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ORIGINAL PAPER

Multi-factor analysis of DTR variability over Israel in the sea/desert border

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Abstract
The contributions of twelve independent factors/variables to the magnitude of the local diurnal temperature range (DTR) in Israel were examined, and five to seven were found to contribute significantly. Israel was chosen due to its complex terrain with several climatic zones and proximity to the Mediterranean Sea. The seven sites for this study represent different terrains, from mountainous with a Mediterranean climate to desert. Each site had 6 years of data available. Stepwise analysis was performed in order to determine the contribution of each factor/variable at each site. The linear correlations between the DTR and each factor were calculated. These were carried out at each site for the whole year and for each season, separately. Relative humidity was found to have the largest DTR contribution at all sites, for 3 seasons, except summer at shoreline sites and in Jerusalem. The daily cloud cover and the wind speed had small contributions in most sites. The magnitude of the DTR was found to vary largely with location and to be considerably smaller in the seashore sites than those inland.

Keywords Diurnal temperature range · Maximum temperature · Minimum temperature · Seashore · Urban · Desert

1 Introduction

Mean temperature is generally accepted as an indicator for the warming of the climate (Braganza et al. 2004). However, mean temperature alone is not enough to analyze the process of climate change. The diurnal temperature range (DTR), i.e., the difference between the daily minimum and maximum temperature, is a powerful tool in this analysis. The DTR has been decreasing worldwide since the 1950s (Easterling et al. 1997; Dai et al. 1999; Qu et al. 2014; Price et al. 1999; Davy et al. 2016). It has been found that the decrease is primarily due to the increase in minimum temperature (Easterling et al. 1997; Stone and Weaver 2002). Changes in the DTR have multiple possible causes including cloud cover, soil moisture, urban heat, land use change, aerosols, and water vapor and greenhouse gases. Lately, it was found by Davy et al. (2016) that PBL depth has a considerable influence on the value of the DTR.

Opposite to these findings, several recent studies have found an increasing DTR trend from the 1970s in Europe and 1980s in North America (Makovsky et al. 2008; Rohde et al. 2013).

Previous studies have shown that the behavior of the DTR is affected by the cloud cover. During the day, clouds tend to backscatter the solar radiation and consequently decrease the surface warming. During the night, the clouds absorb terrestrial infrared radiation, reflecting it back to the surface, thereby causing an increase in the minimum temperature (Karl et al. 1984; Price et al. 1999; Stone and Weaver 2003). Low clouds exert higher influence on the DTR due to being more effective in reflecting radiation upward and downward (Dai et al. 1999).

The moisture is an additional variable affecting the DTR. Enhanced evaporation during the day causes cooling, while the damping of evaporation during the night has the opposite effect (Stone and Weaver 2003; Dai et al. 1999). Since the evaporation is strongly affected by the land cover, the greatest DTR values were found in rural areas, while the smallest values were associated with urban areas (Gallo et al. 1996). Research of the DTR by Remar and advisor Preston (2010) in

Unfortunately the lead author Dr. Joseph Barkan passed away during the final revision on 7 June 2019. This paper is dedicated to his blessed memory.

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Urban Las Vegas and its rural surroundings confirmed these results. It was also found by Scheitlin and Dixon (2010) that agricultural and urban areas experience the smallest DTR, while forested areas exhibit the greatest DTR due to the difference between the evapotranspiration rates between the different land covers. The DTR was also found to vary between the weekdays and the weekend (Forster and Solomon 2003).

While most DTR research deals with global or continental areas, our work will focus on Israel, which despite its small size exhibits extremely variable climate and topography. It is mountainous in the north and east, highly urbanized along the sea shore, and desert climate in the south. In this work, we aim to investigate the effect of very different locations on the DTR, as well as, which factors/variables are the most dominant, annually and in the different seasons.

2 Methodology

For this work, three different kinds of data were used: surface data, satellite data, and upper air radiosonde data during 6 years of 2006–2011. The surface data used was from the database of the Israeli Meteorological Service (IMS). The satellite data was taken from the MODIS Terra satellite, which passes over Israel every day. The upper air data was obtained from the balloon soundings; operated twice a day by the IMS center in Beit Dagan, Israel; and stored in the database of the University of Wyoming.

