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WITHIN- AND AMONG-YEAR EFFECTS OF COLD FRONTS ON MIGRATING RAPTORS AT HAWK MOUNTAIN, PENNSYLVANIA, 1934-1991

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ABSTRACT.—Cold-front passage has long been associated with south-bound raptor migration in northeastern North America. We used Hawk Mountain Sanctuary's 55-year database to calculate abundance indices of 14 raptor species at the site. These indices, together with data taken from coincidental U.S. Department of Commerce daily weather maps, were used to investigate the extent to which raptor migration at Hawk Mountain is associated with the passage of cold fronts. Daily abundance indices for 12 of 14 raptor species exhibited significant increases during one or more of the three days following frontal passage. Three basic patterns emerged, which differed in the number of days after frontal passage on which peak migration occurred. The patterns fit the flight behavior of the species involved. We failed to detect a long-term linear trend in numbers of fall-season cold fronts at the site. Stepwise multiple-regression analyses revealed that annual-abundance indices were not influenced by annual variation in the numbers of cold fronts passing the Sanctuary at the time of fall migration. Overall, our analyses confirm the results of earlier, short-term studies demonstrating within-year effects of frontal passage on raptor migration. Our failure to detect among-year effects of frontal passage rates on annual counts of raptors migrating past the site supports the notion that cold fronts enhance fall migration rather than simply making the birds more visible to observers at such times by forcing them closer to the watch site. *Received 6 December 1994, accepted 25 April 1995.*

IN NORTH AMERICA, many diurnal raptors (order Falconiformes) aggregate during migration along prominent topographical features, including coast lines and mountain ridges (Haugh 1972). Raptors are thought to concentrate along such "leading lines" (sensu Geyr von Schweppenburg 1963:192) because: (1) better flight conditions exist there; (2) adjacent areas provide less favorable habitats; (3) such features orient the birds; or (4) some combination of these factors benefits the birds (Broun 1948, Williamson 1962, Mueller and Berger 1967a, Alerstam 1990).

Long-term monitoring of raptor migration dates from the early 1930s, when counts were initiated at Hawk Mountain Sanctuary in the central Appalachians of eastern Pennsylvania (Broun 1935, 1948), and at Cape May Point at the southern tip of coastal New Jersey (Allen and Peterson 1936). Similar efforts began in Europe shortly thereafter (Rudebeck 1950, Ulfstrand 1958). Migration counts conducted at watch sites along leading lines have been used to study the behavior of migrating raptors (e.g. Kerlinger 1989, Bednarz et al. 1990), as well as to indicate long-term trends in population sizes (e.g. Spofford 1969, Hackman and Henny 1971, Hussell 1985, Bednarz et al. 1990, Fuller and Titus 1990). However, the validity of population-trend analyses has been questioned by some researchers, who cite confounding factors, including a lack of standardized data collection among years, unaccounted-for variation in observer ability and fatigue, a bias towards low-flying migrants, a potentially high proportion of uncounted birds, a disproportionate impact of exceptional single-day flights on annual totals, and weather effects (e.g. Hussell 1981, Kochenberger and Dunne 1985, Sattler and Bart 1985, Kerlinger 1989, Bednarz et al. 1990). Of these, within- and among-season variation in weather is one of the more frequently discussed confounding effects (e.g. Mueller and Berger 1961, 1967b, Broun 1963, Haugh 1972, Alerstam 1978, Kerlinger 1989, but see Hussell 1985).

The consensus in the migration literature is that during fall migration, large flights of raptors (and many nocturnal passerine migrants; Alerstam 1990) typically occur one or two days

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after the passage of a cold front, when northwesterly winds force dry polar air southward (e.g. Trowbridge 1895, 1902, Stone 1922, Allen and Peterson 1936, Mueller and Berger 1961, Haugh 1972, Hall et al. 1992). The phenomenon is especially pronounced in northeastern North America, where the passage of cold fronts is somewhat more frequent than elsewhere on the continent (e.g. Able 1973, Millsap and Zook 1983).

Atmospheric conditions change rapidly once a cold front passes through an area (Alerstam 1990). In eastern Pennsylvania, strong northwesterly ground winds, decreasing temperatures, clouds and, often, precipitation, usually co-occur with the passage of a front. Within one to three days, winds—at least those near ground level—typically subside, temperatures increase, fair skies reappear, and thermals begin to form; thermals develop especially in August and September (Miller 1976). The reasons for increased migration at such times remain unclear (cf. Haugh 1972). The passage of cold fronts often is associated with shifts in several weather parameters, including barometric pressure, relative humidity, temperature, wind speed, wind direction, and atmospheric stability (McIlveen 1992). Some researchers have suggested that one or more of these factors, particularly wind, might be the proximate trigger for raptor migration rather than the fronts themselves (Haugh 1972, Able 1973, Alerstam 1990, but see Millsap and Zook 1983).

