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MEASUREMENTS WITH RADAR OF THE HEIGHT OF NOCTURNAL MIGRATION OVER CAPE COD, MASSACHUSETTS*

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Very little is known of the heights at which nocturnal bird migration takes place. Stebbins (1906) and Carpenter (1906) described a method of measuring heights in which two adjacent observers train telescopes on the moon, but the method gives biased results and has not been applied systematically. Lack (1960) observed migration over England with a radar height-finder, but the usefulness of his results is limited by the fact that he could only observe the highest birds, a small (and unknown) proportion of the whole migration. Other studies made with radar in Europe, quoted by Lack, were based on too few nights to give reliable averages. This paper describes observations made in New England, using a radar height-finder which permitted quantitative observations of all birds except the very lowest. The chief limitation of these observations is that they were made from Cape Cod, a promontory extending some 40 miles into the sea, and may not be representative of migration over the mainland of New England.

Acknowledgements

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OBSERVATIONS

Apparatus

The radar height-finder consists of a narrow beam which is moved up and down in a vertical plane through an angle of about 40°. Figure 1 shows a typical photograph of the screen on which the results are displayed. The radar station corresponds to the apex of the angle at the lower left; height is measured upwards and range to the right. The figures (0, 5 . . . . 25) on the left-hand side give the

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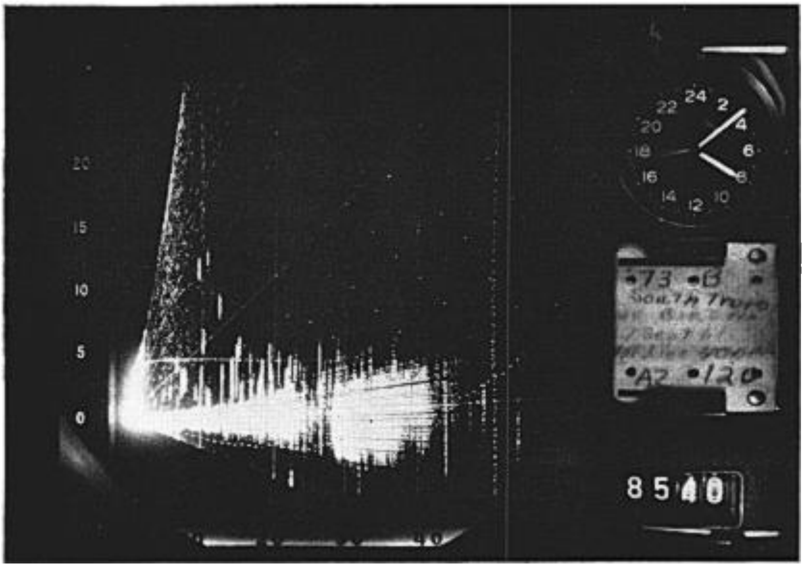
Figure 1. The radar height-finder at South Truro, Massachusetts, photographed at 08.08 on 27 September 1961. The radar station corresponds to the apex of the angle at lower left; the vertical scale is in thousands of feet, the horizontal scale in nautical miles. Except for the faint lines and speckles, the white marks represent echoes from land, sea and birds.



height scale in thousands of feet; the radar station is in fact 140 feet above sea level, but in the example displayed the picture has been displaced relative to the scale, so that the radar station is close to the zero on the scale. The faint horizontal line on the left hand side is about 4,600 feet above sea level. The figures (20, 30, 40) on the bottom give the range in nautical miles. Ground- and sea-level corresponds to the horizontal line through the radar station and is usually marked by a band of bright vertical hatching due to echoes from land and waves. The area below this line has no physical meaning.

At ranges less than about 20 miles echoes from birds (and aircraft) appear as short, bright vertical marks. Stronger echoes give longer, more intense marks on the screen, but the strength of an echo is not always a guide to the size of the birds giving rise to it (see Nisbet in press). Beyond 20 miles the display of discrete echoes turns gradually into a continuous haze: this is because at longer ranges each bird gives a weaker echo, but the radar beam, being wedge-shaped, detects more birds. Usually no echoes at all appear beyond 20 miles' range unless the bird density is high. At long ranges the heights indicated by the instrument are unreliable, because radar waves are often bent upwards or downwards, according to the temperature gradients in the atmosphere.

