Alaska at the Crossroads of Migration: Space-Based Ornithology

by J. L. Deppe, K. Wessels, and J. A. Smith

Abstract

Understanding bird migration on a global scale is one of the most compelling and challenging problems of modern biology. Each year multitudes of migratory birds travel between breeding grounds in Alaska and wintering grounds in the Americas, Asia, and Australia. Here we present the conceptual framework for a spatially explicit, individual-based bio-physical migration model driven by dynamic remote sensing observations of atmospheric and land surface conditions to simulate migration routes, timing, energy budgets, and probability of survival. Understanding temporal and spatial patterns of bird migration will provide insight into pressing conservation and human health issues related to this taxonomic group.

Introduction

Each year millions of birds migrate extensive distances between their breeding and wintering grounds. These migratory journeys are comprised of extended flights interrupted by stopover periods during which birds refuel, rest, molt, and seek shelter from unfavorable weather conditions and predators. Successful migration depends on the availability of favorable atmospheric conditions aloft and suitable habitat during stopovers. Our ability to understand bird migration has generally been hindered by the large geographic scale of migratory movements and the short time period during which migration takes place. However, advances in remote sensing now provide us with near real-time measurements of atmospheric and land surface conditions at high spatial resolution over entire continents, offering new tools and approaches for understanding bird migration *(Table 1)*.

MODIS (TERRA and/or AQUA)		
Surface temperature	1 km	8 Days
Snow cover	500 m	8 Days
Net photosynthesis (PSN)	1 km	8 Days
Leaf area index/Fraction photosynthetically active radiation	1 km	8 Days
Enhanced vegetation index (EVI)	1 km	16 Days
Normalized difference vegetation index (NDVI)	250 m	16 Days
Land cover dynamics (phenology)	1 km	Annual
Land cover type	1 km	Annual
Vegetation continuous fields	500 m	Annual
Vegetation cover conversion	500 m	5 Years
Data assimilation products (NCEP/NARR/GMAO/GDAS)		
Wind fields	Variable	3 hr
Precipitation	Variable	3 hr
Soil moisture (catchment model)	Variable	Daily

Table 1. Remote sensing products used as inputs into bird migration and habitat suitability models and their respective spatial and temporal resolution.

Although migration has fascinated biologists and bird watchers for centuries, population declines in many migratory bird species during the past several decades and the recent emergence of H5N1 Avian Influenza have intensified our interest in this phenomenon. A major concern of conservation biologists is that human-induced changes in climate and land surface conditions along migratory routes, as well as on the breeding and wintering grounds, may negatively impact migratory bird populations by reducing the quantity and quality of habitat or altering the timing of birds' activities. For example, how do changes in the distribution, abundance, and/or quality of stopover habitat influence migratory routes, passage dates, dates of arrival and physical condition upon arrival at breeding and wintering grounds, and probability of survival? Human health officials, resource managers, and public policy makers are interested in the role migratory birds play in the global dispersal of avian-borne diseases and the identification of precise migratory routes of infected species. While general migratory flyways are recognized, such abstractions provide little guidance in identifying high-risk areas for focused surveillance and mitigation efforts.

Alaska is a nexus of migratory bird activity. Over 60% of the species that regularly breed in Alaska migrate to wintering grounds in the Americas, Oceania, and Asia. Many of these species, particularly shorebirds and waterfowl, are susceptible to Avian Influenza *(USGS National Wildlife Health Center)* and represent a potential vector for the spread of this and other avian-borne viruses. Alaska's diverse aquatic and terrestrial ecosystems provide important breeding and stopover habitat for migratory birds. Coastal habitats and meadows are used as stopover/staging sites by millions of shorebirds each year *(Alaska Shorebird Working Group 2000)*, and interior forest, riparian corridors, and shrublands offer stopover habitat for landbirds *(Boreal Partners in Flight Working Group 1999)*. Human-induced loss and alteration of these habitats is expected to have a negative impact on migratory bird populations. Timber harvesting, mining, urbanization, road construction, recreational activities, and oil drilling may eliminate key stopover sites and/or reduce habitat quality. Furthermore, climate-induced changes in land surface and atmospheric conditions in Alaska are expected to be pronounced *(Calef et al. 2005)*, and the effects of global warming, manifested as longer growing seasons, warmer winters, greater productivity, changing wetland and boreal forest distributions, and changing fire regimes, are already evident *(Keyser et al. 2000, Rupp et al. 2000, Jorgenson et al. 2001, Riordan et al. 2006)*. Such changes in environmental conditions and processes will alter the distribution, abundance, and quality of breeding and stopover habitat for Alaska migrants as well as impact the timing of migrants' activities *(Bairlein and Hüppop 2004, Roland and McIntyre 2006)*.