The IMS surface data is available daily with intervals of 10 min. Only the midday data was used, by averaging the 1400 LT measurements with two points before and two after. To obtain the value of the DTR, the same procedure was applied around the 0200 LT for the minimum temperature. The DTR was computed from the difference between the noon and midnight temperatures. It should be noticed that the full DTR is slightly larger because the minimum temperature is reached near sunrise, which is at about 0500 LT. This difference varies from about 0.5 °C in Jerusalem (0.44 in DJF and 0.64 in JJA) and ~ 1 °C in Tel Aviv (0.83 in DJF and 1.16 in JJA). However, the 0200 to 0500 temperature correlations are above ~ 0.97. In addition to the DTR, the following variables were obtained from the aforementioned databases:

a) Surface relative humidity (Rh), wind speed (WS), and wind direction (WD) were taken from the IMS data base for the 7 sites chosen to represent the areas with different topographical features (Table 1, Fig. 1)
b) Aerosol optical thickness (AOT), clouds by day (CL_D), and clouds by night (CL_N) were taken from the MODIS Terra satellite once a day.
c) Upper-level data (in hPa): Rh 850, WS 850, WD 850, Rh 700, WS 700, WD 700 at noon, were taken from the balloon data stored in the Wyoming data base

The data for b) and c) is constant across Israel; b) because of the resolution of the satellite which allows only one measurement point in the area and c) due to the radiosonde measurements being made only in one site in Israel.

The degree of influence of each of the variables and their contribution to the DTR was found through computation of the linear correlations and stepwise multiple regressions, both for the whole year and for each season at every station. For simplicity, the seasons were defined in the usual manner: Winter-DJF, Spring-MAM, Summer-JJA, and Autumn-SON. This in spite of our more advanced approach for seasons' definition based on synoptic classification (Alpert et al. 2004).

Here, data from 7 stations was used, altogether 15337 daily data points—winter—3822 points, spring—3864, summer—3864, and autumn—3787. Each station is situated in a different topography and at a different distance from the sea shore (Table 1, Fig. 1).

From the data acquired, the following values were computed:

1. Stepwise regression analysis in every site for the whole year and every season, based on the variables (at 0.05 significance).
2. Linear correlations between the DTR and each variable in every site.

Table 1 The 7 chosen stations by name, latitude, longitude, and elevation above MSL (m). Locations are given in Fig. 1

Sites	Latitude	Longitude	Elevation (m)	Distance from seashore (km)
Ashdod Port	31° 47′ N	34° 39′ E	27	0
Besor Farm	31° 28′ N	34° 29′ E	150	18
Be'er Sheva	31° 15′ N	34° 48′ E	285	66
Jerusalem Givat Ram	31° 46′ N	35° 13′ E	768	54
Haifa Technion	32° 48′ N	34° 58′ E	257	3.5
Tel Aviv Port	32° 04′ N	34° 46′ E	15	0
Tabor Kadoorie	32° 42′ N	35° 25′ E	170	55

Fig. 1 The research area and the 7 chosen sites on a topographical map of Israel and the eastern Mediterranean

3. Comparison of DTR values for the different sites by year/season.

3 Results

3.1 Stepwise analysis

The contribution of all the variables that are statistically significant (at 0.05 level) at each site (percent) is shown in Fig. 2.

One can see that in the mountainous sites further inland, i.e., Be'er Sheva, Besor, Jerusalem, Tabor Kadoorie, the independent variables can explain a larger part of the DTR (~ 60–70%) than those located in flat seashore sites (Ashdod, Tel Aviv with ~ 30–40%). Since the Haifa Technion station is near the seashore but in a mountainous environment, high above sea level (257 m, Table 1), its maximum explained value (50%) is between the seashore and the mountainous inland sites.

