (e.g. HMSO, 1962, Alpert *et al*., 1990; Shay-El and Alpert, 1991). The spatial distribution of the rainfall in Israel (Figure 1) is dominated by three factors. The first is a decrease in rainfall from north to south as a manifestation of transition from a Mediterranean regime to an arid one. The second is a decrease from west to east due to increased distance from the Mediterranean Sea as the moisture source; and the third, an increase with elevation due to orography (Katsnelson, 1964; Diskin, 1970; Kutiel, 1987; Goldreich, 2003).

Interannual variations of the rainfall over the Mediterranean Basin (MB) have been studied so far mainly by analysing monthly averages. For instance, Conte *et al*. (1989) studied the seasonal flow patterns that determine the rainfall distribution over the MB. Many studies analysed the relationships between the monthly and seasonal values of indices representing large-scale circulation, e.g., North Atlantic Oscillation (NAO), East Atlantic - west Russia (EA -WR), North Sea-Caspian Pattern (NCP), and the rainfall over the EM region (Kutiel *et al*., 1996; Price *et al*., 1998, Ben-Gai *et al*., 1998, 1999; Eshel and Farrell, 2000; Krichak *et al*., 2000; Littmann, 2000; Kutiel and Benaroch, 2002; Kutiel *et al*., 2002; Thompson and Green, 2004; Ziv *et al*., 2006).

The synoptic systems prevailing over the EM, and their associated weather conditions, are extensively reviewed in HMSO (1962), Ziv and Yair (1994) and Goldreich (2003). The main contributor to the rainfall in Israel, imparting 90% of the annual amount, is the Cyprus low (Goldreich, 2003, Goldreich *et al*., 2004). Cyprus lows are mid-latitude disturbances that tend to develop in this cyclogenetic area when upper troughs or cut-off lows penetrate the EM (Zangvil *et al*., 2003). They transport cool air originating from Eastern Europe over the warmer Mediterranean where it becomes moist and unstable (Shay-El and Alpert, 1991).

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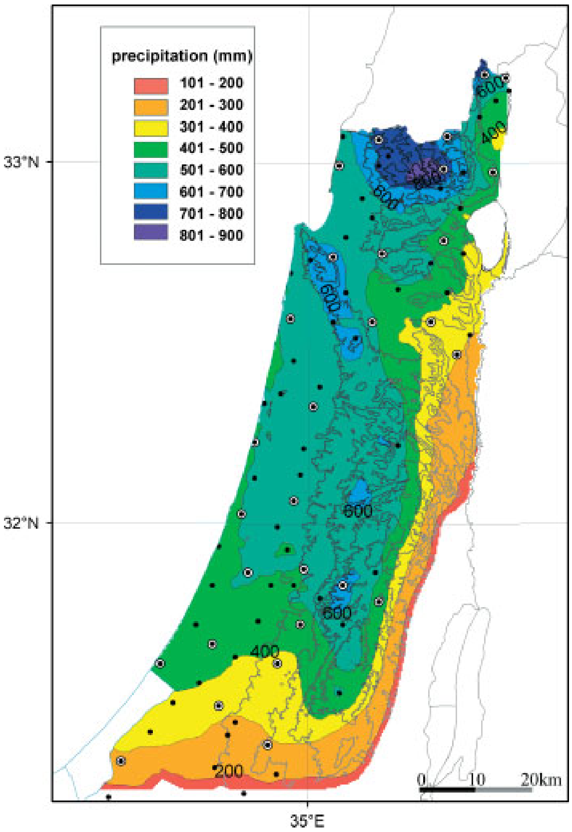

Figure 1. The study region, together with a 50-year average rainfall for the months November–March, based on 1954–2004. Black circles denote the 79 monthly long-record rainfall stations, and the black circles encircled by white denote the 30 daily long-record rainfall stations. Height contours are in resolution of 200 m and rainfall contours (isohyets) are in resolution of 100 mm. This figure is available in colour online at www.interscience.wiley.com/ijoc

Alpert *et al.* (2004b) found, according to their synoptic classification, that the annual average occurrence of Cyprus lows in the study region is 62 days, most of them during the cool season, i.e. DJFM. It is worth noting that lows persist in the study area for approximately 3 days on the average (Karas and Zangvil, 1999), so the number of lows attending the study area is about a third of this number. Enzel *et al.* (2003) compared the characteristics of Cyprus lows in five rainy seasons (October–March) which were the driest, to the five wettest, based on rainfall data from Jerusalem (central Israel) for the years 1950–2000. They found that the number of Cyprus lows crossing the region in the wettest years exceeded by 20% the number for the driest.

The rainfall yield and its spatial distribution over Israel are highly sensitive to the location of the Cyprus low (Ziv and Yair, 1994; Zangvil *et al.*, 2003). This stems from the relationship between the location of the low and the trajectory of the air-stream entering Israel, in particular its path over the waters of the Mediterranean, which determines its moisture content. Rosenfeld and Farbstein (1992) addressed the significance of the wind direction to the rainfall distribution, and showed that the existence of a southerly wind component in the wind direction implies a reduction of the rainfall in central Israel.

Alpert *et al.* (2004a) defined in their semi-objective classification seven synoptic types, which are variants of the Cyprus low (hereafter, 'Cyprus low types'), according to their depth (deep or shallow) and location. The distinction between 'deep' and 'shallow' low is not based on an objective criterion, but on a subjective identification done by trained forecasters for a 'training period' of 450 days. An individual low may thus belong along its life cycle, evolution and movement, to different synoptic types.

One would expect that the deeper the cyclone, the more rainfall it yields. Enzel *et al.* (2003), using the central pressure of Cyprus lows as a proxy for their depth, found no difference between the average central pressure of the cyclones in the five wettest and the five driest rain-seasons. Kutiel and Paz (1998) and Ziv *et al.* (2006) found negligible correlation between the winter rainfall in Israel and the sea-level pressure (SLP) over the EM but significant positive correlation over the other parts of the Mediterranean and over Europe. This suggests that the pressure within a cyclone itself does not reflect its depth, but the pressure difference with respect to its surroundings does. Following this idea, Alpert *et al.* (2004a) defined cyclones as 'deep' primarily according to the pressure gradient at their periphery.

