

Bioacoustic Monitoring Contributes to an Understanding of Climate Change

Laura N. Kloepper and
Andrea M. Simmons

Email:

laura_kloepper@brown.edu
andrea_simmons@brown.edu

Postal:

185 Meeting Street
Box GL-N
Brown University
Providence, RI 02912

Both direct and indirect effects of climate change will impact acoustics, especially in the fields of acoustical oceanography, animal bioacoustics, noise, and underwater acoustics.

Introduction

From policymakers, to funding agencies, to the general public, there is a push to understand more about how anthropogenic activities are impacting our climate, how the changing climate affects our planet, and how we can mitigate these effects. At first glance, acoustics and climate change may seem to have little in common. The reality, however, is that both direct and indirect effects of climate change will impact acoustics, especially in the fields of acoustical oceanography, animal bioacoustics, noise, and underwater acoustics. How can we, as acousticians, identify and understand the impacts in our field so we can contribute to the science and dialogue of climate change?

The earth is warming, and anthropogenic activities are to blame. The latest Intergovernmental Panel on Climate Change report states with 95% confidence that “more than half of the observed increase in global average surface temperature from 1951 to 2010 was caused by the anthropogenic increase in greenhouse gas concentrations and other anthropogenic forcings together” (IPCC, 2013). Although already warming, climate models predict further global warming of up to 4° C by the year 2100 (Figure1).

In addition to increases in global temperature, other effects of climate change include losses of ice on sea and land, a rise in sea level, changes in the distribution of organisms within ecosystems, ocean acidification, changes in weather patterns, and increased threats of disease (IPCC, 2013; CCSP, 2008). These biotic and abiotic effects of climate change may also influence the acoustics of an environment and alter the communication of animals. This, in turn, leads to variations in entire soundscapes of regions and to changes in biodiversity, as some species adapt while others do not. Here, we explain how these effects of climate change may impact bioacoustics and discuss some recent findings on the impact of climate change on underwater and aerially communicating animals.

Effect on Underwater Communicating Animals

One of the better-known impacts of climate change on acoustics derives from increasing ocean acidification. The combustion of fossil fuels has driven atmospheric CO² levels from a pre-industrial level of approximately 280 ppm to a present-day level of higher than 400 ppm worldwide (IPCC, 2013). However, only about half of the CO² that has been produced still resides in the atmosphere. The rest is absorbed by the ocean, which results in ocean acidification.

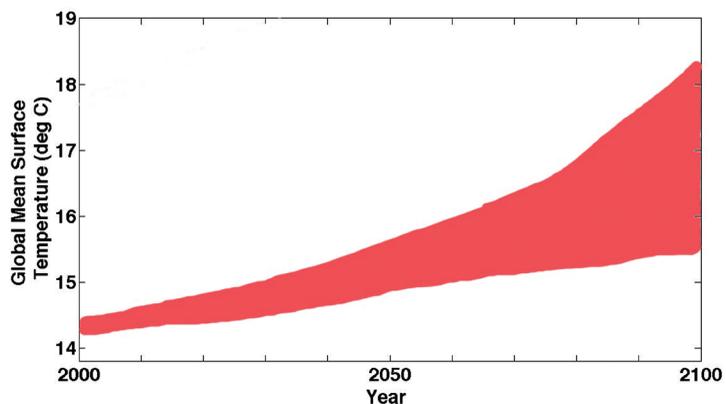


Figure 1: Range of predicted global mean surface temperatures (in Celsius) based on the 2007 IPCC climate models. Temperatures are predicted to increase between 1 and 4 degrees Celsius between the years 2000 and 2100.