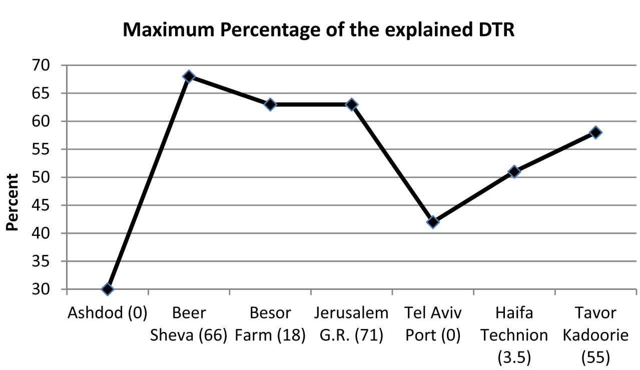

Fig. 2 Maximum percentage explained by the DTR dependence on the independent variable contribution of all the variables, to the DTR in each of the seven sites. Distance from seashore (in km) is indicated in parentheses.

Figure 3 shows the assembled variables that together explain partly the DTR size and the relative contribution of each at every site.

As seen from the graphs in Fig. 3, there is no doubt that the relative humidity (Rh) makes the greatest contribution to the DTR. The size of this contribution depends on the topography and the distance from the sea. The identity and the size of the contribution of the second and third variables differ in every site, though some of them occur more often than others. For instance, the cloudiness during daytime is situated second in four sites (Haifa Technion, Besor Farm, Tabor Kadoorie, and Jerusalem Givat Ram) and third in another site (Be'er Sheva). The wind speed occurs more often at the third place though the wind speed at 850 hPa is situated second in Be'er Sheva. The distribution of the variables in places 1–3 and their contribution to the DTR is shown in Table 2. The contribution of the other variables is not significant.

Table 2 presents for every site the three most dominant variables for the DTR explanation. It is clear that the Rh makes the greatest contribution to the DTR in all sites, while the contribution of the other variables is smaller. However, it is worth mentioning that the daily cloudiness comes in second place at most of the sites and the WS is in the third place. It is also apparent that the contribution from the Rh is larger at inland sites that are situated in higher and more complex topography. Jerusalem is an exception; the contribution of Rh is smaller than in the other mountainous sites, more like Haifa which is also situated in a mountainous environment but much closer to the sea. Additionally, the contributions of the secondary variables are significantly larger in Jerusalem than in the other sites. We think that the reason for this is the location of the site at the western edge of the Judean Hills, without any significant obstacles between Jerusalem and the sea. Consequently, it gets a stronger and more stable sea breeze than the other mountainous sites. The continuous wind removes the humidity and brings more clouds from the sea resulting in lower humidity and more cloudiness. The wind speed contributes 5% to the DTR, more than at any of the other sites.

Similar computation of the contribution of the variables, as shown in Table 2, was made for every season at each site (Tables 3, 4, 5, and 6).

Like in the yearly data (Table 2), the contribution of Rh is again the largest. The Ashdod Port station is an exception, presumably due to its close proximity to the sea. Here, the contribution of the variables to DTR is small. Similar to the yearly data (Table 2), the Rh contribution increases with the distance from the sea. The exception is again Jerusalem probably because of the aforementioned reasons. As was seen in the yearly data, the Cd came in second place and the WS is third in most sites.

Generally, there is no considerable difference between this season and the autumn. The contribution of the Rh is slightly larger. The contribution of the Rh is increases for

