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RELATIONSHIP BETWEEN THE NORTH ATLANTIC OSCILLATION AND SPRING MIGRATION PHENOLOGY OF BROAD-WINGED HAWKS (*BUTEO PLATYPTERUS*) AT HAWK MOUNTAIN SANCTUARY, 1998–2013

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ABSTRACT.—Climatic factors influence migration behavior in both short- and long-distance migratory birds. The Broad-winged Hawk (*Buteo platypterus*) is a long-distance migrant that exhibits a regular calendar-like migration pattern, with some interannual variability during both the northbound and southbound migrations. We examined the relationship between the North Atlantic Oscillation (NAO) and the timing of spring migration in Broad-winged Hawks based on standardized migration count data collected at Hawk Mountain Sanctuary from 1998 to 2013. A strong negative correlation was found between a higher April NAO index and earlier passage dates for the first 50% ($r = -0.723$, $P < 0.01$) and 95% ($r = -0.565$, $P = 0.02$) and mean passage date ($r = -0.730$, $P < 0.01$) of the hawks passing the watchsite. The April NAO values may serve as a useful indicator of the conditions encountered by Broad-winged Hawks during their northbound migration and our analyses suggest a possible climatic effect on their migration timing, as measured at the migration watchsites in the northeastern United States.

KEY WORDS: *Broad-winged Hawk*; Buteo platypterus; *long-distance migrant*; *migration phenology*; *North Atlantic Oscillation*; *passage timing*.

RELACIÓN ENTRE LA OSCILACIÓN DEL ATLÁNTICO NORTE Y LA FENOLOGÍA DE LA MIGRACIÓN PRIMAVERAL DE *BUTEO PLATYPTERUS* EN EL SANTUARIO HAWK MOUNTAIN ENTRE 1998 Y 2013

RESUMEN.—Los factores climáticos influyen el comportamiento migratorio de las aves migratorias tanto de larga como de corta distancia. *Buteo platypterus* es una especie de ave migratoria de larga distancia que exhibe un patrón fenológico regular de migración, con alguna variabilidad interanual durante las

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migraciones hacia el sur y el norte. Examinamos la relación entre la Oscilación del Atlántico Norte (OAN) y las fechas de migración primaveral en individuos de *B. platypterus* basados en los datos de conteos de migración estandarizados en el Santuario Hawk Mountain desde 1998 hasta 2013. Se encontró una relación fuertemente negativa entre un mayor índice OAN de abril y las fechas de paso más tempranas para el primer 50% ($r = -0.723$, $P < 0.01$) y el 95% ($r = -0.565$, $P = 0.02$) y la fecha media de paso ($r = -0.730$, $P < 0.01$) de los halcones a través del lugar de conteo. Los valores de OAN de abril pueden servir como un indicador útil de las condiciones encontradas por *B. platypterus* durante su migración hacia el norte, y nuestro análisis sugiere un posible efecto climático en las fechas de migración, tal como fue medido en puntos de conteo de migración en el noreste de los Estados Unidos.

[Traducción del equipo editorial]

Long-term raptor-migration count data are a critical tool in the conservation and study of migratory raptors. For example, data collected at migration watchsites have been essential in understanding the effects of DDT on the survival and reproductive success of raptors (Carson et al. 1962, Bednarz et al. 1990, Bildstein 1998), the discovery of "migration short-stopping" (Duncan 1996, Viverette et al. 1996, Bildstein 1998), the monitoring of population trends (Farmer et al. 2007, 2008), and understanding the effects of weather on raptor migration (Allen et al. 1996, Shamoun-Baranes et al. 2006, Gordo 2007). The majority of research using count data has focused on outbound or autumn migration, when raptors tend to be more numerous and concentrated than during return or spring migration (Bildstein 2006). Spring migration data, however, are equally important, as they concern the arrival of species to their breeding grounds, and may be important in tracking population trends (Farmer and Smith 2010).

Hawk Mountain Sanctuary is a long-established raptor migration watchsite on the Kittatinny Ridge in eastern Pennsylvania, U.S.A. (Zalles and Bildstein 2000, Bildstein 2006). The most abundant migrant counted at the watchsite in both spring and autumn is the Broad-winged Hawk (*Buteo platypterus*). As long-distance, obligate-soaring migrants, Broad-winged Hawks travel annually between their breeding grounds in the eastern United States and southeastern Canada and their wintering grounds in central and northern South America in flocks of up to tens of thousands (Goodrich et al. 1996, Bildstein 1999). The birds demonstrate a highly consistent migration, to the point where the timing of peak autumn migration can be predicted within a few days every year. In spring, Broad-winged Hawks depart from their wintering grounds in March and pass through southern North America in early April, reaching peak numbers in central Mexico on ca. 11 April (Ruelas 2005, Bildstein 2006), and reaching mid-latitude migration watchsites in mid- to late April (Atkinson et al. 1996, Goodrich et al. 1996, Bildstein 1999).