This study quantifies and maps, for the first time, the correlation between the occurrence, location and intensity of the different types of Cyprus lows and the seasonal rainfall in Israel. The approach is based on correlating the interannual variations in the occurrence of the regional synoptic types with the variations in the rainfall distribution. The study deals with the main rainy season (NDJFM), based on the semi-objective synoptic classification of Alpert *et al.* (2004a), concentrating on the seven types of Cyprus lows. Section 2 specifies the methodology. Section 3 analyses the relationships between the rainfall and its producing synoptic types according to the following steps: first, correlating the seasonal rainfall with the occurrences of Cyprus lows; second, comparing the spatial rainfall distribution of each type; third, investigating the rainfall dependence on the depth and location of the cyclone and finally, reconstruction of seasonal rainfall using the occurrence of the synoptic types. The reconstruction can be a first step towards downscaling synoptic conditions to rainfall distribution over Israel. Section 4 discusses the results and Section 5 specifies their climatological and practical conclusions.

2. Material and methods

The study area covers the regions with Mediterranean and semi-arid climates, where the annual rainfall exceeds 200 mm. The study period is the months November–March, for the years 1954–2004. During these months, 88%–94% of the annual rainfall is obtained, according to the stations included in this study, and this is therefore regarded as the principal rainy season. Figure 1

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shows the long-term mean rainfall distribution over Israel for the study season.

The definition of the synoptic type for each day is specified according to the semi-objective classification of Alpert *et al.* (2004a). This classification is based on the daily SLP maps for 12 UTC, taken from the NCEP-NCAR dataset, 2.5° × 2.5° resolution (Kalnay *et al.*, 1996; Kistler *et al.*, 2001). The rainfall yield and its spatial distribution are analysed for each of the types of the Cyprus low. The rain days that occurred under types that were not defined as one of the Cyprus low types are grouped into one category, named 'no Cyprus Lows'.

Monthly and seasonal rainfall data were taken from all the stations operating in the study region along the study period. The method adopted, to enable the inclusion of all available data (including short record rain-gauges), was to map the monthly data obtained by all stations operated in each year (about 400 stations in $15,000\ \mathrm{km}^2$) and to create monthly and seasonal rainfall rasters (500 × 500 m resolution) for the study area. The dense network of rain gauges in the study area permits relatively reliable mapping. The spatial detrending method used to reduce biases, caused by changes in the location of the operated gauges from year to year, was based on interpolation of the monthly relative (to the local long-term mean) rainfall by the Inverse Distance Weighted (IDW) interpolating method (ESRI, 2004). This method is described in other climatic studies such as Gyalistras (2003) and Kurtzman and Kadmon (1999). In order to retrieve absolute rainfall maps, the relative rainfall rasters were multiplied by the mean monthly rasters. The seasonal rainfall rasters were then used for examining correlations between the seasonal occurrence of the synoptic types and the rainfall yields in the study area (Figures 3(c), 6, 8 and 9(a)), as well as for creating composite maps (Figures 3(a) and (b)) and calculating the mean seasonal amounts in the study area (Figure 2).

In order to show the degree to which the synoptic types can explain the variation in the seasonal rainfall, multi-regression analysis was performed. For each of the 79 long-record stations, a prediction equation was extracted (using linear stepwise method in the SPSS software). The predictors for seasonal rainfall amount included in such an equation were the seasonal occurrences of synoptic types which were found significant at the 0.05 level (Figure 9(a)). The spatial distribution of the first predictor is mapped in Figure 9(b).

3. Results

3.1. Correlation between seasonal rainfall and the occurrence of Cyprus lows

The relative contribution of Cyprus lows to the rainfall was estimated by the percentage of rainfall obtained in days with Cyprus low types (hereafter, Cyprus low days), being 83%. The seasonal average number of Cyprus low days was 45. The interannual variation of Cyprus low days and the seasonal rainfall, averaged over the study area, are shown in Figure 2. The correlation (R) between them is 0.76 and for the annual rainfall it is 0.75, indicating that the seasonal number of Cyprus low days can serve as a good predictor for the annual rainfall as well.

Figure 3(c) shows the correlation between the sum of the occurrences of all types of Cyprus lows and the seasonal rainfall. The correlation over the majority of the study region varies around 0.7, implying that the interannual variation of the cyclone occurrence explains ~50% of the rainfall variation. It is worth noting that the correlation decreases to ~0.55 at the southern border of the study region, suggesting that it denotes the margins of the region in which the Cyprus lows dominate. The rainfall in the five years richest with Cyprus lows (Figure 3(b)) is about twice that for the five poorest seasons (Figure 3(a)).

3.2. The contribution of the individual synoptic types

The study concentrates on the synoptic types regarded as Cyprus lows, which differ in their intensity and location. The SLP and the spatial distribution of the daily rainfall, averaged over the rain days associated with each type,

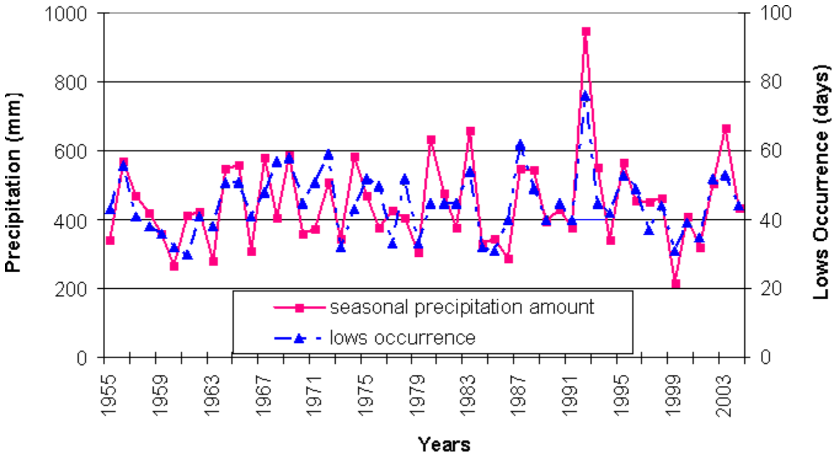

Figure 2. The interannual variation in the seasonal number of Cyprus low days (lows' occurrence) and the seasonal precipitation (mm) for the study area. The correlation coefficient is 0.76. This figure is available in colour online at www.interscience.wiley.com/ijoc