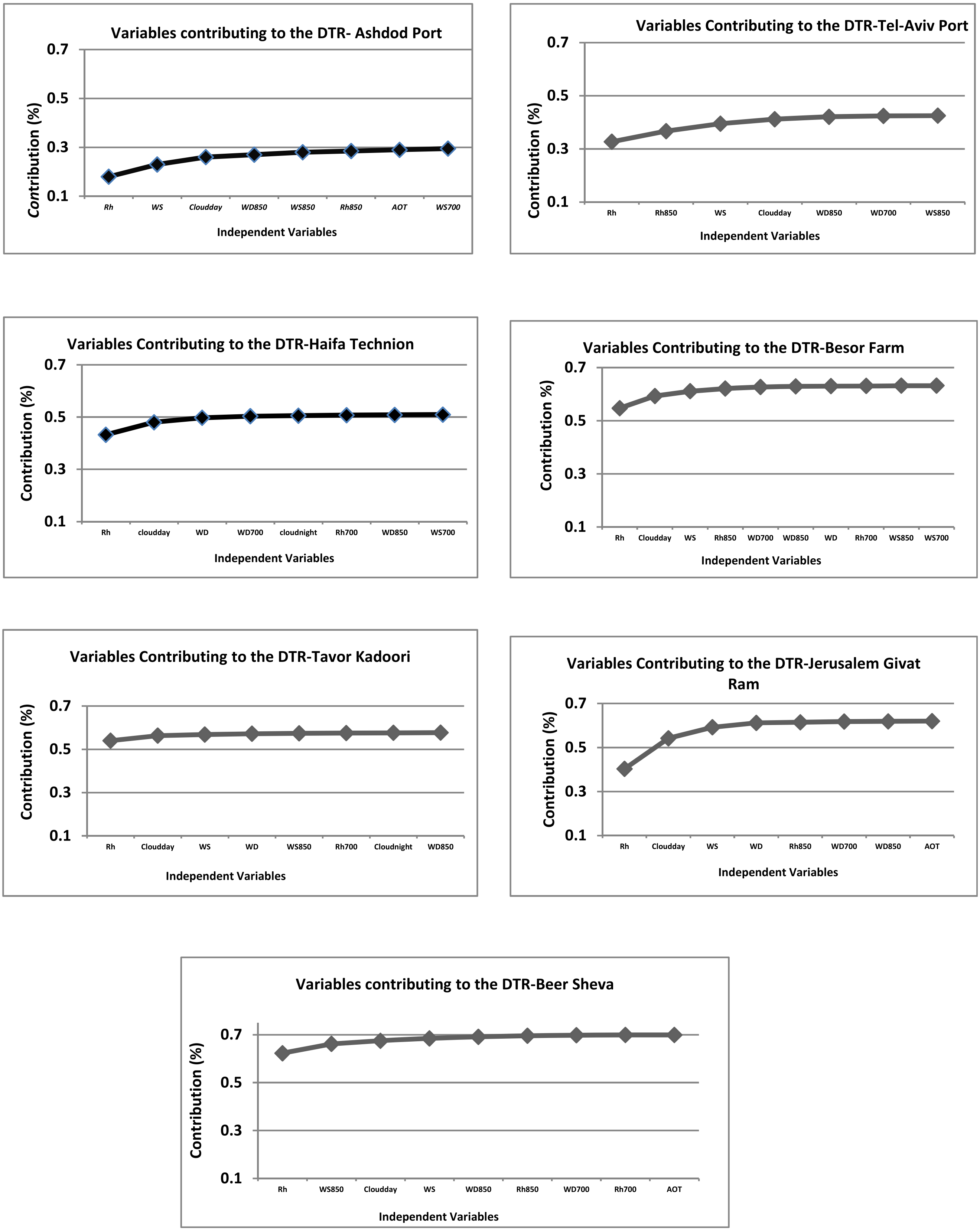

Fig. 3 Variables contributing to the DTR

Table 2 The three most dominant variables in determination of the DTR for each of the seven stations. Based on data of the entire year. The parameters are *Rh* relative humidity, *Cd* daily cloudiness, *WS* wind speed, and *WD* wind direction

Sites	First place	Contribution (%)	Second place	Contribution (%)	Third place	Contribution (%)	Total
Ashdod	Rh	18	WS	5	Cd	3	27
Tel Aviv	Rh	32	Rh850	5	WS	3	42
Haifa	Rh	43	Cd	5	WD	2	51
Besor Farm	Rh	54	Cd	5	WS	2	63
Tabor Kadoorie	Rh	54	Cd	2.5	WS	1	58
Jerusalem	Rh	40	Cd	15	WS	5	62
Be'er Sheva	Rh	64	WS850	4	Cd	2	70

higher sites that are further from the sea. The contribution of the Cd is smaller than in the autumn. An interesting point is the relatively considerable presence of the 850-hPa variables. It is possible that the activity of the upper atmosphere in this transitional season after the winter and toward the summer is more prominent.

For this season, there is a clear separation between the seashore and the inland sites. At the seashore sites, the influence of the sea breeze is very clear. The contribution of the variables to the DTR is small due to the dominance of the sea breeze regime. At the inland sites, the Rh is dominant and the contribution of other variables is minute. Jerusalem is also different in this season. Although it is situated inland, it is under the influence of the sea breeze, and therefore, the dominant variable is found to be the WS, not the Rh. The influence of upper level variables is felt at the higher sites, like Haifa and Jerusalem.