In the last decade, the phenology of migratory birds in the Northern Hemisphere has shown significant changes (Møller et al. 2004, Gordo 2007, Rubolini et al. 2007). A pattern of advanced spring migration and arrival dates in the Northern Hemisphere in recent years has been demonstrated for both short- and long-distance migrants (Tryjanowski et al. 2002, Cotton 2003, Hüppop and Hüppop 2003, Both et al. 2004). The migration timing of many species, including the Broad-winged Hawk, may rely on endogenous rhythms or a photoperiodic cue, which is identified as the most important and reliable trigger for avian migration (Møller 1994, Gwinner 1996, Both and Visser 2001, Gordo 2007). As photoperiodic cues are less variable annually, departure timing triggered by these cues may be stable among years (Gwinner 1996, Shamoun-Baranes et al. 2006).

Weather has been shown to influence migration timing in many bird species (Francis and Cooke 1986, Forchhammer et al. 2002, Cotton 2003, Marra et al. 2005, Shamoun-Baranes et al. 2006, Miller-Rushing et al. 2008). Previous studies have demonstrated that large-scale weather patterns over a vast geographic area were correlated with an earlier arrival date of migratory birds, e.g., Eurasian Hobby (*Falco subbuteo*; Cotton 2003), Bank Swallow (*Riparia riparia*), Barn Swallow (*Hirundo rustica*), Common House-Martin (*Delichon urbicum*), and other passerines (see Cotton 2003 and Lehikoinen et al. 2004, for species examined). An advancing spring arrival date could result from either an earlier departure, or a faster rate of travel during migration.

One of the most commonly studied climatic factors influencing migration phenology of birds are synoptic weather indices such as the North Atlantic Oscillation (NAO; Ottersen et al. 2001, Stenseth et al. 2003, Gordo 2007, MacMynoski and Root 2007). The NAO index is a measure of the difference in sea-level pressure between the Arctic and mid-latitude Atlantic Ocean, which reflects large-scale weather patterns over bordering ecosystems (Stenseth et al. 2003). The winter NAO indices are often used when studying northbound bird migration, especially in western Europe (Forchhammer et al. 2002, Hüppop and Hüppop 2003, Tøttrup et al. 2010). In these studies, higher NAO indices in winter coincided with warmer springs and stronger westerly winds that facilitate favorable migration and breeding conditions for migrants.

Being one of the most important large-scale weather drivers that affects multiple weather phenomena (e.g., local air temperature, dominant wind direction, and precipitation) of the area, the positive NAO index also can be associated with warmer weather with more precipitation in the region, whereas the negative NAO index indicates the opposite effects (Stenseth et al. 2002). Synoptic weather pattern indices such as the NAO are often better predictors of ecological variance than single local weather variables (Stenseth et al. 2002, Stenseth and Mysterud 2005), especially in regard to continental or broad regional patterns. A long-distance migrant, such as the Broad-winged Hawk, cannot detect changes in weather patterns on their breeding grounds while on their nonbreeding range thousands of miles away, and therefore may be particularly reliant on endogenous, circannual cues such as photoperiod (Goodrich et al. 1996, Both and Visser 2001, Cotton 2003). However, many other long-distance migrant species have shown inter-annual variability in spring arrival timing (Cotton 2003 and Lehikoinen et al. 2004), which is also observed in Broad-winged Hawks at Hawk Mountain. Thus, we hypothesize the migration timing of Broad-winged Hawks may be affected by large-scale synoptic weather patterns.

Here, we analyze the timing and magnitude of Broad-winged Hawk spring migration at Hawk Mountain Sanctuary, Pennsylvania, in relation to variability in the spring NAO, to determine if synoptic weather patterns occurring during migration period represented by the NAO, affect the phenology of spring migration of Broad-winged Hawks as detected at a migration watchsite.

Methods

Study Site and Data Collection. We compiled Hawk Mountain migration counts, conducted from 1 April–15 May, from 1998 to 2013, a period encompassing the spring migration of Broad-winged Hawks at the latitude of Hawk Mountain Sanctuary (McCarty et al. 1999). Counts were conducted at the North Lookout (40°38.48′N, 75°59.48′W) at Hawk Mountain Sanctuary, Pennsylvania, from 0900–1500 H daily with at least two counters per day (Therrien et al. 2012). Counters tallied migrating raptors using both binoculars (7–10× power) and the unaided eye to scan for migrants. A 20–60× power telescope was used occasionally to identify distant raptors. Procedure remained consistent with the protocol detailed in Bednarz et al. (1990) and Bildstein and Zalles (1995).

