

# Rapid Advance of Spring Arrival Dates in Long-Distance Migratory Birds

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Several bird species have advanced the timing of their spring migration in response to recent climate change. European short-distance migrants, wintering in temperate areas, have been assumed to be more affected by change in the European climate than long-distance migrants wintering in the tropics. However, we show that long-distance migrants have advanced their spring arrival in Scandinavia more than short-distance migrants. By analyzing a long-term data set from southern Italy, we show that long-distance migrants also pass through the Mediterranean region earlier. We argue that this may reflect a climate-driven evolutionary change in the timing of spring migration.

Many biological processes are affected by climate, and in temperate areas the increasing spring temperature over the past 20 to 30 years has caused an advancement of phenological events in plants and invertebrates (1, 2). The earlier onset of spring has consequences for the timing of breeding in birds, which has evolved to match peak food availability (3, 4). We may therefore expect the timing of breeding to track any temporal shift in food availability caused by a trend in spring temperature (5). Most passerine birds breeding in temperate areas of the Northern Hemisphere are seasonal migrants, and the timing of migration ultimately constrains when breeding can start (6, 7). Short-distance migrants, spending the winter close to the breeding grounds, may be able to adjust the timing of migration in response to local climate change, which will be correlated to the conditions on the breeding grounds. In tropical-wintering long-distance migrants, the timing of migration is under endogenous control (8, 9), and the cues needed to trigger the onset of migration are unlikely to be linked to the climate on their breeding grounds. Therefore, it has been assumed that short-distance migrants are more likely than long-

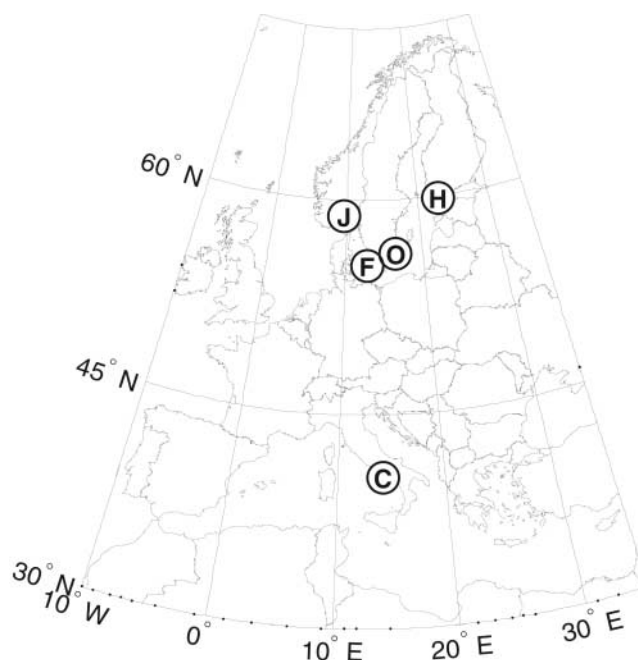
distance migrants to vary migration timing in response to climate change (10). Here we show that such an assumption is not empirically justified.

We estimated trends in arrival time for the early, middle, and late phases of migration (that is, the species- and site-specific 10th, 50th, and 90th percentiles of the spring arrival distribution) in short- and long-distance passerine migrants, based on long-term banding and observational data (from 1980 to 2004) from four bird observatories in Scandinavia and a site in southern Italy (11, Fig. 1). We also investigated whether year-to-year variation in arrival time can be explained by short-term climate variability as measured by the North Atlantic Oscillation (NAO) (12). As explanatory variables we used the calendar year (TIME) and the deviations from linear regression of the winter NAO index on year

[dNAO; the trend in NAO was weakly negative over this time period (11)]. Spring migration might advance for two distinct reasons. First, there can be a microevolutionary (genetic) response to the selection pressures for earlier breeding. Second, the migrants can show a phenotypically plastic response to trends in weather or climatic patterns on the wintering ground and/or along the migration route, whereby if spring arrives early on the wintering grounds, spring migration will also start early. Thus, a response to TIME may reflect either microevolutionary change or phenotypic plasticity, whereas a response to dNAO indicates exclusively phenotypic plasticity in the migratory behavior.

Long-distance migrants have advanced their arrival in northern Europe in all phases of migration (Fig. 2 and tables S1 to S3). The advancement in long-distance migrants is strongest in the early phase of migration, and there is limited variation between species. Furthermore, the analysis of the data set from Italy (from the island of Capri) showed that long-distance migrants wintering south of the Sahara desert are actually arriving in southern Europe progressively earlier. In fact, all of the nine species analyzed show a trend for earlier spring arrival at Capri in most phases of migration (Fig. 2 and table S4). The long-term trend on Capri is at least as strong as that observed in Scandinavia (Fig. 3). In short-distance migrants, instead, we find only a weak trend toward earlier arrival, and there is considerable variation between species (Fig. 2 and tables S1 to S3).

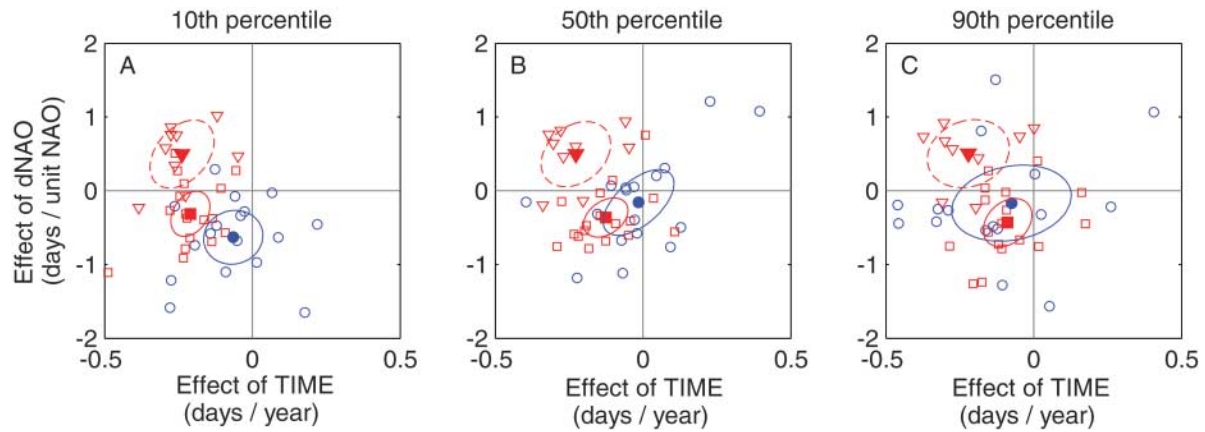
In accordance with previous findings (13–15), a high NAO index is associated with the early arrival of short-distance migrants in Scandinavia, but only in the early phase of migration (Fig. 2).



**Fig. 1.** The locations of the four bird observatories (F, Falsterbo, 55°23'N, 12°49'E; O, Ottenby, 56°12'N, 16°24'E; J, Jomfruland, 58°53'N, 9°37'E; H, Hanko, 59°48'N, 22°53'E) and of the banding site on Capri (C, 40°33'N, 14°15'E).

