

ECOLOGICAL MONITORING

Ecological insights from three decades of animal movement tracking across a changing Arctic

Sarah C. Davidson^{1,2,3}, Gil Bohrer^{1*}, Eliezer Gurarie^{4,5}, Scott LaPoint^{2,6,7}, Peter J. Mahoney⁸, Natalie T. Boelman⁷, Jan U. H. Eitel⁹, Laura R. Prugh⁸, Lee A. Vierling⁹, Jyoti Jennewein⁹, Emma Grier⁴, Ophélie Couriot^{4,10}, Alicia P. Kelly¹¹, Arjan J. H. Meddens¹², Ruth Y. Oliver^{7,13,14}, Roland Kays¹⁵, Martin Wikelski^{2,3}, Tomas Aarvak¹⁶, Joshua T. Ackerman¹⁷, José A. Alves^{18,19}, Erin Bayne²⁰, Bryan Bedrosian²¹, Jerrold L. Belant²², Andrew M. Berdahl²³, Alicia M. Berlin²⁴, Dominique Berteaux²⁵, Joël Bêty²⁵, Dmitrijs Boiko^{26,27,28}, Travis L. Booms²⁹, Bridget L. Borg³⁰, Stan Boutin²⁰, W. Sean Boyd³¹, Kane Brides³², Stephen Brown³³, Victor N. Bulyuk³⁴, Kurt K. Burnham³⁵, David Cabot³⁶, Michael Casazza¹⁷, Katherine Christie³⁷, Erica H. Craig³⁸, Shanti E. Davis³⁹, Tracy Davison⁴⁰, Dominic Demma⁴¹, Christopher R. DeSorbo⁴², Andrew Dixon⁴³, Robert Domenech⁴⁴, Götz Eichhorn^{45,46}, Kyle Elliott⁴⁷, Joseph R. Evenson⁴⁸, Klaus-Michael Exo⁴⁹, Steven H. Ferguson⁵⁰, Wolfgang Fiedler^{2,3}, Aaron Fisk⁵¹, Jérôme Fort⁵², Alastair Franke^{20,53}, Mark R. Fuller⁵⁴, Stefan Garthe⁵⁵, Gilles Gauthier⁵⁶, Grant Gilchrist⁵⁷, Petr Glazov⁵⁸, Carrie E. Gray⁵⁹, David Grémillet^{60,61}, Larry Griffin³², Michael T. Hallworth^{62,63}, Autumn-Lynn Harrison⁶², Holly L. Hennin^{31,64}, J. Mark Hipfner⁶⁵, James Hodson⁶⁶, James A. Johnson⁶⁷, Kyle Joly⁶⁸, Kimberly Jones⁴¹, Todd E. Katzner⁶⁹, Jeff W. Kidd⁷⁰, Elly C. Knight²⁰, Michael N. Kochert⁶⁹, Andrea Kölzsch^{2,3,71}, Helmut Kruckenberg⁷¹, Benjamin J. Lagassé⁷², Sandra Lai²⁵, Jean-François Lamarre⁷³, Richard B. Lanctot⁶⁷, Nicholas C. Larter⁷⁴, A. David M. Latham^{20,75}, Christopher J. Latty⁷⁶, James P. Lawler⁷⁷, Don-Jean Léandri-Breton²⁵, Hansoo Lee⁷⁸, Stephen B. Lewis⁷⁹, Oliver P. Love⁶⁴, Jesper Madsen⁸⁰, Mark Maffei³⁹, Mark L. Mallory⁸¹, Buck Mangipane⁸², Mikhail Y. Markovets³⁴, Peter P. Marra⁸³, Rebecca McGuire⁸⁴, Carol L. McIntyre³⁰, Emily A. McKinnon⁸⁵, Tricia A. Miller^{86,87}, Sander Moonen⁴⁹, Tong Mu⁸⁸, Gerhard J. D. M. Müskens⁸⁹, Janet Ng²⁰, Kerry L. Nicholson²⁹, Ingar Jostein Øien¹⁶, Cory Overton¹⁷, Patricia A. Owen³⁰, Allison Patterson⁴⁷, Aevor Petersen⁹⁰, Ivan Pokrovsky^{2,91,92}, Luke L. Powell^{62,93,94}, Rui Prieto⁹⁵, Petra Quillfeldt⁹⁶, Jennie Rausch⁹⁷, Kelsey Russell⁹⁸, Sarah T. Saalfeld⁶⁷, Hans Schekkerman⁹⁹, Joel A. Schmutz¹⁰⁰, Philipp Schwemmer⁵⁵, Dale R. Seip¹⁰¹, Adam Shreading⁴⁴, Mónica A. Silva^{95,102}, Brian W. Smith¹⁰³, Fletcher Smith^{104,105}, Jeff P. Smith^{106,107}, Katherine R. S. Snell^{2,108}, Aleksandr Sokolov⁹², Vasilij Sokolov¹⁰⁹, Diana V. Solovyeva⁹¹, Mathew S. Sorum¹¹⁰, Grigori Tertitski⁵⁸, J. F. Therrien^{56,111}, Kasper Thorup¹⁰⁸, T. Lee Tibbitts¹⁰⁰, Ingrid Tulp¹¹², Brian D. Uher-Koch¹⁰⁰, Rob S. A. van Bemmelen^{112,113}, Steven Van Wilgenburg¹¹⁴, Andrew L. Von Duyke¹¹⁵, Jesse L. Watson²⁰, Bryan D. Watts¹⁰⁴, Judy A. Williams⁶⁶, Matthew T. Wilson⁴⁸, James R. Wright¹¹⁶, Michael A. Yates¹¹⁷, David J. Yurkowski^{50,85}, Ramūnas Žydelis¹¹⁸, Mark Hebblewhite⁵

