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SPRING MIGRATION STUDIED BY MIST-NETTING, CEILOMETER, AND RADAR

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Three techniques have been used for the study of nocturnal migrant birds flying within 200 m of the ground: watching birds cross the face of the moon, counting birds passing through a light beam, and detecting migrants with radar. Long range surveillance radars do not reliably detect birds at less than 200 m. This is not the case with a number of short range, high resolution radars which have been developed for ornithological work (Eastwood 1967, Schaefer 1969, Williams et al. 1972, Griffin 1973, Bruderer 1978). These smaller instruments also have the advantage of resolving tracks of individual birds, while larger radars can indicate only the general patterns of migration. Mist-netting data have also been used to infer the numbers and identity of nocturnal migrants by noting the daily change in numbers of birds netted. In the present paper we compare observations of birds passing through a light beam, observations taken directly from the screen of a small radar and noted by hand, films of the radar screen analyzed by a computer, and mist-netting results, all taken during the same period at Manomet Bird Observatory on Cape Cod Bay, Massachusetts, during the spring of 1976.

Spring migration over the Manomet area was observed by Nisbet and Drury (1967) with a powerful search radar located at South Truro on the eastern portion of Cape Cod. Migration density was much less in spring than in fall over the entire area of eastern Massachusetts which they surveyed except the area north and west of Boston. The main flow of migrants they observed was parallel to the trend of the North American coastline (about 050°) and did not extend more than a few kilometers out from the coast except as the birds passed over the Gulf of Maine. Thus, they report that the great majority of passerine migrants would be moving over the area northwest of Manomet with only the fringes of the main migration passing over our area of observation. This conclusion agrees with the results of long term netting operations at the Manomet Observatory, fall migration being intense and spring migration being lighter than at inland stations. Nisbet and Drury (1967) also report a light movement of birds moving more easterly (066°) over Manomet and the outer Cape toward Nova Scotia.

METHODS

Radar.—We used a short range, high resolution radar designed for ornithological studies. The modified X Band (3 cm) 3 kW peak power marine radar was mounted on a small van. The radar was operated at 0.08 microseconds pulse width for maximum resolution at 27 rpm. The slotted waveguide antenna produced a fan shaped beam 2.5° wide horizontally and 30° wide vertically, measured at the 3 db points. The axis of this beam was angled upward at 30° above the horizontal. The effective range of the radar for small birds was about 0.6 km, for Herring Gulls (*Larus argentatus*) about 1.0 km, and for Canada Geese (*Branta canadensis*) 1.5 km. The great majority of birds we detected were flying at less than 200 m altitude. Birds detected by the radar at greater than 15° angle of elevation produce a spherically distorted track which is recognized and corrected as described in Cohen and Williams (1980); less than 3% of the 1821 tracks we obtained showed this distortion. There appears to be no minimum altitude since we noted during the day that the radar could detect gulls flying just above the surface of Cape Cod Bay.

Data were recorded from the PPI display with a modified Super 8 mm camera which exposes one frame of film per revolution of the radar antenna. The PPI screen was also observed directly and a log was maintained of the direction of movement and time of occurrence of all moving radar echoes. Each track recorded by film consisted of the position of birds at 2.2 s intervals as detected by the constantly rotating radar beam. These points were traced from the films to sheets of white paper and converted to digital x,y coordinates. We then fitted a straight line to the bird track using the method of finding the major axis (Pearson 1901) and computed the direction of movement of the bird (track) and the speed of movement (groundspeed). Direction and speed of the wind at 80 m above sea level (67 m above ground level) were recorded each 30 min from a tower 600 m southeast of the radar. These recorded winds were used to calculate direction of movement of the bird relative to the air mass, i.e., the direction in which the bird's body was aligned (heading) and the speed of movement of the bird through the air (airspeed).