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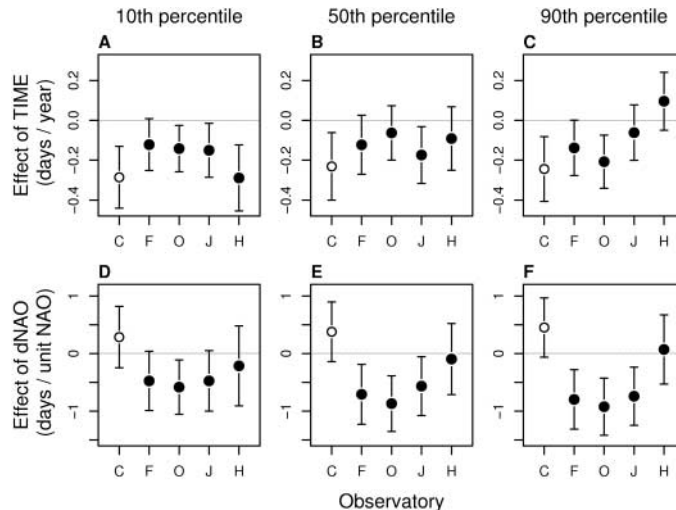
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**Fig. 2.** Long-term trend (TIME) and the effect of short-term climatic fluctuations (dNAO) on the early [(A), 10th percentile], middle [(B), 50th percentile], and late [(C), 90th percentile] phases of the spring arrival distribution in short-distance migrants (blue circles) and long-distance migrants (red squares) in Scandinavia and on Capri (red triangles). The

solid symbols are sample averages, and the ellipses delimit their 95% confidence regions (11). Estimates for each species are given in tables S1 to S4. The differences in effect size for early-phase arrival of short-distance migrants versus long-distance migrants was 0.15 [95% confidence interval (CI): 0.06 to 0.23] days per year for the effect of TIME.

**Fig. 3.** Mean slopes and 95% CIs of the relationships between arrival dates and TIME (A to C) or dNAO (D to F) in the early (10th percentile), middle (50th percentile), and late (90th percentile) phases of migration for six species of long-distance migrants for which time series were available at each observatory (solid symbols; F, Falsterbo; O, Ottenby; J, Jomfruland; H, Hanko) and at the banding site on Capri (open symbol; C). The sites are sorted from south to north.



Species-specific slopes were estimated with a mixed-effect linear model (11). The correlation between species, when species- and observatory-specific effects of both TIME and dNAO were accounted for, was estimated at 0.48 (95% CI: 0.17 to 0.75), 0.25 (95% CI: 0.04 to 0.51), and 0.34 (95% CI: 0.03 to 0.68) for the 10th, 50th, and 90th percentiles, respectively.

On the other hand, most long-distance migrants tend to arrive earlier in Scandinavia during years of high NAO in all phases of migration (Figs. 2 and 3 and tables S1 to S3). The opposite pattern is observed at Capri, where high NAO tends to delay arrival times (Figs. 2 and 3 and data in table S4). The underlying reason for this may be found south of the Sahara desert, because a high NAO index harms productivity over vast areas of northwestern and southeastern Africa (16), which may delay the spring departure of migrants from sub-Saharan wintering areas.

By showing that long-distance migrants have advanced their migration more than short-distance migrants, we have challenged the conventional wisdom that species wintering in temperate Europe should respond

more strongly to climate change than trans-Saharan migrants (10). Furthermore, the earlier arrival of trans-Saharan migrants at Capri shows that the temporal trend for earlier arrival in Scandinavia cannot be explained simply by faster migration through Europe in response to a concomitant trend of increasing temperatures taking place within continental Europe (17). Instead it suggests that (i) the onset of migration has advanced, or (ii) the speed of migration through Africa has increased. Both alternatives could be seen as phenotypic responses to trends in the African climate patterns having a positive effect on the foraging conditions (18), thereby improving the birds' physical conditions, which in turn affects their timing of migration (19) and makes the migration (including flight

and stopover) more efficient. A positive trend in African temperatures (20) has previously been suggested as a reason why long-distance migrants arrive earlier in northern Europe (21). However, increasing African temperatures should decrease productivity (22), thereby delaying long-distance migrants' departure from the wintering ground. Hence, the earlier arrival is probably not a phenotypic response to improved foraging conditions. More likely, the rapid advance in arrival dates of long-distance migrants in Europe is due to climate-driven evolutionary changes in the timing of spring migration. Even though migratory activity is under endogenous control, experiments have demonstrated individual variation in the response to the photoperiodic cues needed to trigger the mechanisms underlying the onset of migration (23). The passerine birds investigated here reproduce at just 1 year of age and thus have the potential for a rapid evolutionary response to environmental changes. Given the considerable heritable genetic variation in the timing of migration (24, 25) and the selection pressure to breed earlier in Europe (6, 7), a change toward earlier arrival is indeed to be expected.

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contribution number 215 from Ottenby Bird Observatory, contribution number 232 from Falsterbo Bird Observatory, contribution number 79 from Jomfrulund Bird Observatory, and results from the Progetto Piccole Isole (Istituto Nazionale per la Fauna Selvatica), paper no. 37.

#### Supporting Online Material

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# Intron Removal Requires Proofreading of U2AF/3' Splice Site Recognition by DEK

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Discrimination between splice sites and similar, nonsplice sequences is essential for correct intron removal and messenger RNA formation in eukaryotes. The 65- and 35-kD subunits of the splicing factor U2AF, U2AF<sup>65</sup> and U2AF<sup>35</sup>, recognize, respectively, the pyrimidine-rich tract and the conserved terminal AG present at metazoan 3' splice sites. We report that DEK, a chromatin- and RNA-associated protein mutated or overexpressed in certain cancers, enforces 3' splice site discrimination by U2AF. DEK phosphorylated at serines 19 and 32 associates with U2AF<sup>35</sup>, facilitates the U2AF<sup>35</sup>-AG interaction and prevents binding of U2AF<sup>65</sup> to pyrimidine tracts not followed by AG. DEK and its phosphorylation are required for intron removal, but not for splicing complex assembly, which indicates that proofreading of early 3' splice site recognition influences catalytic activation of the spliceosome.

A minimal U2AF heterodimer consisting of RNA recognition motifs (RRM) 1 and 2 of U2AF<sup>65</sup> (1) and the U2AF homology motif (UHM or ΨRRM) of U2AF<sup>35</sup> (2) was analyzed by nuclear magnetic resonance (NMR) spectroscopy in the absence or presence of an RNA containing a pyrimidine tract followed by a consensus 3' splice site (3'ss) [5' (U)<sub>13</sub>ACAGG 3']. As expected from the affinity of U2AF<sup>65</sup> for uridine-rich sequences (1), the presence of the RNA caused extensive changes in the NMR spectrum of the U2AF<sup>65</sup> RRM 1+2 subunit (Fig. 1A, left). In contrast, small perturbations concerning few residues were observed in the U2AF<sup>35</sup> ΨRRM spectrum (right). The latter was unexpected, because previous observations suggested that U2AF<sup>35</sup> specifically recognizes the 3'ss-AG (3–5). Gel retardation assays using <sup>32</sup>P-uridine-labeled RNAs [5' GGG(U)<sub>13</sub>AC-AG/CG-GUAAAAUAACUCA 3'] showed that, although U2AF<sup>35</sup> ΨRRM in-

creases the affinity of the complex threefold, the effect is similar for AG-, CG-, UG- or AA-3'ss, strong or weaker pyrimidine tracts (Fig. 1B and figs. S1 and S2). Lack of AG discrimination was also observed when different assays and recombinant full-length U2AF heterodimer or U2AF purified from HeLa cells were utilized (Figs. 1, C and D). In contrast, both endogenous U2AF and the minimal heterodimer showed preferential ultraviolet (UV) light-induced photo-cross-linking of U2AF<sup>65</sup> to AG-3'ss RNAs in nuclear extracts (Fig. 1E). Reconstitution of U2AF-depleted extracts with recombinant U2AF subunits indicated that U2AF<sup>35</sup> is required for AG discrimination (Fig. 1E, bottom). The presence of U2AF<sup>35</sup> and other components of the nuclear extract decreased cross-linking of U2AF<sup>65</sup> to the nonconsensus CG-3'ss, which suggests the existence of a proofreading activity that enforces specific association of U2AF with pyrimidine tracts followed by consensus AG-3'ss.

