IAC-15-B5,2,8,x30258

REMOTE SENSING IN SUPPORT OF ENDANGERED SPECIES MANAGEMENT AND ANIMAL MOVEMENT RESEARCH - THE ENV-DATA TOOL PACK

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The movement of animals is strongly influenced by external factors in their surrounding environment such as weather, habitat types, and human land use. With advances in positioning and sensor technologies, it is now possible to capture animal locations at high spatial and temporal granularities. Likewise, modern space-based remote sensing technology provides us with an increasing access to large volumes of environmental data, some of which changes on an hourly basis. Environmental data are heterogeneous in source and format, and are usually obtained at different scales and granularities than movement data.

Indeed, there remain scientific and technical challenges in developing linkages between the growing collections of animal movement data and the large repositories of heterogeneous remote sensing observations, as well as in the developments of new statistical and computational methods for the analysis of movement in its environmental context. These challenges include retrieval, indexing, efficient storage, data integration, and analytic techniques.

We have developed a new system - the Environmental-Data Automated Track Annotation (Env-DATA) - that automates annotation of movement trajectories with remote-sensing environmental information, including high resolution topography, weather from global and regional reanalysis datasets, climatology, human geography, ocean currents and productivity, land use, vegetation and land surface variables, precipitation, fire, and other global datasets. The system automates the acquisition of data from open web resources of remote sensing and weather data and provides several interpolation methods from the native grid resolution and structure to a global regular grid linked with the movement tracks in space and time. Env-DATA provides an easy-to-use platform for end users that eliminates technical difficulties of the annotation processes, including data acquisition, data transformation and integration, resampling, interpolation and interpretation. The new Env-DATA system enhances Movebank (www.movebank.org), an open portal of animal tracking data. The aim is to facilitate new understanding and predictive capabilities of spatiotemporal patterns of animal movement in response to dynamic and changing environments from local to global scales. The system is already in use by scientists worldwide, and by several conservation managers, such as the consortium of federal and private institution that manage the endangered Californian Condor populations.

I. INTRODUCTION

Animals move constantly across the surface of the earth, travelling locally around breeding sites and globally across continents and oceans during migrations. Global data about animal movements are indispensable to understanding how to protect and manage wildlife. This knowledge plays a fundamental role in our understanding of such things as the propagation of pathogens through their hosts and to humans, the movement and mortality causes of endangered animals, human-wildlife conflict (airplane collisions, crop raids) and the prediction of natural disasters through intelligent sensors on animals. We are also beginning to grasp the interactions between the changing environment and the timing and routs of migrating animals.

Movement ecology is a rapidly growing sub-field within ecology and is focused on understanding the "causes, mechanisms, and spatiotemporal patterns of (organismal) movement and their role in various ecological and evolutionary processes" [1]. Traditional animal-movement studies (ranging from the 1950s) focused on quantifying movement patterns see for example: [2] to make inferences about processes related to habitat selection and resource use. Understanding where the animals are and where they go when they migrate is critical to conservation and population management. Beyond first-order knowledge of animal locations, studying the movement patterns and developing models of movement can be used to suggest different types of behaviors or 'states', to infer how an organism and its environment interact to influence the movement process. This "movement ecology paradigm" was introduced by Nathan et al. (2008) as part of a special issue of *Proceeding of the National Academy of Science USA* see editorial for the special issue: [3] dedicated to movement ecology. The ability to identify behavior types or changes in behavior types based on movement data was recently addressed in a special issue of *Philosophical Transaction of the Royal Society B: Biological Science*s see editorial for this special issue: [4].

There are two observational approaches for studying animal movement: (1) Location based – animals are observed at a certain, fixed location. Insight about movement is provided at the species or population levels by linking the times and places a species was observed over several observation locations. This approach is commonly used, and large databases that collect point observations assist in compiling large-scale movement patterns, for example e-Bird [5], which holds millions of point observations of birds. (2) **Individual-based tracking** – the movements of an individual animal, i.e., its **tracks**, are observed. Tracking animals over large temporal and spatial scales has revealed invaluable and spectacular biological information [6]. By the turn of the 19th century, European scientists started using leg-bands on birds [7]. On rare occasions, these birds where recaptured and their location was reported producing a rudimentary 2-point track. Advancement of cellular and GPS technologies in the last decades have revolutionized animal tracking. Electronic, transmitting tags with GPS can report the location of the animals on which they are deployed at high accuracy and high frequency over long periods. Geologgers, radio telemetry, and satellite telemetry allow smaller tags but provide location data with very large spatial error. Miniaturization of antennae, dataloggers, GPS receivers, batteries, and solar panels allows deployment of automated transmitting tags on animals with body masses as small as 80 grams (e.g., a robin) and ever smaller tags are continuously being developed.