Although many investigators have implied that frontal passage actually enhances fall migration, others have contended that migrants are simply more visible at such times, either because they are diverted longitudinally from broad, frontal migrations toward leading lines, or because they are diverted downward from high-altitude thermal soaring to low-altitude slope soaring (cf. Murray 1964, Millsap and Zook 1983, Kerlinger and Gauthreaux 1984). Whether one or both of these hypotheses is true has important implications for the use of migration watch-site counts to monitor long-term changes in raptor populations.

If, for example, frontal passage enhances raptor migration, annual variation in the frequency of these events should not affect the magnitude of annual counts at individual watch sites, but only the timing of migration movements within years. However, if frontal passage only diverts raptors that are already aloft, either longitudinally or altitudinally—thereby making the birds more visible to counters at traditional watch sites—then annual variation in frontal passage could affect the magnitude of annual counts and their validity as long-term monitors of population change. Of course, it is possible that fronts function both to enhance migration and to divert migrating raptors.

Fall raptor migration has been monitored at Hawk Mountain Sanctuary almost continually since September 1934. The resulting long-term database provides an opportunity to examine the effects of frontal passage on the migration of 14 species of diurnal raptors that regularly use the Appalachian Mountain migration corridor (Brett 1991). Here, we use paired 55-year weather and raptor-migration databases to determine the extent of within- and among-year associations between frontal passage and the magnitude of raptor migration at Hawk Mountain Sanctuary. We use our analyses to examine whether the passage of cold fronts (1) enhances raptor migration, or whether it only (2) increases raptor sightings, either by crowding raptors longitudinally along leading-line watch sites, or by decreasing the altitude at which raptors migrate past such sites. Detecting an effect of frontal passage on the numbers of raptors sighted within years, while at the same time failing to detect an effect of frontal passage rates among years, would support the first hypothesis. Detecting both within- and among-year effects would support the second hypothesis. We discuss our results in terms of using watch-site migration counts to assess long-term trends in regional populations of migratory raptors.

METHODS

Migration counts.—Hawk Mountain Sanctuary, Pennsylvania (40°38′N, 76°59′W), and its raptor migration are described in Brett (1991). With the exception of the "war years" of 1943–1945, fall migration has been monitored annually at Hawk Mountain's North Lookout since 1934. Since 1935, counts have occurred almost every day each fall between early September and late November. Coverage has expanded in recent years, and counts are now conducted each day (weather permitting), at least from 15 August to 15 December. Binoculars and occasionally telescopes have been used to locate and identify 14 species of migrating raptors (Table 1). Typically, one or two experienced counters recorded each day's flight. In most years, six to eight individuals served as counters. Except when curtailed by precipitation, daily

TABLE 1. Sample periods and hourly rates ($\bar{x}$ ± SE) of passage of 14 species of raptors monitored at North Lookout, Hawk Mountain Sanctuary, 1934-1942 and 1946-1991.

Species	Sample period[a]	Passage rate (birds/h ± SE[b])	Total hours observed[b]
Osprey (*Pandion haliaetus*)	25 Aug-21 Oct	0.81 ± 0.04	21,815
Bald Eagle (*Haliaeetus leucocephalus*)	11 Aug-1 Dec	0.07 ± 0.01	35,200
Northern Harrier (*Circus cyaneus*)	23 Aug-23 Nov	0.37 ± 0.01	32,908
Sharp-shinned Hawk (*Accipiter striatus*)	9 Sep-5 Nov	9.93 ± 0.74	23,036
Cooper's Hawk (*A. cooperii*)	4 Sep-18 Nov	0.48 ± 0.04	29,120
Northern Goshawk (*A. gentilis*)	17 Sep-5 Dec	0.16 ± 0.03	26,568
Red-shouldered Hawk (*Buteo lineatus*)	22 Sep-26 Nov	0.57 ± 0.03	23,680
Broad-winged Hawk (*B. platypterus*)	23 Aug-30 Sep	35.38 ± 2.32	13,902
Red-tailed Hawk (*B. jamaicensis*)	14 Sep-24 Nov	6.52 ± 0.32	27,211
Rough-legged Hawk (*B. lagopus*)	6 Oct-9 Dec	0.03 ± 0.003	19,101
Golden Eagle (*Aquila chrysaetos*)	16 Sep-3 Dec	0.09 ± 0.004	26,878
American Kestrel (*Falco sparverius*)	11 Aug-26 Oct	0.77 ± 0.06	25,061
Merlin (*F. columbarius*)	3 Sep-9 Nov	0.07 ± 0.01	26,720
Peregrine Falcon (*F. peregrinus*)	25 Aug-17 Nov	0.04 ± 0.003	31,059

