

SOME CHARACTERISTICS OF NOCTURNAL BIRD MIGRATION IN ISRAEL ACCORDING TO RADAR MONITORING

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ABSTRACT

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The present study is aimed at obtaining radar data on nocturnal bird migration over central Israel to be used for improvement of air traffic safety in complicated ornithological settings. The data obtained, together with the radar monitoring procedure previously developed (Dinevich *et al.* 2004), resulted in establishing a radar network over Israel that forwards information on bird movements to air traffic control stations every 15-30 minutes.

The results of radar monitoring of nocturnal bird migration over central Israel are presented (1998-2002) enabling to determine a number of characteristics which are of importance for air traffic control, including average and maximum flight altitudes, altitudes of maximum bird density, the dominant directions and velocity of bird flights.

The average flight altitude was found to be mainly within the limits of 1800 to 2000 m in autumn and of 2400 to 2900 m in spring. The absolute maximum altitude was estimated at 5700 m in spring and at 5200 m in autumn. Average altitudes of maximum bird density are considerably higher in spring (*ca* 1500 m) than in autumn (*ca* 1000 m). The study of flight directions and speed of over of 20 000 bird echoes showed that the dominant direction of migration was 183° in autumn and 6° in spring. Within the altitude band of 0 to 500 m, deviations from the dominant migratory route were observed, being approximately 135° in autumn and 315° in spring, which can be explained by intensive migration of songbirds from the Mediterranean Sea towards winter-quarters in autumn and back in spring. Cases of reverse migration were relatively rare and were not characteristic for the nocturnal bird migration over central Israel. The average speed of bird flights was found to be around 14 m/s in spring and 13 m/s in autumn, the minimum and maximum flight speed being 8 m/s and 18 m/s, respectively.

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Key words: radar ornithology, radar meteorology, bird migration.

BACKGROUND AND STATEMENT OF THE PROBLEM

The present study was aimed at obtaining reliable radar data on nocturnal bird migration over central Israel to be used for improvement of air traffic safety in complicated ornithological settings. The data obtained, together with the radar monitoring procedure previously developed (Dinevich *et al.* 2004), resulted in establishing a radar network over Israel that forwards information on bird movements to air traffic control stations every 15-30 minutes.

The Middle East is a sort of a bridge between Africa and Palearctic, facilitating one of the most intensive bird migration routes. Numerous studies have been carried out on diurnal migration of soaring birds, (among them: Yom-Tov 1988, Bruderer and Leichti 1995, Leshem 1995, Shirihai *et al.* 2000; Leshem *et al.* 2003). However, there is a significant gap in information on nocturnal migration due to certain technical complexities of its study. At the same time, because of high densities of various flying objects over Israel, data on nocturnal flights is of extreme importance for air traffic safety. High-potential meteorological radar MRL-5 (Abshayev *et al.* 1980), mounted at 270 m a.s.l. in Latrun (Israel), significantly broadens the possibilities for high accuracy bird monitoring at night (Dinevich *et al.* 2003, Leshem *et al.* 2003, Dinevich *et al.* 2004).

Table 1
Altitudes of nocturnal bird migration according to various radar and tower mortality studies: *pas* – data for passerine spp., *sho* – shorebirds, *wfo* – waterfowl

Study	Locality	Birds	Altitude (m), comments
Able 1970	USA		< 915 – 75%
Adams 1962	USA	<i>pas</i>	900-1800, over water
Bellrose 1967	USA	<i>pas</i>	< 1500 – 50-100%
Bellrose 1971	USA	<i>pas</i>	150-310 – 50%
Gauthreaux 1972	USA	<i>pas</i>	244-488, over water
Gauthreaux 1991	USA	<i>pas</i>	< 500
Houghton 1964	USA	<i>pas</i>	≤ 1500
Williams <i>et al.</i> 1972a, b	USA	<i>sho</i>	1000-3000, over water
Williams <i>et al.</i> 1977	USA	<i>pas</i>	1000-2000, over water
Williams and Williams 1979	USA	<i>pas</i>	2000-3500, over water
Beason 1978	USA	<i>wfo</i>	500-2000
Crawford 1981a, b	USA	<i>pas</i>	< 380, tower mortality
Blockpoel and Burton 1975	Canada	<i>pas</i>	1400-3780
Blockpoel and Burton 1975	Canada	<i>wfo</i>	3780 (max)
Richardson 1972a	Canada	<i>pas</i>	< 610
Richardson 1972b	Canada	<i>sho</i>	1300 (average), over water
Richardson 1976	Canada	<i>sho</i>	2000-4000, over land and water
Richardson 1979	Canada	<i>sho</i>	2000 (average), 6650 (max)
Eastwood and Rider 1965	England	<i>pas</i>	< 760 – 80%
Bruderer and Liechti 1995	Israel	<i>pas</i>	< 1800 – 90%

Radar bird monitoring makes it possible to obtain reliable data on nocturnal migration. A number of such investigations were performed in various locations (Table 1). As can be seen, the dispersion of data, even on the observed altitude of nocturnal migration, is significant, which is caused by technical constraints and feasibility of radars used in the research. The main aim of the paper is presenting a general pattern of the nocturnal bird migration over central Israel as a basis for future more detailed studies.

METHODS

Technical equipment and the procedure of recording experimental data

The main parameters of meteorological radar MRL-5 are presented in Table 2.