Sound naturally attenuates in the ocean, and this acoustic absorption is dependent on temperature, pressure, salinity and acidity. This natural attenuation can be further affected by changes in pH. Figure 2 illustrates that the dependence on absorption and pH changes nonlinearly depending on pH and sound frequency. The left panel shows how the absorption (in dB) between a pH of 7.5 and 8.5 changes nonlinearly across a frequency range from 500 Hz to 10 kHz. Changes in

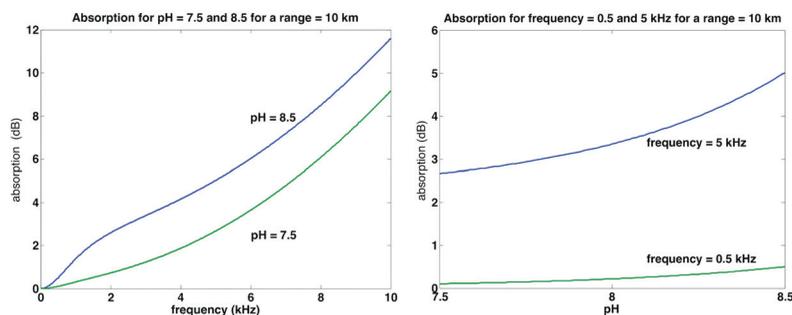


Figure 2: Left panel shows the absorption (in dB) at 10 km for pH values (7.5 and 8.5) as a function of frequency. The right panel shows the absorption (in dB) at 10 km at two frequencies 0.5 and 5 kHz for pH values 7.5 from 8.5. (Miller et al., 2014).

absorption that depend on pH occur for frequencies below 3 kHz, and the maximum difference in absorption for a range of 10 km is approximately 2 dB. The right panel shows how the absorption between a frequency of 500 Hz and 5 kHz changes nonlinearly across a pH range from 7.5 to 8.5. For a pH value of 7.5, the difference in absorption between the low (500 Hz) and high (5 kHz) tone is approximately 2.5 dB, but at a pH value of 8.5 the difference in absorption may be as high as 4.5 dB (Miller et al., 2014).

The global average surface ocean pH is approximately 8.0, but continued solution of CO² in the water is expected to reduce pH by 0.3 or more by the end of the century (Orr et al., 2005). Climate projections estimate future CO² will decrease the open ocean pH by 0.3 units or more in the next 100 years, resulting in a decrease of sound absorption, particularly for low frequencies, by as much as 40% in 100 years (Brewer and Hester, 2009; Hester et al., 2008).

Saltwater Species

The reduction of sound absorption in the ocean means that sounds, both natural and anthropogenic, will travel farther. The increase in anthropogenic sound levels will contribute more noise to the ocean. These changes can impact the acoustic communication behaviors of many marine species, including invertebrates, fishes, and marine mammals. We already know that anthropogenic noise impacts the acoustic behavior of marine mammals. In noisy environments, whales lengthen the duration of their communication sounds (Miller et al., 2000; Foote et al., 2004), increase the intensities of these sounds (Au et al., 1985; Parks et al., 2011), and adjust their sound frequencies (Au et al., 1985). Increased

ambient noise levels can lead to other changes in behavior, such as aborting foraging dives (Aguilar Soto et al., 2006; Cox et al., 2006). These results highlight the negative implications of reduced sound absorption, but potentially there could be positive effects of reduced sound absorption. Baleen whales produce low-frequency communication sounds that travel long distances. These whales currently take advantage of low-attenuation regions of the ocean (SOFAR channels), occasionally singing in these regions so that their songs travel several kilometers (Payne and Webb, 1971). Because these animals use songs to communicate with members of their own species, an acidification-caused reduction in sound absorption may be beneficial to them because it will allow them to remain in communication over longer distances.

Regardless of whether reduced absorption is harmful or beneficial, some investigators disagree over whether ocean acidification will result in changes in absorption large enough to cause measurable changes that will affect animals (Joseph and Chiu, 2010). Additionally, it is important to point out that these predictions are based around theoretical calculations and not experimentation. These predicted changes in sound absorption have yet to be empirically tested in the

Bioacoustic Monitoring Contributes to an Understanding of Climate Change

ocean because logistics have prevented scientists from acidifying the large volumes of seawater necessary to observe decreases in absorption.

In addition to the decrease in sound absorption, the reduction in ocean pH may affect oceanic animals in other ways. Larval fish are thought to rely on sensory cues such as olfaction and hearing for predator avoidance and for localizing reef settlement sites. Noisy reefs indicate the presence of predators, so most larval fish will avoid these noisy sites. Larval clownfish reared in waters with elevated CO² levels did not avoid noisy sites; instead, they demonstrated no preference for sites depending on noise level (Figure 3; Simpson et al., 2011). This suggests that ocean acidification may result in a breakdown of predator avoidance among fish species by disrupting their ability to detect and localize sound sources.