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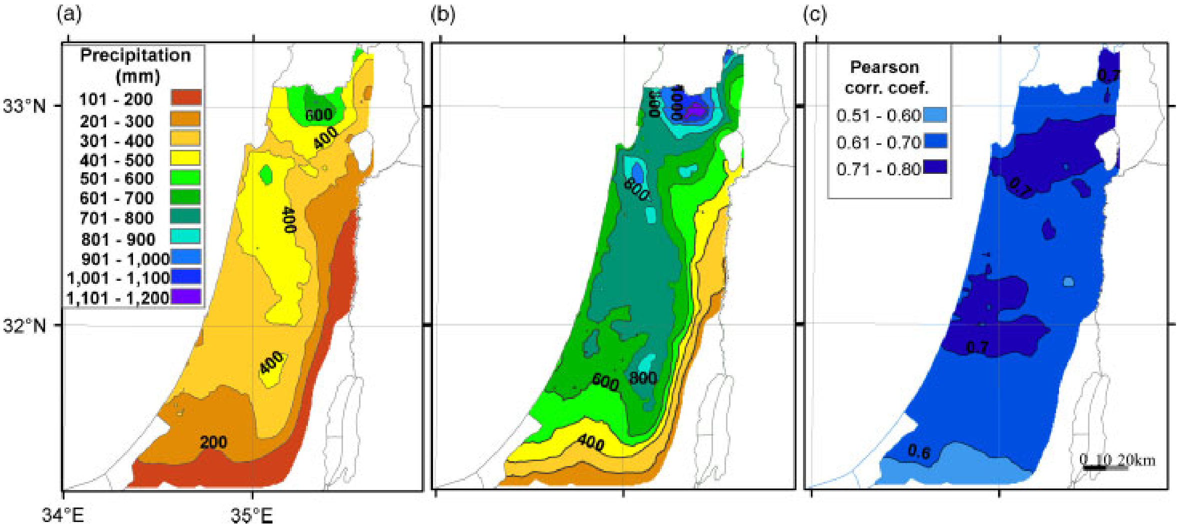

Figure 3. (a) The average rainfall (mm) for the years belonging to the lower tenth occurrence of Cyprus low days (5 years). (b) As for (a), but for the upper tenth. (c) The correlation coefficient between the seasonal rainfall and the number of Cyprus low days. The maps are based on correlations calculated for the grid points (3 km resolution), extracted from the seasonal maps (Section 2). This figure is available in colour online at www.interscience.wiley.com/ijoc

Table I. Rainfall characteristics of the six Cyprus low types, as well as for all rain days which are not identified as any of these Cyprus low types (November–March).

Cyprus low type (Figure 4)	Average occurrence (days/season)	Percentage of days having rain (%)	Average daily rainfall (mm/day)	Relative contribution to the seasonal rainfall (%)
Deep, north of Israel (a)	8.5	97	16.4	28.7
Shallow, north of Israel (b)	8.3	87	6.1	10.4
Deep, east of Israel (c)	6.9	97	10.9	15.5
Shallow, east of Israel (d)	12.9	92	7.2	19.1
South of Cyprus (e)	0.6	93	15.7	2.0
West of Cyprus (f)	7.6	81	4.5	7.0
No Cyprus low exists (g)	106.5	33	0.8	17.3

are shown in Figure 4. The average occurrence of each type, the percentage of days having rain, the daily average and the contribution to the seasonal rainfall, are specified in Table I. Figure 4 and Table I indicate that deep lows located north and east of Israel and lows located south of Cyprus (types *a*, *c* and *e*, respectively) produce the highest amounts of daily rainfall. While the deep lows to the north and to the east contribute together 44% of the seasonal rainfall (Table I), those located south of Cyprus are rare and therefore contribute only 2%. Shallow lows (types *b* and *d*) are characterized by relatively low daily rainfall, but due to their high frequency they contribute 30% of the seasonal rainfall. Lows located west of Cyprus (type *f*) are generally less effective for the seasonal rainfall in Israel (7%) due to the distance of their centres from the study region and their low frequency. Seventeen percent of the rainfall results from synoptic types that are not defined as Cyprus lows. Most of them appear on the day following an occurrence of a Cyprus low. These events are relatively frequent (46% of the rain days), but their low average daily yield (0.8 mm/day) makes their seasonal contribution relatively small. The importance of the cyclones in rain production can also be illustrated when the threshold for rain day is raised, as shown in Figure 5. For instance, when the threshold was changed from 0.1 to 10 mm, less than 10% of the rainfall results from synoptic types that are not defined as Cyprus lows, (compared with 17.3% for the 0.1 threshold), and the contribution of deep lows to the total rainfall increased from 45% to 55%. From a threshold of 30 mm, all rainfall is contributed by synoptic systems defined as cyclones, with deep lows making the dominant contribution (>80%).

3.3. The relation between the synoptic features and the spatial rain distribution

In order to evaluate the impact of the cyclones' intensity on the rainfall regime, the correlation between the seasonal rainfall and the occurrences of deep and shallow lows is mapped, as shown in Figure 6(a) and (b), respectively. The correlation with the occurrence of deep lows is >0.6 over the majority of the study area, quite close to that for all the lows (compare with Figure 3(c)) and decreases from northeast to southwest. As for the shallow lows, the correlation is about 0.5 and decreases in the opposite direction. Comparison between the two