Ceilometer.—Migration was also observed using the ceilometer technique described by Gauthreaux (1969). The observer lay supine about 10 m from the radar looking along the beam of a 100 W narrow beam spotlight with a 20 power telescope. With this technique it was possible to determine the bird's direction of flight through the light beam and the number of migrants seen per hour. We did not attempt to identify birds in their brief flight through the light beam. Gauthreaux (1969) estimates that this technique can detect small passerine birds at altitudes of up to 400 m. Thus, although the area of the light beam is very much smaller than the area surveyed by the radar, the altitude range of the ceilometer technique is somewhat greater.

Mist-netting.—Birds were caught on the grounds of the Manomet Bird Observatory, Manomet, Massachusetts, 5 km SE of the radar site. Fifty standard nylon Japanese mist nets 2.6 m high and 12 m long had four panels, a mesh size of 36 mm (extended) and were tethered along the top. The net lanes used covered a variety of coastal habitats with low vegetation 1–10 m high. Mist nets were run by Observatory staff, except when closed due to inclement weather or temporary shortage of qualified personnel. To allow for trapping effort in total number of birds caught per day, we recorded the number of hours each net was open or closed (one net open for one hour = 1 net-h) and expressed the totals as birds caught per net-h (BPNH). All days recorded between 704 and 784 net-h except the following dates: May 20 (270 n-h), 21 (462 n-h), 22 (245 n-h), and 30 (257 n-h). The greatest effort was expended around the hours of sunrise and sunset. The number of new birds captured each day was determined by subtracting the number of birds banded on previous days and same day repeat captures from the total captures.

Timing of observations.—Simultaneous observations were made from 20–29 May 1976 at Rocky Point, Plymouth, Massachusetts (see Fig. 1). Radar observations were recorded for approximately 1 h between 21:00 and 00:30 (EDST) each night, and 1 h between 02:45 and 05:30 on the mornings of 21, 22, 23, 27, and 29 May. On 24/25 May, due to a malfunction of the radar camera, only the hand-written radar log was available. Ceilometer data were taken for about 1 h between 21:00 and midnight each night.

Banding data from mist-netting were available from 18 May through 30 May with the exception of 23 May.

RESULTS

Overview of migration.—Figure 1 gives the location of the observations and the direction of all tracks recorded from the radar films for evening and morning observations. The majority of the birds we observed appear to have been on tracks between 030° and 060° and would correspond to the edge of the main coastal migration observed by Nisbet and Drury (1967) rather than the offshore movements they observed moving toward 066°. Evening movements involved much larger numbers of birds than did the morning movements. The mean calculated heading for the 1821 tracks we obtained was 019° with an angular deviation of 54° (see Batschlet 1965), and the mean airspeed was 35 km/h with a standard deviation of 12 km/h, suggesting that the majority of birds we observed with radar were passerines. Table 1 gives a breakdown of these data by night.

Table 2 gives the numbers of birds netted for the major groups of migrants. The greatest number of arrivals as determined by netting occurred on the night of 20/21 May, the most prominent species being the Gray Catbird (*Dumetella carolinensis*), Common Yellowthroat (*Geothlypis trichas*), and other warblers, and Rufous-sided Towhee (*Pipilo*