Freshwater Species

Predicting the impact of climate change on freshwater species is more difficult. The size of many freshwater systems is below the resolution of Global Climate Models (GCMs), which constrains the accuracy of climate projections for these environments (Hobday and Lough, 2011). Additionally, unlike the relatively homogenous oceans, freshwater systems are enclosed and habitat specific. Because climate models predict droughts in some regions and heavier rainfall in others, we cannot create a unifying prediction as to how climate change will impact freshwater species (Hobday and Lough, 2011). For example, streams associated with melting glaciers may increase in flow and volume as the planet warms, whereas lakes and ponds in other regions may desiccate as those environments experience droughts. Increased temperatures can result in a decrease in aquatic mixing and turnover, resulting in stratified regions with hypoxic conditions and low pH. Acidification of freshwater systems is predicted, but it is not known if significant changes in sound absorption will occur due to the small size of most freshwater systems. Clearly more data are needed.

An additional factor to consider in predicting the impact on climate change in freshwater environments is the effect of ambient temperature on the auditory system. Fishes are ectotherms that regulate their body temperature by reference to external temperature, rather than by internal physiological setpoints. The water temperature at which animals were housed affects the hearing sensitivities of two species of catfish, the channel catfish (*Ictalurus punctatus*) and the tropical catfish (*Pimelodus pictus*). Thresholds of neural re-

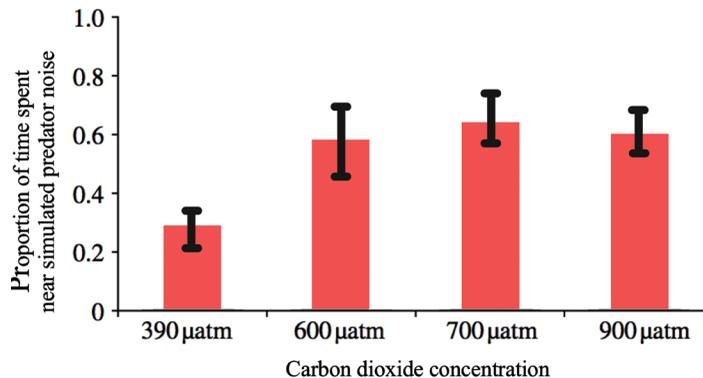


Figure 3: Effect of carbon dioxide concentration on auditory behavior of juvenile clownfish. Fish reared in ambient CO² conditions avoided simulated predator noise, whereas fish reared in elevated carbon dioxide environments did not avoid the noise. Figure adapted from Simpson et al. (2011).

sponses from auditory nuclei in the brain varied with housing temperature (Wysocki et al., 2009); at high temperatures, thresholds increased and hearing sensitivity decreased. The magnitude of these changes varied between the two species, and was further affected by how long the fishes were kept at a particular temperature. These results have particular implications for how fishes may respond to climate change. First, temperature will not affect the hearing sensitivity of all species to the same degree, and second, if animals can acclimate to temperature variations, then the negative consequences of increased temperature on hearing sensitivity may be lessened (Wysocki et al., 2009).

Effect on Aerially Communicating Animals

Climate change impacts terrestrial species as well as aquatic species. Changes in temperature (Figure 1- see page 9), precipitation, and CO² levels, combined with the increased climatic variability caused by global warming, can initiate or exacerbate habitat loss and thus affect biodiversity by altering species distribution, behaviors, and viability. As discussed above for aquatic species, studying these impacts in terrestrial species is also not trivial, because these impacts vary between different habitats (tropical and temperate zones, high and low elevations; Navas, 1996; Deutsch et al., 2008), and between different species (longer-lived species such as birds may be affected in a different manner than shorter-lived species such as insects; Şekercioğlu et al., 2012). Because of the complexity and variability of different habitats and the different life histories of species living in these habitats, we still do not know which species will acclimate and adapt to a changed habitat, which will disperse to other habitats, and which may go extinct. This is where animal bioacoustics can play a major role, both by providing

methods for tracking habitat modification and species distribution by acoustic monitoring, and by quantifying animal sounds and behavioral responses to these sounds as an index of species health.