The Arctic is entering a new ecological state, with alarming consequences for humanity. Animal-borne sensors offer a window into these changes. Although substantial animal tracking data from the Arctic and subarctic exist, most are difficult to discover and access. Here, we present the new Arctic Animal Movement Archive (AAMA), a growing collection of more than 200 standardized terrestrial and marine animal tracking studies from 1991 to the present. The AAMA supports public data discovery, preserves fundamental baseline data for the future, and facilitates efficient, collaborative data analysis. With AAMA-based case studies, we document climatic influences on the migration phenology of eagles, geographic differences in the adaptive response of caribou reproductive phenology to climate change, and species-specific changes in terrestrial mammal movement rates in response to increasing temperature.

The Arctic and adjacent regions are experiencing the most rapid climate and environmental changes on Earth, caused primarily by anthropogenic greenhouse gas emissions (1). Notable trends include warming winter temperatures, ice loss, and earlier spring snowmelt. These changes profoundly affect conditions experienced by animals, including food availability, interspecific

competition, predation, and increased human disturbances (2). Impacts of climate change on Arctic vertebrates include rapid poleward range shifts (3, 4); phenological trophic mismatches (5); and changes in migration (6), foraging, and predator–prey dynamics (7). Because rapid environmental change in the Arctic challenges the ability of the region's fauna to adapt, a primary response will likely occur through phenotypic plasticity in the patterns, locations, and timing of their movements

(2). Documenting and understanding these changes requires multidecadal, pan-Arctic data at multiple trophic levels.

We demonstrate the ecological utility of the Arctic Animal Movement Archive (AAMA), an active, collaborative collection of animal tracking datasets (supplementary materials). Marine ecology archives, such as IOOS-ATN, IMOS, OBIS-SEAMAP, and RAATD (8), provide insight regarding space use, movement, and connectivity (9–11). Terrestrial animal movement archives are rare and tend to have a regional or taxonomic focus (12). AAMA is the first Arctic-focused archive with both terrestrial and marine data and is hosted on the global Movebank database. The geographic scope of the AAMA (Fig. 1) includes the Arctic, Arctic marine, and subarctic “boreal forests/taiga” regions defined elsewhere (13, 14) (see also supplementary materials). Currently, the archive contains more than 15,000,000 occurrences of 8000 individuals representing 86 species, from 1991 to the present (figs. S1 and S2 and tables S1 to S4). Combining data from multiple AAMA studies, we show evidence of (i) climate drivers of golden eagle migration phenology, (ii) climate adaptation of parturition by caribou, and (iii) consequences of increased temperature and precipitation on movements of mammalian predators and herbivores.

Behavioral flexibility enables migrants to optimize energy expenditure during migration and adjust arrival at summering grounds (15, 16). We used tracking data from 103 individuals during 1993 to 2017 [supplementary materials (case study 1) and table S5] to examine arrival timing to breeding grounds of northward-migrating golden eagles (“summering”), modeling it with predictors for age, sex, summering onset latitude, year, and the preceding winter's mean Pacific decadal oscillation index (PDO).