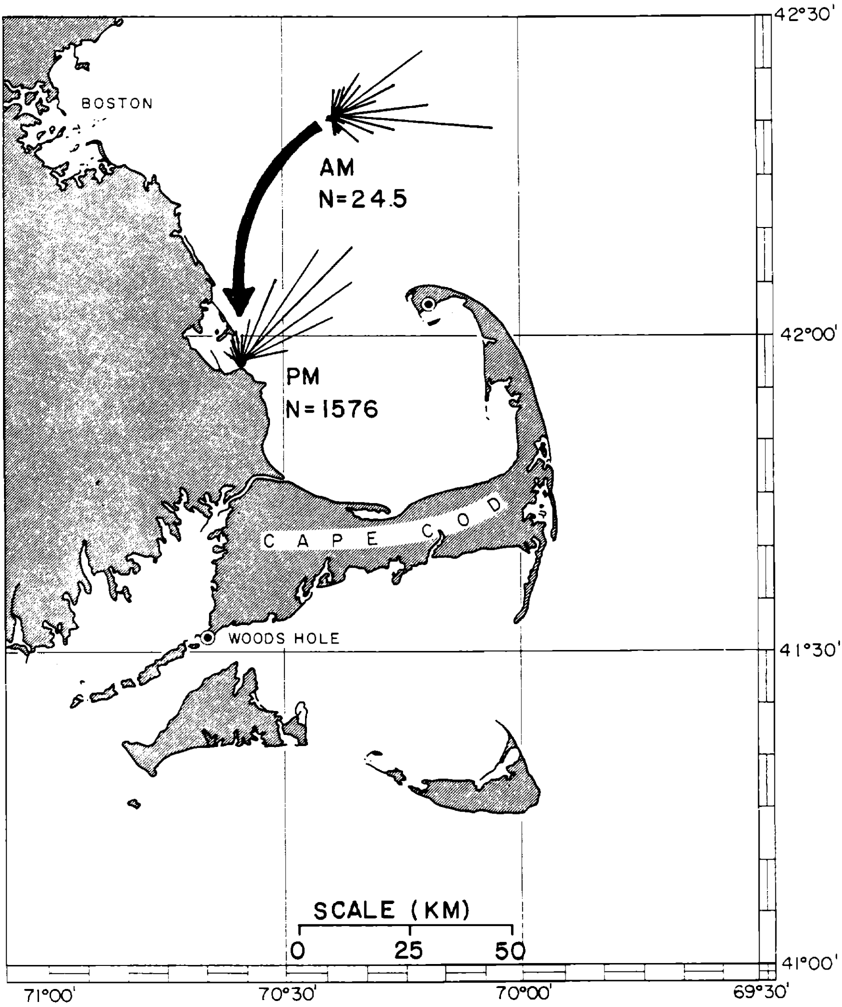


FIGURE 1. Location of observations and distribution of tracks during evening and morning observation periods. Morning observations are offset for clarity. For both histograms the longest bars indicate 17% of the total observed directions.

erythrophthalmus) (see Table 1). Smaller numbers of Swainson's Thrushes (*Catharus ustulatus*) and warblers appeared on 28/29 and 29/30 May.

The weather during our observations was relatively constant (Table 1). Winds were generally from the west to southwest at 26–35 km/h, with clear or partly cloudy skies. On the nights of 24/25 and 25/26 May, the winds shifted to the northeast and the sky was overcast; very light migration was recorded by all methods.

TABLE 1. Radar (film) and weather data.

Date (May 1976)	Time	N	Min. obs.*	N/H	Mean track ± S†	Mean head ± S†	Air speed (km/h) ± SD	Wind dir. (to)	Wind speed (km/h)	Overcast %
20/21	PM	68	58	70	037° ± 48	343° ± 55	36 ± 8	090°	26	60
20/21	AM	28	58	30	092° ± 67	211° ± 74	42 ± 17	065°	29	60
21/22	PM	127	59	129	050° ± 43	003° ± 47	40 ± 9	112°	28	0–30
21/22	AM	77	61	76	085° ± 32	056° ± 52	34 ± 9	110°	29	0–30
22/23	PM	241	56	258	044° ± 24	003° ± 30	40 ± 8	093°	29	20
22/23	AM	16	60	16	084° ± 43	082° ± 67	36 ± 13	090°	35	20
23/24	PM	255	77	199	049° ± 23	004° ± 31	33 ± 8	106°	26	40–60
25/26	PM	4	13	18	307° ± 16	335° ± 21	48 ± 9	231°	23	70–100
26/27	PM	92	61	90	017° ± 56	013° ± 72	35 ± 8	030°	8	100
26/27	AM	96	85	64	073° ± 41	079° ± 66	34 ± 11	070°	26	100
27/28	PM	284	67	254	039° ± 27	020° ± 49	24 ± 10	050°	29	50–30
28/29	PM	218	75	174	041° ± 20	035° ± 40	37 ± 14	046°	35	30
28/29	AM	33	39	51	085° ± 40	105° ± 62	40 ± 15	066°	33	30
29/30	PM	288	125	138	024° ± 43	025° ± 67	33 ± 11	027°	23	85

* Minutes of observation.
† Angular deviation (see Batschlet 1965).