Many terrestrial species, including insects, frogs, birds, and mammals, use vocalizations as part of their social and reproductive behaviors (Bradbury and Vehrencamp, 1998). Mating calls, advertisement calls, and territorial calls are essential for maintaining reproductive isolation between different species and for regulating aggressive interactions within species. Sounds, either self-generated or from the environment, are also used for foraging, orientation, and navigation. The acoustic content of animal vocalizations is molded by constraints imposed by the physical features (temperature, precipitation, vegetation) of the species' local habitat (Wiley and Richards, 1978). Throughout evolutionary time, sounds used for long distance communication between members of the same species have been molded by the environment so that they can transmit efficiently from the sender to the receiver, with minimal interference and degradation ("acoustic adaptation" hypothesis; Morton, 1975). The implication of these environmental constraints on the acoustic structure of communication sounds is that, as the environment changes, the sounds themselves may need to change, too.

Vegetation is a particularly significant environmental constraint on the structure of animal vocalizations. It provides perches from which animals can call, but it can also affect the acoustic parameters of the call. As one example, songbirds living in forests tend to produce long tonal, whistle-like songs with low modulations while songbirds living in more open habitats tend to produce songs with rapid modulations (Morton, 1975). The presence and type of vegetation interacts with atmospheric conditions such as temperature gradients, absorption, scattering, refraction and reflection to influence call propagation and degradation (Bradbury and Vehrencamp, 1998). As patterns of vegetation become modified by climate change, will communication sounds still propagate efficiently in these changing habitats?

The physical environment also impacts the receiver of the vocalization. The receiver must detect the call at various distances from the source (the sender) and against environmental noise that can mask it; otherwise, communication will fail. One strategy to make the receiver's job easier has been identified in some orthopteran insects (crickets, grasshoppers, katydids) and anuran amphibians (frogs and toads). These animals have evolved an auditory system (ear, auditory nerve, and auditory brain areas) that are special-

ized to detect (that is, are maximally tuned to) important frequencies in their species' mating and advertisement calls (Gerhardt and Huber, 2002). In the Puerto Rican coqui frog *Eleutherodactylus coqui*, the two notes in the male's advertisement call are at frequencies of about 1000 Hz and 2000 Hz. The second, higher qui note is important for attracting a female to the calling male, and the female's auditory nerve responds best to this note. In this way, the male sender and the female receiver are coupled, suggesting that the vocal production system and the acoustic processing system have co-evolved (Narins and Capranica, 1976). But, will climate change disrupt this balance between the sender and the receiver? Will the receiver's hearing change quickly enough so that any communication sounds that have been modified by the environment can still be detected and discriminated? If not, then acoustic communication essential for reproductive behaviors and species viability will be disrupted.

Sound Absorption

Some researchers are now beginning to address the effects of the changing climate on the acoustic structure of vocalizations. Snell-Rood (2012) analyzed acoustic features of songs from 50 species of North American wood warblers and of echolocation sounds from 11 species of Southwestern bats, and correlated these features with levels of atmospheric absorption at various locations in the geographic ranges of these species. She found small but significant correlations between some acoustic features and atmospheric absorption. In wood warblers, the frequency bandwidth of song was narrower in habitats with greater sound absorption. Differences in absorption were on the order of 0.03 dB/m to 0.1 dB/m, which translate into differences in the intensity of the song by as much as 10 dB over a 100 m propagation distance, a typical communication range for these birds. Mean frequency of the echolocation calls in the 11 bat species was lower in habitats with higher absorption. For two representative species of bats, absorption ranged from 1.53 to 1.73 dB/m, which translate into a change of about 4 dB in intensity for a prey 5 m away (10 m travel time, from the bat to the prey and back), a distance over which these small bats can detect prey.