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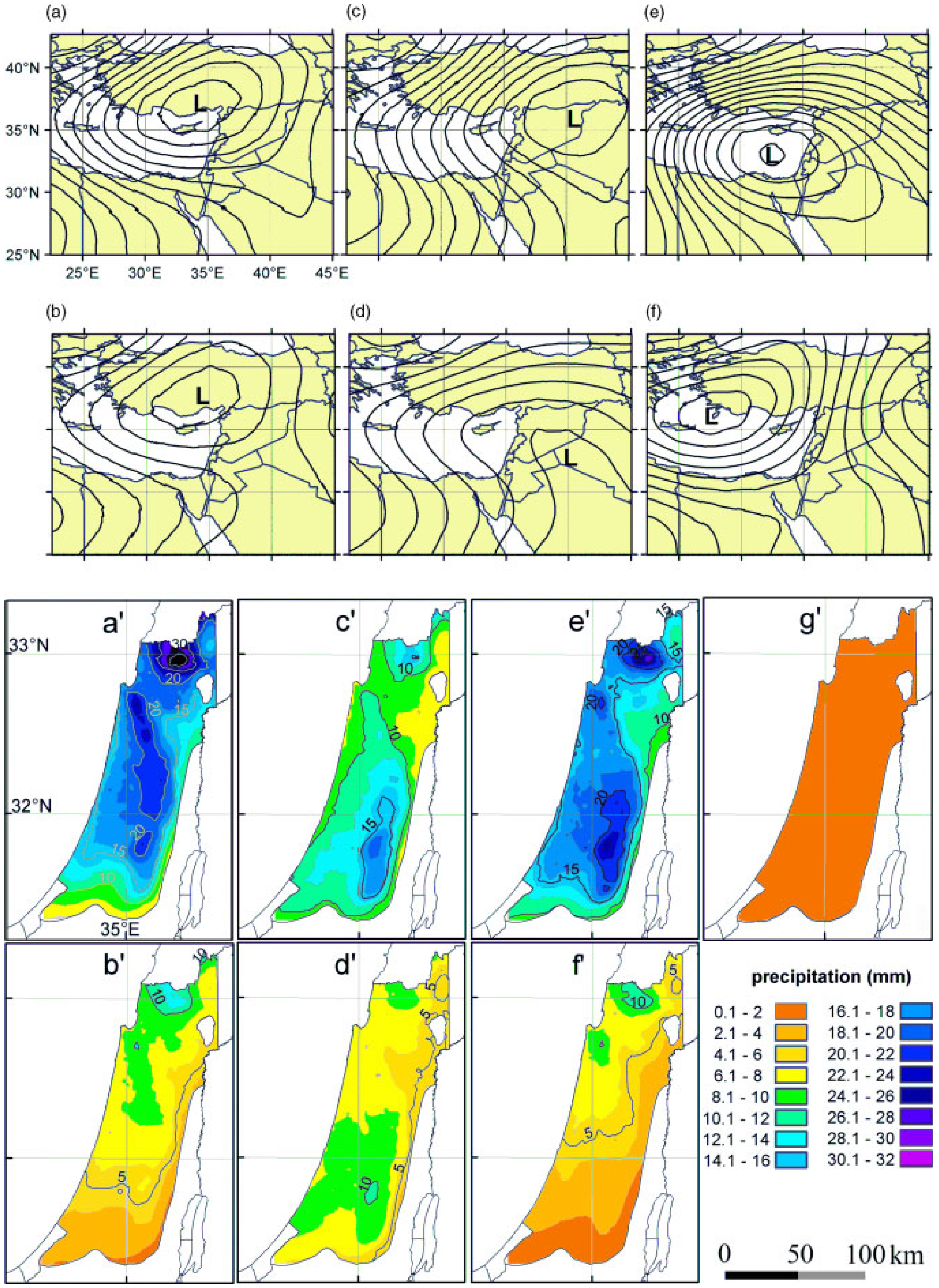

Figure 4. Composite sea-level pressure maps for each of the low types, with 1 hPa intervals (a–f, upper panels, annotated following Table I) and the daily average rainfall distribution for each of them (a′–f′, lower panels), together with that of the days in which no Cyprus low existed (g′) for the study period. The absence of a distinct low in the map corresponding to 'shallow low to the east' (d) is due to the large variability of the location of their centres. This figure is available in colour online at www.interscience.wiley.com/ijoc

correlation maps suggests that the influence of the deep lows decreases more sharply with distance from their centres than that of the shallow. One implication of the spatial distributions is that the deep lows are more effective for the inner parts of Israel, further from the coast, whereas the shallow ones are relatively more effective in the coastal regions. The importance of the depth of cyclones on the rainfall distribution is also addressed by mapping the average daily rainfall for the deep and the shallow lows (Figure 7(a) and (b), respectively). The amounts are about double for the deep lows, in particular over the mountain regions, as is illustrated in the

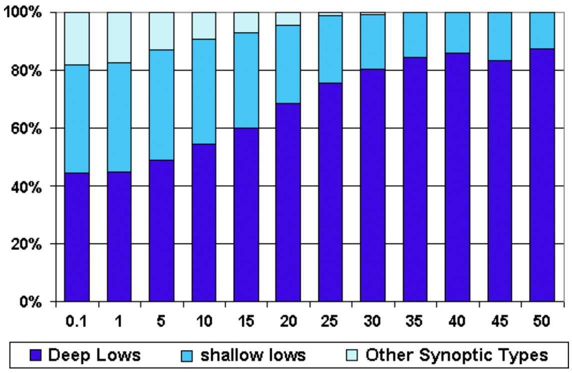

Figure 5. Relative seasonal rainfall contribution of deep lows (black), shallow lows (dark grey) and other synoptic types (light grey) for different thresholds of minimum daily rainfall. The daily rainfall was averaged over the 30 daily rainfall stations (marked on Figure 1). This figure is available in colour online at www.interscience.wiley.com/ijoc

map of the ratio between them (Figure 7(c), note the mountain regions seen in Figure 1 by the height and rainfall contours).

The seasonal rainfall course in Israel shows that rainfall accumulation in the coastal plain is earlier compared to the mountain regions, located further from the Sea (Goldreich, 1976). This might result from intra-annual variations in the ratio between deep and shallow lows. Analysing this ratio reveals that there is a non-significant increase in this ratio along the season for the Cyprus lows located east of Israel and no trend for the Cyprus lows located north of Israel.

The spatial distribution of the daily rainfall associated with each type of cyclones (Figure 4) shows that the cyclones located to the north and to the west are more productive for the northern part of the study area, while those located to the east are more productive for its southern part. This relationship is further elaborated by the spatial distribution of the correlation between the number of cyclones, according to their location, and the seasonal rainfall. Figure 8 shows the correlation between the seasonal rainfall and the number of the cyclones located to the north or west (a) and those located to the east (b). The maximum correlation for the cyclones to the north and to the west, >0.6, is at the northern end of the study region and it drops to zero at its southwestern end (Figure 8(a)). The picture is almost reversed for the cyclones to the east, where the maximal correlation, >0.7, is found over the southwest of the study region and drops to <0.3 over the majority of its northern part (Figure 8(b)). These findings stress the importance of the cyclone location for the rainfall spatial distribution over the study area. The explanation for these findings is given in Section 4 below.