MRL-5 radar has two simultaneously operating wave lengths of 3.2 and 10 cm. Its potentials on both wave lengths are high enough to detect a single stork flying at the altitude of more than 700 m, at the distance of 90 km; a single sparrow at the altitude of more than 200 m, at the distance of 8 km; a flock of about 50 sparrows at the altitude of 300 m, at the distance of 30 km (Dinevich *et al.* 2000). The ellipsoid antenna forms two (for both wave lengths) asymmetrical pencil beams. Due to angular dimensions of the beam, the accuracy of determination of a target altitude at 3.2 cm wave length does not exceed 100 m for 25-km range. Since the range of observations over night birds in this investigation did not exceed 50 km, the accuracy of the altitudinal measurement did not exceed 200 m, whereas measurement errors at 10 cm wave length are considerably higher. For this reason, we used both wave lengths to detect birds, while for measuring flight altitudes only 3.2 cm waveband was used. To record experimental data, we photographed the radar screen, the primary task being to find a simple way of selecting signals from birds on the photos.

Table 2
Parameters of MRL-5 radar

	Unit	X-Band	S-Band
Transmitter frequency	Mhz	9595	2950
Wave length	cm	3.14	10.15
Transmitter power	kW	250	800
Pulse duration	ms	1/2	1/2
Pulse repetition frequency	Hz	500/250	500/250
Beam width	deg	0.5°	1.5°
Antenna gain	dB	40	39
Azimuth rotation rate	rotations/min	0-6	0-6
Elevation scan rate	scans/min	0-6	0-6
Receiver sensitivity	dB/W	130	140

For this purpose, the camera shuttle was kept open during 1.5 minutes for each picture, with the help of a special valve and a timer. During this time interval, the radar beam, at the antenna scan rate of 6 revolutions per minute, performed 9 revolutions. The dotted signals from birds were converted into lines, forming a certain pattern of tracks, the length of such tracks corresponding to birds' flight velocities. The direction of bird flights was easily determined by the shift of dotted echo on the screen. Aiming the radar beam strictly to the north or to the south and registering the radio echo shifts within a preset time interval (1.5 minutes), we obtained both the velocity and the direction of bird flights. It was found that flight directions had a predominantly southern component in autumn and a northern component in spring. In rare cases, usually in those of non-migratory flights, these tracks had chaotic spatial orientation. Dotted echoes or area echoes that do not change their spatial position with time are not related to birds. Reflections from aircraft, due to their high velocities, are converted into dotted lines on the photos and could be easily identified. Figure 1 (A-C) shows dotted echo from birds, as well as tracks of both distinctly directed and chaotic movements of birds' echoes. Figure 1 (D-F) shows an example of vertical scanning of bird echoes. The white spots in the photographs represent ground clutter.

Recording of experimental data was carried out in two operational radar modes: (1) in horizontal scans, at angles of 0, 0.5, 1.0, 1.5 and so forth, in steps from 0.5 to the extreme level at which signals from birds were still obtainable; (2) in vertical scans, at various azimuths.

Thus, one photography cycle consisted of series of horizontal scans at several elevation angles, as well as of series of vertical scans at various azimuths. A 12-15 min cycle was performed once an hour. The photography began before the onset of civil twilight and continued till 0.00-1.00 *a.m.*, sometimes being prolonged till dawn.

Experimental data and their analysis

Systematic collecting of experimental data started in spring 1998. By 2000, data had been collected covering five migration periods (two spring and three autumn seasons). Due to specific regional features of bird migration, data collected in August were added to autumn data sets. Over 40 000 photos were processed and analysed, out of them about 20 000 were obtained from the radar screen in vertical scans. These photos served as the basis for building up experimental series containing altitude flight parameters. Therefore, the volume of sample used for the analysis of nocturnal flight altitudes was 20 000. The other batch of about 20 000 photos was obtained from the same screen in horizontal scans. The data collected formed the basis for experimental series used in calculations of flight directions and velocities.

In 2000-2001, these sources of data were complemented by data on over 2000 nocturnal flights obtained *via* monitoring and parameter measurements of radar echo movements observed directly on the radar screen and the oscillograph, with-