Mean summering date changed slowly over 25 years (−0.5 days/year). The long-term trend differed among age classes, with adults arriving earliest, then subadults, and then juveniles, and it was influenced by winter climate (PDO) (Fig. 2 and tables S8 and S9). Eagles of all age classes began summering later at northern latitudes (1.08 days/degree). The significant interaction of year and previous “warm-phase” PDO explains earlier summering dates for subadults and juveniles, highlighting their known responsiveness to environmental conditions (16). These warm-phase winters cause a warmer and drier climate with reduced snowpack and an earlier snow-free date. Earlier adult arrival to summering grounds should result from selection and competition for territories, yet local climatic variables affect eagle condition before, and energy expenditure during, northward migration (16). For subadults sampled after 2011, the direct effect of PDO is significant (−8.27 days), whereas the full subadult dataset does not show a

Author affiliations are listed at the end of this paper.

*Corresponding author. Email: bohrer.17@osu.edu

significant effect of winter PDO (Fig. 2). This period-related difference in inference of climatic drivers highlights the importance of compiling long-term, multigenerational observations. Given the importance of the winter PDO and known impacts of global climate change, golden eagles could face age-specific challenges during migration and at their warming Arctic summering grounds.

The timing of parturition is a key to the demography of wildlife populations and can be an adaptive response to climate shifts (17). For many mammals, the period from late pregnancy through weaning has the highest energetic demands and thus is timed to occur when vegetation productivity is highest (18). Caribou occur in five different ecotypes (Fig. 3) across boreal and Arctic North America and are facing global declines (19). On the basis of data from 917 individuals during 2000 to 2017 in northern Canada, we used characteristic patterns of low movement during the calving season to estimate 1630 parturition dates in five populations of barren-ground, northern and southern boreal woodland, and northern and southern mountain woodland caribou [supplementary materials (case study 2) and table S6].

We found differences in parturition timing and trends among the five populations. The southern and northern boreal populations calved earliest, followed by northern and southern mountain populations (table S10). Barren-ground caribou calved later despite occupying a similar latitudinal range as the northern boreal caribou (Fig. 3). Most importantly, barren-ground and northern woodland caribou, but not southern woodland caribou, exhibited significant trends toward earlier parturition [0.4 to 1.1 days/year (table S10)]. This is the first continental-scale retrospective evidence of potential adaptive responses to climate trends by caribou.

Animals conserve energy by modifying their behavior in response to weather conditions, with important implications for individual fitness and species resilience under climate change (20). We tested for effects of temperature and precipitation on seasonal movement rates (in meters per minute) using records from 1720 individuals of two herbivore and three predator species (black bear, grizzly bear, caribou, moose, and wolf) during 1998 to 2019 [supplementary materials (case study 3) and table S7]. We predicted that winter movement rates would decline relative to summer, when energetic costs of self-maintenance would be highest. Rate would also decline within seasons, during weather conditions that increase the energetic cost of movement (e.g., snow that increases energy requirements for movement or higher ambient temperatures during the summer that accelerate metabolism).

All species exhibited lower movement rates during winter relative to summer (Fig. 4). As