TABLE 2. Daily new banding totals at Manomet Bird Observatory.

	May 1976										
Taxa	20	21	22	24	25	26	27	28	29	30	Total
Flycatchers (Tyrannidae)		3		2				1	4	1	11
Black-capped Chickadee, *Parus atricapillus*	1	1		2		2	1	3	2	1	13
Gray Catbird, *Dumetella carolinensis*	4	62	19	14	9	8	12	15	7	4	154
Thrushes (Turdidae)	1	2	1	12	3	3	4	8	30	5	69
Vireos (Vireonidae)					1	1		1	5	1	9
Wood Warblers (Parulidae)	3	66	14	69	15	14	36	40	53	27	337
Finches (Fringillidae)		1		1		1	2	1	3		9
Sparrows (Emberizidae)		6	2		3	2	2	3	2	2	22
Other taxa	1	4	1	3	3	4			4	2	22
	10	145	37	106	33	35	58	71	110	41	646

Comparison of methods.—Figure 2 gives the numbers of birds recorded per hour (or net-h) for each of the 4 methods with the data from netting referenced to the previous night (PM only) of ceilometer or radar observations. All techniques recorded low migratory activity during the nights of 24/25 and 25/26 May when weather conditions were unfavorable for northerly migration, and all measures showed good migratory activity on 22/23, 23/24, and 27/28 May when conditions were more favorable. There were, however, nights when there were major discrepancies: in particular 20/21 May, a night of only moderate radar activity, when a large number of warblers and catbirds were caught in the next day's netting, and 27/28 May when radar detected the maximum number of birds per hour and netting yielded only average returns the next day. We can find no obvious factors to reconcile the difference between radar observations and netting data (for the night of 20/21 May) unless the arrival of the birds was different in timing from other nights, occurring when the radar was not in operation. For the night of 27/28 May the radar may have detected migrants overflying the area, or species poorly sampled by netting.

The great range in numbers of birds detected on the radar films and netted (as compared with the other measures) suggested the need for non-linear comparison techniques. A Spearman rank-order correlation coefficient matrix was computed for the following variables: number of birds detected per hour with the radar films, radar log, and ceilometer; total bird captures per net-h; new birds captured per net-h; and percent of captures that represented new birds for that day. All 3 nocturnal observation techniques showed insignificant positive correlations with the data from netting; only the correlation of the radar log and percent new birds netted was greater than .50 (rho = .55; P = .077). Birds per

