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SEASONAL SHIFTS IN THE EFFECTS OF WEATHER ON THE VISIBLE MIGRATION OF RED-TAILED HAWKS AT HAWK MOUNTAIN, PENNSYLVANIA, 1992–1994

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ABSTRACT.— We used hourly counts of Red-tailed Hawks (*Buteo jamaicensis*) migrating at Hawk Mountain during the autumns of 1992, 1993, and 1994, to examine the possibility that the extent to which time of day and local weather parameters affected the numbers of birds seen at the site varied over the course of autumn migration. Data were analyzed separately for early-, mid-, and late-season periods of migration. High versus low winds, following versus opposing winds, low versus high relative humidity, and high versus low barometric pressure were associated with increased hourly passage rates of Red-tailed Hawks. Relative humidity had a greater effect during early-season migration. Wind speed and wind direction had greater effects during late-season migration. We suggest that shifts in the extent to which weather affects the numbers of Red-tailed Hawks seen at Hawk Mountain Sanctuary result from seasonal shifts in the species' dependence on thermal- versus slope-soaring. *Received 6 March 1996, accepted 20 Nov. 1996.*

Counts of migrating raptors at traditional raptor these sites suggest that time of day and local weather are associated with changes in the numbers of raptors counted at these sites (Haugh 1972, Kerlinger 1989). The extent to which such associations vary over the course of autumn migration—a period of considerable seasonal change in weather—remains unstudied.

In eastern North America, many Red-tailed Hawks (*Buteo jamaicensis*) breeding in northern areas migrate south each autumn. Migration begins in August and ends in December (Bednarz et al. 1990, Preston and Beane 1993). At Hawk Mountain Sanctuary, counts of several thousand Red-tailed Hawks (55 years [1934–1991] $\bar{x}$ = 3231 ± 19.0 [SE]) peak in late October or early November each year (Allen et al. 1996).

Haugh (1972) found that northerly winds, low temperatures, decreasing humidity, and increasing barometric pressure were associated with high counts of Red-tailed Hawks migrating past Hawk Mountain Sanctuary. Titus and Mosher (1982) reported that Red-tailed Hawks migrating through the region were affected by wind direction, wind speed, temperature, and day of year. Brinker and Erdman (1983) reported that Red-tailed Hawks migrating in Wisconsin were affected by wind drift (i.e.,

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more birds were pushed to the shores of Lake Michigan during westerly winds).

Here, we use Hawk Mountain count data collected during 1992, 1993, and 1994, to (1) document the extent to which time of day, wind direction, wind speed, relative humidity, and barometric pressure affect hourly counts of Red-tailed Hawks at the site and (2) examine the extent to which such effects shift over the course of autumn migration. We discuss our results in terms of seasonal changes in weather during autumn migration.

METHODS

Migrating raptors have been counted at Hawk Mountain, eastern Pennsylvania (40°58′N, 75°59′W at 464 m ASL), since 1934. Currently, hourly counts are conducted each day (weather permitting) between 15 August and 15 December. Except when precipitation interrupts the count, coverage begins at 08:00 and ends at 17:00 EST (Bednarz et al. 1990, Allen et al. 1996).

Staff and volunteers recorded the numbers of Red-tailed Hawks flying past the Sanctuary from 15 August to 15 December in 1992, 1993, 1994. Hourly records of wind direction and wind speed, the latter using the Beaufort scale (Lincoln et al. 1982) also were recorded. Barometric pressure (mm Hg) and relative humidity (measured every three hours) were obtained from the National Weather Service Station at the Lehigh Valley Airport in Allentown, Pennsylvania, 34 km east of the site (NOAA 1992, 1993, 1994).

We analyzed data collected between 14 September and 28 November each year, the period during which 98% of all Red-tailed Hawks counted at the site between 1934 and 1986 were recorded (Bednarz et al. 1990). We divided this period into three relatively equal periods of 25–26 days each (14 September to 8 October, 9 October to 2 November, and 3 November to 28 November, i.e., early-, mid-, and late-season, respectively).

We considered winds of 20 km/h and above to be high winds, and classified wind direction as "following" (i.e., tail-winds from the WNW, NNW, NW, N, NNE, NE, ENE, or E) versus "opposing" (i.e., head-winds from the W, WSW, SW, SSW, S, SSE, SE, ESE), variable, or none. We classified relative humidity and barometric pressure as either high (all values above the above the median; i.e., $>68\%$, >754 mm, respectively) or low (all values below the median; i.e., $\leq 68\%$, and ≤ 754 mm, respectively).