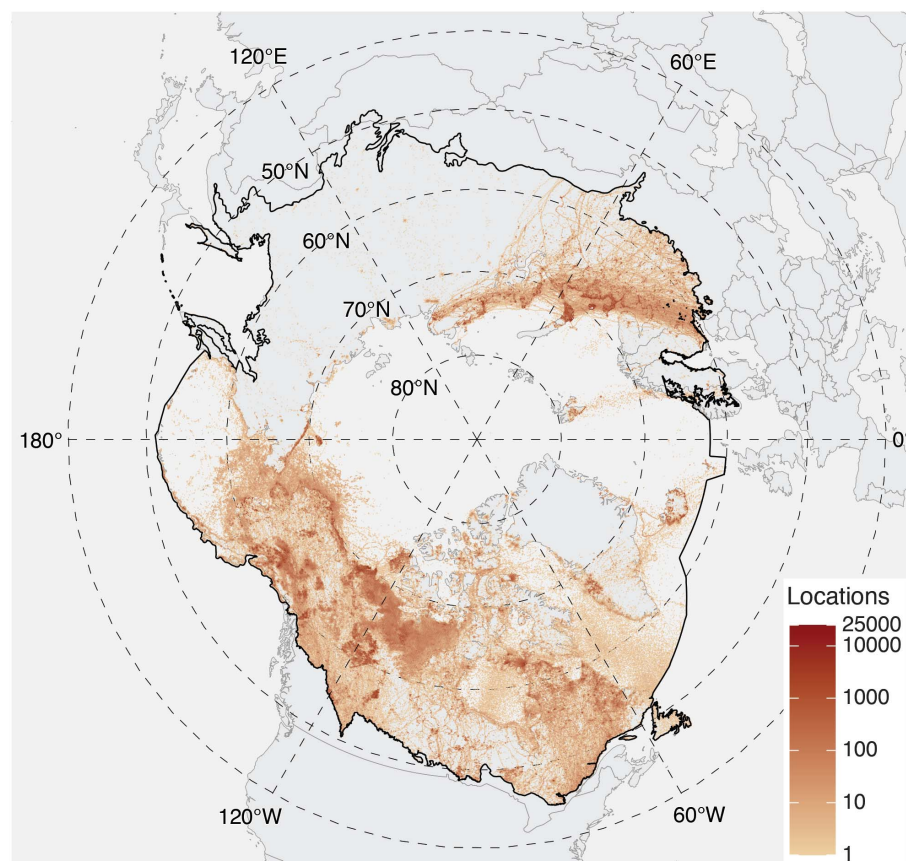


Fig. 1. Map of the AAMA boundary and data. Density of animal locations (number of observations per ~100 km²) at logarithmic scale characterizes data availability, not animal density or utilization.

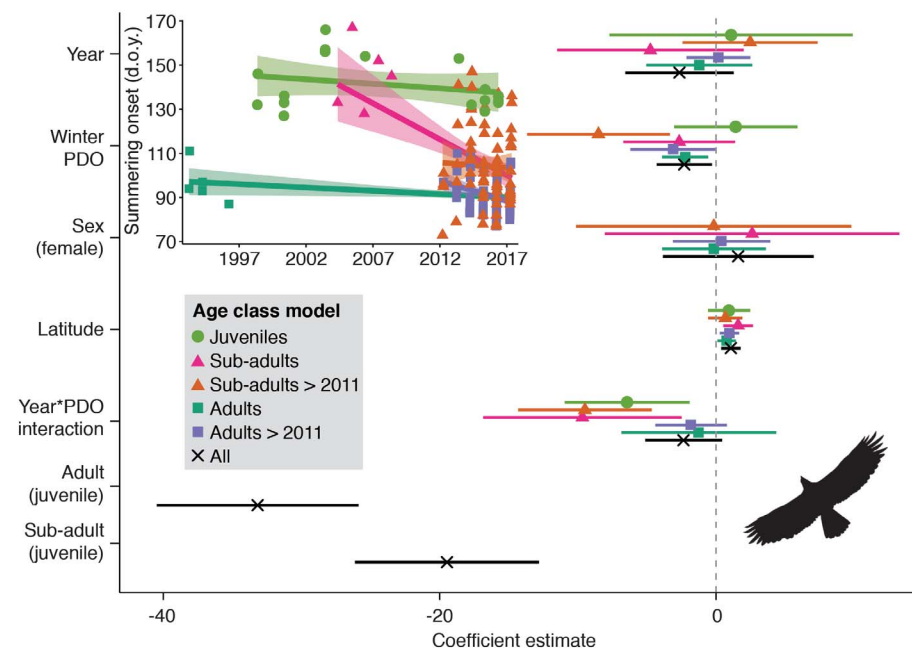


Fig. 2. Changes in the onset date of golden eagles' summering. Coefficient estimates (±95% confidence intervals) reflecting age-specific changes in response to year, previous winter PDO, sex (reference: females), latitude, interaction of year and PDO, and age class [reference: juveniles (tables S8 and S9)]. (Inset) Time series of model-estimated summering onset date (d.o.y., day of year).