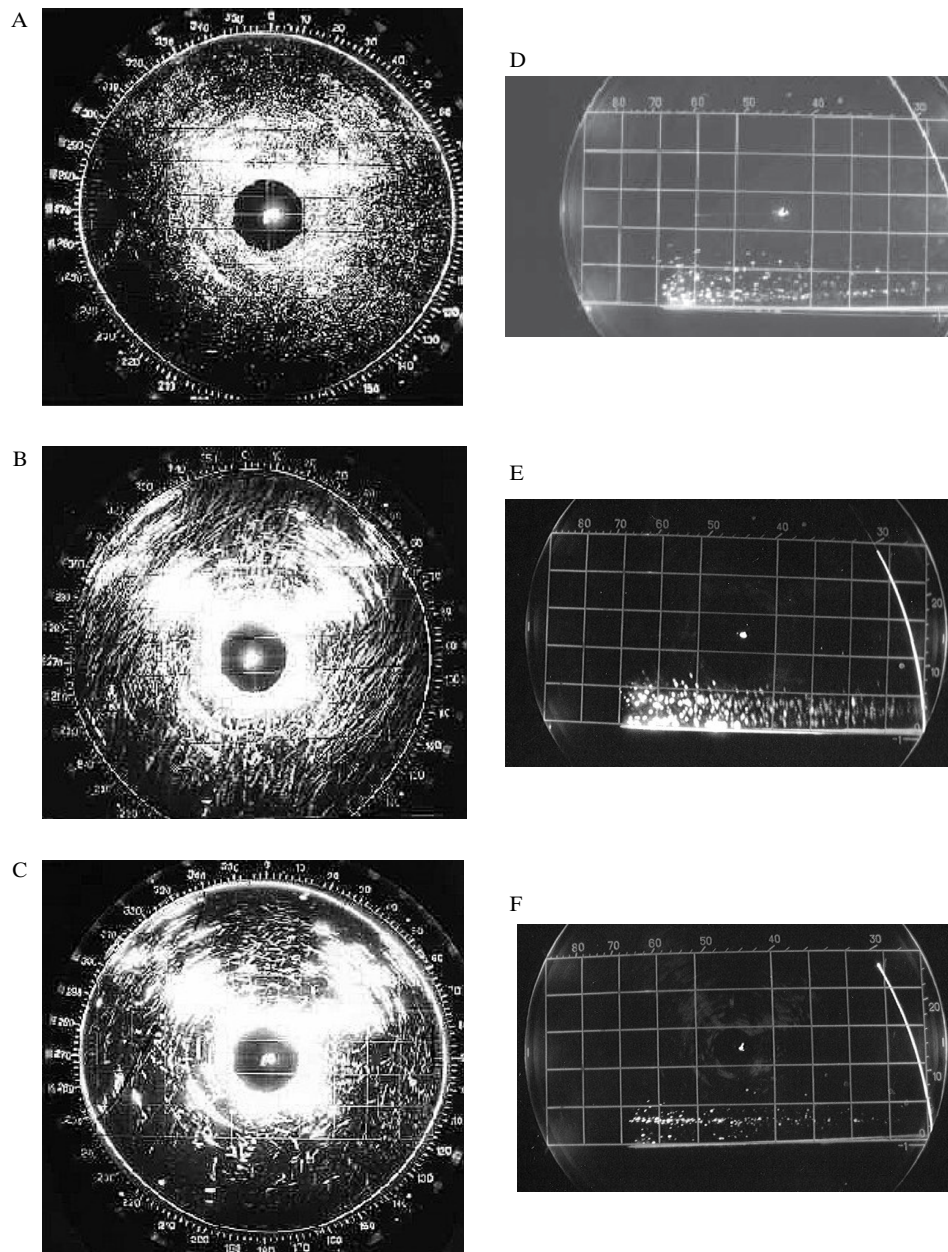


Fig. 1. Screens with the birds radio echos. A-C – horizontal antenna scans (radius 25 km): A. dot echos (single antenna scans), B. echos tracks of flight following a distinct direction (18 scans during a 3-minute antenna rotation), C. echo tracks of chaotic movements (18 scans during a 3-minute rotation); D-F – vertical antenna scans at a stable azimuth (a scale of the visible grid is 2×2 km).

out taking photos of the screen. The data characterized flight directions and velocities, thus making the total observation sample amount to 22 000 flights.

The following characteristics of bird migration were selected as the experimental variables. (1) average flight altitude over different time intervals (a night, a month, a season); (2) maximum flight altitude; (3) altitude of maximum bird density; (4) flight directions by altitude and season; (5) flight speed by altitude and season.

Calculations of altitudinal parameters over periods of a night, a month and a season were performed by the formulas given below:

$$\overline{H_{max}} = \frac{1}{m} \prod_{i=1}^m \frac{1}{k} \prod_{j=1}^k h_{mij} \quad (1)$$

$$H_{max} : \max\{\max[h_{mij}]\} \quad (2)$$

$$\overline{H_{max.con}} = \frac{1}{m} \prod_{i=1}^m \frac{1}{k} \prod_{j=1}^k h_{m.con.ij} \quad (3)$$

where:

$\overline{H_{max}}$ – average from maximum bird flight altitudes for the preset period,

$\overline{H_{max.con}}$ – average from the upper level of birds' maximum density,

H_{max} – extreme maximum of bird flight altitudes over the entire observation period,

j (from 1 to m) – number of night observation sessions,

i (from 1 to k) – number of hour-by-hour observation sessions during a given night,

h_{mij} ; $h_{m.con.ij}$ – maximum flight altitude and the level of maximum bird density in each photo.

Two databases were used to determine flight direction and velocity, namely, the data from the photographs of bird tracks, as well as the data of direct observations of the radar screen and the oscilloscope in the manual radar mode. In each photograph, the most distinct tracks were selected for calculating directions and velocities of flights within previously selected squares located in the north, the south, the east and the west. The calculated values were related to altitude values that were determined by the distance between the radio echo and the station, as well as by the elevation angle.

RESULTS

Average flight altitudes and maximum flight altitudes

Average flight altitudes were very variable both between migration seasons and between subsequent days (Fig. 2). There was the same general pattern in autumn and in spring although some differences could be observed.

In autumn 1998 during August flight altitudes were rather low (around 1000 m) and later on they were on a higher level (around 2000 m), but more stable. However, even in the late season some nights with low migration occurred. In 1999 all September to November migration was rather stable on the same level as in the mid and in the late season of 1998. Low migration nights were exceptional in this year. In contrary, in 2000 most of migration was relatively stable at the higher level (even

in August), but low migration nights occurred rather frequently during all season. Maximum flight altitudes in autumn varied even more than average flight levels and reached 5200 m.

In spring in both years average flight altitudes fluctuated much around the smoothed curve, but low level migration was observed practically at the beginning of the season. During a course of the season the mean level of migration grew from the beginning till the end of April and then slightly decreased. Spring patterns of maxima of the passage level were similar to these of the average flight altitudes. However, generally flight altitude in spring was higher than in autumn. The highest observed flight maximum was in spring 5700 m. Cases when flight altitude was over 4000 m did not exceed 1% of observation throughout all the years.