3.4. Reconstruction of seasonal rainfall using the synoptic types

In order to integrate the above findings, we built a multi-regression prediction equation for the seasonal rainfall for each of the 79 monthly stations (Figure 1) along the study period. The potential predictors used were the occurrences of each of the relevant synoptic types (i.e. each type of Cyprus low) and groups of them (e.g. all lows to the east, the total number of low days etc.). As an example, the multi-regression equation for the Kfar Giladi station, at the northern tip of the study region (33°15′N, 35°34′E) is shown below.

$$Y = 23.3X_1 - 14.8X_2 - 25.4, \qquad (1)$$

where Y is the seasonal rainfall, X_1 and X_2 are the occurrences of total low days and of shallow low days in the pertinent season, respectively. The minus sign in

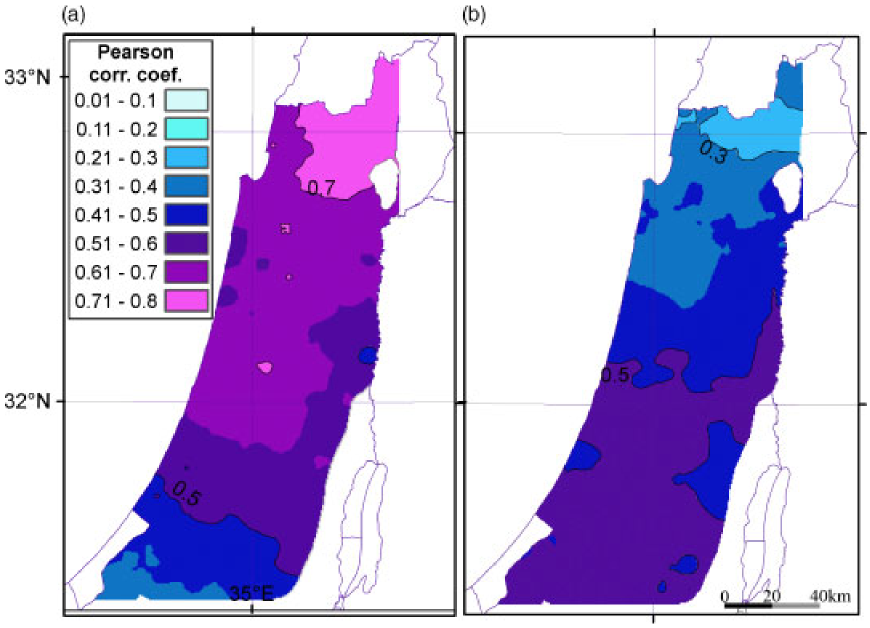

Figure 6. Correlation map of the seasonal rainfall (November–March) with the occurrence of deep (a) and shallow (b) Cyprus lows. This figure is available in colour online at www.interscience.wiley.com/ijoc

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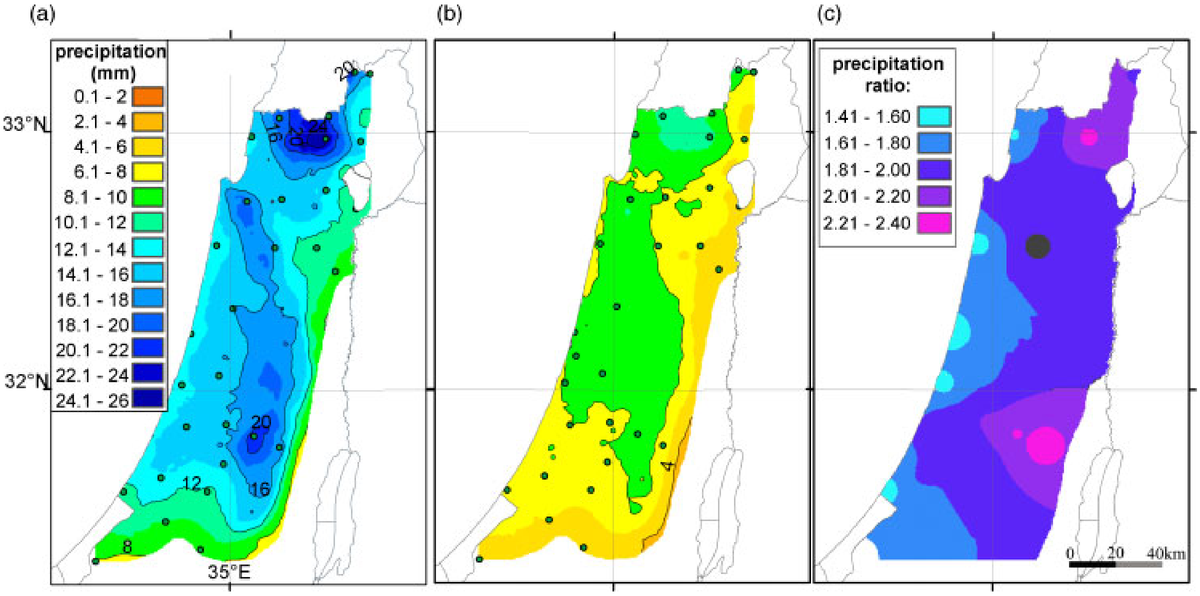

Figure 7. The mean daily rainfall distribution for all types of deep lows (a), shallow lows (b), and the daily rainfall amounts ratio between deep and shallow low days (c). This figure is available in colour online at www.interscience.wiley.com/ijoc