The photograph also includes a clock (in this case recording Eastern Daylight Time), a frame counter, and a board which records reference information, the direction in which the height-finder is pointing, and the operator's estimate of the date. In fact, many of the dates which appear on the films are wrong, but the correct dates can be established because the film magazines are numbered in the same sequence as those of the films of the Plan/Position Indicator on the same nights. The latter films can be dated because the numbers run in sequence throughout the season concerned. This laborious task was carried out by Drury, who is satisfied that all the films used for this study are correctly dated. Observations for this study were made from 35 mm. cine-film pictures of the screen and the ancillary apparatus. Each frame of the film recorded one complete vertical sweep of the beam, lasting 3 seconds. Usually the film covered 5 minutes' observation (100 frames) in each of 3 directions (usually 030°, 120° and 300° — NNE, ESE and WNW of the radar station), repeated at two-hour intervals for all or part of the night.

Low-flying birds

The chief limitation of the height-finder is that echoes from the ground and the sea overlap the echoes from low-flying birds, so that it is usually impossible to observe birds below about 600 feet. On some occasions, when the ground echoes were unusually weak, it was possible to see that there were few or no bird echoes below this height. On other such occasions, many bird echoes were present below 600 feet, but attempts to track their movement by projecting the films, with a cinematic viewer, gave confused results, although a coherent direction of movement could be determined for the higher birds. After examining films for 45 nights, I believe that, on average, only 10-20 percent of the echoes were below 600 feet, and that many of these were of non-migrating birds (e.g. gulls, shorebirds, ducks, geese and other seabirds). For practical reasons, the quantitative study was restricted to heights above 600 feet.

Flocking

Another limitation of this study (and of other observations by radar) is that only one echo is received from each flock or loose group of birds. It should be understood that quantitative observations in this paper refer to the height distribution of flocks, which is not necessarily the same as that of birds. Terms such as "average height of migration" are used in the former sense only.

RESULTS

Films were examined for 45 nights, including seven nights when there was no migration because of continuous rain. In all, measurements were made of the heights of more than 22,000 echoes.

Observations at 22.00 hours

On most nights one period of observation was between 22.00 and 22.15 local time. In April, September and October this was between 2½ and 4 hours after local sunset; in May it was only about 2 hours after sunset, but on five of the nine May dates, the observations were in fact made at 23.00-23.15. Hence all these observations were made at roughly comparable times and they are listed together in Table 1.

TABLE 1. HEIGHTS OF ECHOES AT 22.00-22.15 (THREE TO FOUR HOURS AFTER SUNSET), RELATED TO MIGRATION DENSITY AND WEATHER

Date		Main Range	% of Birds above 600′				Cloud amount/height		Migration density		Wind Direction
			600-2,000′	2,000-4,000′	4,000-6000′	Over 6,000	Boston	Nantucket	Large	Small	
11 Apr.	1960	0-6,500′	28	29	28	15	10/13,000′	4/—	2	4	Tail
12 Apr.	1960	0-3,700′	43	52	5	0	10/5,000′	3/—	2	2	Beam
14 Apr.	1960	0-6,800′	17	32	31	20	10/12,000′	7/—	2	4	Tail
17 May	1960	0-3,000′-6,700′	29	43	9	10	3/—	2/—	2	3	Light
*17 May	1961	0-1,900′-3,300′	76	12	2	0	0/—	no record	2	0	Head & Tail
*18 May	1961	0-1,600′; 3,500′-8,000′	60	13	15	12	10/12,000′	no record	2	0	Beam
*20 May	1961	0-3,500′	46	39	13	2	10/12,000′	no record	1	1	Beam
*21 May	1961	500′-2,900′-5,600′	48	35	11	6	10/10,000′	no record	2	3	Tail
22 May	1961	500′-2,600′; 4,100′-7,000′	38	29	22	11	3/fog	no record	1	2	Light
27 May	1961	0-2,800′		not countable			10/3,600′	no record	0	0	†Various
*28 May	1961	0-2,600′-5,000′	64	25	9	2	4/—	no record	2	3	Tail
2 Sep.	1961	2,100′-5,100′	16	49	27	8	10/400′ fog	10/100′ fog	2	0	Tail
3 Sep.	1961	0-2,900′-6,000′	43	32	20	6	10/200′ fog	10/100′ fog	1	1	Light
4 Sep.	1961	500′-1,900′; 3,100′-11,000′	25	22	24	28	0/—	10/100′ fog	2	1	Light
5 Sep.	1961	500′-2,800′-7,500′	38	36	11	15	0/—	4/—	2	3	Tail
6 Sep.	1961	500′-9,000′	19	38	21	22	1/—	10/100′ fog	3	3	Light
7 Sep.	1961	0-1,300′; 2,000′-4,000′	29	59	6	6	6/10,000′	8/—	1	0	Light
8 Sep.	1961	0-2,100′-4,500′	51	30	12	7	8/5,000′	8/10,000′	2	?	Light
14 Sep.	1959	0-3,400′	43	40	13	4	10/9,000′	2/—	1	1	Light
15 Sep.	1961	0-4,500′	37	48	14	2	10/7,500′	5/—	3	1	Beam
17 Sep.	1961	0-2,400′-3,500′	53	33	14	0	0/—	2/—	2	2	Beam
18 Sep.	1961	0-2,800′-5,500′	39	39	18	3	7/—	10/5,500′	1	2	Light
19 Sep.	1961	1,400′-4,000′	58	32	10	0	10/thin	10/3,500′	1	1	†Light