[a] Based on information collected between 1934-1942 and 1946-1986, and presented in Bednarz et al. (1990).
[b] SE of annual means. Based on data collected between 1934-1942 and 1946-1991.

coverage usually begins at 0800 EST and ends at 1700. Mean hours sampled per day have ranged from a low of 6.8 h/day in 1957 to a high of 8.5 h/day in 1941. Additional details concerning count procedures and the database are in Bednarz et al. (1990).

For our analyses, annual count data were standardized using a species-specific truncation procedure that eliminated 1 to 2% of the total number of birds counted at the extremes of each species' overall temporal distributions between 1935 and 1986 (i.e. birds observed either very late or very early in season; Bednarz et al. 1990). Count data were converted to mean daily and annual passage rates (i.e. numbers of birds/h) by dividing the number of birds sighted each day (or year) by the number of hours of observation during the day (or year). Data for Red-shouldered Hawks and Broad-winged Hawks collected in 1935-1936 were not included in our analyses because of known inaccuracies in the identification of these two species during those years.

Cold fronts.—We determined the passage of cold fronts at Hawk Mountain Sanctuary from U.S. Government synoptic weather maps. For the period 1934 through 1940, our map source was the *Daily Series, Synoptic Weather Maps, Part I, Northern Hemisphere Sea Level* (U.S. Department of Commerce 1934-1940). From 1941 through 1991 our source was the National Oceanographic and Atmospheric Administration's *Daily Weather Map* series (U.S. Department of Commerce 1941-1991). Daily weather maps for different years reflected weather conditions at different times: 1934-1938, weather conditions at 1300 GMT; 1939-1940, 1230 GMT; 1941-1956, 0130 EST; 1957-1967, 0100 EST; and 1968-1991, 0700 EST. Dates of frontal passage were assigned by interpolating daily maps taking these time differences into account.

Cold fronts are large-scale, high-energy, synoptic weather events, resulting from the interaction of adjacent, moving masses of air (Neiburger et al. 1971). Most cold fronts we identified were well-defined systems that had formed in northwestern North America and progressed southeasterly until passing over Hawk Mountain. Fronts that passed within 100 km, but not over Hawk Mountain, were not counted. Cold fronts that appeared or disappeared on successive weather maps over or near eastern Pennsylvania were not recorded as having passed Hawk Mountain, unless they were accompanied by the rapid drops in temperature (>5°C in sequential daily maximums) and strong north or northwest winds (>10 m/s) typically associated with frontal passage. Fronts that became stationary (i.e. those that remained over or within 50 km of Hawk Mountain without moving farther east for more than 24 h) were considered to have passed over the area on the last day they were stationary.

Weather maps were examined for all periods for which fall raptor-migration data were available. All migration data were characterized with regard to the number of days after frontal passage. Coverage of fall migration at Hawk Mountain has expanded in recent years to include all of November and the first half of December; such was not the case before the mid 1960s. Therefore, we restricted our analysis of annual fluctuations in the frequency of frontal passage to data collected between 1 September and 23 November, and eliminated from our interannual analyses data collected in 1934, when continual observations of fall migration began on 30 September.

Statistical analyses.—Data were analyzed using SAS statistical procedures (SAS Institute 1988). Except in the backward stepwise procedure mentioned below, results were considered significant when statistical

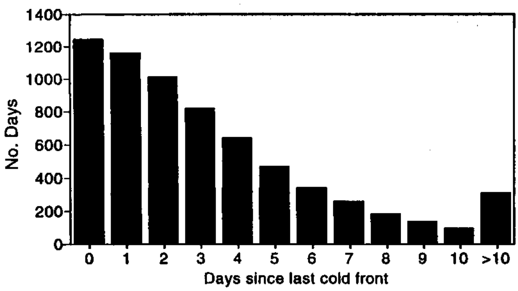


Fig. 1. Distribution of observation days as function of days since passage of most recent cold front.