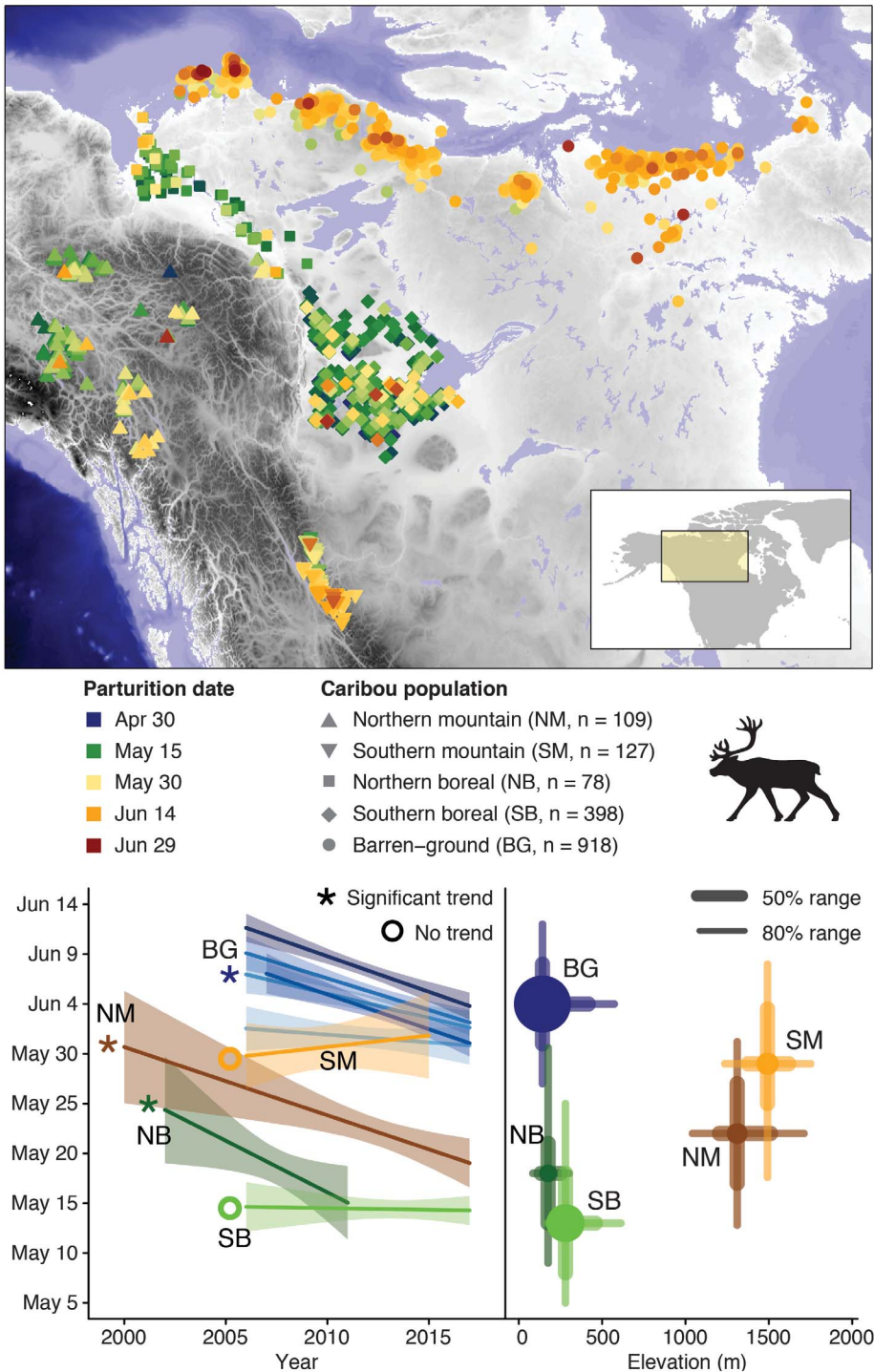


Fig. 3. Climate change adaptation of parturition times (PT) of caribou. (Top) PT by population. (Bottom left) PT trends by population, including five barren-ground subpopulations. (Bottom right) PT dates by elevation.

temperatures increased in summer, wolves and black bears slowed their movement rates, whereas moose increased their movement rates. In winter, only barren-ground caribou increased movement rates as temperature increased. Snow impeded wolves, boreal caribou, and moose,

whereas all species were generally insensitive to summer precipitation. These patterns may reflect asynchronous responses to climate change within and across trophic levels. Climate-driven variation in animal activity is likely to affect species interactions, altering energy