22 Sep.	1961	1,400′-4,800′	17	56	25	2	10/200′ fog	10/200′ fog	2	3	Light
23 Sep.	1960	0-3,100′-5,800′	47	35	12	5	9/—	2/—	1	3	Light
23 Sep.	1961	0-3,400′-8,000′	33	47	7	13	10/200′ fog	10/100′ fog	2	2	Light
26 Sep.	1961	0-3,400′-7,000′	37	45	13	4	0/—	1/—	2	3	Tail
27 Sep.	1961	0-3,900′	33	48	17	2	0/—	5/—	2	3	Various
5 Oct.	1961	1,000′-4,900′-8,000′	24	38	26	13	0/—	0/—	2	3	Light
10 Oct.	1960	0-4,500′	30	56	13	2	1/—	0/—	3	1	Tail & Beam
10 Oct.	1961	0-3,800′-7,000′	26	54	16	6	0/—	0/—	1	1	Tail
11 Oct.	1961	0-1,200′; 3,000′-5,000′	30	35	26	10	10/400′ fog	3/—	1	1	Tail
12 Oct.	1961	500′-3,700′-7,000′	26	52	11	10	0/—	0/—	2	2	Light
13 Oct.	1961	900′-4,000′	51	39	7	3	10/400′ fog	10/500′ fog	1	0	Beam & Tail
15 Oct.	1961	0-2,600′	56	34	8	2	0/—	0/—	1	3	Beam
16 Oct.	1961	1,000′-4,400′	25	44	23	7	3/—	6/3,500′	1	2	Beam
21 Oct.	1960	300′-5,200′	37	39	20	3	1/—	0/—	1	2	Light
25 Oct.	1961	0-5,800′	43	36	20	3	0/—	0/—	1	1	Beam

Notes. The 'main range' column gives the range in which 80-95 percent of the echoes were concentrated. Four heights are given if there were two separate concentrations of echoes; three heights if echoes were concentrated up to a certain level and scattered above it. The 'cloud' columns give the amount of cloud in tenths and the height of cloud ceiling. 'Migration density' is given on an arbitrary scale, explained in the text, for 'small' and 'large' echoes separately.

*Count made at 23.00-23.15.

†No coherent direction of movement.

The information given in Table 1 is as follows:

(1) Date.

(2) Main range or ranges of heights: this is a subjective estimate, and usually inclues 80-95% of the echoes.

(3) Percentages, *among the echoes above 600 feet,* of echoes in four ranges of height, *viz.* 600′-2,000′; 2,000′-4,000′; 4,000′-6,000′; over 6,000′. Usually 100-500 echoes were counted, within 12 miles of the radar station.

(4) Cloud in tenths and height of cloud ceiling, at Boston (50 miles WNW of the radar station) and Nantucket (46 miles south).

(5) Amount of migration observed on simultaneous films of Plan/Position Indicator radar. "Small" echoes are of the type attributed by Drury & Keith (1962) to small passerines; "large" echoes are probably non-passerines and/or flocks of large passerines. Density of migration is given on an arbitrary scale; very roughly, scales 1, 2, 3, 4 correspond to 2, 10, 50 and 250 birds per square mile. Especially in spring, the migration over Cape Cod itself is often at least one scale-unit less dense than that recorded in Table 1, which is estimated from echoes over Massachusetts Bay.