We used the principal-component based NAO index from the same period of migration counts, which is a more optimal representation of the full NAO spatial pattern than station-based indices (Hurrell and Deser 2010, Hurrell and NCAR 2013). NAO data were obtained online from the Climate Analysis Section of the National Center for Atmospheric Research, Boulder, Colorado, U.S.A. (Hurrell and NCAR 2013). Monthly average NAO indices were used, corresponding to the two months during which the Broad-winged Hawks migrate north past Hawk Mountain (April and May), and the average NAO of wintering period (December–March), for comparison.

Statistical Analysis. We used four benchmark indices of migration phenology (Vähätalo et al. 2004, Tøttrup et al. 2008); the Julian date (the number of days counted from each year's 1 January) of the first 5%, 50%, and 95% of the migrating hawks at Hawk Mountain, as well as the mean Julian date of passage of all migrant birds. The 5%, 50%, 95% dates indicate the date that 5%, 50% and 95% of the total birds observed during spring migration had passed, and mean passage dates are arithmetic means of passage dates for all individual birds in spring migration. In addition, the number of days between the first 5% of passage and 95% of passage represented the length of passage period. Pearson correlation analyses were performed among each of the migration magnitude (the number of birds per each migration season), phenology indices of the birds, the NAO Index data, and years, using SigmaPlot 12.0 (Systat Software, Inc., San Jose, California, U.S.A.). Results of the correlations are summarized in Table 1. P-values $\leq$0.05 were considered to be statistically significant.

Results

Migration Magnitude and Timing. The magnitude of the migration of Broad-winged Hawks at Hawk Mountain varied annually from 1998 to 2013, but

Table 1. Results of correlation analyses among NAO indices, different passage dates, passage period, and migration magnitude.

VARIABLE	STATISTIC	5% DATE	50% DATE	95% DATE	MEAN PASSAGE DATE	PASSAGE PERIOD (5–95%)	MIGRATION MAGNITUDE
Year	*r*	−0.253	0.137	0.353	0.079	0.399	−0.028
	P	0.345	0.613	0.180	0.770	0.126	0.918
NAO April	*r*	−0.062	−0.723	−0.565	−0.730	−0.401	−0.189
	P	0.819	0.002	0.023	0.001	0.124	0.482
NAO May	*r*	0.234	−0.136	−0.394	−0.061	−0.421	−0.003
	P	0.383	0.615	0.131	0.821	0.104	0.991
NAO winter	*r*	0.256	0.308	−0.193	0.231	−0.278	0.233
	P	0.338	0.245	0.474	0.389	0.296	0.384

was not correlated with year (df = 14, $\bar{x}$ = 364.0 birds, SD = 118.6, $r = -0.028$, $P = 0.92$; Table 1). There was no significant relationship between flight magnitude and passage period length (df = 14, $r = -0.297$, $P = 0.26$), nor between flight magnitude and mean passage date (df = 14, $r = 0.414$, $P = 0.11$).

Mean passage dates remained stable across the study years (df = 14, $\bar{x}$ = 111.9 Julian date, SD = 2.1 d, $r = 0.0794$, $P = 0.77$), starting on 15 April (SD = 3 d) and ending on 2 May (SD = 5 d), with the mean and median (50%) dates of passage occurring on 23 April (SD = 2 and SD = 3 d; respectively). Overall, the lengths of the passage period (df = 14, $\bar{x}$ = 17.5 d; SD = 6.1 d, $r = 0.399$, $P =$ 0.13), first 5% (df = 14, $\bar{x}$ = 104.1 d, SD = 3.1 d; $r = -0.253$, $P = 0.35$), first 50% (df = 14, $\bar{x}$ = 112.1 d, SD = 3.0 d; $r = 0.137$, $P = 0.61$), and 95% of passage (df = 14, $\bar{x}$ = 121.6 d, SD = 4.7 d; $r = 0.353$, $P =$ 0.18) did not show any significant trend in the study period (Table 1).