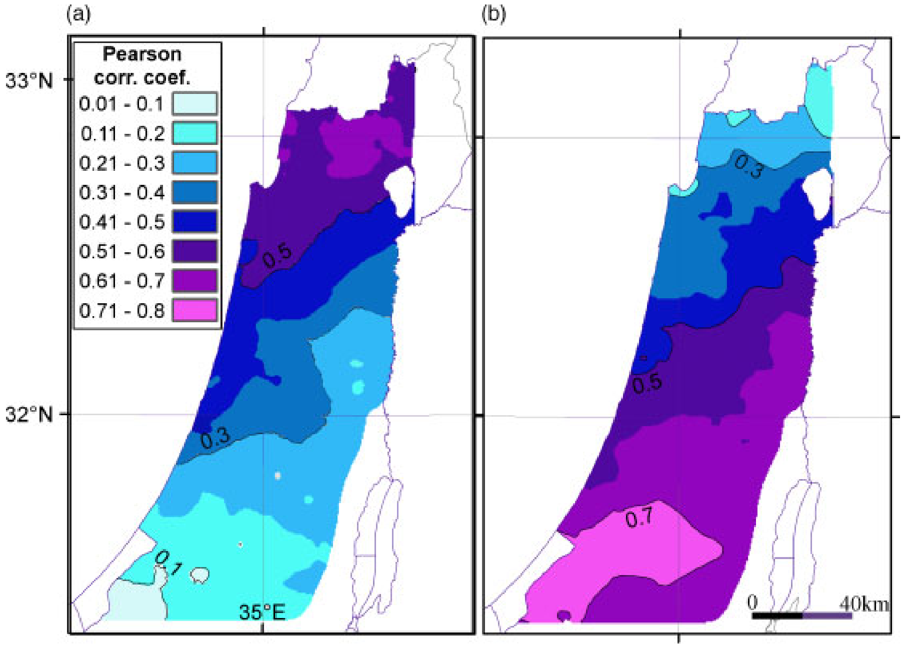

Figure 8. Similar to Figure 6, but for the occurrence of lows to the north and west (a) and to the east (b). This figure is available in colour online at www.interscience.wiley.com/ijoc

the coefficient of X_2 is a manifestation of the larger contribution that the deep lows have over the shallow ones to the local rainfall. The correlation (R) between the observed rainfall and that predicted by Equation 1 was 0.79 for the study period.

The number of predictors that was found significant at the 0.05 level varies between one and four (the mode is two). Figure 9(a) shows the spatial distribution of the correlation between the predicted and observed rainfall. The typical values vary between 0.7 and 0.8, implying that the synoptic types explain over half of the interannual variance. The correlation is higher over the mountain regions in both the northern and southern parts of the study region, i.e. the Galilee and Judean Mountains. Figure 9(b) shows the distribution of the first predictor. The most widespread predictor is the total number of low days. In the southern part of the study region, the lows to the east dominated and in the northern part the deep lows dominated, in agreement with the above findings.

4. Discussion

This study examines the ability of lower level synoptic systems to explain the daily rainfall yield and its spatial distribution over Israel. It belongs to a wide spectrum of

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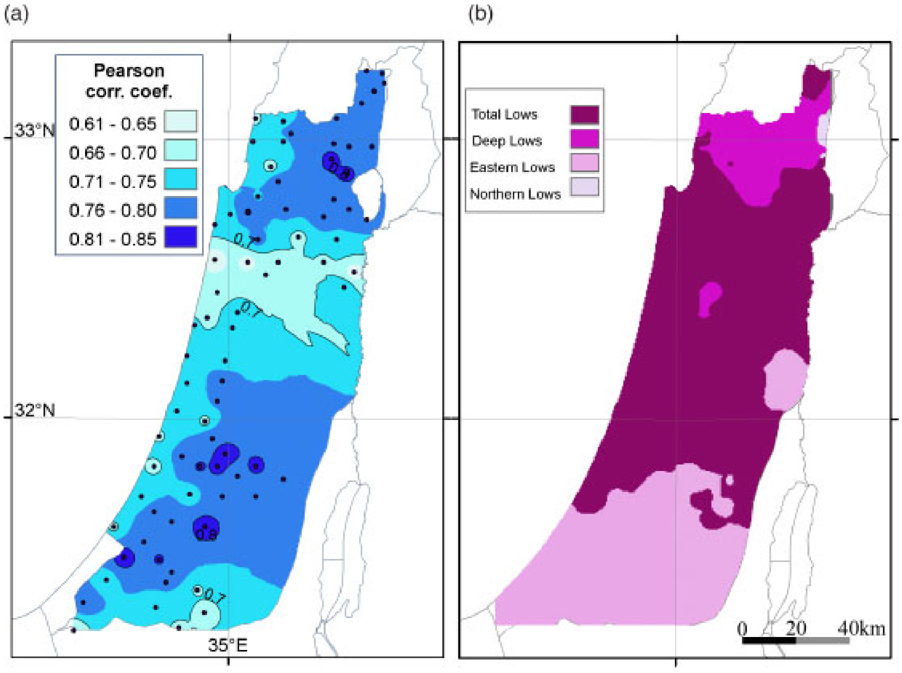

Figure 9. The correlation between the observed seasonal rainfall and the rainfall predicted by the multi-regression equations calculated for each of the 79 monthly stations. The predictors used are the occurrences of the synoptic types found significant at the 0.05 level for each of the stations (a). The spatial distribution of the most significant predictor (synoptic type) for the pertinent location (b). This figure is available in colour online at www.interscience.wiley.com/ijoc

researches linking the Mediterranean rainfall to synoptic features. The most common approach refers to large-scale upper level circulations, mostly applied for the monthly or seasonal scale (Xoplaki *et al*., 2000; Krichak *et al*., 2002; Maheras *et al*., 2004; Ziv *et al*., 2006; Hatzaki *et al*., 2009). Traboulsi and Camberlin (2004) studied the rain regime of the Levant region (defined as the eastern coast of the Mediterranean, including Syria, Lebanon, Israel and Jordan) with respect to the location and orientation of the upper level trough. They distinguished between three different homogeneous regions so that our study region is considered as one entity without considering the spatial variations within it. Another approach combines lower and upper level synoptic features. A good example is the canonical correlation done by Dunkeloh and Jacobeit (2003) for the rotated EOF of the 500- and 1000-hPa geopotential height and the rainfall distribution over the entire MB.

Our study is one of those showing that the lower level circulations alone can explain quite well the rainfall regime. Bartzokas *et al*. (2003) found a relation between distinct anomaly patterns in the 850-hPa relative vorticity over Europe and the MB and the precipitation patterns over Greece. Trigo and DaCamara (2000) derived a prediction scheme for daily rainfall over Portugal, based on vorticity and wind direction at the 850-hPa level. They found that their prediction scheme explained over 60% of the rainfall variation over the majority of the country. Bartzokas *et al*. (2003) showed that the relationship between the location of the centre of the cyclonic system and the spatial rainfall distribution holds on a scale of 1000 km. Trigo and DaCamara showed that this holds also for a smaller scale characterizing the Iberian Peninsula. Our analysis shows that the synoptic-scale systems, defined by the SLP, explain the daily and the seasonal rain distribution in Israel on a spatial scale of 100 km.