(6) General direction of wind, categorized either as "Light" or, if 10 knots or stronger, as "Head", "Tail" or "Beam" to the *observed* direction of migration.

Table 1 shows that, in general, most of the echoes (about 90% on average) were within 5,000 feet of the sea. On some nights most of the echoes were lower than 2,500 feet, but on other nights echoes ranged commonly up to 6,000 or 8,000 feet. There was usually a peak in the density of echoes between 1,500 and 2,500 feet, even on nights when there was another peak at 4,000 or 5,000 feet.

Hour-to-hour variation in height

On 31 nights films were taken at 20.00-20.15 as well as at 22.00-22.15. Except for five nights in May when it was not fully dark at 20.00, this period was usually 1-2 hours after sunset. The counts of bird echoes for the 26 nights in April, September and October have been added together and summarized in Table 2. Comparison with the figures for the period 22.00-22.15 shows that, on average, the echoes were about 10% higher at the later time. In fact, on only four of the 26 nights was the average height of flight higher at 20.00 than at 22.00.

On 16 nights films were also taken at midnight. Counts for these nights have also been averaged and summarized in Table 2. On average, the birds flew slightly lower at midnight than at 22.00-22.15.

On 6 autumn nights films were taken at intervals throughout the night. Rain continued throughout one of these nights, but counts made from the remaining five films are summarized in Table 3. The average height of flight rose (with two exceptions) between 20.00 and 22.00, declined steadily, being only about 75 percent of its peak

TABLE 2. DISTRIBUTION OF OBSERVED HEIGHTS AT DIFFERENT TIMES OF THE NIGHT

The figures give the percentages of echoes, among those above 600 feet, counted within four ranges of height. The first two lines give the averages of the counts for 26 nights in April, September and October; the third line gives averages for 19 of the same nights and two nights in May

Time	600′-2,000′	2,000′-4,000′	4,000′-6,000′	Over 6,000′
20.00 - 20.15	40%	40%	14%	6%
22.00 - 22.15	36%	41%	16%	7%
00.00 - 00.15	39%	38%	15%	8%

value at 04.00, then rose sharply again after dawn. This morning increase in the average height was associated with a decrease in the density of echoes, which suggests that the lower birds settled or descended very low, while the higher birds continued to migrate.

Observations to the west

On 24 nights migration was sufficiently dense for bird echoes to be detected from the area 35-50 miles to the west-north-west of the radar station, including Boston Harbor and parts of the mainland. On about half these nights the upper limit of the mass of echoes in this area was very close to that of the echoes within 10 miles of the radar station. On the remaining nights it appeared higher, sometimes by 50% or more. However, the heights indicated by the height-finder on the latter nights were certainly exaggerated by the phenomenon known as "anomalous propagation", in which the radar beam is bent downwards by a temperature inversion in the atmosphere. Anomalous propagation is easily detected on the screen of the Plan/Position Indicator (PPI) type of radar, because echoes from land and ships appear at ranges beyond the visual horizon. In fact, films of the PPI screen were available for all of the nights concerned, and every one of them showed evidence of anomalous propagation. Hence it seems likely that on most nights migration over the Boston area was little, if at all, higher than that recorded in Table 1.

DISCUSSION

Different sizes of birds

Table 1 shows that on most of the nights when there was a large migration of "small" targets, the average height of migration was high. It is not possible to identify individual echoes with "small" or "large" targets, because large birds sometimes give weak echoes, and flocks of small birds sometimes give strong echoes. However, large migrations of small passerines give echoes which are weaker, *en masse*, than those from migrations of larger species (see Drury & Keith (1962) and Nisbet (in press) for discussion). In fact, on some occasions (e.g. 17 May 1960, 22 May and 11 October 1961) when there were two distinct ranges of heights, the echoes in the upper range were clearly weaker than the lower echoes. My subjective im-