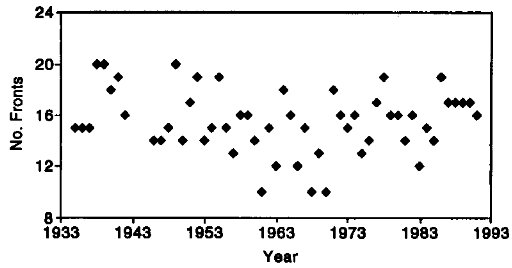


Fig. 2. Numbers of cold fronts passing Hawk Mountain Sanctuary, Pennsylvania from 1 September to 23 November 1934-1991.

analyses yielded a probability of less than 0.05. Experimentwise type I error rates for simultaneous inferences were controlled for using the Bonferroni method (Beal and Khamis 1991). Trends in annual numbers of cold fronts were examined using a Spearman rank correlation.

Because earlier analyses revealed significant differences in numbers of birds counted before, during, and after the widespread use of DDT in North America earlier this century (Bednarz et al. 1990), we also examined variation in the annual numbers of cold fronts passing Hawk Mountain using a SAS generalized linear model (GLM) one-way ANOVA and Tukey's Studentized range tests (Sokal and Rohlf 1981). Years were classified as pre-DDT era (1934-1942), DDT era (1946-1972), and post-DDT era (1973-1991; sensu Bednarz et al. 1990).

Preliminary examinations of residuals associated with regression analyses of daily and annual raptor passage rates suggested that the residuals were not normally distributed and that mean values were positively correlated with variance. Therefore, we log transformed the data using $\mathrm{Ln}(n + 1)$, where n is the mean number of birds/h. We then backtransformed the estimated means to calculate the values reported in the text and accompanying figures, which are estimates of the median of $(n + 1)$ minus 1 (Sokal and Rohlf 1981).

Several analyses were performed to determine the extent of the relationship between the passage of cold fronts and the magnitude of raptor migration. To test for within-year effects, we used a SAS one-way ANOVA model and Tukey's Studentized range tests to examine the relationship between the log-transformed daily passage rates (reported as birds/h) and the numbers of days since passage of the most recent cold front. To test for among-year effects of cold fronts on annual passage rates, we used the following multiple regression models in separate analyses for each species:

$$\mathrm{Ln}(N + 1) = a + b_1Y + b_2Y^2 + b_3Y^3 + b_4Y^4 + cF_1, \quad (1)$$

and

$$\mathrm{Ln}(N + 1) = a + b_1Y + b_2Y^2 + b_3Y^3 + b_4Y^4 + cF_2, \quad (2)$$

where N is the mean annual passage rate, Y is the year, cF_1 is the annual number of cold fronts passing during each species' sample period, cF_2 is the annual number of cold fronts passing during the briefer time period when the central 75% of the individuals of each species passed the site (i.e. the peak migration period for each species), and a, b_1, b_2, b_3, b_4, and c are regression coefficients that differ in the two models. To assess the relative importance of numbers of cold fronts and linear and nonlinear trend terms (i.e. Y variables) in explaining the mean annual passage rates, we used a backward stepwise procedure in which variables with $P < 0.10$ were retained in the model. Significant Y variables would indicate long-term linear or nonlinear trends in bird numbers. A positive and significant cF variable would indicate that cold fronts concentrated birds at Hawk Mountain.

RESULTS

Frontal passage rates.—Although the interval between successive cold fronts ranged from less than 1 day to as many as 26 days, 50% of all cold fronts passed within three days, 75% passed within five days, and 95% passed within 10 days of the previous front (Fig. 1). Total fronts varied considerably among years, ranging from lows of 10 to highs of 20 (Fig. 2). Overall, however, there is no indication of a long-term trend in the numbers of cold fronts passing the site during the 55-year course of the study ($r_s = 0.04$, $P = 0.78$). When we organized the same data into pre-DDT (1935-1942), DDT (1946-1972), and post-DDT (1973-1991) eras, we found a significant difference among eras (one-way ANOVA, $P = 0.039$), with accompanying Tukey's Studentized range tests indicating a significant difference ($P < 0.05$) in numbers of cold fronts annually (1 September–23 November) during the pre-DDT ($\bar{x} = 17.25 \pm$ SD of 2.25) and DDT eras ($\bar{x} = 14.81 \pm 2.69$), but not between either of these eras and the post-DDT era ($\bar{x} = 15.79 \pm 1.84$).