Calculated average values for the seasons were found as follows: 2068 m ($SD = 755$) in autumn and 2655 m ($SD = 760$) in spring.

As can be seen in all the graphs, day-to-day differences in bird flight altitudes varied significantly, which can be attributed to weather changes, especially to temperature distributions and wind parameters. Another important factor causing changes in flight altitudes can be birds species, but further research is needed to establish precise correlations. This last factor can explain a good part of variation.

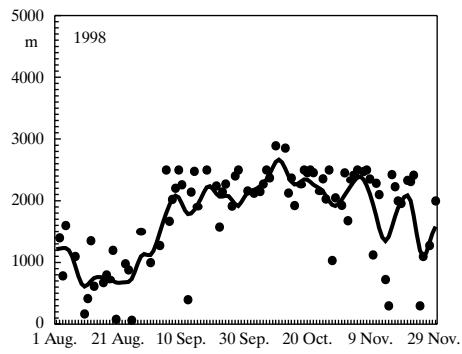
Altitude of birds' maximum density

Radar monitoring makes it clear that altitudes of nocturnal flights of birds are not evenly distributed. Most often, birds fly within a rather narrow band starting close to the ground and reaching a certain maximum that does not exceed usually 500 m. In all the observations, the altitude of maximum bird density was found to be within the said band. In Figure 1 (D-F) respective altitudes of maximum bird concentration are 400, 1600 and 1200 m.

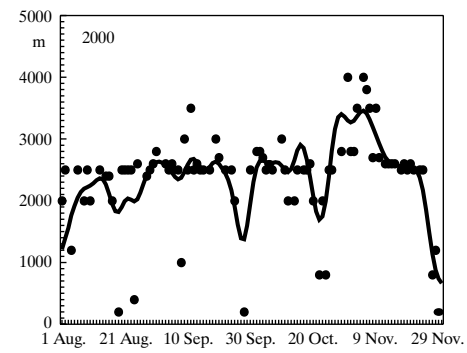
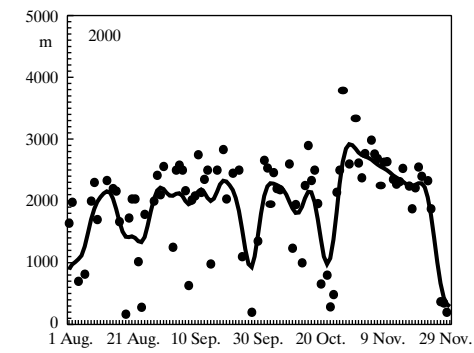
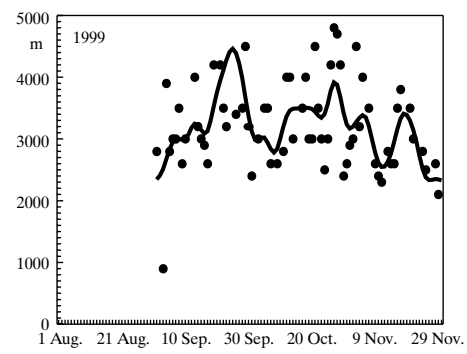
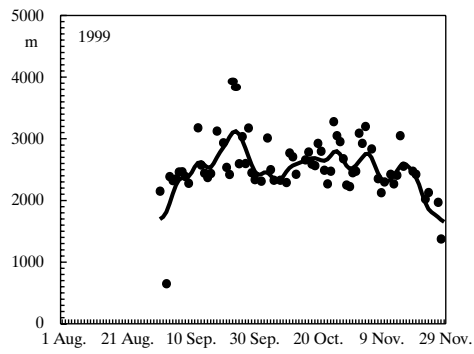
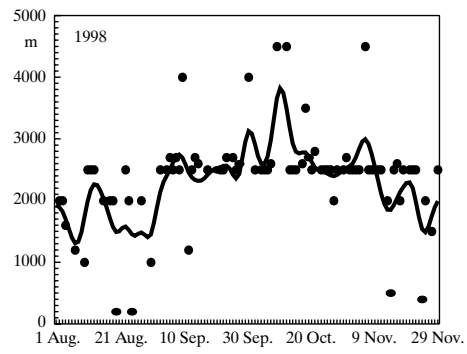
Figure 3 shows seasonal changes in the altitudes of the highest bird density and the maximum flight density level observed at night. Maximum density levels varied from day to day and generally followed the pattern established for parameters discussed earlier. Lower values were observed at the beginning of a season in comparison to its end, although weather conditions at the beginning of autumn and spring were different. Spring bird migration starts when the weather is rather cool, windy and rainy; autumn bird migration starts in August, with the weather being hot, dry and windless. The differences in air temperatures in August-September vs March reach 10-11 degrees. As can be seen, the difference between zero isotherm levels in August vs March can reach 2.6 km, and the difference in tropopause altitudes can be as high as 5.6 km (Table 3). However, despite this diversity in weather conditions, the altitudinal characteristics of nocturnal bird migration have similar trends. In our view, this can be only explained by the fact of species differences between birds initiating migration. Both in autumn and in spring, nocturnal migration is triggered by low-flying birds that are less dependent on weather conditions, while weather apparently influences high-flying birds.