We modeled hourly counts of Red-tailed Hawks seen between 08:00 and 17:00 EST using SAS generalized linear model (Proc GLM) one-way and two-way ANOVAs in which the main effects consisted of a single weather parameter or hour (one-way ANOVAs) or a single weather parameter or hour and time of season and their interaction term (two-way ANOVAs) (SAS Institute 1988). Although hourly counts used in our analyses are not temporally independent, substantial hour-to-hour variability in the count data suggest considerable independence, overall.

Results were considered significant when analyses yielded probabilities of less than 0.05.

RESULTS

In 1992, 1993, and 1994, 2984, 3582, and 4140 Red-tailed Hawks, were counted at Hawk Mountain Sanctuary between 14 September and 28 November, during 602, 518, and 633 h of observation, respectively. Significant shifts in hourly counts of Red-tailed Hawks migrating past the site were associated with time of day, wind direction, wind speed, relative

TABLE 1

ONE- AND TWO-WAY ANALYSIS OF VARIANCE FOR HOURLY COUNTS OF MIGRATING RED-TAILED HAWKS AT HAWK MOUNTAIN, PENNSYLVANIA, 1992–1994

Model and source of variation	df	Sum of squares	Mean square	*F*-test	*P*
Model hour					
Hour	8	6394	799	3.37	0.0008
Model wind speed					
Wind speed	1	7285	7285	30.8	<0.0001
Model wind direction					
Wind direction	1	14,892	14,892	64.4	<0.0001
Model relative humidity					
Relative humidity	1	8206	8206	34.9	<0.0001
Model barometric pressure					
Barometric pressure	1	6194	6194	26.2	<0.0001
Model hour and time-of-season					
Hour	8	6828	853	3.66	0.0003
Time-of-season	2	26,445	13,222	58.8	<0.0001
Interaction	16	4484	280	1.25	0.22
Model wind speed and time-of-season					
Wind speed	1	6300	6300	28.2	<0.0001
Time-of-season	2	21,912	10,956	49.1	<0.0001
Interaction	2	2678	1338	6.00	0.0025
Model wind direction and time-of-season					
Wind direction	1	13,799	13,799	64.0	<0.0001
Time-of-season	2	27,421	13,710	63.6	<0.0001
Interaction	2	8113	4056	18.8	<0.0001
Model relative humidity and time-of-season					
Relative humidity	1	7563	7563	34.1	<0.0001
Time-of-season	2	22,371	11,185	50.4	<0.0001
Interaction	2	4088	2044	9.21	<0.0001
Model barometric pressure and time-of-season					
Barometric pressure	1	1539	1539	6.76	<0.0001
Time-of-season	2	22,146	11,073	48.7	<0.0001
Interaction	2	427	213	0.94	0.39

humidity, and barometric pressure (Table 1). Numbers of migrating Red-tailed Hawks increased around mid-day, were higher during periods of high versus low wind speeds, higher during following versus opposing winds, higher during low versus high relative humidity, and higher during high versus low barometric pressures (Fig. 1).

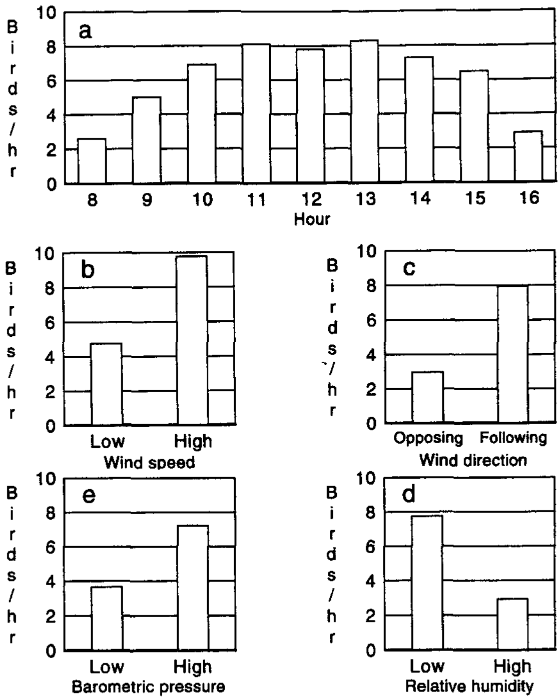

FIG. 1. Numbers of Red-tailed Hawks counted per hour of observation, 14 Sept.–28 Nov., 1992–1994, at Hawk Mountain Sanctuary, as a function of time (E.S.T) (a), low versus high wind speed (b), opposing versus following wind (c), low versus high relative humidity (d), and low versus high barometric pressure (e). See text for details regarding categories of weather parameters.