Within-year effects of frontal passage on raptor migration.—Raptors were counted migrating past Hawk Mountain during 36,173 h of observations on 6,725 days between 1934 and 1991. Except for Rough-legged Hawks, all 14 species analyzed showed significant shifts in the magnitudes of their hourly passage rates as a function of frontal passage (Fig. 3). Furthermore, with the exception of Northern Harriers, all species demonstrating significant shifts as a function of frontal passage were seen on the day of the passage of a cold front, or within three days thereafter, significantly more frequently than on the fourth, fifth, or sixth day following frontal passage (Fig. 3).

These 12 species fell into three response groups (Fig. 3). Bald Eagles, Ospreys, and the three falcons (Merlins, Peregrine Falcons, and American Kestrels) all had highest sighting rates on the day of frontal passage (or, in the case of American Kestrels, approximately equal rates on both the day of and day after passage), and all had decreased sighting rates between the day of and four days after frontal passage (Fig. 3). Sightings of migrating Bald Eagles, for example, averaged 44% lower during the two to four days after a cold front than on the day of and the first day after frontal passage. Similar declines were found for Ospreys (−23%), American Kestrels (−49%), Merlins (−52%), and Peregrine Falcons (−48%).

Passage rates for Golden Eagles and the three species of accipiters (Sharp-shinned Hawks, Cooper's Hawks, and Northern Goshawks), although higher on the day of a frontal passage than four days later, all peaked the day after frontal passage, before declining steadily for the next three days (Fig. 3). Sightings of Golden Eagles, for example, averaged 32% lower during the latter period than during the day of and the day after frontal passage. Sightings of Sharp-shinned Hawks (−26%), Cooper's Hawks (−27%), and Northern Goshawks (−24%) exhibited similar declines.

Peak passage rates for the three species of buteos with significant effects were later still, occurring either on days 1 and 2 (Red-shouldered and Red-tailed hawks), or days 2 and 3 (Broad-winged Hawks) following frontal passage. In all three instances, sighting rates on the day of frontal passage were significantly lower than on the day after passage (Tukey's Studentized range tests, $P < 0.05$). As a result, although sighting rates for Red-tailed Hawks declined 18% between the day of and the day after frontal passage and the following three days, rates for Broad-winged Hawks increased 10%, and those of Red-shouldered Hawks remained the same (Fig. 3).