This activity cofractionated with U2AF during the two first chromatographic steps of U2AF purification (6) (fig. S3). In fig. 2A, compare lanes 3 and 4 with 7 and 8 for the U2AF-containing complex (identified in lane 2 by supershift with antibodies against U2AF<sup>65</sup>). The activity

was, however, separated from U2AF on the next chromatographic step [poly(U)-Sephacrose]; whereas U2AF was retained in the column (6), the flow-through fraction provided AG versus CG discrimination to the truncated heterodimer in both UV-mediated cross-linking (Fig. 2B) and gel-retardation assays (fig. S4). The activity present in this fraction was retained on an affinity column containing the truncated U2AF heterodimer (Fig. 2D, lanes 1 to 4). Comparison of the protein profiles of the input and flow-through fractions revealed that a 50-kD protein was retained in the U2AF column (Fig. 2C, lower component of the 50-kD doublet). Mass spectrometry analyses identified this protein as DEK, a chromatin-, pre-mRNA- and mRNA-associated protein overexpressed or mutated in certain cancers (7, 8). Consistent with a role for DEK in providing AG discrimination to U2AF, depletion of DEK from HeLa nuclear extracts (fig. S5) resulted in reduced AG versus CG discrimination by endogenous U2AF<sup>65</sup> (Fig. 2E, lanes 1 to 4), an effect that was reversed when recombinant purified DEK was added to the depleted extracts (lane 5). Cross-linking between U2AF<sup>35</sup> and an RNA radioactively labeled at the 3'ss dinucleotide (A-[<sup>32</sup>P]-G or C-[<sup>32</sup>P]-G) was reduced in DEK-depleted extracts, which indicated that DEK is required for 3'ss recognition by U2AF<sup>35</sup> (Fig. 2F). Collectively, the results described above indicate that DEK provides a proofreading function that allows U2AF to discriminate between bona fide AG-containing and nonconsensus 3'ss regions.

DEK retention in U2AF affinity columns suggested the possibility of an interaction between these factors. Pull-down experiments using *in vitro* translated, <sup>35</sup>S-labeled U2AF<sup>65</sup> or U2AF<sup>35</sup> and recombinant purified glutathione *S*-transferase (GST)-DEK revealed formation of a complex between DEK and U2AF<sup>35</sup>, which was, at least in part, RNA-independent and involved the 100 amino-terminal residues of DEK (Fig. 3, A and B). Interestingly, the interaction was disrupted by phosphatase treatment (Fig. 3B, lanes 3 versus 4 and 11 versus 12), which suggests the requirement for protein phosphorylation. Indeed, DEK is a phospho-

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## Supporting Online Material for

### Rapid Advance of Spring Arrival Dates in Long-Distance Migratory Birds

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## Supporting Online Material

### ***Data***

We analyzed banding data collected during spring migration in the period 1980–2004 at the bird observatories of Falsterbo (Sweden), Ottenby (Sweden), Jomfruland (Norway) and Hanko (Finland) (Fig. 1). For Hanko and Jomfruland, we also included observations from standardized counts of migrants (see below). A total of 34 species were investigated (Tables S1–S3; see below for selection criteria), of which 17 were classified as short-distance (wintering north of the Sahara desert, mainly in Europe) and 17 as long-distance migrants (wintering south of the Sahara or in South Asia). For trapping and observation data, care was taken not to include any species for which local wintering or breeding birds potentially could influence our sample percentiles.

For comparison with southern Europe, we used banding data based on standardized mist-netting from the island of Capri (southern Italy). Below we summarize details of the data collection procedures at each observatory.

### ***Jomfruland***

Jomfruland Bird Observatory (*SI*) is located close to the northern end of the island of Jomfruland, along the outer coastline of southeastern Norway (58°53'N, 9°37'E). We used data on birds trapped in mist-nets during the period April 1 - June 15. For some common species with low trapping efficiency or an early migration (i.e. where migrating birds may occur prior to the start of the mist-netting period), we instead used daily observation sums for the period March 18 - June 15. From 1990 onwards, the mist-netting protocol has remained unchanged, with the number, positions, and operating hours of mist-nets kept constant. Trapping was performed daily, but the number of nets and/or their hours of operation were

reduced on days with strong wind and/or heavy rain. Prior to 1990, sampling efforts were less strictly standardized, but trapping occurred on a daily basis throughout the selected period. For these early years, care was taken to use only data from the same trapping location as later years, and we did not include any observation data for years with incomplete coverage before the onset of mist-netting.

### ***Falsterbo***

The banding site at the Falsterbo Bird Observatory is situated on the south-westernmost tip of Sweden (55°23'N, 12°50'E). Standardized mist-netting in spring is performed daily at the Lighthouse Garden, a small (ca. 1 ha) stand of mixed trees and bushes surrounding the Falsterbo Lighthouse (S2), within an open field area (golf course). Since 1980, the spring trapping season started on March 21 and lasted till June 10. Depending on weather conditions (wind in particular), the daily number of mist-nets used varied, up to a maximum of 21. On days with heavy rain or very strong winds, all trapping efforts were canceled. The nets were opened before dawn and controlled every half hour. The daily trapping period lasted at least four hours and continued thereafter as long as the number of captured birds exceeded ten individuals per hour. Nets have been positioned at the same location during all years.

### ***Ottenby***

Ottenby Bird Observatory (56°12'N, 16°24'E) is situated on the southernmost tip of Öland, a 137 km long island, ca.10 km off the coast of south-eastern Sweden. Migratory birds have been caught according to strictly standardized procedures during 1980–2004 (S3). Birds were caught in stationary mist nets and in two funnel traps of Helgoland type (S4), every morning from dawn to 11 am. In case of rain or strong winds only the funnel traps were used. The



spring trapping period was March 15 – June 15, and only 14 out of 2,325 trapping days had to be cancelled over the years (all comprised between 15–24 March in the years 1980–1987).

### *Hanko*

Hanko bird observatory (59°48'N, 22°53'E) is located on a peninsula in the south-western part of Finland (S5). Data were collected by means of two daily routines: standardized counts of actively migrating birds and counts of resting migratory passerines. For further analysis, we used either one of the methods or the sum of both, depending on the species-specific breeding status in the area, the migratory behavior and commonness in the respective set of data. We used data from the period March 10 to June 15. To avoid bias due to non-randomly missing days early in the season, we excluded some early-migrating short-distance migrants from the analyses (see Tables S1-S3). Standardized migration counts consisted of four hours of continuous observation from sunrise onwards in a tower near the tip of the peninsula. Poor weather conditions (heavy rain and/or very strong wind) occasionally reduced observation activity, but during such weather conditions passerine migration is extremely scarce. Resting migratory passerines were counted along routine walking paths at the small (ca. 12 ha) observatory area at the tip of the peninsula after the standardized migration counts.