In parallel to advancements in understanding and interpreting the movement patterns themselves, incorporating the effects of environmental variables that are contextual to the movement (Figure 1) is becoming an increasingly popular and productive approach in movement ecology. Movement models that include environmental context are instrumental in determining the divers of movement behavior and the parameters that describe it, and in shaping path choices. Recent special issues in the journals *Movement Ecology* "Special issue: Animal movement and the environment", and *Philosophical Transaction of the Royal Society B: Biological Sciences* see [8 for introduction] and a review in *Science* [9] highlight these recent developments and the increasing popularity and scientific prospects of this approach.

Environmental conditions, such as land-use change, habitat loss, and climate change can and do disturb migration patterns at a risk to the conservation of migratory species [10-13]. Weather has strong effects on the movement of animals through their environment, especially flying animals. Recent studies combining satellite-based tracks of animals with satellite- and model-based weather reanalysis data have shown dramatic effects of weather on bird migration [14-21], but also on large mammals [22, 23]. Protecting the constant flux of migrating organisms is critical to maintaining healthy ecosystems [24], but challenging due to the difficulty of studying mobile creatures. Concerns about the response of migrating species to climate change, other anthropogenic habitat disturbances, and increased human-wildlife interface risk, such as disease transmission e.g., [25], collisions (airplanes [26], wind turbines [27, 28]) and animal raids on crops [29], have drawn attention to studies of current migration and animal movement patterns in the context of population management and risk prevention. With improved tag technology and availability of contextual environmental data from remote sensing and global reanalysis models, movement ecology has transitioned from a data-poor to a data-rich discipline. Big-data approaches and large databases are needed to collect, access and manage animal movement data.

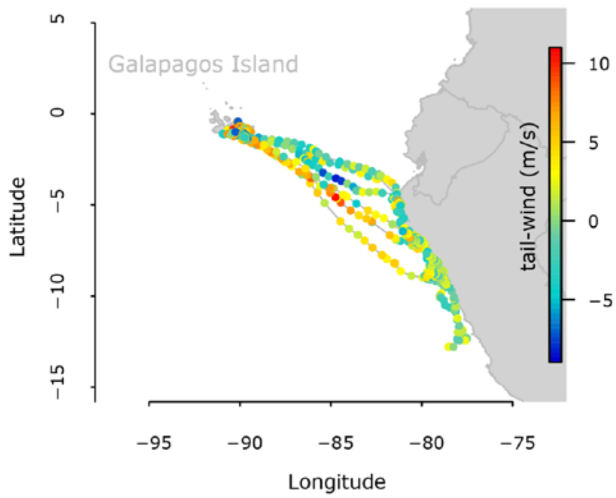

Figure 1. Tracks of albatrosses, nesting at the Galapagos Islands and foraging in the Peruvian coast, annotated with the derived environmental variable "rail-wind", which is calculated by Env-DATA as a function of the bird flight direction and NCEP Reanalysis-2 U and V wind speed components. The study is described in details in [30] and the movement data is available from [31].

Climate trends and immediate weather conditions are recognized as important factors in determining animal movement [1]. Despite the availability of remote sensing and weather data, scientists have not yet determined general relationships that can be used to forecast the effects of future climate change on animal migration. Discovering these principals is hampered by the complexity of spatial and temporal co-registration of the extensive time-series data of animal movement with the even more complex data on weather and land use. Indeed, published relationships have, thus far, been restricted to local weather data from meteorological stations or radar at a small number of points at some distance from the migration path [32], e.g., [33, 34] or have used relatively simple sub-sets of available satellite and weather data [14, 16, 35, 36].

In part, the reasons for this gap between broad data availability and its narrow application are embedded in technical barriers and lack of awareness across the disciplinary gaps dividing biologists and land wildlife managers who collect animal movement data, and the remote sensing community and atmospheric scientists that provide environmental data [37]. One of the great obstacles is the technical challenge of access to different data resources. Different datasets have different data portals, with different compression and data formats, and require different utilities or scripting languages to obtain large subsets of the data in prescribed locations and times. Other challenges involve the geographic co-registration of the environmental data with the observed point in the animal movement track, which involves translation from the grid system on which the data is provided to the longitude-latitude system that is reported by the GPS or satellite tag. Furthermore, many researchers are unaware of the availability of many of the satellite data sources, or do not understand the meaning, relevance, and limitations of the available variables. The few animal-movement research groups that have developed tools to use one climate or remote sensing data resource rarely expanded those to include other datasets.