Effects of NAO. A higher average April NAO value coincided with earlier passage for the first 50% (df = 14, $r = -0.723$, $P < 0.01$; Fig. 1b) and 95% (df = 14, $r = -0.565$, $P = 0.02$; Fig. 1c), but not with the first 5% of the passage period (df = 14, $r = -0.0624$, $P = 0.818$; Fig. 1a) nor the overall length of the passage period (df = 14, $r = -0.401$, $P =$ 0.12; Table 1). Mean passage dates of the birds advanced with stronger April NAO indices as well (df = 14, $r = -0.730$, $P = 0.001$; Fig. 1d). The May NAO values did not show any significant relationships with migration phenology measures. The averages of the winter period NAO indices (December to March) also did not show any significant correlation to migration phenology (df = 14 for all indices; 5%: $r = 0.256$, $P = 0.338$; 50%: $r = 0.308$, $P = 0.245$; 95%: $r = -0.193$, $P = 0.474$; mean passage date: $r = 0.231$, $P = 0.389$; passage period: $r = -0.278$, $P = 0.296$). The magnitude of migration was not associated with average winter (df = 14, $r = 0.233$, $P = 0.384$) nor spring NAO values (df = 14, April: $r = -0.189$, $P = 0.482$; May: $r = -0.003$, $P = 0.991$).

In year 2011, the April monthly NAO index was extremely high (+2.30), and the mean passage date (Julian Date = 106) was the most advanced among all years. When we removed the data of 2011, the April NAO index was still correlated with the first 50% date (df = 13, $r = -0.564$, $P = 0.028$) and mean passage dates (df = 14, $r = -0.510$, $P = 0.052$). However, the correlation between NAO index and the first 95% dates (df = 14, $r = -0.409$, $P = 0.130$) was not statistically significant.

DISCUSSION

The spring migration dates of the bulk of migrating Broad-winged Hawks at Hawk Mountain, Pennsylvania, correlated with the strength of the April NAO index, which supports the possible effect of NAO on phenology of these long-distance migrants at migration watchsites in eastern North America. Although the NAO fluctuated during study years (df = 14 for all indices, April: $r = 0.227$, $P =$ 0.398; May: $r = -0.240$, $P = 0.371$; winter-average: $r = -0.280$, $P = 0.293$) and there was substantial variation of Broad-winged Hawk migration magnitudes every year, shifts of NAO did not influence the number of Broad-winged Hawks each year. From this, we suggest that there was a minimal effect of biases related to detectability and availability of birds induced by NAO-related weather effects on migration during migration count surveys. Yet, the lack of correlation of the first 5% to April NAO in