### *Capri*

The island of Capri (40°33'N 14°15'E) is located in the Tyrrhenian sea, ca. 5 km off mainland southern Italy. During spring, many long-distance migratory birds stop there to rest, mainly for a short time (often only a few hours), after the consecutive crossing of the Sahara desert and of the Mediterranean Sea (S6 – S9). Birds were trapped with mist-nets, whose location was kept standardized during the study period (see below), while vegetation structure was affected during few years by a fire event (S8); however, this should not affect changes in the

phenology of migration. The trapping area comprises ca. 2 ha of the dry and bushy vegetation (*garrigue* and “*macchia*”) typical of this region of the Mediterranean. Data were collected during the period 1981-2004, although no data were available for the years 1982 to 1985, and for the year 2000, when the coverage was insufficient (S8). Trapping activities were carried out every day (from dawn to dusk) during the selected time period (see below), except in cases of heavy wind or rain; this occurred on average 1.05 days each year, with no temporal trend over the study period (slope =  $0.060 \pm 0.056$  SE). In order to standardize the trapping effort across years (see S8), the data used in this study was restricted to the period April 17 – May 15. Since the proportions of the birds arriving outside these dates may vary from year to year, simple percentiles from banding dates may be biased and underestimate the variation in mean arrival dates. We therefore fitted a Gaussian curve in a Poisson regression on the daily banding numbers and used the distribution derived from this analysis to estimate percentiles of the yearly migratory distributions. To be able to account for large extra-Poisson variation in the data, the model was fitted with Bayesian MCMC methods (see *Methods*).

### **Climate data**

We used the mean winter (December–March) NAO index (<http://www.cgd.ucar.edu/cas/jhurrell/>) as a measure of climate fluctuations, because it is known to affect the timing of spring events in Europe (S10). As an explanatory variable, we used the deviations from linear regression of the winter NAO index on year (dNAO). The trend was weakly negative over this time period (slope = -0.052, 95% c.i.: -0.167 to 0.063).

### **Methods**

For each species and year in which at least 20 individuals were trapped/observed at a Scandinavian bird observatory, we estimated the 10<sup>th</sup>, 50<sup>th</sup> and 90<sup>th</sup> sample percentiles. Dates



are given as Julian dates (day-of-year). Note that the estimated percentiles are not, strictly speaking, independent, and fitting a Gaussian curve to the Capri data results in a different statistical dependence between the percentiles.

## **Models and statistics**

We tested whether regression coefficients for short- and long-distance migrants differed significantly from each other by constructing a 95% confidence interval for the difference using maximum likelihood and checked whether zero was excluded. To test whether the regression coefficients differed from zero, we checked whether the bivariate 95% confidence region of their means (Fig. 2) excluded zero with respect to the TIME or dNAO axis.

For each species and percentile (10<sup>th</sup>, 50<sup>th</sup> and 90<sup>th</sup>) of the arrival distribution (*SII*) we fitted a linear mixed-effects model having TIME and the residuals of the regression of NAO on TIME (dNAO) as explanatory variables, ‘observatory’ as a fixed effect and a random between-year variance component in common for all observatories. Note that a unit change in NAO implies an identical change in dNAO, even if the origins of the two scales differ. Thus, we have framed our discussion simply in terms of effects of a change in NAO. Furthermore, to facilitate comparison between the observatories and the banding site on Capri, the mean effects of TIME and dNAO were estimated for the six long-distance migrants for which sufficient data were available both at the four Scandinavian bird observatories and on Capri (see “Estimating mean arrival date in the Capri data by over-dispersed Poisson regression”). Estimates were obtained from a linear mixed model assuming compound symmetry for the year-to-year variation of different species (i.e., same variance for all species and all species equally correlated), and a different residual variance for every combination of species and locations (because the amount of data, and hence measurement error, behind every data point in the analysis vary mainly at this level). The mixed models were fitted with restricted

maximum likelihood (REML) by the ‘lme’ function in the nlme package (S12) of the software R (version 2.1) (S13).

### **Estimating mean arrival date in the Capri data by over-dispersed Poisson regression**

Because data from the Capri banding site did not cover the entire migration period (see *Data*), mean arrival date at this location was estimated by fitting a Gaussian seasonal distribution curve in a Poisson regression on the daily banding numbers. There is typically large day-to-day variation in banding data of migrating birds (presumably mostly due to local weather conditions), and it is difficult to adequately model this over-dispersion in generalized linear models when using maximum likelihood methods. We therefore used Bayesian MCMC methods implemented in the program WinBUGS 1.4 (S14).

A Gaussian (normal) seasonal distribution curve can be fitted as a quadratic function on a logarithmic scale ( $\log(\{\text{expected number on day } x_i\}) = \mu_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2$ ).

However, the following re-parameterization gave lower autocorrelations in the MCMC simulations: “mean” =  $\tau = -\beta_1 / (2\beta_2)$ , “peak” =  $\rho = \beta_0 + \beta_1 \tau + \beta_2 \tau^2$ , and “standard deviation” =  $\kappa = -\sqrt{-2\beta_2} / (2\beta_2)$ .

Two alternative models were considered for modeling the over-dispersion in the data; either a log-normal component of the Poisson parameter ( $\log(\lambda_i) = \mu_i + \varepsilon_i$ , where  $\varepsilon_i \sim N(0, \sigma^2)$ ), or a stochastic day-effect from a Gamma distribution with shape parameter being 1/scale parameter ( $\lambda_i = e^{\mu_i} v_i$ , where  $v_i \sim \Gamma(\alpha, 1/\alpha)$ ,  $E(v_i) = 1$ ). In the first model, the expected number of ringed birds on day  $i$  is  $E(\lambda_i) = e^{\mu_i + \sigma^2/2}$ . In the latter model, the expected number is  $E(\lambda_i) = e^{\mu_i}$ . The Gamma-model gave somewhat better goodness of fit statistics (see below) and lower DIC (=Deviance Information Criterion) value, and was hence used in the analysis. The model was fitted for each species separately, and all parameters except  $\alpha$  were

year-specific ( $\alpha$  was constant across years). As estimates of mean arrival dates (see Table S5) we used the medians of posterior distributions of the parameter  $\tau$ .

To facilitate numerical convergence and eliminate nonsensical parameter values from the posterior distributions, we constrained the parameter space by using uniform and rather vague priors on the parameters  $\tau$  (mean passage date) and  $\kappa$  (standard deviation in passage date). For  $\kappa$  of all years and species, we used a Uniform (0.25,10) prior, meaning that the time elapsed between the 2.5 percentile and the 97.5 percentile of banding dates could take any value between 1 and 40 days. The priors for mean banding date,  $\tau$ , depended on species and spanned what we considered the maximum reasonable range for that species (Table S4). The peak of the expectation curve, represented by the parameter  $\rho$ , was allowed to vary between 0 and 10 times the maximum observed daily count of the species, which is essentially an uninformative prior. The prior of the parameter in the Gamma-term accounting for over-dispersion,  $\alpha$ , was set to an uninformative  $\Gamma(\text{scale} = 1/1000, \text{shape} = 1000)$  distribution.

We used relatively long chains in the MCMC simulations due to persistent long-legged autocorrelations in some parameters (6 parallel chains of 80,000 iterations with an initial burn-in period of 10,000 iterations and thereafter sampling at every 5<sup>th</sup> iteration). Convergence was confirmed by the Gelman and Rubin statistic, which compares the within-chain to the between-chain variability of chains started at different and dispersed initial values (S15).