II. THE ENVIRONMETAL-DATA AUTOMATED TRACK ANNOTATION (ENV-DATA) SYSTEM

The Env-DATA system [30] expands the capabilities of animal movement researchers and offers access, interpretation, interpolation, and co-registration of environmental data from global remote sensing and model reanalysis datasets. Env-DATA is hosted by Movebank (www.movebank.org) and interfaces directly with the Movebank web Graphic User Interface (GUI), and the Movebank database.

The Env-DATA system includes the Track Annotation Service, and the Knowledge Discovery and Visualization Service. Thousands of variables are available through Env-DATA from the following datasets: NASA's MODIS TERRA and AQUA vegetation, ocean colour, ice and fire; National Center for Environmental Prediction (NCEP) Global Reanalysis 2, and North American Regional Reanalysis (NARR); the European Centre for Medium-Range Weather Forecasts (ECMWF) moderate resolution reanalysis; Oregon State University Ocean Net Primary Productivity (NPP); NOAA's Ocean Surface Current Analyses (OSCAR) ocean currents and sea surface temperatures; NASA's Tropical Rainfall Measuring Mission (TRMM) precipitation; long-term record of AVHRR NDVI; ESA's GlobeCover land cover/land use; NOAA's SST reanalysis (OI SST); NASA's ASTERGDEM, SRTM and ETOPO1 digital elevation models (DEM)s; and the Columbia University Human Geography dataset. Env-DATA also calculates derived variables by combining several datasets from different sources, such as tail-wind support and orographic and thermal uplift availability (Figure 2).

Track annotation is an analysis approach, according to which, environmental data fields are interpolated in space and time to the coordinate (space and time) where and when an animal location was registered by an automated tag, or reported in any other means [15] (Figure 1). A request for track annotation with environmental data is generated by the user through a GUI (accessed through the Movebank web portal) that assists in variable selection and in selection of the appropriate interpolation method. The GUI provides easy and intuitive access for users including those that are not familiar with the system. Additionally, Env-DATA services can be accessed through an API, that allows access for very large annotation requests, over long periods and many individual tracks, and permits automation of the annotation-request process by analysis software and user's web-pages. The annotation results are then stored in the Env-DATA storage system. An email notification, including an http download link, is sent to the user through the Env-DATA web server when the data are available for download. Data is available in text (csv) format, and GIS and Google Earth formats (Figure 2).

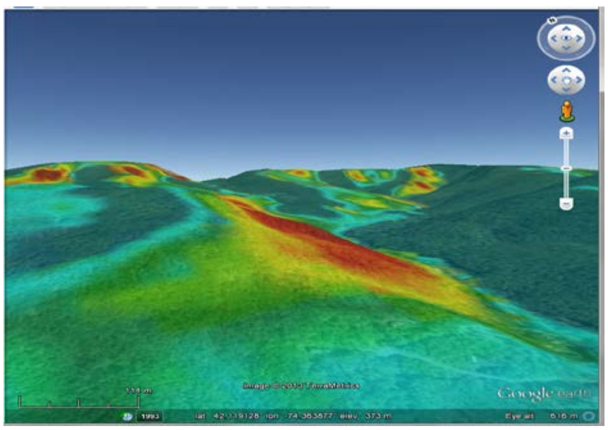

Figure 2. Env-DATA derived variable of orographic uplift, the strength of wind uplift that is generated by interaction between the wind and topography [18]. This derived variable is calculated from weather variables (wind speed, and direction) provided either ECMWF global reanalysis data, from NCEP reanalysis-2, or from NARR, combined with a remote-sensing based digital elevation model (DEM), either ASTERGDEM or SRTM. The data illustrated here was obtained as a rasterized grid, and not as an annotated track, through the API. It was downloaded in kml format and illustrated using Google-Earth.

The Knowledge Discovery and Visualization Service is made by R and JAVA scripts that allow the user to obtain environmental data for a contextual region of interest, to prepare these data for R packages that study habitat selection and niche analysis (such as Max-Ant, and Random Forest), and to plot annotated tracks and contextual environmental data layers using various software tools including R, Google Earth (Figures 1-3), and the dynamic track visualization tool (Figure 4)[38]. The Knowledge Discovery and Visualization Services communicate with the Env-DATA server through an API. Additional tools currently in the testing phase provide a flexible on-line mapping interface and allow users to link maps of tracks and environmental data to a user-defined website, select variables for display, and define the graphic details of the mapped objects.

