SPACE-BASED REMOTE SENSING – A TOOL FOR STUDYING BIRD MIGRATION ACROSS MULTIPLE SCALES

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ABSTRACT

The study of bird migration on a global scale is one of the compelling and challenging problems of modern biology with major implications for human health and conservation biology. Migration and conservation efforts cross national boundaries and are subject to numerous international agreements and treaties. Space based technology offers new opportunities to shed understanding on the distribution and migration of organisms on the planet and their sensitivity to human disturbances and environmental changes.

Our working hypothesis is that individual organism biophysical models of energy and water balance, driven by satellite measurements of spatio-temporal gradients in climate and habitat, will help us to explain the variability in avian species richness and distribution.

Further, these models provide an ecological forecasting tool for science and application users to visualize the possible consequences of loss of wetlands, flooding, or other natural disasters such as hurricanes on avian biodiversity and bird migration.

KEY WORDS

Modelling of natural phenomena, visualization, remote sensing, avian energetics and bird migration

1. Introduction

There is an increasing need to understand the distribution and migration of bird species and other organisms on a global scale as is evident, for example, with the recent examples of threats to human health via avian vector transmission. The distribution limits and migration of organisms also serve as a potential indicator for global change and provide guidance for conservation efforts at local and global scales.

On a biogeographical scale, there have been several studies that relate patterns of bird distributions to such bioclimatic factors as latitudinal variations in air temperature, precipitation, and photo-period [1] [2]. While these correlative studies are insightful and provide guidance, they do not explicitly include underlying physical, biological, or ecological mechanisms that can predict organism responses to anthropogenic or other changes in the environment.

In our approach, we use species-specific features of physiology, ecology, morphology, behavior and biophysical ecology to characterize species-specific, dynamic habitats, distribution, and abundance of species [3]. Energy constraints and organism response to the physical and biological environment are first order determinants of pattern that are then modified by competition, predator-prey, and management actions.

In an earlier paper, we outlined an approach using biophysical modeling, driven by remote sensing inputs, to set theoretical constraints on the geographic limits to avifauna distributions [4]. We also described a potential space-based mechanism to track individual bird migration using very low-power ground transmitters that could be used to test such models [5].

In this paper, we illustrate our first steps in showing that individual-based biophysical organism models, driven by remote sensing data assimilation products, can be used to study bird migration at global scales

Our work suggests that avian migration, to first order, may be an emergent behavior in response to changes in the geospatial and temporal variation in the climatic variables that define the underlying climate space niche of birds.

2. Approach

We assume that observed patterns in the distributions of bird species can be related to species-specific energy costs and gains in response to climate or resource gradients.

Migration could be explicitly included as a separate mechanism by considering energetic costs of feeding, resting, and flying to migratory stop-overs.

Here, we first develop a simple individual bird energy balance model based on morphological, physiological, and thermal properties and observe that migration arises as a natural emergent property when our simple model is driven by temporally varying remote sensing spatial fields of climatic factors.

2.1 Energy Balance Model

We start with the energy balance model for an individual bird [6]. An endothermic organism must maintain its body temperature within acceptable limits subject to internal and external energy sources and sinks. There is a reference basal metaboloic existence threshold, M, and associated costs for behavior patterns, such as foraging, coping with competitors, avoiding prey, reproduction, and self-maintenance. Activity costs are manifested in a modification to the metabolic rate affecting available energy and need for food resources to maintain thermoregulation.

An individual organism is subject to net incoming short and long wave radiation, i.e. net radiation, Rn; respiration, LE; and sensible heat, H, Figure 1.