AUTUMN

Average height of passage



Maximum height of passage



SPRING

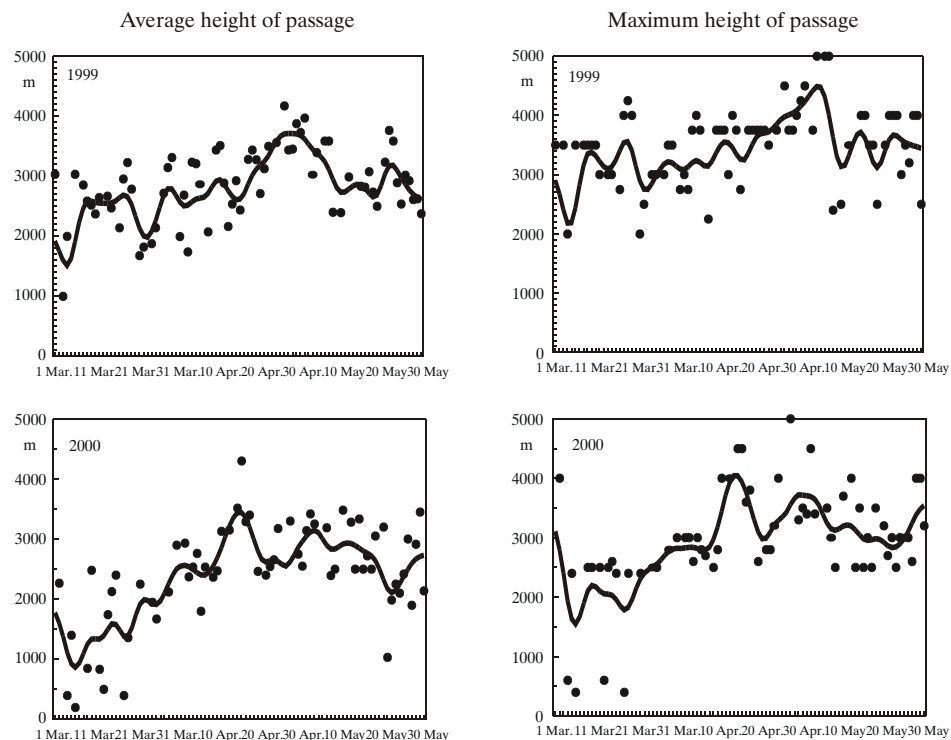


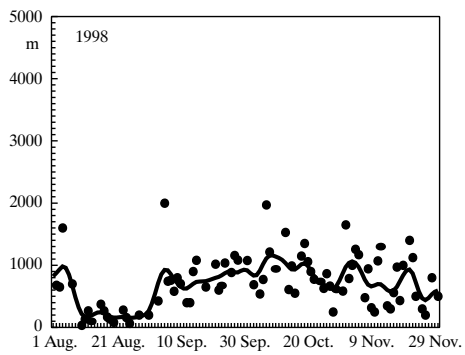
Fig. 2. Average altitude of passage and maximum altitude of passage in autumn (left page) and spring (right page) in subsequent years. Dots – individual nights values, line – smoothed using five days moving average.

The altitudes of maximum bird density were generally greater in spring (around 1500 m) than in autumn (*ca* 1000 m). In single cases, the altitude of maximum density reached 2000 m in autumn and 3000 m in spring. However, the frequency of such high values did not exceed 1%. Throughout the observation periods, the altitude of maximum bird densities tended to increase, spring values being steadily higher than those in autumn.

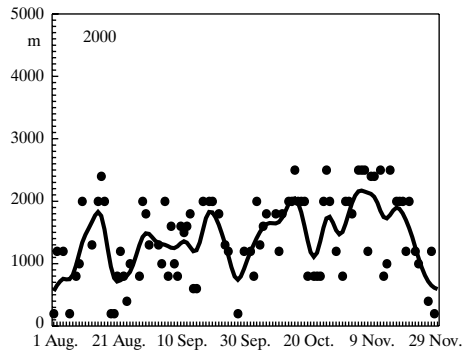
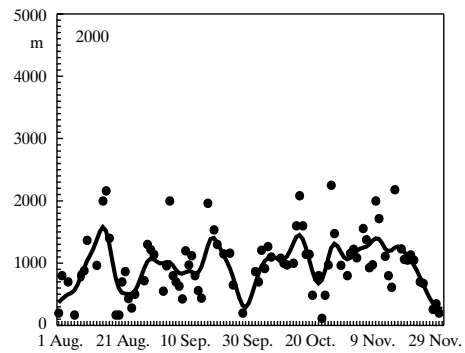
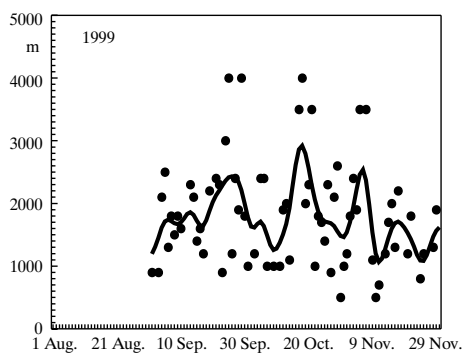
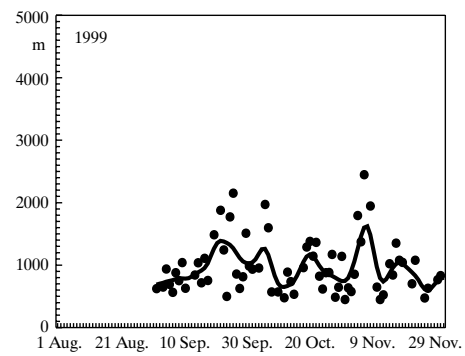
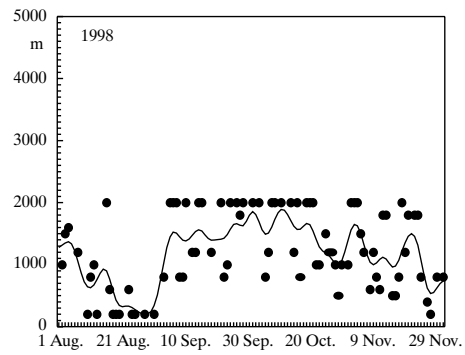
The variations in the altitudes of nocturnal bird migration can be explained by the fact that in spring, the level of the tropopause increases together with the temperature of the underlying surface and the atmospheric temperature, followed by positive convection currents above the land. The breeze processes and mountain-valley circulation also plays an important role in the formation of stable convection currents (Burman 1969). At the beginning of spring, the land is considerably warmer than the sea during cloudless daytime, which strengthens the positive convective component in the boundary atmospheric layer. In the evening, temperatures of the sea and the land get almost even, which causes cessation of breeze in the evening and may even result in alteration of the convective component. Such meteorological conditions facilitate bird migration in the daytime, but have little influ-