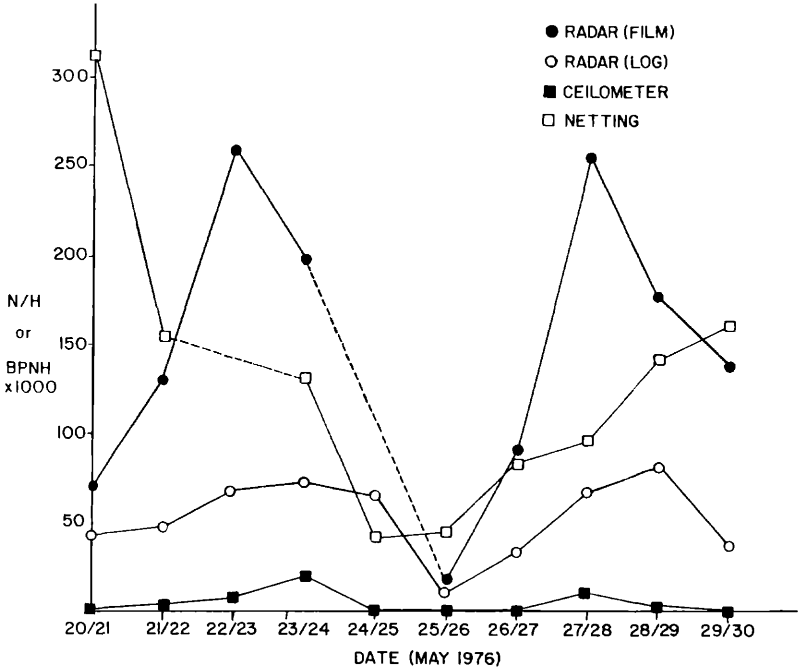


FIGURE 2. Rate of detection of migrants by 4 techniques. Numbers of birds detected per hour of evening observation for the films of radar data, the radar log (visual observation of the screen), and the ceilometer (see text). Numbers of new birds captured per net-hour (×1000) for the day following the radar and ceilometer observations. Solid lines connect successive evening observations and dotted lines connect non-successive observations.

net-h and new birds per net-h were strongly correlated (rho = .97), but neither measure was significantly correlated with percent new birds.

Pairwise correlation of the radar films, radar log, and the ceilometer all gave significant ($P < .01$) Spearman correlations of between .81 and .78. The correlation between the data taken by log vs by film from the radars is of considerable interest as ornithologists frequently have access to small boat radars and if complex recording equipment were not essential, much could be learned from direct observation of the radar screen. In Fig. 3 we plot the log of the number of birds detected by radar (film) vs the number recorded visually in the radar log (Pearson $r = .85$; $P < .01$).

We used a log transform of the radar film data to obtain the linear correlation shown in Fig. 3. The same log transform of radar film data produced the only significant association between netting (percent new birds) and any of the other measures (Pearson $r = .71$; $P < .05$).

The mean directions of migration as determined by the radar and

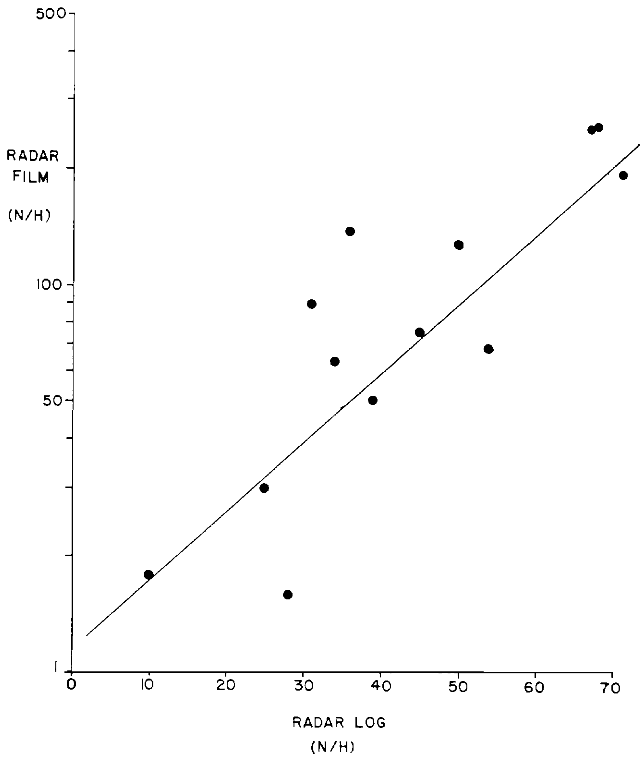


FIGURE 3. Semi-log plot of numbers of birds detected on radar films vs numbers detected visually from the radar screen and recorded in the radar log. Regression equation indicated.

the ceilometer are shown in Fig. 4. These means were compared by standard linear methods as they differed by less than 180° (see Batschlet 1965). The methods are in good agreement: $r = .93$ for the 2 radar methods and $r = .87$ for the radar films and the ceilometer (all $P <$ .01). Perhaps more important than these correlations are the mean differences among the 3 methods. The mean difference between the film and the radar log was 9° with the greatest differences recorded on 2 nights with bimodally distributed tracks (see Fig. 5); omitting these nights, the mean difference was 6°. The mean difference between the radar log and the ceilometer was 16° despite the very low N for the ceilometer data.