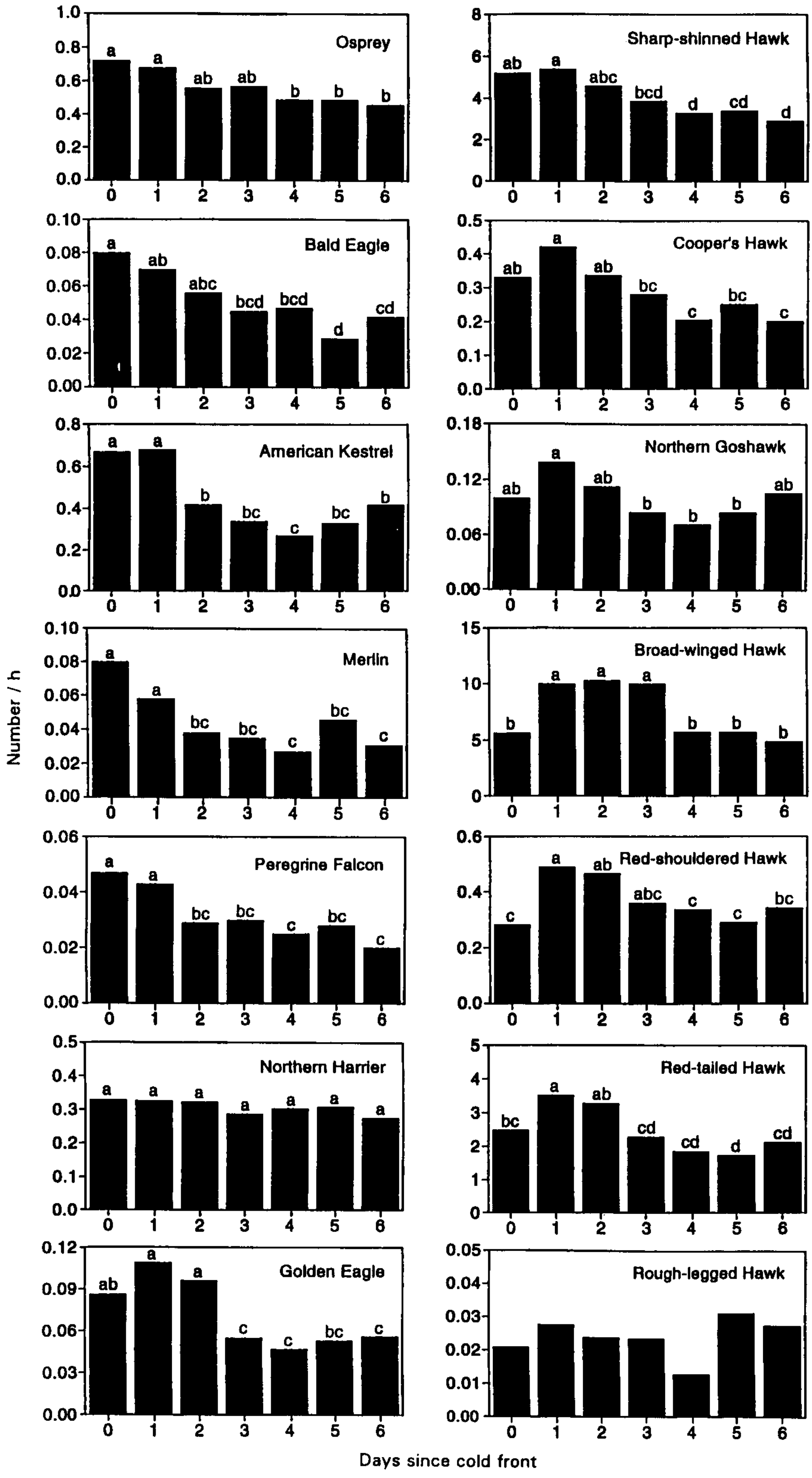
Among-year effects of frontal passage on raptor migration.—Stepwise multiple-regression analyses revealed that there were various linear and nonlinear trends in annual-abundance indices, but that annual deviations from those trends were not significantly influenced by annual variation in the numbers of cold fronts passing the Sanctuary. This was true for both multiple-regression models (see Methods; Table 2).

Discussion

Our analyses demonstrate two major patterns. First, with the exception of Rough-legged Hawks, which are relatively uncommon at the site, our within-year analyses support the widely held hypothesis that frontal passage increases the numbers of raptors sighted at migration watch sites (Fig. 3). Second, our among-year analyses suggest that, in spite of considerable annual variation in numbers of cold fronts passing the Sanctuary each fall, annual counts of raptors at the site are not affected by this variation. These results have important implications for understanding the behavior of migrating raptors, as well as for the use of raptor-migration counts in monitoring long-term fluctuations in populations. We discuss within- and among-year cold-front effects separately below.

Within-year effects.—Our analyses enable us to test the generality of the relationship between frontal passage and raptor migration using more species and a longer time period than in previous studies (for review, see Richardson 1978). We believe the three response patterns we describe result from a combination of rapidly changing weather conditions following the passage of cold fronts and the different aerodynamic capabilities and flight behavior of the different species involved.

Falcons, for example, have long, pointed wings and medium-length tails, whereas accip-


Osprey
Sharp-shinned Hawk
Bald Eagle
Cooper's Hawk
American Kestrel
Northern Goshawk
Merlin
Broad-winged Hawk
Peregrine Falcon
Red-shouldered Hawk
Northern Harrier
Red-tailed Hawk
Golden Eagle
Rough-legged Hawk
Number / h
Days since cold front

iters have short, rounded wings, and long, narrow tails, and buteos have broad wings, and short, broad tails (Brown and Amadon 1968, Dunne et al. 1988). Falcons flap more, and glide and soar less on migration than do accipiters, which in turn flap more, and glide and soar less than do buteos (Kerlinger 1989). The fact that passage rates of each of the nine species within these three anatomically distinct genera (Brown and Amadon 1968) tend to resemble those of their congeners more than those of other species suggests an anatomical basis for the patterns.

Although falcons occasionally soar on migration, they spend much of their time in fast, direct flapping flight, frequently at low altitudes (Dunne et al. 1988, Brett 1991). This style of flight is well adapted to the high-speed, ground-level tail winds that typically occur during the day of frontal passage (Miller 1976). Accipiters, however, fly higher, soar more, and flap less on migration than falcons (cf. Kerlinger and Gauthreaux 1984, 1985, Dunne et al. 1988). Substantial accipiter flights often are associated with westerly or northwesterly winds (Ferguson and Ferguson 1922, Mueller and Berger 1967b, Haugh 1972, Titus and Mosher 1982). Accipiters appear well suited to the lighter, updraft-producing northwesterly winds and weak thermals that typically start the day after frontal passage (Miller 1976).