TABLE 3. DISTRIBUTION OF OBSERVED HEIGHTS DURING FIVE AUTUMN NIGHTS

Date	Time (E.D.T.)	Percentage of observed echoes above 600′ 600′-2,000′	2,000′-4,000′	4,000′-6,000′	Over 6,000′
	20.00	28	46	20	6
	22.00	37	45	13	4
26-27 Sep. 1961	23.00	39	46	12	2
	00.00	47	40	10	3
Sunset 18.35	01.00	50	39	10	3
Sunrise 06.36	02.00	54	37	7	3
	03.00	58	31	8	3
	04.00	65	29	5	3
	05.00	78	15	5	2
	06.00	32	43	18	7
	07.00	16	38	28	18
	08.00	25	40	22	13
27-28 Sep. 1961	20.00	31	50	13	5
	22.00	33	48	17	2
Sunset 18.34	00.00	39	52	5	3
Sunrise 06.37	02.00	44	42	8	4
	04.00	61	31	5	3
	06.00	52	41	6	1
5-6 Oct. 1961	20.00	28	43	23	5
	22.00	24	38	26	13
Sunset 18.20	00.00	24	38	28	10
Sunrise 06.46	02.00	22	38	23	16
	04.00	36	33	15	16
	06.00	28	44	23	5
16-17 Oct. 1961	20.00	30	52	13	7
	22.00	25	44	23	7
Sunset 18.02	00.00	28	45	19	8
Sunrise 06.59	02.00	28	43	26	3
	04.00	45	32	18	5
	06.00	36	44	12	6
25-26 Oct. 1961	20.00 ?	34	39	22	5
	22.00 ?	43	36	20	3
Sunset 17.48	00.00 ?	45	36	16	2
Sunrise 07.09	02.00 ?	43	43	14	0
	04.00 ?	50	38	12	0
	06.00 ?	79	21	0	0

Note. Times are uncertain on 25-26 Oct. 1961 because the clock stopped twice during the night.

pression was that on most nights the weaker echoes tended to be higher than the stronger echoes. Drury also informs me that on the PPI screen, weak echoes are usually visible at greater ranges than strong echoes, suggesting that the latter are lower and hence disappear over the horizon at closer ranges. These pieces of evidence suggest that small passerines tend to migrate higher than most larger species. Lack's (1960) observations suggest the same conclusion.

Very high targets

On most nights very few bird-echoes were detected above 10,000 feet (much less than one in 1,000, on average). On 18 May 1961, however, many birds were tracked between 6,000 and 9,000 feet, with a number scattered higher, up to 15,000 feet. The cinematic record showed that these birds were approaching the radar station when the beam was pointed ESE, and preceding when the beam was pointed WNW. Reference to the film of the PPI screen showed that many bright echoes were coming in over the sea from the southeast, progressing at a ground-speed of over 30 knots in spite of a strong northerly wind. Similar high movements of fast, bright echoes from the southeast were tracked on 21 and 22 May 1961; on the latter date two were detected as high as 19,000 feet.

On 2, 4, 5, 6 and 8 September 1961, and on a few occasions in late September and October 1961, a number of strong echoes were again tracked at heights between 8,000 and 15,000 feet, with scattered echoes as high as 20,000 feet (one example is shown on Figure 1.) These echoes were usually most numerous before midnight, but they were also observed before and after sunrise on 26 September 1961, after the clearance of rain which had blotted out the films taken during the night. The PPI films showed bright echoes moving southeast out to sea at ground-speeds of 40 to 70 knots.

Drury informs me that similar fast-moving, bright echoes, going northwest in May and southeast in autumn, have been observed by radar in earlier years, and he attributes them to shorebirds migrating directly across the Atlantic to and from eastern South America and the Lesser Antilles. Drury & Keith (1962) listed a number of species which may be involved in autumn, but in spring only four of these— the Black-bellied Plover, *Squatarola squatarola*, Semipalmated Sandpiper *Ereunetes pusillus*, Knot *Calidris canutus* and Sanderling *Crocethia alba* — are numerous enough in Massachusetts to account for the observed migration. In fact, the Black-bellied Plover and Semipalmated Sandpiper are known to have been arriving in the period 17-22 May 1961.

Lack (1960) attributed all his very high echoes to passerines, and stated that he did not observe "wader-type" echoes above 11,000 feet. However, this classification referred only to short-distance migrants (Lapwing *Vanellus vanellus* and Eurasian Curlew *Numenius arquata*), although he had briefly mentioned other shorebird species in an earlier paper (Lack 1959). In fact, long-distance migrants (including Black-bellied Plover, Knot and Sanderling) are abundant in the area covered by Lack's radar data.