Our second series of analyses indicate significant interactions between time of season and wind direction (with a greater effect later in the season [i.e., ratios of counts on following versus opposing winds of 1.99:1, 2.24: 1, and 3.12:1, during early, mid-, and late-season migration periods, respectively]), wind speed (with a greater effect later in the season [i.e., ratios of counts on low versus high winds of 1.26:1, 2.43:1, and 1.79:1, during early, mid-, and late-season migration periods]), and relative humidity (with a greater effect early in the season [i.e., ratios of counts during low versus high relative humidities of 4.77:1, 1.99:1, and 2.62:1, during early, mid-, and late-season migration periods]) but not between time of season and time of day or barometric pressure (Table 1; Fig. 2).

DISCUSSION

Evidence suggests that some species of birds vary their migratory behavior depending upon time of season (cf. O'Reilly and Wingfield 1995).

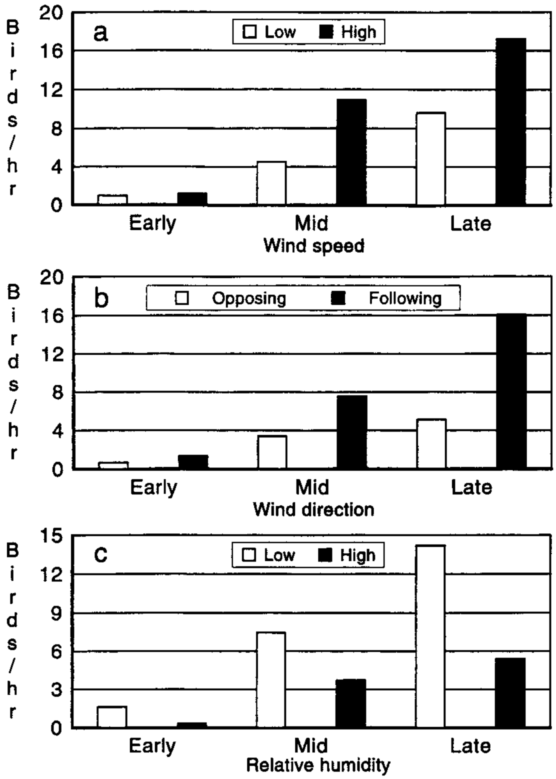

FIG. 2. Numbers of Red-tailed Hawks counted per hour of observation, 14 Sept.–28 Nov., 1992–1994 at Hawk Mountain Sanctuary as a function of wind speed (a), wind direction (b), and relative humidity (c) during early season (15 Sept.–8 Oct.) mid season (9 Oct.–2 Nov.), and late season (3–28 Nov.) migration periods. See text for details regarding categories of weather parameters.

Our results indicate that this may be true for Red-tailed Hawks migrating past Hawk Mountain Sanctuary.

Red-tailed Hawks typically engage in energy-saving slope and thermal soaring while migrating (Kerlinger 1989). An analysis of Hawk Mountain data from 1934 through 1991 (Allen et al. 1996) revealed that counts of Red-tailed Hawks increase significantly during the two days following the passage of cold fronts. At such times, temperatures moderate, fair skies reappear, following winds frequently occur, and thermals begin to form—the latter, especially, in August and September (Miller 1976).

At Hawk Mountain, Red-tailed Hawks migrate from mid September to late November (Bednarz et al. 1990), a period of considerable change in

TABLE 2

MEAN DAILY TEMPERATURES AND AMOUNTS OF DAYLIGHT HOURS AT ALLENTOWN, PENNSYLVANIA, DURING EARLY, MID AND LATE SEASON AUTUMN MIGRATION OF RED-TAILED HAWKS AT HAWK MOUNTAIN SANCTUARY, 1992–1994

	Period of autumn migration		
	Early[a]	Mid	Late
Hours of daylight[b]	11:57 ± 19.6	10:54 ± 18.6	9:56 ± 15.1
Mean daily temperatures (°C)	16.6 ± 1.63	10.8 ± 1.50	5.85 ± 1.60

[a] Early season = 14 Sept.–8 Oct.; Mid season = 9 Oct.–2 Nov.; late season 3–28 Nov.
[b] Hours of daylight and mean daily temperatures are from local climatological data monthly summary, Allentown, Pennsylvania. (NOAA 1992–1994).

weather patterns in the region (Miller 1976). Decreasing day length and solar azimuths combine to produce lower temperatures as the season progresses (Table 2), as well as fewer and less-powerful thermals relative to earlier in the season (Kerlinger 1989). In Pennsylvania, average daily temperatures drop 15°C between September ($\bar{x}$ = 17°C) and November ($\bar{x}$ = 2°C) (Cuff et al. 1989).