Buteos, and to a lesser extent the large buteolike Golden Eagle (Brett 1991), soar more on migration and fly higher than do many diurnal raptors (Dunne et al. 1988, Brett 1991). These species are particularly well-suited for flights during the fair weather conditions that occur two to six days after frontal passage (Miller 1976). Buteos passing Hawk Mountain at such times are often migrating in stable or rising temperatures, conditions under which strong, vertical thermals once again begin to form in the area.

Although harrier numbers increased following frontal passage, the effect was not marked (Fig. 3). This suggests that, once individual harriers have begun to migrate, they are less affected by synoptic weather patterns than are other raptor species. Northern Harriers migrate on a broad front in North America (Bildstein 1988) and are less likely to travel along established migratory corridors than other raptors. Harriers engage in more flapping, and less soaring and gliding flight than do many other migrating raptors, and individuals often fly closer to the ground (Haugh 1972), where they use obstructional air currents at the boundary layer to assist their flight. There are numerous reports of harriers flying without regard to weather (Ferguson and Ferguson 1922, Broun 1948, Haugh 1972, Dunne et al. 1988). Such observations suggest the species is less dependent upon the trailing winds and thermals associated with the passage of cold fronts than are other species of migrating raptors.

Counts of several species, most notably the American Kestrel, Northern Goshawk, Red-shouldered Hawk, and Rough-legged Hawk, increased five and six days after the passage of a front over what they had been on day 4 (Fig. 3). Similar patterns have been reported for migrating Sharp-shinned Hawks (Trowbridge 1902, Mueller and Berger 1967b), as well as for nocturnal passerines (Able 1973). Mueller and Berger (1967b) ascribed the phenomenon to birds that had over-reached and flown through a slow-moving or stationary cold front. Another possible explanation for lower numbers on days 4 and 5 following frontal passage is that it represents a depletion in the numbers of birds that were ready to migrate on the preceding front, and that increases in numbers thereafter, but before the next front passes, represent individuals in the population that are then coming into migratory readiness. That three of the five species displaying this pattern—Northern Goshawks, Rough-legged Hawks, and Golden Eagles—are relatively late-season migrants suggests another possibility. Such species may be

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Fig. 3. Per-hour passage rates of 14 species of raptors at Hawk Mountain Sanctuary, Pennsylvania in 1934–1942 and 1946–1991 as function of days since passage of most recent cold front. One-way ANOVAs to determine significance of shifts of numbers of birds/h as function of day since frontal passage yielded probabilities of <0.001 for all species except Northern Harrier (0.0195) and Rough-legged Hawk (0.091). Adjusted Bonferroni probability for 14 simultaneous tests is $P < 0.05/14 = 0.004$. Within species, bars with same letter are not significantly different from one another (Tukey's Studentized range test in association with one-way ANOVA for all species in which the ANOVA probability was <0.05).

TABLE 2. Results of backward stepwise regression analyses (with SLS set at $P < 0.10$)[a] to determine the extent to which annual variation in migratory passage rates of 14 species of raptors seen at Hawk Mountain, Pennsylvania (1935–1942 and 1946–1991) was affected by annual variation in number of cold fronts passing through the region. Two models were used. The first (1) assessed the relationship between annual variation in migration counts and annual variation in frontal passage rates. The second (2) assessed the relationship between annual variation in migration counts and annual variation in frontal passage rates during the period in which the central 75% of a species migrated past the site. Both models were significant for all species ($P < 0.001$).