Goodness of fit (GOF) was assessed by using Bayesian  $p$ -values (comparing the distributions of GOF-statistics computed from both the actual data and from simulated data at every step of the MCMC chain (S16). An acceptable fit was verified with respect to the following statistics: deviance, skewness and kurtosis of deviance residuals, correlation

between deviance residuals and day of year ( $x_i$ ), and correlation between the deviance residuals and the fitted expectations  $e^{\mu_i}$ .

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## Supplementary Tables

**Table S1.** Species and observatory specific parameter estimates and variance components when analyzing the early phase of migration (10<sup>th</sup> percentile) using a linear mixed model with ‘observatory’ as a fixed effect and a random between-year variance component in common for all observatories.

Common name	Scientific name	Migration category (SHORT or LONG distance migrant)	Mean date (day of year)*				Variance components (SD units)		Estimates of slope (± SE)		Estimated unexplained between-year variation (SD)
			Falsterbo	Ottenby	Jomfru- land	Hanko	Between years (% of total variance)	Between years within observatories	TIME (days / year)	dNAO (days / unit)	
White wagtail	<i>Motacilla alba</i>	SHORT	100.6	107.1	103.0	105.1	3.3 (31 %)	4.9	-0.13 ± 0.15	0.29 ± 0.54	3.3
Winter wren	<i>Troglodytes troglodytes</i>	SHORT	90.1	89.7	-	-	4.0 (52 %)	3.8	-0.09 ± 0.13	-1.10 ± 0.47	3.6
Hedge accentor	<i>Prunella modularis</i>	SHORT	91.2	89.1	95.8	-	4.4 (57 %)	3.9	-0.05 ± 0.14	-0.68 ± 0.52	4.4
European robin	<i>Erithacus rubecula</i>	SHORT	95.1	99.7	-	-	1.9 (15 %)	4.6	-0.03 ± 0.11	-0.28 ± 0.40	2.1
Common blackbird	<i>Turdus merula</i>	SHORT	86.5	80.3	-	-	1.1 (5 %)	4.5	-0.14 ± 0.09	-0.58 ± 0.32	0.0
Song thrush	<i>Turdus philomelos</i>	SHORT	91.8	94.9	98.0	101.5	3.2 (31 %)	4.8	-0.12 ± 0.11	-0.47 ± 0.41	3.2
Redwing	<i>Turdus iliacus</i>	SHORT	97.6	90.8	93.6	-	4.8 (32 %)	6.9	0.18 ± 0.19	-1.65 ± 0.70	3.9
Chiffchaff	<i>Pylloscopus collybita</i>	SHORT	101.6	112.5	108.8	114.7	2.3 (17 %)	5.1	-0.26 ± 0.08	-0.21 ± 0.32	1.4
Goldcrest	<i>Regulus regulus</i>	SHORT	89.7	99.7	90.4	-	2.0 (19 %)	4.2	-0.04 ± 0.09	-0.34 ± 0.34	2.1
Blue tit	<i>Parus caeruleus</i>	SHORT	83.5	78.7	-	-	0.0 (0 %)	2.7	-0.06 ± 0.15	-0.07 ± 0.39	0.0
Great tit	<i>Parus major</i>	SHORT	82.9	80.1	-	-	3.1 (40 %)	3.8	-0.20 ± 0.12	-0.74 ± 0.47	2.7
Chaffinch	<i>Fringilla coelebs</i>	SHORT	89.4	89.8	-	100.4	3.6 (47 %)	3.9	0.02 ± 0.11	-0.97 ± 0.41	3.3
Brambling	<i>Fringilla montifringilla</i>	SHORT	-	105.3	-	103.5	0.0 (0 %)	7.4	0.09 ± 0.20	-0.63 ± 0.76	4.5
European greenfinch	<i>Carduelis chloris</i>	SHORT	93.4	91.2	-	-	2.7 (16 %)	6.0	0.07 ± 0.15	-0.03 ± 0.59	3.0
Common linnet	<i>Carduelis cannabina</i>	SHORT	109.5	117.1	-	-	1.6 (10 %)	4.9	-0.28 ± 0.15	-1.59 ± 0.76	0.0
Yellowhammer	<i>Emberiza citrinella</i>	SHORT	-	84.5	-	-	-	5.9	-0.27 ± 0.23	-1.21 ± 0.69	5.4
Reed bunting	<i>Emberiza schoeniclus</i>	SHORT	107.2	86.2	92.7	-	0.0 (0 %)	7.5	0.22 ± 0.24	-0.45 ± 0.84	0.0
Barn swallow	<i>Hirundo rustica</i>	LONG	-	137.1	134.1	129.5	2.2 (25 %)	3.8	-0.25 ± 0.09	-0.07 ± 0.33	1.8
Tree pipit	<i>Anthus trivialis</i>	LONG	121.4	122.0	121.7	118.9	3.0 (32 %)	4.4	-0.14 ± 0.11	-0.69 ± 0.40	2.8
Thrush nightingale	<i>Luscinia luscinia</i>	LONG	132.8	131.6	-	-	3.4 (58 %)	3.0	-0.16 ± 0.16	-0.39 ± 0.52	3.3

Table S1 (continued)

Common name	Scientific name	Migration category (SHORT or LONG distance migrant)	Mean date (day of year)*				Variance components (standard deviations)		Estimates of slope (± SE)		Estimated unexplained between-year variation (standard deviations)
			Falsterbo	Ottenby	Jomfru- land	Hanko	Between years (% of total variance)	Between years within observatories	TIME (days / year)	dNAO (days / unit)	
Bluethroat	<i>Luscinia svecica</i>	LONG	-	131.3	-	130.1	2.8 (63 %)	2.2	-0.06 ± 0.11	0.28 ± 0.47	3.0
Common redstart	<i>Phoenicurus phoenicurus</i>	LONG	123.2	125.8	125.4	127.2	3.8 (50 %)	3.8	-0.23 ± 0.11	-0.79 ± 0.40	3.3
Whinchat	<i>Saxicola rubetra</i>	LONG	130.0	-	127.9	128.0	3.2 (43 %)	3.6	-0.25 ± 0.11	0.27 ± 0.42	2.6
Marsh warbler	<i>Acrocephalus palustris</i>	LONG	147.8	145.7	-	-	2.8 (50 %)	2.7	-0.11 ± 0.14	0.03 ± 0.57	3.0
Eurasian reed warbler	<i>Acrocephalus scirpaceus</i>	LONG	137.1	141.3	141.7	-	2.4 (25 %)	4.2	-0.09 ± 0.11	-0.57 ± 0.46	2.4
Icterine warbler	<i>Hippolais icterina</i>	LONG	140.7	140.9	137.7	-	2.9 (52 %)	2.8	-0.22 ± 0.09	-0.37 ± 0.34	2.5
Lesser whitethroat	<i>Sylvia curruca</i>	LONG	123.0	127.0	130.9	133.7	4.1 (70 %)	2.7	-0.23 ± 0.10	-0.91 ± 0.39	3.5
Common whitethroat	<i>Sylvia communis</i>	LONG	132.0	133.3	134.9	-	2.9 (53 %)	2.7	-0.23 ± 0.08	-0.32 ± 0.30	2.4
Garden warbler	<i>Sylvia borin</i>	LONG	137.6	139.9	140.5	145.7	2.3 (30 %)	3.6	-0.21 ± 0.06	-0.64 ± 0.24	1.3
Blackcap	<i>Sylvia atricapilla</i>	LONG	120.0	122.0	127.2	133.6	5.2 (60 %)	4.3	-0.49 ± 0.11	-1.11 ± 0.42	3.2
Willow warbler	<i>Phylloscopus trochilus</i>	LONG	119.2	123.2	124.3	133.8	3.1 (35 %)	4.2	-0.28 ± 0.09	-0.27 ± 0.33	2.4
Spotted flycatcher	<i>Muscicapa striata</i>	LONG	136.9	136.4	138.0	143.4	2.7 (33 %)	3.8	-0.23 ± 0.09	0.10 ± 0.34	2.2
Pied flycatcher	<i>Ficedula hypoleuca</i>	LONG	124.7	124.1	127.9	128.9	3.5 (50 %)	3.6	-0.14 ± 0.12	-0.38 ± 0.44	3.5
Red-backed shrike	<i>Lanius collurio</i>	LONG	135.2	135.4	140.0	142.2	3.9 (49 %)	4.0	-0.26 ± 0.12	0.51 ± 0.45	3.6

\*Where mean date is not given, data from this species and observatory has not been included in the analysis.