The study refers to the main rainy season, November–March, in which ~90% of the annual rainfall is obtained. Over 50% of the variance in the seasonal rainfall, as well as the annual totals, is explained by the number of days in which the region is dominated by Cyprus lows. We have found that 45 Cyprus low days contribute 83% of the seasonal rainfall (averaged over the study region), which is 75% of the annual total. These results are lower than the 90% contribution of Cyprus lows denoted by Goldreich *et al*. (2004) for the entire rainy season. Seventeen Cyprus low days that occur in the transition months (April, May, September and October) contribute only <10% of the annual rainfall. This implies that a Cyprus low day within the rainy season contributes over 3 times than one in the transition seasons. We suggest that the lower productivity of Cyprus lows in the transition seasons results from the stronger influence of the subtropical descending branch of the Hadley cell.

The location of the cyclones relative to the study region was found crucial for the rainfall spatial distribution. This indicates that the behaviour revealed in the synoptic scale exists also in the smaller scale of Israel, of 100 km. The prominent factor found for the rain distribution was the direction of the cyclone centre with respect to the study region rather than its distance. One may expect that the closer an area is to the cyclone centre, the larger the rainfall yield. Following the latter idea, the maximum rainfall associated with lows to the east (e.g. Figure4(c)) is expected to be found in the northeastern end of the

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study region, which is the closest to the cyclone centre. In fact, the opposite happens and the rainfall maximum is found in the south of the study region (Figure 4(c′)). This can be explained by the crucial role of the wind direction, which determines the moisture transport, as implied by the location of the cyclone centre.

The winds associated with cyclones located to the north and to the west are southwesterly (Figures 4(a), (b) and (f)) while those associated with cyclones to the east are northwesterly (Figures 4(c) and (d)). The inland moisture transport from the Mediterranean, implied by the onshore wind direction and by the fetch of the airflow over the sea, is maximal in the north of the study region under southwesterly winds and in its southern part under northwesterly winds. These results support those obtained by Zangvil *et al*. (2003). Traboulsi and Camberlin (2004) found similar linkage between the longitudinal location of the upper level troughs (at the 500-hPa level) and the north–south rainfall distribution over the Levant. This seems to be consistent with our results. High sensitivity of the rainfall amounts to the location of the cyclones and the maritime trajectories was found also in Greece and its surrounding islands by Kutiel *et al*. (1996) and Maheras *et al*. (2004).

The intensity of the lows was found important for both the rainfall yield and its spatial distribution. The average daily rainfall in days of deep lows was twice that of shallow (Figure 7) and the contribution of deep lows to the seasonal rainfall is found larger compared to the shallow ones (Table I and Figure 10). Moreover, the occurrence of the deep lows was highly correlated with the seasonal rainfall (>0.6) over the majority of the study region, almost equal to the correlation with the total number of low days (Figure 6(a)). As for the shallow ones, the correlation was ∼0.4 (Figure 6(b)). These findings do not agree with Enzel *et al*. (2003), who did not find a difference in the average depth of Cyprus lows between wet and dry winters in Israel. This apparent contradiction seems to stem from the difference in the definition of lows' depth which in their approach was based on the pressure minimum, whereas in this study it is based on the pressure gradient (Alpert *et al*., 2004a).

The deep lows are also found more productive in the mountain regions rather than along the coastline. This can be attributed to two factors, both related to the stronger wind associated with deeper cyclones. The first is the implied enhanced orographic effect and the second is the higher efficiency of stronger winds in transporting rain-producing clouds from the Mediterranean Sea inland. The implied contribution of wind velocity to orographic rainfall is in agreement with Alpert and Shafir (1989) and Shafir and Alpert (1991).