Model	Significant variables[a]	Model R^2	Cold-front probability
	Osprey[b]		
1	Y, Y^3	0.67	0.36
2	Y, Y^3, cF	0.69	0.05
	Bald Eagle		
1	$\mathbf{Y}, Y^2, \mathbf{Y^3}$	0.56	0.62
2	$\mathbf{Y}, Y^2, \mathbf{Y^3}$	0.56	0.94
	Northern Harrier		
1	$\mathbf{Y}$	0.21	0.53
2	$\mathbf{Y}$	0.21	0.29
	Sharp-shinned Hawk		
1	$\mathbf{Y}, \mathbf{Y^2}, \mathbf{Y^3}, Y^4$	0.57	0.13
2	$\mathbf{Y}, \mathbf{Y^2}, \mathbf{Y^3}, Y^4$	0.57	0.14
	Cooper's Hawk		
1	$\mathbf{Y^2}$	0.64	0.97
2	$\mathbf{Y^2}$	0.64	0.39
	Northern Goshawk		
1	$\mathbf{Y}, \mathbf{Y^3}$	0.33	0.65
2	$\mathbf{Y}, \mathbf{Y^3}$	0.33	0.11
	Red-shouldered Hawk		
1	$\mathbf{Y}, \mathbf{Y^3}, \mathbf{Y^4}$	0.32	0.70
2	$\mathbf{Y}, \mathbf{Y^3}, \mathbf{Y^4}$	0.32	0.88
	Broad-winged Hawk		
1	$Y, \mathbf{Y^2}, Y^3$	0.31	0.11
2	$Y, \mathbf{Y^2}, Y^3, cF$	0.37	0.04
	Red-tailed Hawk		
1	$\mathbf{Y}, Y^2, \mathbf{Y^3}$	0.43	0.55
2	$\mathbf{Y}, Y^2, \mathbf{Y^3}$	0.43	0.79
	Rough-legged Hawk		
1	$\mathbf{Y}, Y^3$	0.23	0.94
2	$\mathbf{Y}, Y^3$	0.23	0.52
	Golden Eagle		
1	Y, Y^2, Y^4	0.29	0.55
2	Y, Y^2, cF	0.30	0.05
	American Kestrel		
1	$\mathbf{Y}, \mathbf{Y^2}, Y^3$	0.66	0.85
2	$\mathbf{Y}, \mathbf{Y^2}, Y^3$	0.66	0.59
	Merlin		
1	$Y, \mathbf{Y^3}, \mathbf{Y^4}$	0.60	0.37
2	$Y, \mathbf{Y^3}, \mathbf{Y^4}$	0.60	0.37
	Peregrine Falcon		
1	$\mathbf{Y}, \mathbf{Y^3}, \mathbf{Y^4}$	0.57	0.84
2	$\mathbf{Y}, \mathbf{Y^3}, \mathbf{Y^4}$	0.57	0.44

[a] Y = year, cF = number of cold fronts (see Methods for details). Variables with SLS (significant level of stay) ≤ 0.10, without Bonferroni adjustment, were retained in model. Adjusted Bonferroni probability for 14 simultaneous tests in $P < 0.10/14 = 0.007$. Terms that remain significant with adjustment are bold.

[b] n = 54 years for all species but Red-shouldered and Broad-winged hawks (n = 52).

less likely to wait for the next available cold front than are early-season migrants, which would be doing so in more benign environmental conditions.

Among-year effects.—Our analyses demonstrate that there are long-term linear and nonlinear trends in annual numbers of birds seen, but that annual variation in frontal passage rates does not explain significant additional variation in annual counts of raptors. In none of the 14 species investigated was annual passage rate affected by annual variation in the number of cold fronts passing during their migration, in spite of the fact that 12 of the 14 species demonstrated within-year effects. This suggests that frontal passage enhances migration rather than simply making the birds visible to the counters.

We used the Bonferroni method to control for experimentwise type I error rates for simultaneous inferences (Beal and Khamis 1991). This method is most effective when the number of simultaneous tests involved is small. As the number of tests increases the probability of making a type II error becomes a concern (Beal and Khamis 1991). In our case, 14 species were examined simultaneously. If we had not employed this correction factor, our analyses would have demonstrated that counts of 13 species (as opposed to 12 using the method) were influenced within years by frontal passage, and that annual counts of three species (as opposed to none using the method) were marginally influenced by annual variation in frontal passage rates (Table 2). Thus, with or without the Bonferroni method, our findings lead to essentially the same conclusions.

Sighting rates for most of the species that pass Hawk Mountain declined during the DDT era (Bednarz et al. 1990), as did the numbers of cold fronts passing the site. If an association existed between annual numbers of raptors sighted and the numbers of cold fronts passing the site, the use of the Sanctuary's database to support links between the use of DDT and declines in raptor populations (e.g. Hickey 1969, Bednarz et al. 1990) would be open to question. Our analyses, however, indicate that declines in numbers of cold fronts passing the site during the DDT era versus the numbers of fronts passing the site before that time are not responsible for concurrent declines in the numbers of birds sighted.

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