AUTUMN

Average height of passage concentration



Maximum height of passage concentration



SPRING

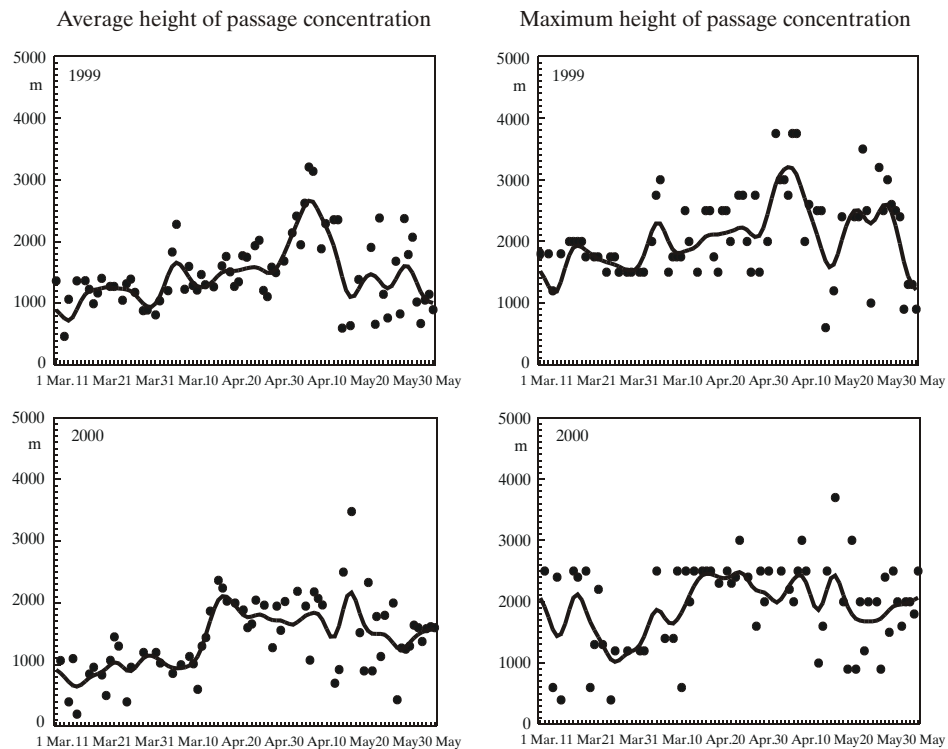


Fig. 3. Average altitude of passage concentration (maximum density) and maximum altitude of passage concentration in autumn (left page) and spring (right page) in subsequent years. Dots – individual nights values, line – smoothed using five days moving average.

ence on conditions of nocturnal bird migration. For birds that migrate at night, flight altitude apparently depends very little on weather conditions. As lower layers of the atmosphere and the troposphere get warmer, nocturnal migration is joined by birds of which high-altitude flight parameters depend more significantly on the weather factor.

Table 3
Spring and autumn climatic traits in central Israel based on observations
by Beit-Dagan meteorological station (Tel Aviv)

Atmospheric parameters	Spring			Autumn			
	Mar.	Apr.	May	Aug.	Sep.	Oct	Nov
Average temperature (°C)	15	18	21	26	25	22	18
Altitude of zero isotherm (m)	2600	3300	4000	5300	4700	4000	3300
Altitude of tropopause (m)	11 200	12 000	13 100	16 700	17 000	14 600	13 200

During autumn bird migration, the underlying surface and the lower layers of the atmosphere in Israel remain warm. Temperature contrasts between the sea and the land are considerably lower than those in spring. The sea-land temperature leveling begins in the evening, while at night the sea becomes warmer than the land and the convective component above the land often becomes negative. Only at the end of November, the temperature drop becomes noticeable. However, in spite of the fact that autumn weather changes are reverse in respect to those in the spring period, the altitude parameters of nocturnal bird migration for both seasons are similar, which means that in autumn, bird migration is also initiated by low-flying birds of which flight altitudes depend less on the weather.

Altitudinal and seasonal patterns of flight directions

Figure 4 shows distributions of directions chosen by migrants. To analyse flight directions, we selected four altitude bands from 0 to 2000 m, in step of 500 m. Only those directions that were observed at the frequency not lower than 70% are presented in the diagrams – this procedure cleans pictures from an information noise, but can dump less pronounced directions. Radar graphs in the figure are presented in 10 sectors. Both unimodal and bimodal distributions are observed.