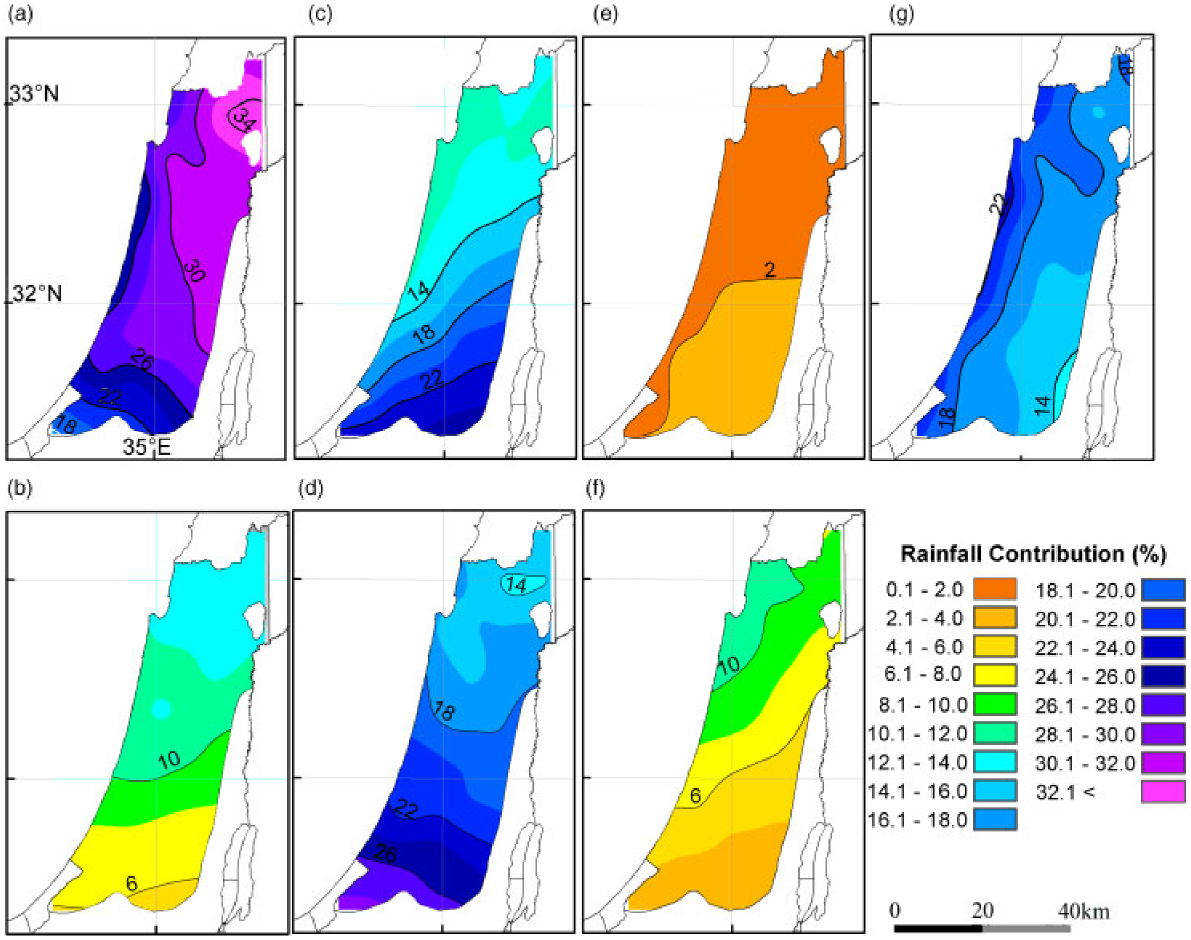

Figure 10. The contribution (%) of rain-producing synoptic types to the seasonal rainfall, based on the 30 daily stations (Fig. 1). The notations of the types are as in Figure 4 (following Table I). This figure is available in colour online at www.interscience.wiley.com/ijoc

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Beside the overall effect of the lows' intensity, a difference was found between the two most frequent deep lows; those located to the north produce twice as much daily rainfall as the deep lows to the east do (compare Figures 4(a) and (c)). This can be explained by the difference in the upper level dynamics. Typically, the upper level trough is located west of the surface cyclone, as is common for mid-latitude cyclones (e.g. Holton, 1992) and for Cyprus lows (Shay-El and Alpert, 1991, Zangvil *et al.*, 2003). Hence, for lows to the north the upper trough is located west of Israel, implying upper level positive vorticity advection over Israel, which enhances upward air motion and rain production (e.g., Holton, 1992). When a deep low is located east of Israel, the upper trough is located over Israel and therefore does not induce upper level positive vorticity advection (and upward motion), as shown by Kahana *et al.* (2002) and discussed by Zangvil *et al.* (2003). Moreover, for lows to the east, the fetch of the air crossing the Mediterranean Sea and entering Israel is shorter, implying that it contains less moisture and has a lower precipitation potential. For the shallow lows, this difference is less pronounced, presumably due to the weaker dynamics involved. In addition, the shallow lows to the east have an advantage, related to the low speed of the winds associated with shallow lows. The slower movement of the air enables longer time for absorbing sufficient moisture for rain production, in spite of the short fetch over the sea.

The limited variance (<60%) of the interannual variability of the rainfall explained by the occurrences of Cyprus lows can be attributed to two factors. One is the contribution of other rain-producing systems, particularly of tropical source (active Red Sea trough, e.g. Dayan *et al.*, 2001, or Tropical plume, e.g. Rubin *et. al.*, 2007) or small-scale Mediterranean cyclones not resolved by the $2.5^\circ \times 2.5^\circ$ resolution data used. It should be noted that the daily average rainfall observed in rainy days when no Cyprus low was present was found one order of magnitude smaller (<2 mm/day) than observed when they existed (Figure 4(g′)). A large difference between the amounts of rainy days related to cyclones and those imparted by other systems is not unique for Israel and was found in other places in the Mediterranean such as Greece (Maheras *et al*, 2004) and the Iberian Peninsula (Trigo and DaCamara, 2000; Goodess and Jones, 2002). However, this difference in Israel is relatively larger. Another factor that may limit the contribution imparted by Cyprus lows is the convective rain (Goldreich 2003). This factor can also explain the larger rate of rainfall imparted by Cyprus lows in the inner region (85%) than in the coastal (75–80%), which can be attributed to the higher contribution of convective rain in the latter (Sharon and Kutiel, 1986).

A feature that has not been explained by the occurrences of synoptic types is the intra-seasonal distribution of rain. In the coastal plain, seasonal rainfall accumulates faster than in the mountains and in other inland areas. Since deep cyclones were found to be more effective for the mountain areas, one would expect that this seasonal course denotes a gradual increase in the percentage of deep lows towards the end of the season. Such a seasonal course was not found. We, therefore, suggest that the sea–land temperature difference (discussed by Goldreich *et al.*, 2004 and simulated by Khain *et al.*, 1993, 1996) is the major factor responsible for this intra-annual rainfall course.

5. Summary and conclusions

This study is the first attempt to quantify the relationship between the synoptic conditions and the rain regime in Israel. The results confirm that the Cyprus lows contribute the vast majority of the rainfall in the months November–March. The contribution is higher over the inland areas, around 85%, and slightly lower (77%) along the coastal region. The interannual variations in the number of Cyprus lows explain over 50% of the variance in the seasonal and the annual rainfall. The temporal change in the seasonal distribution of the regional synoptic types was found effective for reconstructing the seasonal rainfall through multi-regression scheme. The correlation between the 'predicted' and the actual rainfall varied between 0.7 along the coastal region and 0.8 in the mountains.

The location of the cyclone centre was found crucial for the spatial distribution of the rainfall since it determines the wind direction, and hence the moisture transport. More specifically, the existence of direct onshore wind and a sufficiently long fetch of the airflow over the Mediterranean Sea are crucial for obtaining considerable rainfall. The intensity of the lows was found important for the rainfall yield as well as for its spatial distribution. The deep lows were found more productive in the mountain areas rather than along the coastal region due to the enhanced orographic effect induced by their stronger winds.

In spite of the inherent limitation of the synoptic classification used here and the absence of direct upper level information, the surface systems were found to be a highly effective tool for reconstructing the rain regime over Israel. Nevertheless, a future complementary study that incorporates upper level feature may upgrade our ability to reconstruct the rainfall regime over the study region.

The approach presented here can serve as a tool for climatic prediction, since it enables to directly interpret the occurrences of specific synoptic types to local rain features. This methodology can also be applied on future regional model predictions of SLP in order to interpret the potential change in rainfall distribution and amounts.

Acknowledgements

This study was supported by the Israeli Science Foundation (ISF, grant no. 764/06) and partly supported by the GLOWA and CIRCE EU projects. The authors wish to thank the Israel Meteorological Service for providing the rainfall data.

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