During the winter season, the greatest contribution is from the Rh at all sites, though less in the seashore sites where the influence of the sea breeze is significant on some days. Even in Jerusalem, the sea breeze influence disappeared and the contribution of Rh reached 46%, unlike for the other seasons. An interesting point is the increased frequency of upper air variables, presumably due to the enhanced activity of the atmosphere in this season.

3.2 Linear correlation

It was shown in the previous section that according to the stepwise analysis, the relative humidity has an overwhelming influence on the DTR. In the following section, we will examine the linear correlation between the DTR and the five leading independent variables in each site. Only the annual correlations were computed. Note that the correlations in all the sites are negative (Fig. 4).

Ashdod Port Linear correlations between the DTR and for the five mostly correlated variables in the Ashdod Port station. The variables from left to right are relative humidity, wind speed, 850-hPa relative humidity, 850-hPa wind direction, and the daily cloud amount.

By far the highest correlated variable is the Rh. The correlation for all other variables is quite low—even very low from the second place down.

Tel Aviv Port Linear regression between Tel Aviv Port and the DTR, for the five highest correlated variables: from left to right, relative humidity, wind speed, relative humidity at 850 hPa, cloud amount at daylight, wind speed at 850 hPa.

A similar result was found for Tel Aviv as for the other seacoast site, Ashdod Port. The leading variable is again Rh, the second is WS, and the third is Rh850. The correlations for the other variables are significantly lower. For both coastal

Table 3 As in Table 2 but for the autumn

Sites	First place	Contribution (%)	Second place	Contribution (%)	Third place	Contribution (%)	Total
Ashdod	WS700	10	Rh	8	Rh850	7	25
Tel Aviv	Rh.	21	WS	9	WS700	6	36
Haifa	Rh	33	Cd	9	WS	2	44
Besor Farm	Rh	46	Rh850	9	WS700	3	58
Tabor Kadoorie	Rh	55	Cd	5	WS	2	62
Jerusalem	Rh	35	Cd	11	WS	4	50
Be'er Sheva	Rh	62	Cd	4	WS	2	68

Table 4 As in Table 2 but for the spring

Sites	First place	Contribution (%)	Second place	Contribution (%)	Third place	Contribution (%)	Total
Ashdod	Rh	19	Rh850	8	WS850	4	31
Tel Aviv	Rh	34.5	Rh850	6	WD850	4	44.5
Haifa	Rh	35	WS	8	Cd	4	47
Besor Farm	Rh	63	Cd	4	Wd850	2	69
Tabor Kadoorie	Rh	57	WS	4	Cd	7	68
Jerusalem	Rh	43	WS	11	Cd	5	59
Be'er Sheva	Rh	63	Cd	4	WD850	2	69

sites, WS came in second place which can be explained by the sea breeze strong effect due to the proximity to the sea.

Haifa Technion Linear regression between Haifa Technion and the DTR, for the five highest correlated variables: from left to right, relative humidity, cloud amount at daylight, relative humidity at 850 hPa, cloud amount at night, wind speed at 850 hPa.

This Haifa-Technion site is a transition between the seashore and inland sites. Accordingly, the correlation with Rh is relatively high while the correlation with the other variables is still low. The Cd situated in the second place, replacing the WS found for the other seashore sites. The WS at 850 hPa is only in the fifth place with very low correlation.

Besor Farm Linear regression between Besor Farm and the DTR, for the five highest correlated variables: from left to right, relative humidity, relative humidity at 850 hPa, cloud amount at daylight, cloud amount at night, wind speed at 850 hPa.

This site is located at a further distance from the sea, i.e., 18 km (Table 1) and in a semiarid zone. As expected, the Rh and the Rh850 are in the two highest places and both (especially the Rh) are most highly correlated with the DTR with about − 0.75 and − 0.45, respectively.

Tabor Kadoorie Linear regression between Tabor Kadoorie and the DTR, for the five highest correlated variables: from left to right, relative humidity, cloud amount at daylight, relative humidity at 850 hPa, cloud amount at night, wind speed at 850 hPa.