Radar observations.—Figure 5 presents histograms of the directions of both tracks and the computed headings with the direction and speed of the winds (data from 25/26 May with only 4 birds observed are omitted). Few studies of bird migration have obtained such a large number of tracks with winds recorded so near the birds. Thus, despite the small

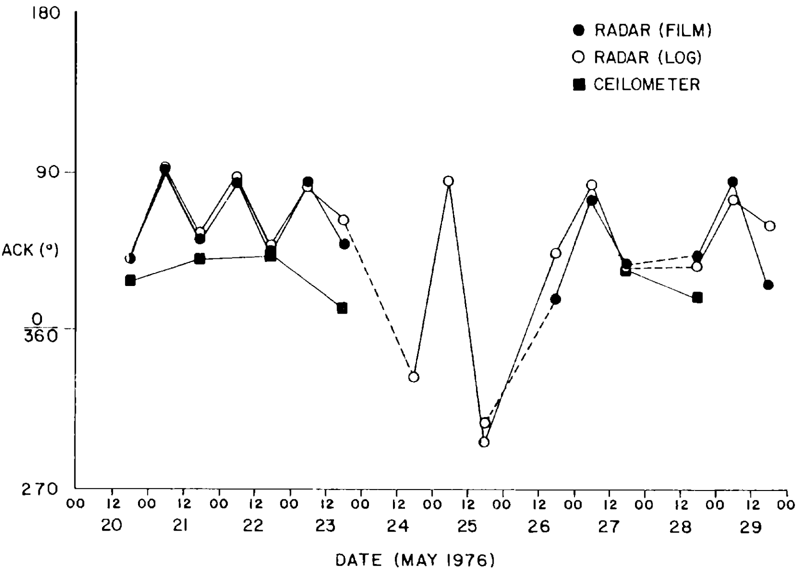
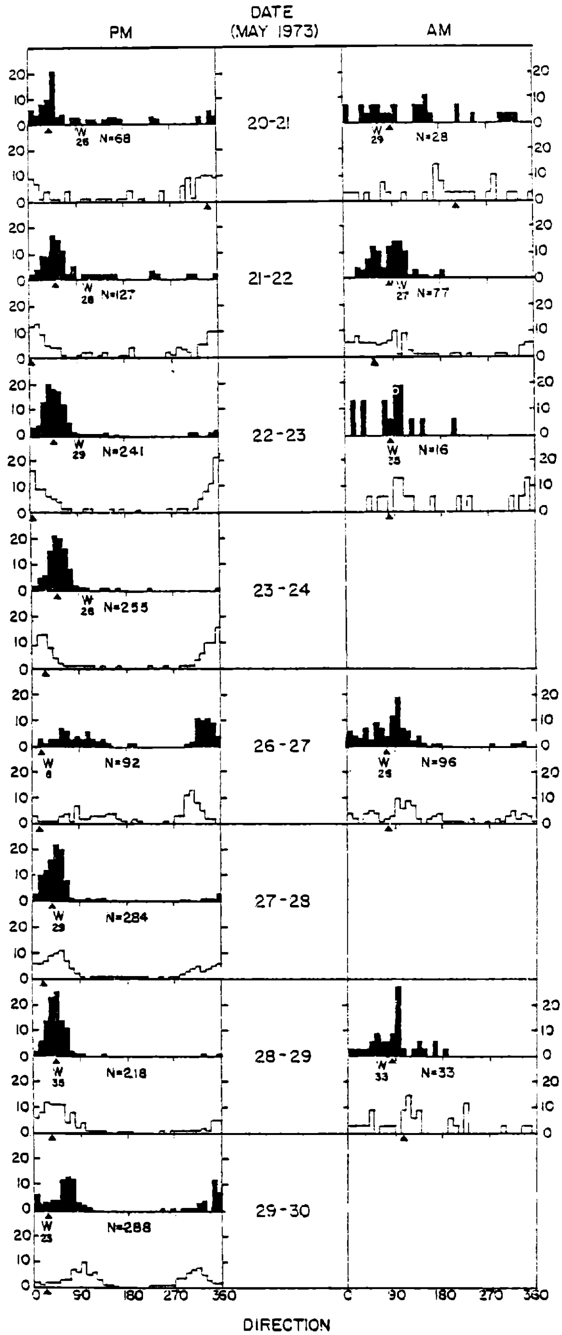