Effect of weather

During the nights when the wind was classed as "Tail" in Table 1, the average number of echoes over 4,000 feet was 29 percent of the total number counted; during the nights of "Light" wind the average number was 25 percent; and during the nights when the wind was "Beam" the average number was 17 percent. Thus, on average, migration was lower with beam winds than with tail winds or light winds, the difference being statistically significant ($p < 0.05$). Migration with a head-wind is rare over Cape Cod at night, but on 17 May 1961, when there was a light northeast wind (7-10 knots at the surface), there were two movements of birds in opposite directions: a northeasterly movement against the wind and a "reversed" movement with the wind. Both movements were unusually low.

Another interesting night was 10 October 1961, when a cold front passed southwards over the radar station at about 22.00. Before the passage of the front there was a light southwest wind and a small northeastward movement of birds; behind the front there was a moderate northeast wind and a larger southwestward movement of birds. Both movements had a tail wind, but the "reversed" movement was much lower, few echoes being above 4,000 feet.

Clouds are not normally detected by radar, but if they contain water droplets or ice, they appear on the screen as dense bright masses, indistinguishable from the echoes from rain. On 11 and 14 April 1960, 21 May 1961 and 16 October 1961 the echoes from birds stopped about 1,000 feet below such an echo from a cloud. On 12 April 1960, 27 May 1961, 14, 18 and 19 September 1961 clouds were not detected by radar, but a low cloud ceiling was recorded by one or both weather stations; on all five nights the birds were rather low and very few were seen above the reported cloud-level. The only definite observation of birds above cloud level was of a number of shorebirds on 8 September 1961. All this evidence suggests that birds normally remain below clouds at medium and high levels and do not climb through them. Nevertheless, the films of the PPI screen show that on these occasions the birds remained well oriented.

No birds at all were seen migrating on nights when there was steady rain, but on 21 May 1961 many birds were migrating through showers. On the cinematic record from the height-finder many birds could be seen flying into a squall of rain about one mile wide, and other birds could be seen emerging from the other side of the squall at the same heights as those entering it.

There are several records of birds flying above areas of low-lying coastal fog. In at least three such cases (2 and 22 September and 13 October 1961) the lowest targets were unusually high, suggesting that the birds had risen to fly above the fog.

Comparison with European observations

It is difficult to compare my results with those made in England by Lack (1960), because Lack could only observe the highest echoes. However, Lack's records for nocturnal migration of passerines seem to average appreciably higher than mine. This may indicate that European birds migrate higher than North American birds, but there are several other possible explanations:

(1) Lack may have observed only a very small fraction—say 1-2 percent—of the total number of birds in the air; if so, his observations would overemphasize the numerical importance of these high birds. This seems unlikely, however, because on some occasions he gave figures for the most frequent height of migration, which average higher than those I recorded.

(2) Lack may have used the height-finder mainly on nights of large migration, when the weather was favourable.

(3) Lack's migration may have contained a larger proportion than mine of small and medium-sized passerines.

(4) Lack's high-flying species may have had less tendency to migrate in flocks than mine.

SUMMARY

1. Observations of migration were made during 45 nights with a radar height-finder on Cape Cod, Massachusetts. The instrument permits quantitative measurements of the heights of birds except within 600 feet of the ground.

2. Three or four hours after sunset, the most frequent height of migration was usually between 1,500 and 2,500 feet above sea level. On average, 90 percent of the birds were below 5,000 feet and over 99 percent below 10,000 feet. There is a little evidence that few birds migrate at night below 600 feet. The average height of migration was about the same over the mainland as over Cape Cod.

3. At 20.00 (one or two hours after sunset) the average height of migration was about 10 percent lower than that at 22.00. On at least five nights the average height reached a peak before midnight and declined slowly thereafter, rising again at dawn.

4. Small passerines usually flew higher than larger species, but the highest echoes of all (up to 20,000 feet) appeared to be from shorebirds starting or completing a long sea-crossing.

5. Birds often flew over low-lying fog, but they did not fly through or over medium and high clouds. On one occasion birds flew through a rain-squall without changing height.

6. The average height of migration over Cape Cod was lower than that over England, recorded by Lack.

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