The Tabor Kadoorie site is situated far from the sea (55 km) but further to the north and in a more complex terrain. The Rh has the high correlation with the DTR (~− 0.75), which is very similar to the Besor Farm correlation; however, in the second place comes the daily cloudiness (Cd) and in the third place is the Rh850, but both with similar correlation values.

Jerusalem Givat Ram Linear regression between Jerusalem Givat Ram and the DTR, for the five highest correlated variables: from left to right, cloud amount at daylight, relative humidity, relative humidity at 850 hPa, cloud amount at night, wind speed at 850 hPa.

As mentioned earlier, Jerusalem is somewhat exceptional. The Cd and Rh are equally correlated, though the value is lower than for the other inland sites, i.e., correlation value of ~− 0.63. The following three variables are also highly correlated when compared to other inland sites (like Tabor Kadoorie and Besor farm). It follows that in this site, all the variables influence the DTR as can be also seen in the stepwise analysis in Table 2.

Be'er Sheva Linear regression between Jerusalem Be'er Sheva and the DTR, for the five highest correlated variables: from

Table 5 As in Table 2 but for the summer

Sites	First place	Contribution (%)	Second place	Contribution (%)	Third place	Contribution (%)	Total
Ashdod	Cd	8	WS	3	WS700	1	12
Tel Aviv	WS	8	WD	5	Cd	3	16
Haifa	Rh	39	Cn	1	Rh850	1	41
Besor Farm	Rh	56	Cd	2	WS	1	59
Tabor Kadoorie	Rh	43	WS	6	Cn	2	51
Jerusalem	WS	28	Rh850	4	Rh	1	33
Be'er Sheva	Rh	54	WD850	2	Rh850	1	57

Table 6 As in Table 2 but for the winter

Sites	First place	Contribution (%)	Second place	Contribution (%)	Third place	Contribution (%)	Total
Ashdod	Rh850	27	Rh	8	WS850	7	42
Tel Aviv	Rh	30	Rh850	10	WS850	8	48
Haifa	Rh	48	Cd	6	WS	2	56
Besor Farm	Rh	56.5	WS850	9	Cd	3	68.5
Tabor Kadoorie	Rh	44	Cd	9	WS	6	59
Jerusalem	Rh	46	WS	11	Cd	3	60
Be'er Sheva	Rh	61.5	WS850	8	Cd	2	

left to right, relative humidity, relative humidity at 850 hPa, cloud amount at daylight, wind speed at 850 hPa, cloud amount at night.

Since Be'er Sheva is the farthest from the sea (66 km, Table 1) it was expected that the correlation with the first variable, namely Rh, will be the highest. But even the second variable, i.e., Rh850 (∼− 0.6), and the third variable, i.e., the daily cloudiness (Cd), are relatively highly correlated (∼− 0.5).

3.3 Distribution of DTR magnitudes by year and seasons

In Fig. 5, we show the distributions of the DTR magnitudes for the whole year and each season for all sites. The Ashkelon station was used here, because we had full records, which are necessary for this climatological figure. This should not be of any problem since Ashdod and Ashkelon are both nearby on the southern coast of Israel and are most highly correlated (0.96–0.98).

The most obvious feature in this figure is the difference between the seashore and the inland sites, with the seashore DTR found to be considerably smaller than inland. The three coastal stations (Ashkelon, Tel Aviv, and Haifa) show DTR average values which are less than about 4 for all seasons. This is probably the result of the strong temperature mitigation near the coast due to sea and land breezes. This difference can also be seen when comparing among the inland sites; the DTR is highest in Be'er Sheva, which is the furthest from the sea, for all seasons. In Besor Farm and Tabor Kadoorie sites, the DTR is somewhat smaller, because they are closer to the sea. Jerusalem is located further from the sea than Be'er Sheva, but is exceptional as mentioned earlier, and its DTR is larger than on the shore but smaller than in the other inland sites. Also, in Jerusalem, the DTR in summer is considerably higher and in the winter smaller compared with other seasons. This is not true for the other sites in which there is not a large difference between the seasons. Generally, inland sites had the smallest DTR in winter, whereas those on the seashore had a larger DTR in winter and autumn.