FIGURE 4. Mean track for each period of observation (AM and PM for films of the radar and the radar log and PM only for the ceilometer) for 3 methods of observing nocturnal bird migration. Solid lines connect successive observations and dotted lines connect non-successive observation separated by less than 24 h.

number of nights of observation, calculation of airspeed and heading of these birds may shed some light on the method of orientation they employed.

A striking feature of low altitude nocturnal migration shown in Fig. 5 (PM) is the presence on every night of a clearly defined group of tracks to the northeast. On 26/27 and 29/30 May there is a second group of migrants with tracks to the north (moving along the Massachusetts coast). The mean track of the northeast migrants varies only 13° from 037° to 050°, while winds ranged from 030° to 112° at speeds of between 26 and 35 km/h (see Table 1). Each group of tracks appears matched by a similar group of headings (open histograms) with a similarly shaped distribution. Thus, tightly grouped tracks are not the result of relatively confused birds being blown in one direction by a strong wind; the widely distributed tracks on 26/27 May are matched by widely distributed headings, and the tightly grouped tracks (e.g., the first three nights) are matched by a sharply unimodal distribution of headings.

The birds moving to the northeast were not flying with the wind nor did they appear to be maintaining a constant heading regardless of wind conditions as has been suggested for birds moving over the Atlantic Ocean (Williams et al. 1977, Williams and Williams 1978). When the wind was toward the northeast, headings and tracks were both to the


PM
DATE (MAY 1973)
AM
20-21
N=68
N=28
21-22
N=127
N=77
22-23
N=241
N=16
23-24
N=255
26-27
N=92
N=96
27-28
N=284
28-29
N=218
N=33
29-30
N=288
DIRECTION

northeast (27/28 and 28/29 May). When winds were toward the east (first 4 nights), headings shifted to the north, and when winds were toward the north (26/27 and 29/30 May), headings of the northeast migrants were to the east or southeast. Thus, these birds appeared to be adjusting their heading to maintain a northeast track under differing wind conditions.

What of the second population of birds, those moving north along the Massachusetts coast on 26/27 and 29/30 May? Correction for wind drift would also account for their behavior if we assume that their goal was to move north rather than northeast. On the same nights that birds moving northeast were heading to the east of their tracks due to winds blowing to the north-northeast, birds moving north-northwest were heading to the west of their tracks.

Compensation for wind drift was not complete. Regression of mean PM track direction on wind direction in Fig. 5 gives a slope of 0.28 (r = .84, $P < .01$).

Morning observations are in sharp contrast to the evening observations. Except for 21/22 May AM, both track and heading were widely scattered. The mean flight direction was downwind except 21/22 May, but caution must be used in interpreting these means due to the large angular deviation. These results could be due to contamination of the migrant data with observations of gulls or other coastal birds moving to their feeding areas, or we were observing the behavior of migrants preparing to land after a night's migration. On the morning of 21/22 May we apparently observed the continuation of the nocturnal migratory pattern into the morning hours.