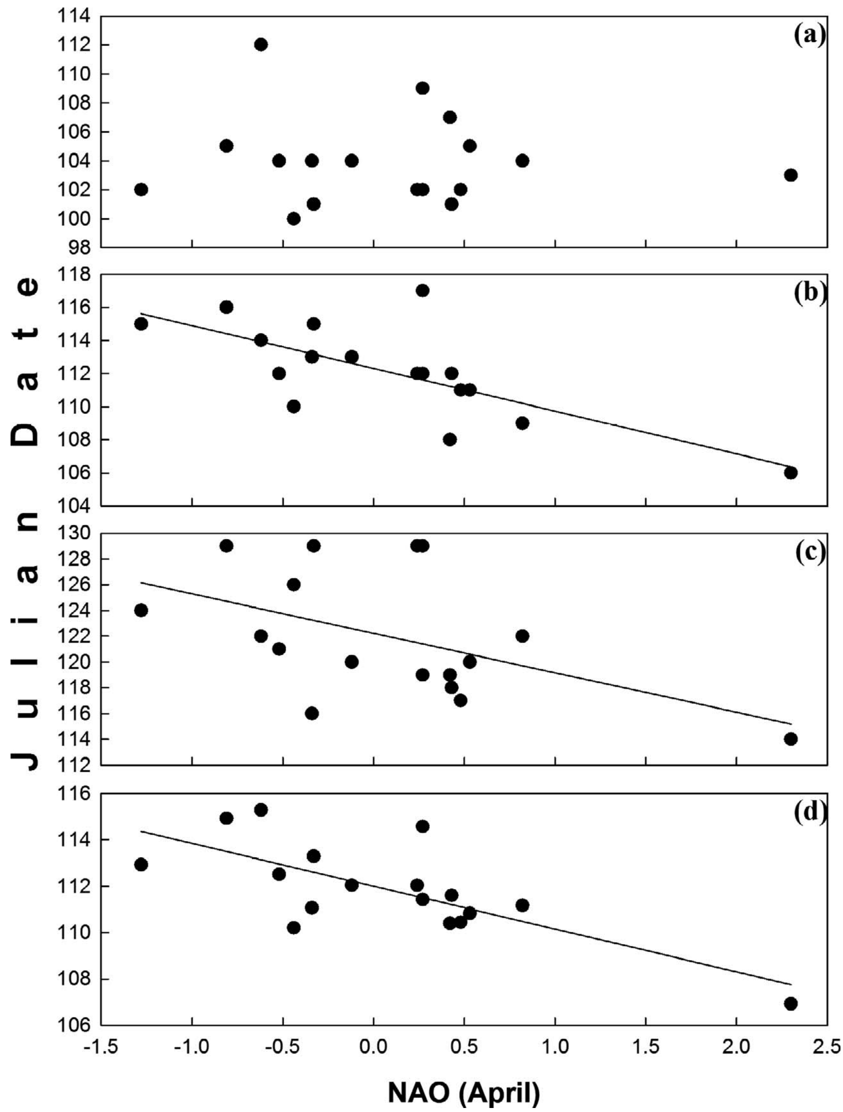

Figure 1. Relationships between April NAO indices and Julian dates of migration phenology of Broad-winged Hawks based on the first (A) 5%; (B) 50%; and (C) 95% of the passage; and (D) mean passage dates. Lines indicate statistically significant relationships.

this study may be a result of the inherently greater variability in detection rates of early arriving birds at migration watchsites (Linden 2011). The 50% passage date and 95% date may be better indicators of migration timing for analyses than the first 5%, which is more likely to be affected by observer bias and outlier birds (Lehikoinen and Sparks 2010). We believe this is the case for our results, which showed a relationship of NAO only to the bulk of migrating individuals.

Weather on the departure grounds has been shown to determine departure dates in the fall migration of long-distance soaring migrants in Europe (Shamoun-Baranes et al. 2006). It is therefore unclear whether changes in migration phenology are attributable to a change in departure timing or a change in the rate of migration itself. For this reason, we looked at average winter NAO values, as compared with NAO values during migration. However, in this study we found no correlation between average winter NAO index and migration phenology of Broad-winged Hawks, which suggests that the earlier migration timing of Broad-winged Hawks in some years is unlikely to be due to changes in the departure timing from wintering grounds (Cotton 2003).

Positive NAO indices are known to be correlated with warmer climates in coastal regions of eastern North America and negative indices are related to the cooler weather (Stenseth et al. 2002, 2003). Assuming warmer conditions extend inland as well, the high April NAO indices may correlate with better *en route* migration conditions for North American soaring migrants in spring, such as the Broad-winged Hawk. The positive NAO may promote strengthened westerly winds over southeastern United States, extending farther north in years of higher NAO (Stenseth et al. 2002), and thus increased tailwind conditions may benefit Broad-winged Hawks that are migrating from central America to northeastern United States and Canada (Kemp et al. 2010, Lehikoinen and Sparks 2010).

Broad-winged Hawks may use different flight modes during their journey, depending on the meteorological and geographical conditions. Another soaring long-distant migrant species, the Golden Eagle (*Aquila chrysaetos*), has been shown to shift flight strategies from using thermal lift to orographic lift, in response to the availability of lift types that occur variably during the northbound migration in the eastern United States, possibly to reduce migration time (Duerr et al. 2012, Lanzone et al. 2012). If the NAO affects wind speed or direction, this could increase opportunities for orographic lift for northbound migrants. Further research is needed to investigate that possibility. Our analyses suggest that the weather that Broad-winged Hawks encounter during spring migration may have a greater effect on the spring passage dates at Hawk Mountain than does the weather on their wintering grounds. We suggest that higher NAO values in April are correlated with conditions that allow faster movements northward.

Broad-winged Hawks showed an earliest passage date in 2011, coincidental with a high April NAO index. Researchers reported that 2011 showed extreme weather events over all the United States, including especially frequent severe storms and warm temperatures (Coumou and Rahmstorf 2012). Because climate change may induce more frequent extreme weather (Meehl et al. 2000, Parmesan et al. 2000), events in 2011 highlight the importance of tracking effects of extreme large-scale climate shifts on bird migration phenology.

Further study is needed to determine if the frequency of advanced passage may be increasing for Broad-winged Hawks or other soaring raptors, and what the effects of climate change may be on advanced passage, breeding success, and the long-term conservation of these species. Research on fine-scale movements during migration to look at individual direct responses to weather conditions may reveal more insights into the migration ecology of these and other long-distance migrants in eastern North America. Although the underlying relationship between more direct climatic measures and the NAO in aiding the northbound bird migration warrants further investigation, this and other studies show it is a useful indicator of conditions long-distance migrants encounter during northbound passage (Liechti and Bruderer 1998).

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