4 Discussion and conclusions

According to the results in the previous section, the stepwise analysis showed that the relative humidity makes the greatest contribution to the size of the DTR in all the 7 sites, using data from the whole year. Analyzing the different seasons, some exceptions were found, both in the seashore sites and in Jerusalem, especially in summer. In these sites, i.e., seashore and Jerusalem, the first place (most dominant factor) is occupied by the wind speed and the daily cloudiness. This is a result of the dominance of the sea breeze particularly in summer. The changing strength, direction, and duration of the westerly wind influence the maximum and minimum temperatures and, consequently, the DTR. Although Jerusalem is relatively far from the sea (71 km), the location of the site in the Hebrew University in Givat Ram on the western edge of the Judean Hills which allows the wind to reach the site without much disturbance, through the lowland to its west. In the other sites which are more screened from the sea by mountainous terrain, the influence of the wind is weaker.

The second place in the influence on the DTR is occupied, mainly, by the daily cloudiness and the third by the wind speed, though the wind direction and the upper level variables also have some influence.

One can ask why the relative humidity takes such a great part in the shaping of the DTR. It was found in the analysis of the linear correlation that the correlation coefficient is negative, meaning that that the greater the humidity, the smaller is the DTR. Israel is a humid country due to its proximity to the sea. The western wind dominates most of the year bringing a lot of humidity inland. At night, with the decrease in temperature, the atmosphere becomes nearly saturated. At this stage, it contains a great quantity of moisture or tiny water drops which are very efficient as greenhouse agents. Hence, the minimum temperature stays relatively high and the difference between the minimum and maximum temperatures decreases and DTR decreases.

This is the reason for an additional phenomenon, shown in Section 3, namely, that the DTR size increases away from the seashore and further inland (Fig. 2).