Objectives

The objectives of our research are twofold:

- to develop and evaluate a spatially explicit, individual-based biophysical simulation model driven by near real-time atmospheric and land surface conditions to describe temporal and spatial migration patterns, and
- to use our model to provide insight into the complex relationships among animal movement, climate, habitat change, and disease dispersal.

Concept-driven individual-based simulation models offer a valuable tool for studying bird migration, because they integrate information on migrant ecology, physiology, and behavior with remote sensing data on atmospheric and land surface conditions *(Simons et al. 2000, Erni et al. 2003)*. Such models allow us to assimilate information about processes that take place at multiple spatial and temporal scales to understand global and hemispheric migration as a whole. While there are gaps in our current understanding of large-scale migration patterns and processes, the comprehensive development of the model will provide guidance for future research efforts in this

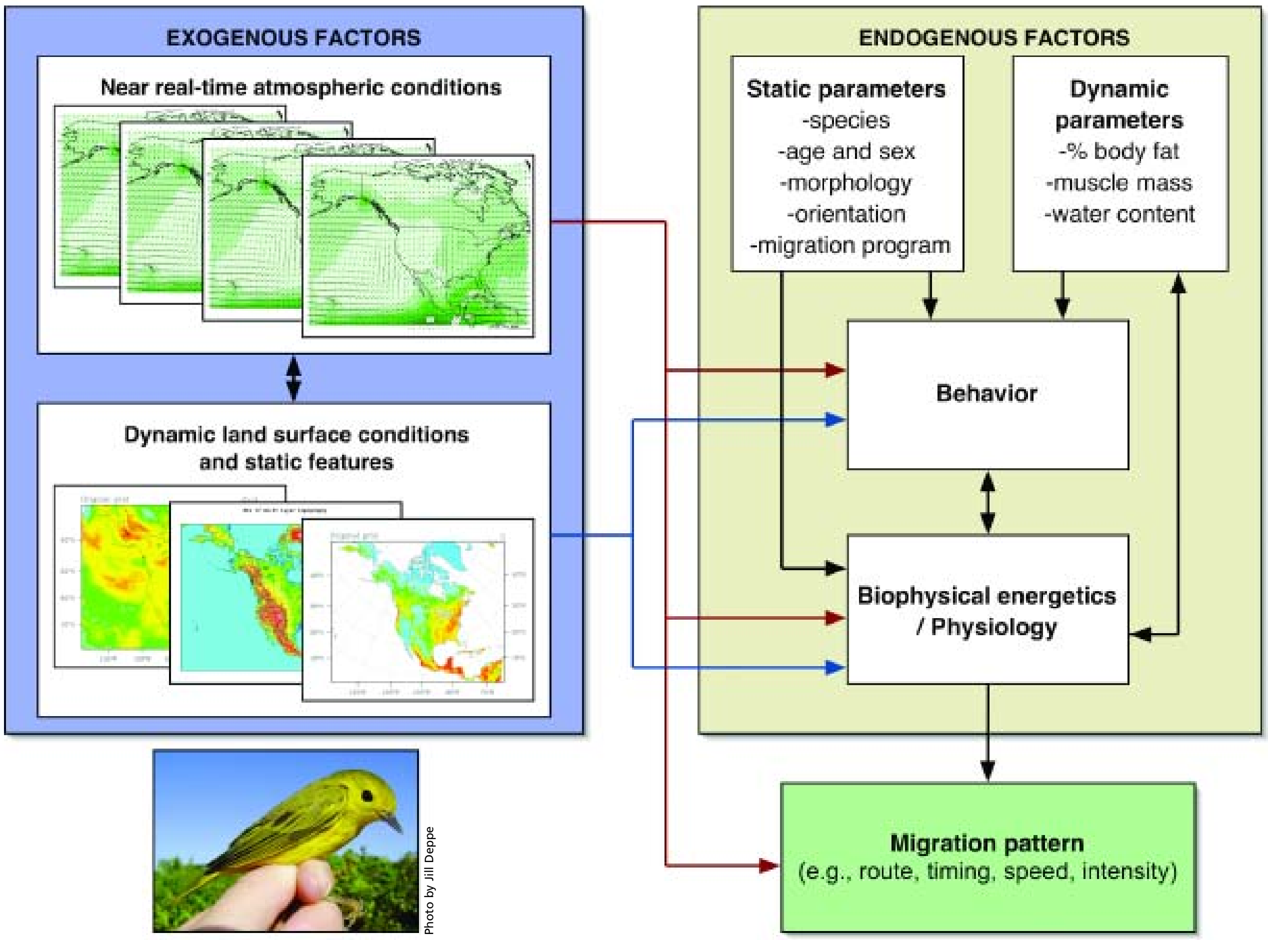

Figure 1. Modeling framework illustrating the general factors that influence bird migration and their interactions.

area and identify relevant questions and hypotheses that need to be addressed to further our knowledge of bird migration. Once validated and refined, the migration model may be used to evaluate our second objective and provide insight into conservation- and health-related questions. Here, we provide a coarse conceptual view of our bird migration model by outlining the general factors that interact to shape bird migration.

Migration Model Framework

Large-scale bird migration patterns are strongly influenced by exogenous factors that are unrelated to the bird. These factors may be divided into two main categories—atmospheric and land surface conditions/attributes *(Figure 1, blue box)*. Dynamic atmospheric conditions, such as wind, precipitation, temperature, and cloud cover impact migration patterns *(Gauthreaux et al. 2005, Cochran and Wikelski 2005)*. These conditions shape migration patterns directly through their influence on migration direction and speed *(Gauthreaux and Able 1970, Butler et al. 1997)* and indirectly through their impact on birds' activity budgets and energy balance, which in turn determine migrants' flight range and overall migration speed (total number of days to reach endpoint) *(Figure 2) (Berthold 2001, Cochran and Wikelski 2005)*. Land surface attributes (e.g., land cover), as well as temporally dynamic conditions, such as soil moisture, temperature, and leaf cover, influence migration patterns via their impact on habitat quality and, in turn, migrants' behavior, energy budget, and survival *(Bairlein and Hüppop 2004, Smith et al. 2007)*. Topographic features such as mountains or coastlines represent ecological barriers and function as landmarks to guide birds while aloft *(Berthold 2001)*.

Endogenous factors related to the bird itself also influence migration patterns *(Figure 1, brown box)*. Static parameters, including species, sex, age (static during a migratory period), morphology, and inherited migration programs and orientation, influence birds' behavior, ecology and physiology during migration *(Woodrey 2000, Berthold 2001)*. Dynamic endogenous characteristics, such as fat load, muscle mass, and water content, also influence migrants' behavior and energy dynamics but, unlike static parameters, are themselves modified as a consequence of birds' activities and environmental conditions *(Moore and Aborn 2000, Smith et al. 2007)*.

Behavioral decisions are dependent upon exogenous and endogenous factors. An individual's activity budget, habitat choice, static and dynamic endogenous characteristics, and atmospheric and land surface conditions interact to determine an individual's energetic state and survival. The precise outcome of this interaction is mediated by the bird's physiology. By keeping track of a bird's activity, physical condition, and location over the course of a migration period, individual-based simulations may project the migratory route, date of passage or arrival, physical condition at key stopover sites or endpoints, overall speed of migration (km/day), intensity of migration for a population of simulated birds, and likelihood of survival (based on energy and time constraints).