The analysis of flight directions revealed both some uniformities and differences. In autumn and spring, the spectra of flight direction expand with an increase in flight altitudes. This phenomenon was also observed in different regions, by a number of researchers (Bruderer *et al.* 1995, Shirihai *et al.* 2000). We have found that in spring this expansion is significantly larger than in autumn, which can be best accounted for by weather characteristics. In Israel, in the period from March to May the weather rapidly changes from cold to warm, whereas in autumn it remains hot for a long period (in fact, almost the entire period of bird migration). In spring, the wind component is more variable in time and altitude; in autumn and spring, wind direction at the levels of maximum bird density coincides with the direction of migration, due to large-scale circulating processes (Jaffe 1988).

We observed bird migration towards the Mediterranean Sea in spring and in the reverse direction in autumn, within the low-altitude band of 0 to 500 m. A sector of these directions differs from the general path of seasonal bird migration, averaging at about 135° in autumn and at 315° in spring. This phenomenon was observed mainly within 2 hours after the beginning of nocturnal bird migration at the altitude of 250-350 m. At the altitudes over 500 m, practically no flights in this direction were observed. This deviation from the dominant direction may be attributed to the fact that some songbird species cross the Mediterranean Sea directly on the route to the Cyprus in spring and back in autumn. Figure 5 (A and B) presents radar screen photos of two observations of birds flying towards the sea (spring: 17 March, at 9.10 *p.m.*) and from the sea into land (autumn: 25 August, at 10.20 *p.m.*). Since the camera shuttle was kept open during 1.5 minutes, the dotted echoes turned into streaks oriented along flight direction. The wide band directed from the north to the south is the land-sea boundary. The ellipses encircle larger bird groups flying to or from

the sea. As can be seen in the photos, significant part of the birds do not cross the sea, following the dominant migration route.

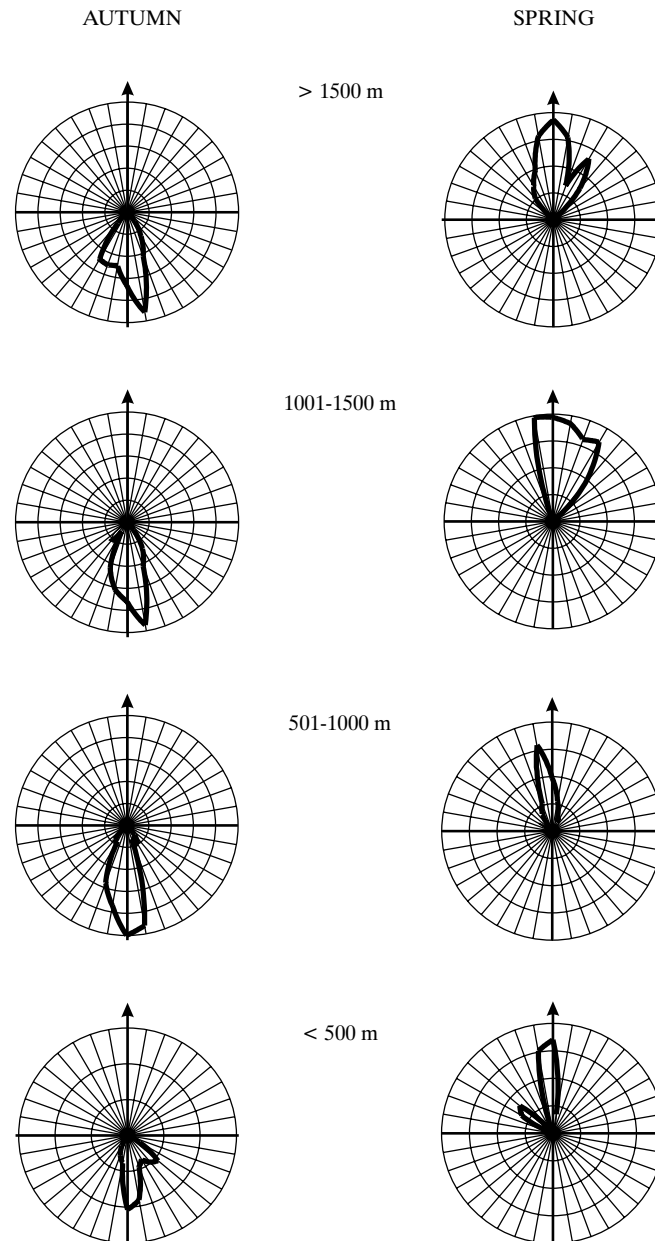


Fig. 4. Main flight directions in autumn and spring at different altitudes. Note uni- and bi-modal patterns.