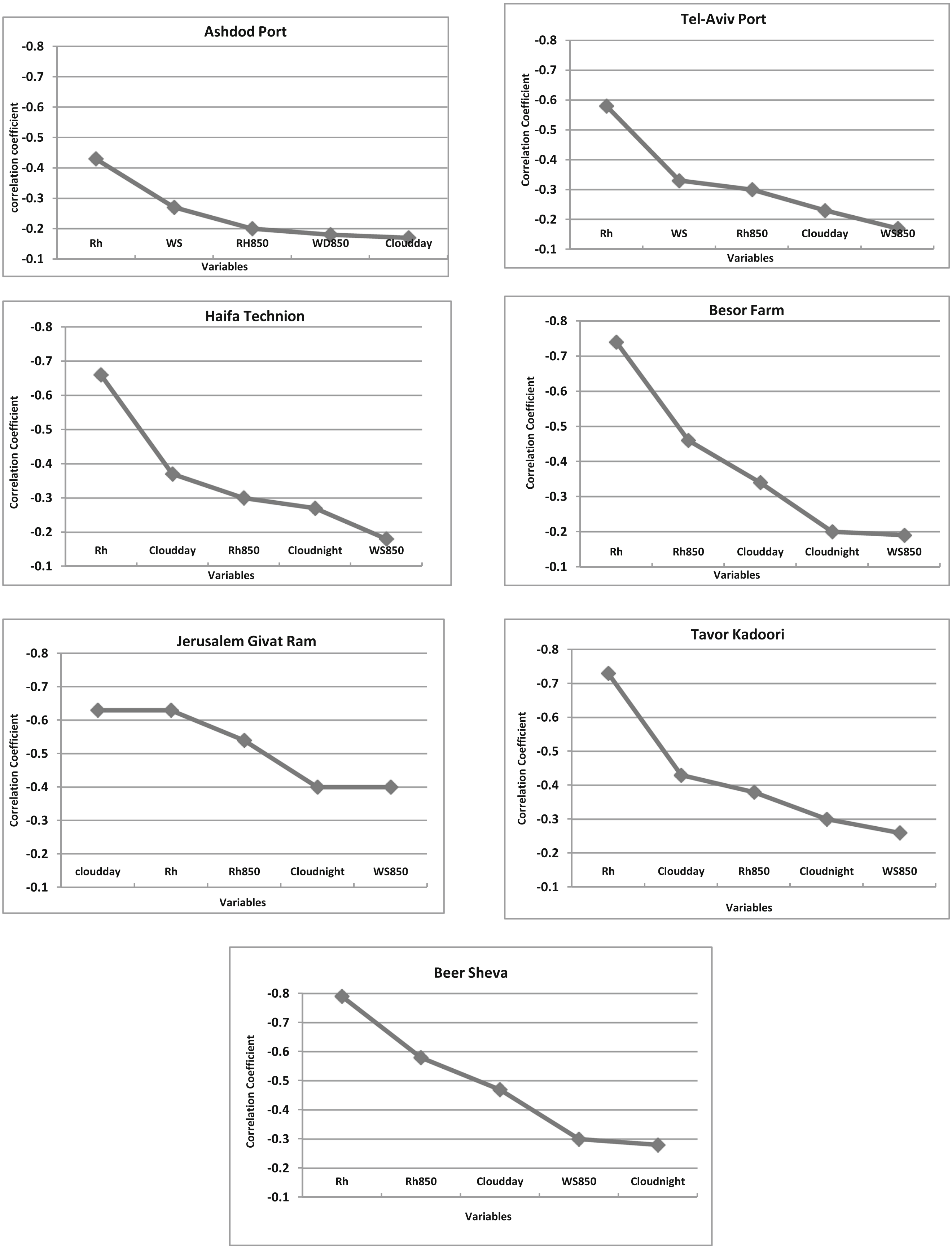

Fig. 4 Linear correlation by sites

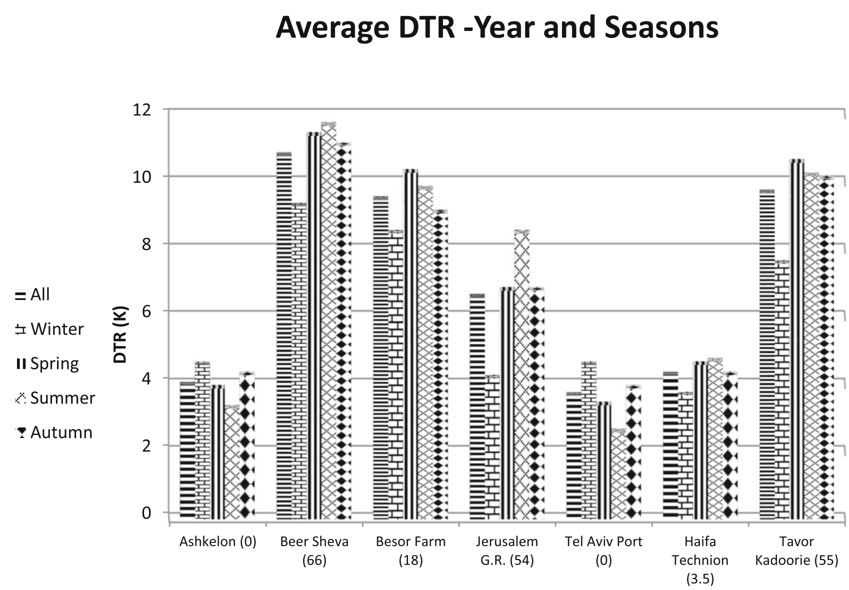

Fig. 5 Average DTR (*K*) for the 7 stations (from left to right: Ashkelon, Be'er Sheva, Besor Farm, Jerusalem, Tel Aviv Port, Haifa Technion, Tabor Kadoorie). For each station, 5 bars indicating the DTR average value for the full year, and the four seasons as noted to the left. The distance from the seashore in km is indicated in the parentheses below the site's name

The two other variables that influence the DTR, though to a much lesser extent, are the daily cloudiness and the wind speed. The wind speed is correlated negatively with the DTR, the higher it is, the more humidity it brings and therefore helping to increase the greenhouse effect as explained above. The cloudiness is also correlated negatively with the DTR. Since, as larger cloud cover, especially low clouds (which are the most frequent in Israel) more efficiently prevent thermal radiation from escaping to space and lead to higher minimum temperatures.

In summary, the local DTR in a complex terrain near the sea, like in Israel, is influenced mainly by the relative humidity and to a lesser extent by the daily cloudiness and the wind speed.

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