**Table S2.** Species and observatory specific parameter estimates and variance components when analyzing the middle phase of migration (50<sup>th</sup> percentile) using a linear mixed model with ‘observatory’ as a fixed effect and a random between-year variance component in common for all observatories.

Common name	Scientific name	Migration category (SHORT or LONG distance migrant)	Mean date (day of year)*				Variance components (SD units)		Estimates of slope ( $\pm$ SE)		Estimated unexplained between-year variation (SD)
			Falsterbo	Ottenby	Jomfru-land	Hanko	Between years (% of total variance)	Between years within observatories	TIME (days / year)	dNAO (days / unit)	
White wagtail	<i>Motacilla alba</i>	SHORT	124.5	129.4	117.0	112.5	0.0 (0 %)	7.6	0.07 $\pm$ 0.19	0.31 $\pm$ 0.64	0.0
Winter wren	<i>Troglodytes troglodytes</i>	SHORT	107.2	108.4	-	-	1.5 (6 %)	5.8	-0.07 $\pm$ 0.12	-0.68 $\pm$ 0.45	1.5
Hedge accentor	<i>Prunella modularis</i>	SHORT	106.8	100.2	103.1	-	4.1 (42 %)	4.8	-0.03 $\pm$ 0.14	-0.40 $\pm$ 0.53	4.2
European robin	<i>Erithacus rubecula</i>	SHORT	109.4	112.6	-	-	4.7 (74 %)	2.8	0.04 $\pm$ 0.15	0.20 $\pm$ 0.55	4.9
Common blackbird	<i>Turdus merula</i>	SHORT	106.0	91.3	-	-	1.6 (4 %)	8.1	-0.06 $\pm$ 0.17	0.04 $\pm$ 0.64	2.4
Song thrush	<i>Turdus philomelos</i>	SHORT	110.1	111.4	107.6	113.1	3.3 (26 %)	5.5	-0.11 $\pm$ 0.12	0.07 $\pm$ 0.46	3.4
Redwing	<i>Turdus iliacus</i>	SHORT	100.7	104.4	103.4	-	3.4 (22 %)	6.5	-0.22 $\pm$ 0.16	-1.18 $\pm$ 0.58	1.8
Chiffchaff	<i>Pylloscopus collybita</i>	SHORT	117.0	123.7	119.1	125.6	3.1 (26 %)	5.3	-0.40 $\pm$ 0.09	-0.15 $\pm$ 0.32	1.2
Goldcrest	<i>Regulus regulus</i>	SHORT	96.9	112.6	99.7	-	3.1 (24 %)	5.5	-0.06 $\pm$ 0.13	0.01 $\pm$ 0.48	3.3
Blue tit	<i>Parus caeruleus</i>	SHORT	91.0	90.5	-	-	0.0 (0 %)	5.8	-0.03 $\pm$ 0.32	0.05 $\pm$ 0.85	0.0
Great tit	<i>Parus major</i>	SHORT	90.1	87.5	-	-	5.1 (71 %)	3.2	-0.07 $\pm$ 0.16	-1.12 $\pm$ 0.64	4.9
Chaffinch	<i>Fringilla coelebs</i>	SHORT	105.8	109.4	-	112.4	1.8 (9 %)	5.7	0.13 $\pm$ 0.10	-0.49 $\pm$ 0.38	1.6
Brambling	<i>Fringilla montifringilla</i>	SHORT	-	116.9	-	113.0	0.0 (0 %)	4.7	-0.02 $\pm$ 0.12	-0.58 $\pm$ 0.45	0.0
European greenfinch	<i>Carduelis chloris</i>	SHORT	118.8	114.0	-	-	0.0 (0 %)	10.0	0.39 $\pm$ 0.19	1.08 $\pm$ 0.77	0.0
Common linnet	<i>Carduelis cannabina</i>	SHORT	127.5	128.0	-	-	1.2 (3 %)	6.5	0.09 $\pm$ 0.21	-0.76 $\pm$ 1.09	1.2
Yellowhammer	<i>Emberiza citrinella</i>	SHORT	-	98.1	-	-	-	6.4	-0.15 $\pm$ 0.30	-0.32 $\pm$ 0.89	6.9
Reed bunting	<i>Emberiza schoeniclus</i>	SHORT	128.1	127.6	108.2	-	8.3 (75 %)	4.9	0.23 $\pm$ 0.31	1.21 $\pm$ 1.07	9.6
Barn swallow	<i>Hirundo rustica</i>	LONG	-	148.9	147.2	138.9	2.8 (28 %)	4.6	-0.29 $\pm$ 0.10	-0.75 $\pm$ 0.39	2.0
Tree pipit	<i>Anthus trivialis</i>	LONG	128.2	131.6	129.1	127.5	3.2 (35 %)	4.4	-0.23 $\pm$ 0.11	-0.59 $\pm$ 0.41	2.8
Thrush nightingale	<i>Luscinia luscinia</i>	LONG	137.2	137.8	-	-	2.3 (47 %)	2.4	0.04 $\pm$ 0.13	-0.10 $\pm$ 0.41	2.6

Table S2 (continued)