Figure 1. Schematic of Energy Balance Relationships
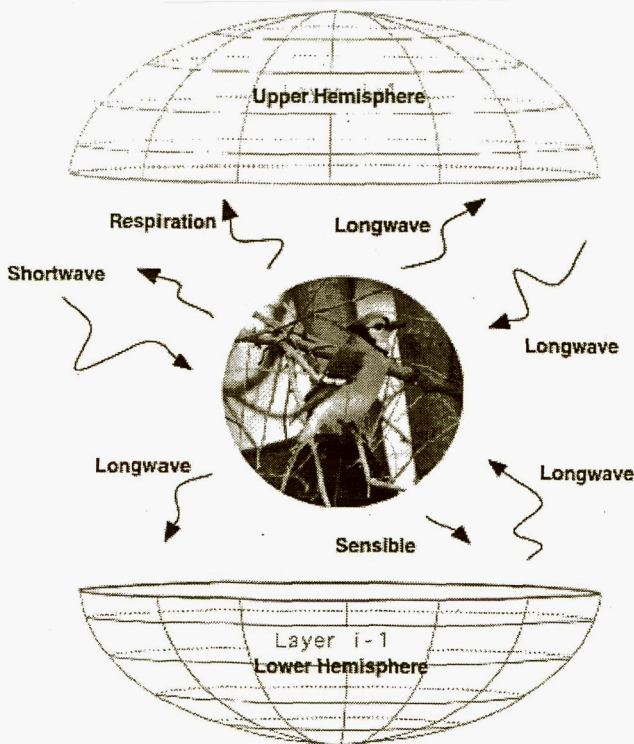
The energy balance equation may be summarized as:

$$(1) \qquad F = Rn - H - \lambda E + M = 0$$

Rewriting the equation to show the explicit dependence on climatic driving variables (Air temperature, Ta; Solar radiation, S; wind speed, u; and relative humidity, RH), bird physiologic and morphological features, (Metabolic rate, M; size, d; area, A; emission and conductance properties, e and g), and landscape level variables related to habitat and available food (Net primary production, NPP; leaf area index, LAI) and inverting the model as a function of body temperature, Tb, we obtain:

$$(2) \qquad T_b = F ($$

$$\{T_a, S, u, RH,...\},$$

$$\{ M, d, A, e, g_i ...\}$$

$$\{NPP, LAI, ...\}$$

$$)$$

Equation (2) can be used to determine whether an organism of specified characteristics could exist and where it can maintain a feasible metabolic rate for its mass within the climate space niche spanned by the abiotic driving variables. In practice, this means finding all possible combinations of, e.g. air temperature and solar radiation, that yield an acceptable core temperature within the allowable upper and lower critical temperatures for the species.

That is, find all $\{Ta,S\}$ that satisfy

$$(3) \qquad T_L < Tb < T_U$$

We use satellite remote sensing, data assimilation products to obtain the driving variables for our models. Figure 2 shows the July global distribution for net absorbed radiation (left side) and air temperature (right side) estimated on a 1 degree by 1 degree grid cell resolution using the CASA integrated ecosystem/climate model [7]. The grayscale bars indicate watts per square meter (left) and degrees Centigrade (right).

The set of all permissible solutions for each species defines the allowable climate space niche for that species, which can then be mapped to the landscape.

2.2 Example

We illustrate the use of our model by applying it to Pectoral Sandpipers (*Calidris melanotos*). This is one of about 30 shorebird species that migrate from its wintering range in South America through central North America to its summer breeding grounds in the Arctic and back again during fall migration.

It has a lean mass of 50 g and its maximum fat storage is equal to about 70% of its lean mass.

Figure 3 shows the results of using the individual bird energy budget model using the parameters for Pectoral Sandpiper and driving the model with monthly time series solar radiation and air temperature data fields interpolated to a one degree by one degree latitude and longitude grid.

The top row of the figure corresponds to January, February, and March. The next row corresponds to April, May, and June and so forth until December is reached in the lower right.

For each month, the geographic region corresponding to the allowable climate space niche for the species is indicated in white. These regions correspond to the geographic potential niche for each time period based on our energy balance model and climatic driving variables. The actual or realizable niche also will depend upon food availability and other biotic factors.

The general pattern for North America predicts that Pectoral Sandpiper will reach the southern coast of the U.S. (after a trans-Gulf of Mexico migration) around the beginning of April and, subsequent, arrive at the northern breeding grounds in the June time frame. The reverse, fall migration is initiated in late August. These patterns are consistent with observed trends during normal years.

3. Conclusion

We have taken the first steps in illustrating how an individual-based biophysical model of avian energy state, driven by abiotic driving variables derived by satellite data, can be used to predict the spatial and temporal distribution limits of individual bird species.

Further, our example suggests that avian migration may be an emergent behavior in response to changes in the geospatial and temporal variation in climatic variables. These climatic variations also govern the concurrent spatial-temporal distributions of underlying food sources and, hence, an alternative interpretation may be made that migrating birds follow these gradients as well [8].