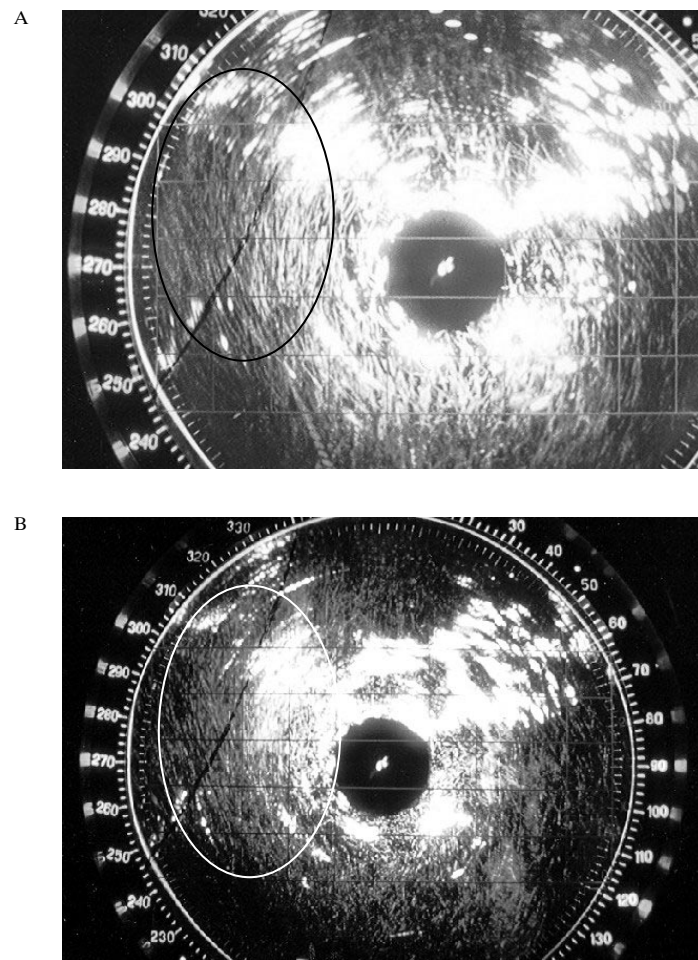


Fig. 5. Screens with radio echoes directing to the sea (A. 25 August, 10.20 *p.m.*) and from the sea (B. 17 March, 9.10 *p.m.*), bird movements seen within bordered area. Black line – the Mediterranean Sea coast.

Bird flight speed and altitudes

The altitudinal distribution of bird speed in autumn and spring is shown in Figure 6, which presents the average value, standard deviation and standard error for different altitudes.

The average flight speed in spring was found to be about 14 m/s, the speed values being distributed in the following way: 10-12 m/s in 24% of birds; 12-14 m/s in over 35%; 14-16 m/s in 27% of the birds. The average flight speed in autumn was about 13.2 m/s, the distribution being: 7% for speed of 10-12 m/s; 70% for speed of 12-16 m/s; 11% for speed of 16-18 m/s; about 12% flights were beyond the 10-16 m/s range. It was found that flight speed increased when flight altitudes rose in spring

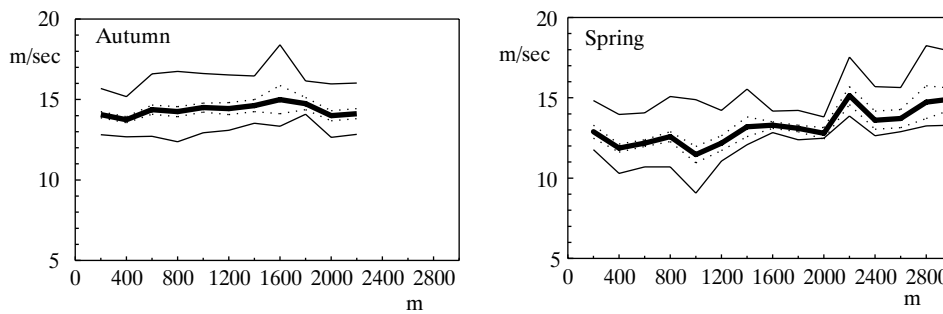


Fig. 6. Relation between ground speed of birds and altitude of flight. Thick line – average value of speed at different altitudes, dotted lines – a stripe within $\pm 1 SE$ (standard error), thin lines – a stripe within $\pm 1 SD$ (standard deviation).

(Pearson's correlation coefficient: $r = 0.80$, $p < 0.001$), but in autumn such relation was not found ($r = 0.34$, $p < 0.05$). It should be noted that the data under discussion are related to flight speed in respect to the radar location (groundspeed), while the wind effect was not taken into account.

CONCLUSIONS

1. In the present research, altitudinal characteristics of nocturnal bird migration over central Israel is described, which enables to establish parameters highly significant for air traffic control services that are to determine optimum air routes.
2. Altitudes of nocturnal bird migration are invariably lower at the beginning and at the end of a season. Regardless the considerable difference in weather conditions between autumn and spring, initial flight altitudes for nocturnal migrations are similar. The nocturnal flight altitudes of high-flying birds are found to be considerably higher in spring than in autumn.
3. The altitudinal characteristics of nocturnal bird migration are determined by two factors:
 - ornithological (first of all differences in the species composition of birds migrating in different periods of spring and autumn) – Nocturnal bird migration is initiated by birds of which flight altitudes are less affected by weather.
 - meteorological (among them warming-up of the ground surface, the increase in the tropopause level, convective processes in the atmosphere, wind direction, etc.) – Birds seek to use the atmosphere layers that are optimum for the flight. The effect of the meteorological factor on the altitudinal parameters of nocturnal migrations will be the subject of our further research.
4. The dominant direction of nocturnal bird migration is found to be 183° in autumn and 6° in spring. The migration towards the Mediterranean Sea in spring and in the reverse direction in autumn is observed. A sector of these directions differs from the general area of seasonal migration, averaging at 135° in autumn and at 315° in spring. These deviations within the low-altitude band can be accounted for by massive migration of songbirds in vicinity of the Mediterranean Sea.

5. The average velocity of bird migration is found to be about 13 m/s in autumn and 14 m/s in spring.

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