A Closer Look at Flight Physiology and Wind

At the core of any bird migration model is a biophysical sub-model that describes how birds burn energy, primarily from fat but also protein, while in flight. The flight model estimates the maximum distance a bird can fly based on its morphology, physiology, energy load, and atmospheric conditions. Simulations using morphological and physiological parameters of virtual birds illustrate the general relationship between fat load and potential migration distance *(Figure 2)*: as the amount of fat increases, a bird can fly farther *(Pennycuick 1998)*. This association highlights how habitat quality may influence large-scale migration patterns. Birds occupying higher quality habitat on breeding, winter, and/or stopover sites may accumulate

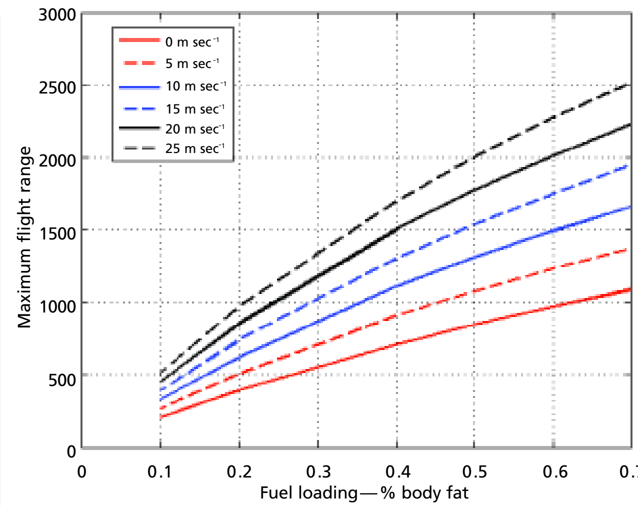

Figure 2. Estimated maximum flight ranges of virtual birds with variable fat loads and tail wind velocities; all other flight parameters held constant *(Pennycuick 1998)*. As percent body fat, or energy load, increases, birds are able to fly longer distances, and faster tail winds result in higher maximum flight ranges for any given fat load. Birds are assumed to fly until they exhaust their fat reserves.

U.S. Fish & Wildlife Service photo by Donna Dewhurst

Blackpoll warblers are champion migrants. Some birds migrate more than 4,900 miles from their breeding grounds in Alaska to wintering grounds in South America. During fall migration most individuals are hypothesized to make overwater flights up to 1,800 miles from the northeastern United States to northern South America.

Static parameters, including species, sex, age (static during a migratory period), morphology, and inherited migration programs and orientation, influence birds' behavior, ecology and physiology during migration.

more fat and be able to fly farther.

Wind has a significant impact on large-scale migration patterns. Tail winds assist migrants by reducing energy consumption, increasing speed, and/or increasing potential flight ranges *(Figure 2)*, whereas head winds have the opposite effect and may prevent migrants from flying at all. Additionally, wind exerts a direct influence on the direction of migration; for example, crosswinds may cause birds to drift off course. Wind conditions experienced by

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Figure 3. Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) Model predicts the movement of air parcels and is used here to illustrate the wind structure experienced by migratory birds originating at Denali National Park and Preserve. HYSPLIT analysis shown here was run directly on NOAA's Real-time Environmental Applications and Display System (READY) website. Trajectories were modeled using the FNL data set with 6-hr and 119 mi (191 km) resolution. The red, blue and green lines illustrate wind conditions at 0.3, 0.6 and 0.9 mi (500, 1000 and 1500 m) above ground level, respectively, for a 7-day period beginning August 1 2001.

migratory birds aloft are dynamic and complex. Particle trajectory models, such as NOAA's HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model (http://www.arl.noaa.gov/ready/hysplit4.html) are valuable in exploring and quantifying short-term dynamics in wind structure in three dimensions plus time along a bird's migratory route *(Figure 3)*. Such models have been used to describe the wind conditions associated with migratory departure events from Alaska *(Gill et al. 2005)* and the seasonal migration strategies that birds use during migration over the Gulf of Mexico *(Gauthreaux et al. 2005)*.