Common name	Scientific name	Migration category (SHORT or LONG distance migrant)	Mean date (day of year)*				Variance components (SD units)		Estimates of slope (± SE)		Estimated unexplained between-year variation (SD)
			Falsterbo	Ottenby	Jomfru- land	Hanko	Between years (% of total variance)	Between years within observatories	TIME (days / year)	dNAO (days / unit)	
Bluethroat	<i>Luscinia svecica</i>	LONG	-	135.6	-	136.5	2.7 (57 %)	2.3	0.01 ± 0.11	0.76 ± 0.44	2.8
Common redstart	<i>Phoenicurus phoenicurus</i>	LONG	134.4	136.6	134.0	135.2	4.0 (53 %)	3.8	-0.18 ± 0.12	-0.78 ± 0.43	3.7
Whinchat	<i>Saxicola rubetra</i>	LONG	133.0	-	135.9	135.3	2.0 (14 %)	4.8	-0.13 ± 0.12	-0.68 ± 0.44	1.5
Marsh warbler	<i>Acrocephalus palustris</i>	LONG	149.6	151.9	-	-	3.8 (79 %)	1.9	-0.28 ± 0.13	-0.14 ± 0.54	3.4
Eurasian reed warbler	<i>Acrocephalus scirpaceus</i>	LONG	146.8	151.4	153.7	-	2.9 (35 %)	3.9	-0.15 ± 0.12	-0.03 ± 0.48	3.0
Icterine warbler	<i>Hippolais icterina</i>	LONG	149.3	149.0	144.4	-	2.1 (32 %)	3.0	-0.15 ± 0.08	-0.34 ± 0.30	1.9
Lesser whitethroat	<i>Sylvia curruca</i>	LONG	132.1	136.7	139.6	144.8	3.1 (35 %)	4.2	-0.05 ± 0.10	-0.61 ± 0.39	3.1
Common whitethroat	<i>Sylvia communis</i>	LONG	140.8	144.4	144.2	-	2.8 (41 %)	3.4	-0.09 ± 0.09	-0.44 ± 0.35	2.7
Garden warbler	<i>Sylvia borin</i>	LONG	145.2	146.9	148.0	153.5	2.6 (34 %)	3.5	-0.19 ± 0.08	-0.47 ± 0.29	2.0
Blackcap	<i>Sylvia atricapilla</i>	LONG	132.3	135.2	138.5	147.9	4.4 (37 %)	5.7	-0.22 ± 0.15	-0.62 ± 0.54	4.1
Willow warbler	<i>Phylloscopus trochilus</i>	LONG	130.8	134.8	135.0	145.2	2.4 (27 %)	4.1	-0.20 ± 0.08	-0.54 ± 0.28	1.8
Spotted flycatcher	<i>Muscicapa striata</i>	LONG	140.7	144.3	146.4	150.5	3.9 (58 %)	3.3	-0.04 ± 0.13	-0.41 ± 0.47	4.0
Pied flycatcher	<i>Ficedula hypoleuca</i>	LONG	132.0	133.4	137.6	138.8	5.2 (69 %)	3.5	0.11 ± 0.16	-0.56 ± 0.61	5.3
Red-backed shrike	<i>Lanius collurio</i>	LONG	142.6	145.6	150.2	152.5	3.5 (41 %)	4.3	-0.10 ± 0.13	0.14 ± 0.48	3.7

\*Where mean date is not given, data from this species and observatory has not been included in the analysis.

**Table S3.** Species and observatory specific parameter estimates and variance components when analyzing the late phase of migration (90<sup>th</sup> percentile) using a linear mixed model with ‘observatory’ as a fixed effect and a random between-year variance component in common for all observatories.

Common name	Scientific name	Migration category (SHORT or LONG distance migrant)	Mean date (day of year)*				Variance components (SD units)		Estimates of slope ( $\pm$ SE)		Estimated unexplained between-year variation (SD)
			Falsterbo	Ottenby	Jomfru-land	Hanko	Between years (% of total variance)	Between years within observatories	TIME (days / year)	dNAO (days / unit)	
White wagtail	<i>Motacilla alba</i>	SHORT	154.8	160.9	132.0	121.8	0.0 (0 %)	5.4	0.00 $\pm$ 0.13	0.23 $\pm$ 0.45	0.0
Winter wren	<i>Troglodytes troglodytes</i>	SHORT	120.9	124.2	-	-	5.1 (80 %)	2.6	-0.32 $\pm$ 0.14	-0.25 $\pm$ 0.52	4.7
Hedge accentor	<i>Prunella modularis</i>	SHORT	129.9	114.0	119.9	-	2.4 (10 %)	7.4	-0.14 $\pm$ 0.14	-0.48 $\pm$ 0.52	2.4
European robin	<i>Erithacus rubecula</i>	SHORT	119.7	123.2	-	-	5.9 (90 %)	2.0	-0.46 $\pm$ 0.15	-0.19 $\pm$ 0.55	5.1
Common blackbird	<i>Turdus merula</i>	SHORT	140.3	109.5	-	-	0.0 (0 %)	6.7	-0.12 $\pm$ 0.13	-0.51 $\pm$ 0.49	0.0
Song thrush	<i>Turdus philomelos</i>	SHORT	123.1	126.5	124.5	128.4	1.3 (2 %)	8.5	-0.16 $\pm$ 0.13	-0.53 $\pm$ 0.47	1.3
Redwing	<i>Turdus iliacus</i>	SHORT	101.4	116.8	114.6	-	2.0 (10 %)	6.1	-0.46 $\pm$ 0.12	-0.44 $\pm$ 0.45	0.0
Chiffchaff	<i>Pylloscopus collybita</i>	SHORT	137.1	149.0	133.0	142.9	3.1 (14 %)	7.5	-0.33 $\pm$ 0.12	-0.42 $\pm$ 0.47	2.2
Goldcrest	<i>Regulus regulus</i>	SHORT	108.5	123.2	114.5	-	4.9 (27 %)	8.2	-0.29 $\pm$ 0.19	-0.26 $\pm$ 0.71	4.8
Blue tit	<i>Parus caeruleus</i>	SHORT	114.5	104.2	-	-	0.0 (0 %)	9.6	0.05 $\pm$ 0.51	-1.57 $\pm$ 1.33	2.6
Great tit	<i>Parus major</i>	SHORT	114.7	102.2	-	-	0.0 (0 %)	9.3	0.26 $\pm$ 0.21	-0.22 $\pm$ 0.87	0.0
Chaffinch	<i>Fringilla coelebs</i>	SHORT	136.5	140.9	-	126.0	1.1 (2 %)	8.4	0.03 $\pm$ 0.14	-0.32 $\pm$ 0.53	1.7
Brambling	<i>Fringilla montifringilla</i>	SHORT	-	123.0	-	120.7	0.5 (1 %)	5.2	-0.11 $\pm$ 0.12	-1.28 $\pm$ 0.45	0.0
European greenfinch	<i>Carduelis chloris</i>	SHORT	145.4	142.4	-	-	5.7 (35 %)	7.9	0.41 $\pm$ 0.21	1.06 $\pm$ 0.82	4.7
Common linnet	<i>Carduelis cannabina</i>	SHORT	147.2	154.4	-	-	0.0 (0 %)	7.2	0.67 $\pm$ 0.18	0.03 $\pm$ 0.93	0.0
Yellowhammer	<i>Emberiza citrinella</i>	SHORT	-	118.8	-	-	-	6.3	-0.18 $\pm$ 0.28	0.81 $\pm$ 0.84	6.5
Reed bunting	<i>Emberiza schoeniclus</i>	SHORT	136.6	143.2	133.2	-	6.7 (100 %)	0.0	-0.13 $\pm$ 0.18	1.50 $\pm$ 0.66	6.2
Barn swallow	<i>Hirundo rustica</i>	LONG	-	159.2	161.2	150.2	2.2 (16 %)	5.1	-0.20 $\pm$ 0.09	-1.26 $\pm$ 0.36	0.0
Tree pipit	<i>Anthus trivialis</i>	LONG	133.4	143.2	140.8	136.1	2.3 (12 %)	6.3	-0.28 $\pm$ 0.11	-0.75 $\pm$ 0.40	0.0
Thrush nightingale	<i>Luscinia luscinia</i>	LONG	144.7	146.4	-	-	3.5 (56 %)	3.1	-0.11 $\pm$ 0.17	-0.44 $\pm$ 0.55	3.5

Table S3 (continued)