Both Figs. 1 and 5 clearly show a clockwise shift in track and heading between the evening and morning observations. The shift is similar in magnitude and direction to that reported for autumnal migrants moving off the eastern coast of North America (see Richardson 1978). That this shift is not entirely due to downwind flight is suggested by the single data point taken from the radar log on the morning of 25/26 May when the mean track was 84° and the wind was blowing toward 227°. Further observations will be needed to support this point.

DISCUSSION

The radar films, radar log, and the ceilometer all showed good correlations for the number of birds detected. These measures all gave poor correlations with data from netting, the most promising measure being the percent of new birds netted showing a marginally significant

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FIGURE 5. Distributions of heading and track from radar film data for each night, divided into evening and early morning observations. Closed histograms indicate the observed tracks; open histograms indicate calculated heading. W indicates direction the wind was blowing toward; wind speed in km/h is indicated below the W. Solid triangle below histogram indicates vector mean of directions.

correlation. Gauthreaux (1970) has compared the ceilometer technique with long range radar observations and also reported a logarithmic relation for numbers of birds. Nisbet and Drury (1969) compared netting with watching birds across the full moon and also found discrepancies for autumnal migrants moving southeast over Massachusetts.

Lindgren and Nilsson (1975) compared observations of Scandinavian nocturnal migrants with a light beam, a long range surveillance radar, ground counts of species abundance, and netting results. Surprisingly they report "No agreement between the ringing figures and the ground counts." This extreme disparity is certainly not the case at Manomet, but although netting returns are the only way to reliably distinguish new birds, ground counts may prove to be a better indicator of migrant activity. The relative worth of the 2 methods will probably depend upon local habitat and the predominant migrant species. Lindgren and Nilsson report good agreement between directions as observed with the radar and with the ceilometer but less good agreement between the numbers as estimated by the 2 techniques. This is not surprising since the radar they used could not distinguish birds at different altitudes nor distinguish individual tracks.

The mean directions of migration as determined by the 3 observational techniques we used were well correlated and showed a mean angular difference on the order of 10°. Thus, we urge ornithologists to use the ceilometer technique and direct visual observation of the readily available marine radars on small boats to determine the direction and numbers of nocturnal, low altitude migrants. Analysis of radar data from films is time consuming and expensive (analysis of 9 nights reported here required more than 1000 man-h plus computer time).

Our observations of compensation for wind drift by spring migrants in this area are the first such data based on wind velocities measured near the migrants. Nisbet and Drury (1967) drew similar conclusions from 85 nights of observation but estimated geostrophic winds over the area. Both studies found incomplete compensation for wind drift. Nisbet and Drury (1967) suggested that this phenomenon might be due to pseudodrift (in which migrants with differing optimal track directions take off selectively dependent upon wind direction). Our data support their hypothesis; if we consider the northeast and northwest migrants as distinct populations, the proportion of migrants in each direction appears to shift as predicted with wind direction (more northwestward tracks in northward winds and more northeastward tracks in eastward winds).

SUMMARY

Observations of nocturnal bird migration with a short range, high resolution search radar and with a ceilometer light beam were compared with the next day's captures of birds in mist nets. Correlations of the numbers of birds detected per hour by radar or the light beam with netting results were insignificant except for the percent of birds cap-

tured which were previously unbanded giving a significant ($P < .05$) correlation with the log transform of the data recorded from the radar by film.

Data were recorded from the radar screen by visual observation and by a film record which was later analyzed by computer. Both radar methods and the ceilometer are strongly correlated for both numbers of birds detected and direction of movement. Direct visual observation of short range radars such as marine radars may thus be a useful tool in ornithological research.

During 9 nights of observation in late May, the principal direction of migration was toward the northeast on the western shore of Cape Cod Bay, Massachusetts. Comparison of heading and track of these birds with winds recorded continuously within 1 km of the birds suggested that these migrants were compensating for wind drift by altering their heading.

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