Future Challenges

The role of static and/or dynamic characteristics of the land surface in shaping migration patterns has received relatively little attention *(Tankersley and Orvis 2003)*. Dynamic (e.g., soil moisture, leaf cover) and seasonally static features (e.g., land cover class) influence migrant distributions as well as birds' rate of fat deposition, potential flight ranges, and overall migration speed. Remote sensing data from NASA combined with empirical data on the occurrence and abundance of migratory birds can be integrated to develop dynamic habitat suitability models for en-route migrant birds and enhance our ability to model foraging energetics and behavior at stopover sites *(Table 1)*.

A critical future step is the validation and refinement of the overall migration simulation model and its component parts using field data. Satellite tracking of individuals provides excellent data on migratory routes of large birds *(McIntyre et al. 2006)*, and progress is underway to develop similar technologies for small birds *(Wikelski et al. 2007)*. We can test the overall migration model by comparing observed migration routes and timing of migration to probabilistic routes and passage/arrival dates predicted by the model. Field data on migrant abundances (e.g., number of captures/net-hour, number of birds/day), mean and range of passage dates, and energetic condition (fat levels, mass, muscular atrophy) collected from banding stations and count

U.S. Fish & Wildlife Service photo by Tim Bowman

Many shorebirds like the bar-tailed godwit migrate extensive distances. Bar-tailed godwits nest in the treeless tundra and coastal and alpine meadows of Alaska and spend the nonbreeding season in marshes, sandy beaches, and inland wetlands and fields of Australasia.

surveys at stopover sites *(see Skagen et al. 1999, Deppe and Rotenberry 2005)*, as well as the dates of arrival and physical condition of birds upon arrival at their Alaska breeding grounds, can be used to validate and fine-tune the model by comparing spatially-explicit predicted and observed values.

Once validated and refined, we can use the migration model to explore conservation and health-related issues pertaining to bird migration in Alaska including:

- How do the environmental changes observed in Alaska, such as permafrost degradation, thermokarst draining of tundra ponds, erosion, submergence, sedimentation, salinization of coastal ponds, changing fire regimes, longer growing seasons, greater productivity, and warmer winters alter the quality, abundance, size, and spacing among suitable stopover sites for Alaska migrants?

- How do such habitat alterations impact spatial and temporal patterns of migration, birds' probability of survival, and population growth?
- If a bird tests positive for an avian-borne virus, where was that bird in the days prior to capture, and if released after sample collection, where is that bird likely to have gone?

Ecological modeling of habitat suitability based on historical and current remote sensing data can be used to map the spatial distribution and abundance of stopover habitat, as well as quantify changes in habitat availability. We can then perform simulations of bird migration through environments reflecting current, historical, and forecasted land surface conditions and compare the predicted migration patterns to identify negative impacts. Answers to these and similar questions are critical for conserving migratory bird species and maintaining the biological integrity of global ecosystems.

Management Implications for Alaska's National Parks

The fundamental objective of our migration model is to understand migration as a whole, in other words, understand connectivity among stopover sites and stages of the annual cycle and identify the large-scale factors and processes shaping migration patterns. An effective conservation strategy for this group requires a holistic approach under which breeding, winter, and stopover habitat along species' entire fall and spring migratory routes need to be protected. Management activities at the level of individual national parks may contribute to the conservation of migratory birds by reducing particular sources of ecological stress. The tested and refined migration model may be used by park managers to provide insight into how historical, current, and future activities or changes in land surface conditions within individual Alaska national parks, such as Denali National Park and Preserve, or networks of protected areas, may impact large-scale migration patterns, such as migration routes and birds' probability of survival. Additionally, the model may be used to generate probabilistic estimates of the spatial and temporal movement of disease-infected birds through Alaska that can be used by park managers to estimate the risks proposed to wildlife within park boundaries and plan focused surveillance and mitigation efforts.

U.S. Fish & Wildlife Service photo by Donna Dewhurst

Semipalmated plover, a medium- to long-distance migrant, breeds throughout Alaska and winters along the Pacific and Atlantic coasts of the southern United States, Mexico, and Central and South America. In Alaska the species breeds in riverine alluvia and gravel beaches, and during migration it occupies silt tidal flats and sandy beaches (Alaska Shorebird Working Group 2000).

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