Common name	Scientific name	Migration category (SHORT or LONG distance migrant)	Mean date (day of year)*				Variance components (SD units)		Estimates of slope (± SE)		Estimated unexplained between-year variation (SD)
			Falsterbo	Ottenby	Jomfru- land	Hanko	Between years (% of total variance)	Between years within observatories	TIME (days / year)	dNAO (days / unit)	
Bluethroat	<i>Luscinia svecica</i>	LONG	-	140.2	-	141.9	3.8 (83 %)	1.7	0.16 ± 0.13	-0.02 ± 0.53	3.8
Common redstart	<i>Phoenicurus phoenicurus</i>	LONG	144.2	148.7	143.6	144.7	4.5 (55 %)	4.1	-0.17 ± 0.12	-1.24 ± 0.44	3.7
Whinchat	<i>Saxicola rubetra</i>	LONG	139.0	-	146.2	147.3	3.3 (50 %)	3.4	-0.12 ± 0.12	-0.73 ± 0.44	3.2
Marsh warbler	<i>Acrocephalus palustris</i>	LONG	155.1	159.2	-	-	3.0 (53 %)	2.9	-0.15 ± 0.14	0.27 ± 0.59	3.2
Eurasian reed warbler	<i>Acrocephalus scirpaceus</i>	LONG	153.5	160.0	161.7	-	0.0 (0 %)	3.4	-0.10 ± 0.07	-0.02 ± 0.30	0.0
Icterine warbler	<i>Hippolais icterina</i>	LONG	156.0	157.5	154.6	-	1.8 (30 %)	2.7	-0.16 ± 0.07	0.04 ± 0.26	1.5
Lesser whitethroat	<i>Sylvia curruca</i>	LONG	147.7	150.5	151.4	156.6	2.8 (23 %)	5.1	0.02 ± 0.10	-0.75 ± 0.37	2.5
Common whitethroat	<i>Sylvia communis</i>	LONG	151.4	157.2	152.7	-	2.6 (42 %)	3.1	-0.15 ± 0.08	-0.56 ± 0.30	2.2
Garden warbler	<i>Sylvia borin</i>	LONG	154.0	153.5	157.4	160.9	2.3 (35 %)	3.1	-0.16 ± 0.07	-0.12 ± 0.27	2.0
Blackcap	<i>Sylvia atricapilla</i>	LONG	148.7	150.5	154.5	159.3	3.3 (37 %)	4.3	-0.09 ± 0.12	-0.26 ± 0.43	3.4
Willow warbler	<i>Phylloscopus trochilus</i>	LONG	142.1	146.9	146.0	156.4	2.1 (28 %)	3.3	-0.05 ± 0.07	-0.66 ± 0.25	1.7
Spotted flycatcher	<i>Muscicapa striata</i>	LONG	149.1	153.4	157.0	156.5	4.0 (58 %)	3.4	-0.11 ± 0.13	-0.79 ± 0.47	3.9
Pied flycatcher	<i>Ficedula hypoleuca</i>	LONG	140.9	142.6	146.0	153.6	3.4 (22 %)	6.4	0.17 ± 0.15	-0.45 ± 0.55	3.2
Red-backed shrike	<i>Lanius collurio</i>	LONG	150.2	152.8	159.8	161.1	3.4 (50 %)	3.4	0.01 ± 0.12	0.40 ± 0.43	3.5

\*Where mean date is not given, data from this species and observatory has not been included in the analysis.

**Table S4.** Species-specific parameter estimates on Capri.

Species	Mean date (day of year)	Standard deviation	Estimates of slope ( $\pm$ SE)		R <sup>2</sup>
			TIME (days / year)	dNAO (days / unit)	
Early phase of migration (10 <sup>th</sup> percentile)					
Tree pipit	106.7	4.2	-0.05 $\pm$ 0.19	0.47 $\pm$ 0.50	0.07
Common redstart	109.2	4.1	-0.23 $\pm$ 0.15	-0.06 $\pm$ 0.46	0.12
Whinchat	111.7	5.3	-0.28 $\pm$ 0.18	0.86 $\pm$ 0.56	0.26
Icterine warbler	126.3	3.4	-0.29 $\pm$ 0.10	0.58 $\pm$ 0.29	0.51
Common whitethroat	114.8	4.0	-0.26 $\pm$ 0.13	0.75 $\pm$ 0.38	0.38
Garden warbler	121.6	3.0	-0.26 $\pm$ 0.09	0.34 $\pm$ 0.28	0.41
Willow warbler	105.5	4.4	-0.38 $\pm$ 0.15	-0.23 $\pm$ 0.45	0.30
Spotted flycatcher	121.3	4.0	-0.12 $\pm$ 0.13	1.02 $\pm$ 0.40	0.35
Pied flycatcher	107.5	4.7	-0.28 $\pm$ 0.16	0.76 $\pm$ 0.47	0.30
Middle phase of migration (50 <sup>th</sup> percentile)					
Tree pipit	117.3	3.8	-0.05 $\pm$ 0.16	0.58 $\pm$ 0.43	0.13
Common redstart	119.9	3.8	-0.20 $\pm$ 0.14	-0.14 $\pm$ 0.43	0.11
Whinchat	121.8	4.9	-0.32 $\pm$ 0.16	0.76 $\pm$ 0.48	0.33
Icterine warbler	134.9	4.3	-0.30 $\pm$ 0.14	0.64 $\pm$ 0.43	0.35
Common whitethroat	125.7	4.1	-0.28 $\pm$ 0.12	0.82 $\pm$ 0.38	0.43
Garden warbler	132.2	3.4	-0.27 $\pm$ 0.11	0.46 $\pm$ 0.33	0.38
Willow warbler	116.4	3.6	-0.34 $\pm$ 0.12	-0.20 $\pm$ 0.36	0.34
Spotted flycatcher	129.9	4.7	-0.06 $\pm$ 0.17	0.94 $\pm$ 0.51	0.19
Pied flycatcher	117.5	3.9	-0.23 $\pm$ 0.13	0.60 $\pm$ 0.40	0.28
Late phase of migration (90 <sup>th</sup> percentile)					
Tree pipit	127.8	3.7	-0.05 $\pm$ 0.15	0.73 $\pm$ 0.41	0.20
Common redstart	130.6	3.9	-0.20 $\pm$ 0.15	-0.23 $\pm$ 0.45	0.10
Whinchat	131.8	4.9	-0.37 $\pm$ 0.16	0.73 $\pm$ 0.47	0.38
Icterine warbler	143.5	5.7	-0.30 $\pm$ 0.20	0.67 $\pm$ 0.61	0.21
Common whitethroat	136.7	4.4	-0.30 $\pm$ 0.13	0.92 $\pm$ 0.40	0.45
Garden warbler	143.0	4.1	-0.27 $\pm$ 0.14	0.57 $\pm$ 0.42	0.31
Willow warbler	127.2	3.2	-0.31 $\pm$ 0.10	-0.16 $\pm$ 0.31	0.36
Spotted flycatcher	138.7	5.9	0.00 $\pm$ 0.23	0.85 $\pm$ 0.69	0.09
Pied flycatcher	127.4	3.6	-0.19 $\pm$ 0.13	0.44 $\pm$ 0.40	0.20

**Table S5.** Priors for mean passage dates on Capri. The parameters  $\tau$  were constrained to fall within the intervals indicated for each species by using a uniform prior. The range of estimated values of  $\tau$  (based on the medians of the posterior distributions over all years) are shown to the right.

Species	Earliest allowed mean date	Latest allowed mean date	Range in estimated mean date
Tree pipit	March 25	May 10	April 21–May 6
Common redstart	March 10	May 15	April 24–May 6
Whinchat	April 5	May 20	April 23–May 11
Icterine warbler	April 25	May 25	May 7–May 21
Common whitethroat	March 25	May 25	April 29–May 14
Garden warbler	April 15	May 30	May 8–May 17
Willow warbler	March 15	May 15	April 20–May 3
Spotted flycatcher	April 20	May 25	May 3–May 18
Pied flycatcher	April 15	May 20	April 19–May 2