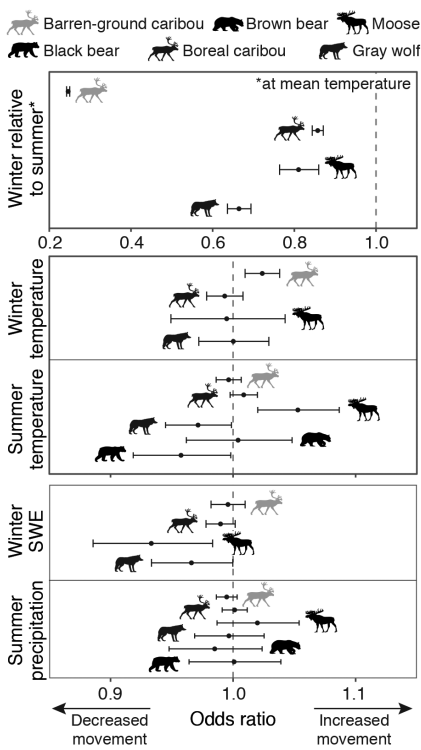


Fig. 4. Changes in species-specific movement rates in response to daily maximum temperature, summer precipitation, and winter snow-water equivalent (SWE). Odds ratios for continuous covariates represent the positive or negative change in movement rates per one unit change in temperature or precipitation, respectively. Ratios were identified as neutral if credible intervals overlapped with 1.0.

expenditure, encounter rates, and foraging success with demographic implications for both predators and prey.

As we demonstrate, the AAMA provides a solution to Arctic data collection and sharing challenges. It serves as a critical baseline and resource to identify early signals of local or large-scale changes in animal distribution, movement responses, and adaptive traits. Continued shifts in phenology in the Arctic pose challenges to migratory species that encounter changing seasonal fluctuations along migration routes and at Arctic summering and southern wintering grounds (21). Key drivers of population responses, such as migration, parturition, and foraging movement, are undergoing rapid changes, suggesting that climate change is affecting animals in ways that will shape the future of the Arctic.