We have demonstrated that the extent to which Red-tailed Hawks respond to decreasing relative humidity declined over the migratory period, while their responses to wind direction and speed increased. Decreases in relative humidity, typically, are associated with the thermal-producing, fair-weather period that follows the passage of cold fronts at the site (Miller 1976). On the other hand, strong winds from the northwest produce ideal conditions for slope soaring along the southwest-to-northeast oriented ridge at Hawk Mountain (Brett 1991).

We believe seasonal differences in the way Red-tailed Hawks respond to environmental variables reflect a shift in migratory behavior from thermal to slope soaring, as conditions for the former decline during autumn, while those for the latter continue. A shift from thermal soaring to flapping flight in the second half of the autumn migratory season has been reported for the Levant Sparrowhawk (*Accipiter brevipes*) in Israel (Stark and Liechti 1993). The extent to which other species of raptors change their flight behavior over the course of autumn and spring migration remains an unexplored topic.

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LITERATURE CITED

ALLEN, P. E., L. J. GOODRICH, AND K. L. BILDSTEIN. 1996. Within- and among-year effects of cold fronts on migrating raptors at Hawk Mountain, Pennsylvania, 1934–1991. Auk 113:329–338.

BEDNARZ, J. C., D. KLEM, L. J. GOODRICH, AND S. E. SENNER. 1990. Migration Counts of raptors at Hawk Mountain Sanctuary, Pennsylvania, as indicators of population trends, 1934–1986. Auk 107:96–109.

BRETT, J. J. 1991. The mountain and the migration. Cornell Univ. Press, Ithaca, New York.

BRINKER, D. F. AND T. C. ERDMAN. 1983. Characteristics of autumn Red-tailed Hawk migration through Wisconsin. P 107–136 *in* Proceedings of the Hawk Migration Conference IV, Hawk Migration Association of North America (M. Harwood, ed.). Hawk Migration Association of North America, Lynchburg, Virginia.

CUFF, D. J., W. J. YOUNG, E. K. MULLER, W. ZELINSKY, AND R. E. ABLER. 1989. The atlas of Pennsylvania. Temple Univ. Press, Philadelphia, Pennsylvania.

HAUGH, J. R. 1972. A study of hawk migration in eastern North America. Search 2:1–60.

KERLINGER, P. 1989. Flight strategies of migrating hawks, University of Chicago Press, Chicago, Illinois.

LINCOLN, R. J., G. A. BOXSHALL, AND P. F. CLARK. 1982. A dictionary of ecology, evolution and systematics. Cambridge Univ. Press, Cambridge, England.

MILLER, A. 1976. Meteorology. C. E. Merrill Co., Columbus, Ohio.

NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION. 1992–1994. Local climatological data, monthly summary, Allentown, Pa. National Oceanic and Atmospheric Administration, National Climatic Data Center, Asheville, North Carolina.

O'REILLY, K. M. AND J. C. WINGFIELD. 1995. Spring and autumn migration in Arctic shorebirds: same distances, different strategies. Am. Zool. 35:222–233.

PRESTON, C. R. AND R. D. BEANE. 1993. Red-tailed Hawk (*Buteo jamaicensis*). *In* Birds of North America, No. 52 (A. Poole and F. Gill, eds.). The Academy of Natural Sciences, Philadelphia, Pennsylvania; The American Ornithologists' Union, Washington, D.C.

SAS INSTITUTE. 1988. SAS/STAT user's guide, release 6.03 edition. SAS Institute, Cary, North Carolina.

STARK, H. AND F. LIECHTI. 1993. Do Levant Sparrowhawks *Accipiter brevipes* also migrate at night? Ibis 135:233–236.

TITUS, K. AND J. A. MOSHER. 1982. The influence of seasonality and selected weather variables on autumn migration of three species of hawks through the central Appalachians. Wilson Bulletin 94:176–184.