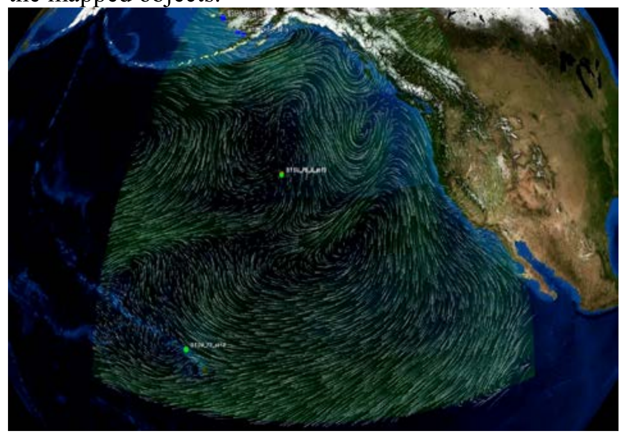

Figure 3. Bristle-thighed curlew migrating from Alaska to Polynesia across the Pacific Ocean. 2 migrating birds' locations are illustrated in green dots. The wind field over the ocean is illustrated in green vectors. Using the wind field at multiple time steps and animating the view showed that the birds' movement is adapted to large patters of weather systems across the ocean.

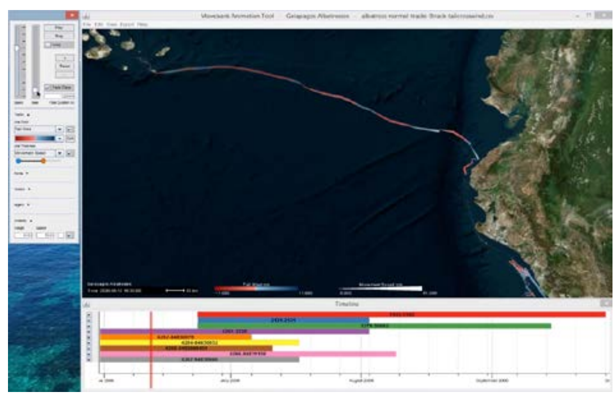

Figure 4. The Env-DATA visualization tool allows plotting tracks (lines) and up to two additional annotated environmental datasets, illustrated using track-point color and width, and an annotated environmental vector datasets (wind speed and direction, ocean currents) as arrows at each track point (not illustrated). A GUI allow selecting variable and visualization type (left bar). A visual time-table (bottom bar) provides information about the temporal extent of overlapping tracks by different individuals and allows choosing the time-step for visualization. It also produces animations of the tracks and the environmental context over selected time periods.

II.1 Env-DATA current use and potential for growth

A limited version of Env-DATA was initially released in July 2013. The full version is available since August 2014. The AmoveE Symposium www.AmoveE2014.com) was held in Raleigh NC in May 2014 and introduced the system to potential users. 200 Movement ecology researchers attended the symposium. Since the release of the full version, the system was used by more than 250 users that generated >3000 annotation requests through the GUI or the API interfaces. The rate of use and annotation requests is growing rapidly. During the last 4 weeks prior to submitting this manuscript (8/11-9/11/2015), there were 150 annotation requests by 84 users, which included requests to annotate 9.1 million locations and resulted in retrieval of 8.9 million environmental data files (each file is composed of a single remote sensing "scene" or "frame", or a global snapshot of a reanalysis variable) with a total size of 15.16 Terabytes, from which data was processed and provided to the users.

Env-DATA is a component of the recently developed data flow procedure that was adopted by the US Geological Survey (USGS) to service the data management of the Californian Condor reintroduction and population manaement projects by the US Fish and wildlife Service, National Parks Service and other NGOs [39]. Several manuscripts that describe research enabled by Env-DATA have already been published. Some of these manuscripts are studies in which one of us participated, and used early, pre-launch test versions of Env-DATA [21-23, 40, 41]. However, our users are already independent and "early-bird" Env-DATA-enabled papers have already been published, or are in the review process, without direct involvement of the Env-DATA development team [42-44].

III.ACKNOWLEDGEMENTS

The creation of Env-DATA was funded by NASA, project NNX11AP61G. Additional support for the development of specific features within Env-DATA was provided by the US Geological Survey project G14AC00091 and by the US National Science Foundation projects IOS-1145952 and by NASA ABoVE project NNX15AT91A. Computational infrastructure support was provided by the Max Planck Computing and Data Facility and by the Ohio Supercomputer Center (allocation grant PAS0626-1). We acknowledge the contribution and participation of Jiawei Han, David Brandes, David Douglas, and Johnny Wilson in the creation of Env-DATA and related analysis tools. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of NASA, the USGS, or the National Science Foundation.

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