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- ⁸School of Environmental and Forest Sciences, University of Washington, Seattle, WA, USA. ⁹Department of Natural Resources and Society, University of Idaho, Moscow, ID, USA. ¹⁰National Socio-Environmental Synthesis Center, Annapolis, MD, USA. ¹¹Department of Environment and Natural Resources, Government of the Northwest Territories, Fort Smith, NT, Canada. ¹²School of the Environment, Washington State University, Pullman, WA, USA. ¹³Department of Ecology and Evolutionary Biology, Yale University, New Haven, CT, USA. ¹⁴Center for Biodiversity and Global Change, Yale University, New Haven, CT, USA. ¹⁵College of Natural Resources, North Carolina State University, Raleigh, NC, USA. ¹⁶BirdLife Norway, Trondheim, Norway. ¹⁷U.S. Geological Survey, Western Ecological Research Center, Dixon Field Station, Dixon, CA, USA. ¹⁸Department of Biology & CESAM, University of Aveiro, Aveiro, Portugal. ¹⁹South Iceland Research Centre, University of Iceland, Laugarvatn, Iceland. ²⁰Department of Biological Sciences, University of Alberta, Edmonton, AB, Canada. ²¹Teton Raptor Center, Jackson Hole, WY, USA. ²²Global Wildlife Conservation Center, College of Environmental Science and Forestry, State University of New York, Syracuse, NY, USA. ²³School of Aquatic & Fishery Sciences, University of Washington, Seattle, WA, USA. ²⁴U.S. Geological Survey, Patuxent Wildlife Research Center, Laurel, MD, USA. ²⁵Centre d'études nordiques, Université du Québec à Rimouski, Rimouski, QC, Canada. ²⁶Latvian National Museum of Natural History, Riga, Latvia. ²⁷Institute of Biology, University of Latvia, Salaspils, Latvia. ²⁸Latvian Swan Research Society, Kalnciems, Latvia. ²⁹Alaska Department of Fish and Game, Fairbanks, AK, USA. ³⁰National Park Service, Denali National Park and Preserve, Denali Park, AK, USA. ³¹Science & Technology Branch, Environment & Climate Change Canada, Delta, BC, Canada. ³²Wildfowl & Wetlands Trust, Slimbridge, UK. ³³Manomet, Inc., Saxtons River, VT, USA. ³⁴Biological Station Rybachy, Zoological Institute of Russian Academy of Sciences, St. Petersburg, Russia. ³⁵High Arctic Institute, Orion, IL, USA. ³⁶School of Biological, Earth and Environmental Sciences, University College Cork, Cork, Ireland. ³⁷Alaska Department of Fish and Game, Anchorage, AK, USA. ³⁸Aquila Environmental, Fairbanks, AK, USA. ³⁹High Arctic Gull Research Group, Bamfield, BC, Canada. ⁴⁰Department of Environment and Natural Resources, Government of the Northwest Territories, Inuvik, NT, Canada. ⁴¹Alaska Department of Fish and Game, Palmer, AK, USA. ⁴²Biodiversity Research Institute, Portland, ME, USA. ⁴³Reneco International Wildlife Consultants, Abu Dhabi, United Arab Emirates. ⁴⁴Raptor View Research Institute, Missoula, MT, USA. ⁴⁵Vogeltrekstation—Dutch Centre for Avian Migration and Demography, Wageningen, Netherlands. ⁴⁶Department of Animal Ecology, Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, Netherlands. ⁴⁷Department of Natural Resource Sciences, McGill University, Ste Anne-de-Bellevue, QC, Canada. ⁴⁸Washington Department of Fish and Wildlife, Olympia, WA, USA. ⁴⁹Institute for Avian Research “Vogelwarte Helgoland,” Wilhelmshaven, Germany. ⁵⁰Fisheries and Oceans Canada, Winnipeg, MB, Canada. ⁵¹Great Lakes Institute for Environmental Research, School of the Environment, University of Windsor, Windsor, ON, Canada. ⁵²Littoral Environnement et Sociétés (LIENSs), CNRS, La Rochelle University, La Rochelle, France. ⁵³Arctic Raptor Project, Rankin Inlet, NU, Canada. ⁵⁴Boise State University, Raptor Research Center, Boise, ID, USA. ⁵⁵Research and Technology Centre (FTZ), Kiel University, Büsum, Germany. ⁵⁶Département de Biologie & Centre d'Études Nordiques, Université Laval, Quebec City, QC, Canada. ⁵⁷Environment & Climate Change Canada, National Wildlife Research Centre, Carleton University, Ottawa, ON, Canada. ⁵⁸Institute of Geography, Russian Academy of Sciences, Moscow, Russia. ⁵⁹School of Biology and Ecology, University of Maine, Orono, ME, USA. ⁶⁰Centre d'Études Biologiques de Chizé, CNRS, La Rochelle University, Villiers en Bois, France. ⁶¹Percy Fitzpatrick Institute of African Ornithology, University of Cape Town, Rondebosch, South Africa. ⁶²Migratory Bird Center, Smithsonian Conservation Biology Institute, National Zoological Park, Washington DC, USA. ⁶³Northeast Climate Adaptation Science Center, University of Massachusetts Amherst, Amherst, MA, USA. ⁶⁴Department of Integrative Biology, University of Windsor, Windsor, ON, Canada. ⁶⁵Environment & Climate Change Canada, Pacific Wildlife Research Centre, Delta, BC, Canada. ⁶⁶Department of Environment and Natural Resources, Government of the Northwest Territories, Yellowknife, NT, Canada. ⁶⁷U.S. Fish & Wildlife Service, Migratory Bird Management, Anchorage, AK, USA. ⁶⁸National Park Service, Gates of the Arctic National Park & Preserve, Fairbanks, AK, USA. ⁶⁹U.S. Geological Survey, Forest and Rangeland Ecosystem Science Center, Boise, ID, USA. ⁷⁰Kidd Biological, Inc., Anacortes, WA, USA. ⁷¹Institute for Wetlands and Waterbird Research e.V., Verden (Aller), Germany. ⁷²Department of Integrative Biology, University of Colorado, Denver, CO, USA. ⁷³Polar Knowledge Canada, Cambridge Bay, NU, Canada. ⁷⁴Department of Environment and Natural Resources, Government of the Northwest Territories, Fort Simpson, NT, Canada. ⁷⁵Manaaki Whenua—Landcare Research, Lincoln, New Zealand. ⁷⁶U.S. Fish & Wildlife Service, Arctic National Wildlife Refuge, Fairbanks, AK, USA. ⁷⁷National Park Service, Alaska Inventory and Monitoring Program, Anchorage, AK, USA. ⁷⁸Korea Institute of Environmental Technology, Yuseonggu, Daejeon, Republic of Korea. ⁷⁹U.S. Fish & Wildlife Service, Juneau, AK, USA. ⁸⁰Department of Bioscience—Kalø, Aarhus University, Rønde, Denmark. ⁸¹Biology Department, Acadia University, Wolfville, NS, Canada. ⁸²National Park Service, Lake Clark National Park and Preserve, Anchorage, AK, USA. ⁸³Department of Biology and the McCourt School of Public Policy, Georgetown University, Washington, DC, USA. ⁸⁴Wildlife Conservation Society, Arctic Beringia Program, Fairbanks, AK, USA. ⁸⁵University of Manitoba, Winnipeg, MB, Canada. ⁸⁶Conservation Science Global, Inc., West Cape May, NJ, USA. ⁸⁷Division of Forestry and Natural Resources, West Virginia University, Morgantown, WV, USA. ⁸⁸Department of Ecology and Evolutionary Biology, Princeton University, Princeton, NJ, USA. ⁸⁹Wageningen Environmental Research, Wageningen University & Research, Wageningen, Netherlands. ⁹⁰Independent researcher, Reykjavik, Iceland. ⁹¹Laboratory of Ornithology, Institute of Biological Problems of the North FEB RAS, Magadan, Russia. ⁹²Arctic Research Station of Institute of Plant and Animal Ecology UB, RAS, Labytnangi, Yamal-Nenets Autonomous District, Russia. ⁹³Durham University, Durham, UK. ⁹⁴University of Glasgow, Glasgow, Scotland. ⁹⁵Marine and Environmental Sciences Centre, Institute of Marine Research and Okeanos R&D Centre, University of the Azores, Horta, Portugal. ⁹⁶Justus-Liebig University, Gießen, Germany. ⁹⁷Environment & Climate Change Canada, Yellowknife, NT, Canada. ⁹⁸Environment Yukon, Whitehorse, YT, Canada. ⁹⁹SOVON, Nijmegen, Netherlands. ¹⁰⁰U.S. Geological Survey Alaska Science Center, Anchorage, AK, USA. ¹⁰¹British Columbia Ministry of Environment, Prince George, BC, Canada. ¹⁰²Biology Department, Woods Hole Oceanographic Institution, Woods Hole, MA, USA. ¹⁰³U.S. Fish & Wildlife Service, Migratory Bird Management, Denver, CO, USA. ¹⁰⁴Center for Conservation Biology, College of William & Mary, Williamsburg, VA, USA. ¹⁰⁵Georgia Department of Natural Resources, Brunswick, GA, USA. ¹⁰⁶HawkWatch International, Salt Lake City, UT, USA. ¹⁰⁷H. T. Harvey & Associates, Los Gatos, CA, USA. ¹⁰⁸Center for Macroecology, Evolution and Climate, Globe Institute, University of Copenhagen, Copenhagen, Denmark. ¹⁰⁹Institute of Plant and Animal Ecology, Ural Division Russian Academy of Sciences, Ekaterinburg, Russia. ¹¹⁰National Park Service, Yukon-Charley Rivers National Preserve, Central Alaska Inventory and Monitoring Network, Fairbanks, AK, USA. ¹¹¹Hawk Mountain Sanctuary, Kempton, PA, USA. ¹¹²Wageningen Marine Research, IJmuiden, Netherlands. ¹¹³Bureau Waardenburg, Culemborg, Netherlands. ¹¹⁴Canadian Wildlife Service, Environment & Climate Change Canada, Saskatoon, SK, Canada. ¹¹⁵North Slope Borough, Department of Wildlife Management, Utqiagvik, AK, USA. ¹¹⁶School of Environment and Natural Resources, The Ohio State University, Columbus, OH, USA. ¹¹⁷Earthspan Foundation, Minden, NV, USA. ¹¹⁸Ornitela UAB, Vilnius, Lithuania.

SUPPLEMENTARY MATERIALS

science.sciencemag.org/content/370/6517/712/suppl/DC1
Materials and Methods
Figs. S1 and S2
Tables S1 to S10
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MDAR Reproducibility Checklist

12 March 2020; resubmitted 16 March 2020
Accepted 15 September 2020
10.1126/science.abb7080

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Science **370** (6517), 712-715.
DOI: 10.1126/science.abb7080

Ecological "big data"

Human activities are rapidly altering the natural world. Nowhere is this more evident, perhaps, than in the Arctic, yet this region remains one of the most remote and difficult to study. Researchers have increasingly relied on animal tracking data in these regions to understand individual species' responses, but if we want to understand larger-scale change, we need to integrate our understanding across species. Davidson *et al.* introduce an open-source data archive that currently hosts more than 15 million location data points across 96 species and use it to show distinct climate change responses across species. Such ecological "big data" can lead to a wider understanding of change.

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