Satellite data and individual organism models allow us to study bird behavior at multiple scales. In our future work, we plan to incorporate explicit mapping of underlying landscape biotic factors and dynamic programming to allow us to address fundamental questions of what are the possible consequences of loss of wetlands, flooding, drought, or other natural disasters such as hurricanes, on avian biodiversity and bird migration [9].

References:

[1] David J. Currie. Energy and large-scale patterns of animal and plant species richness, *American Naturalist 137*, 1991, 27-29.

[2] Terry Root, Energy constraints on avian distributions and abundances, *Ecology, 69*, 1998, 330-339.

[3] E. Gwinner, *Bird migration: physiology and ecophysiology* (Berlin, Springer-Verlag).

[4] James A. Smith, Simulation of avifauna distributions using remote sensing. *Proc. IEEE International Geoscience and Remote Sensing Symposium*, Anchorage, Alaska, 2004.

[5] George W. Swenson, Martin Wikelsi, and James A. Smith, Tracking very-low power ground transmitters from near-Earth orbit, *Proc. IEEE International Geoscience and Remote Sensing Symposium*, Anchorage, Alaska, 2004.

[6] David M. Gates, *Biophysical ecology* (New York, Springer-Verlag, 1980).

[7] C. S. Potter, J. T. Randerson, C. B. Field, et al, Terrestrial ecosystem production: a process model based on global satellite and surface data, *Global Biogeochemicl Cycles 7*, 1993, 811-841.

[8] T. R. Simons, S. M. Pearson, and F. R. Moore, Application of spatial models to the stopover ecology of trans-Gulf migrants, *Studies in Avian Biology 20*, 2000, 4-14.

[9] A. H. Farmer and John Weins, Optimal migration schedules depend on the landscape and the physical environment: a dynamic modeling view, *J. Avian Biology, 29*, 1998, 405-415.

Figure 2. July Global Distribution of Solar Radiation (left) and Air Temperature (Right)
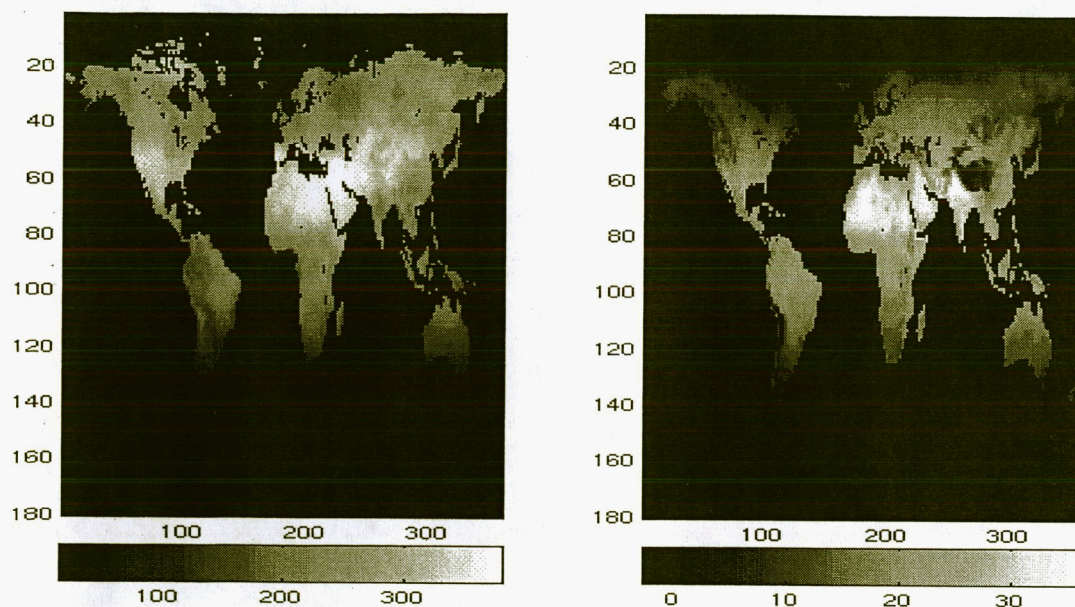

Figure 3. Predicted Geographic Distribution and Migration Pattern for Pectoral Sandpiper