Precipitation

Changes in patterns of precipitation produced by climate change can impact animal sounds both by varying humidity and thus sound absorption by the atmosphere, and also by altering the times at which animals will vocalize. Snell-Rood (2012) observed that in the same bat species, acoustic

features of echolocation calls differed between rainy and dry seasons. In rainy seasons, when precipitation and humidity were high, absorption was higher (0.58 dB/m greater than in the dry season) and echolocation sounds were both longer in duration and lower in frequency. An increase of this magnitude would translate into about 6 dB greater absorption, and thus a lower sound intensity, for a bat detecting a prey 5 m away. Such changes may impact the bat's foraging success by altering the distance over which its echolocation operates.

The calling behavior of tawny owls (*Strix aluco*) also is affected by precipitation. During dry days with lower sound absorption, these birds showed better signal-to-noise ratios for detection of their territorial calls and thus a larger communication range (Lengagne and Slater, 2002). Tawny owls did not call during nights of heavy rain, even within the breeding season. The authors estimated that to maintain the same communication range during rainy and dry nights, the owls would need to increase the intensities of their calls by 20 dB, increases that are not physiologically realistic (Lengagne and Slater, 2002). Thus, if overall precipitation levels increase and rainy seasons become longer, then owl acoustic behaviors will become less efficient.

Precipitation also affects communication by its impact on vegetation. Moller (2011) compared the location of calling sites ('song posts') in 34 species of Danish birds in the period 1986-89 and in 2010. Over this time span, local ambient temperatures increased on average by 2° C (20%), precipitation increased by 75 mm (30%), and vegetation was overall higher. Over all species sampled, male birds sang on average from higher perches in 2010 than in 1986, an 18% (1.2 m) increase in "song post height." Moller (2011) suggested that the increased precipitation and temperature produced increased vegetation which in turn triggered changes in song post height. The extent to which an individual species of bird moved to higher perches was related to their local microhabitat: Birds singing in forested areas showed larger increases in song post height than birds singing in grassland. We do not know how these changes in song post height affect the propagation or degradation of song. Details of the mating interactions within a species as well as their susceptibility to predation also influenced the magnitude of the changes in song post height. Because not all species reacted in the same way to similar climatic changes, this suggests that local ecosystems might become unbalanced by favoring some species over others.

Temperature

Like fishes, ectotherms such as insects, reptiles, and amphibians are physiologically vulnerable to external temperature fluctuations (Deutsch et al., 2008; Paaajmans et al., 2013). Ectotherms living in temperate zones have been shown to have a broader tolerance range for changing temperatures than those living in the tropics (Deutsch et al., 2008). Because of this broader tolerance range, these species might suffer fewer physiological, and thus behavioral, consequences of increased temperatures than tropical species (Navas, 1996).

Laboratory studies in both insects and anuran amphibians have shown that temperature affects call production and the operation of the ear and auditory nerve (Stiebler and Narins, 1990; Gerhardt and Huber, 2002; Meenderink and van Dijk, 2006). For example, wing-stroke rate in stridulating, singing insects is linearly related to temperature over a fairly broad range. And in some anurans, the rate and duration of the male's advertisement call vary with temperature, although these effects are not always linear but show considerable individual and species variability (Gerhardt and Huber, 2002). Currently, we have little information as to how these effects would manifest in the natural environment under conditions of global warming.

How a changing thermal environment affects calling behavior in temperate zone anurans has been examined by Llusia et al. (2013). These investigators monitored atmospheric temperatures and calling temperatures (atmospheric temperatures during the times the animals were actively vocalizing) of 10 species of Iberian anurans for a continuous three year period. Males of all of these species vocalized across a range of environmental temperatures, exhibiting a wide "thermal breadth" of activity. These data suggest that anurans can adapt to changing environmental temperatures. Species living in habitats with hotter temperatures had longer calling seasons and longer periods of calling than those living in habitats with cooler temperatures. For both hotter and cooler habitats, when ambient temperatures rose, so did calling temperatures. Llusia et al. (2013) suggested that temperate zone anurans can acclimate to increased external temperatures by shifting their preferred calling temperatures, but again, different species do not all react in the same way.

The onset of the breeding season in temperate zone frogs is typically indexed acoustically, by the beginnings of chorus formation and advertisement calling (Blair, 1961). Gibbs and Breisch (2002) showed that over the time periods 1900-

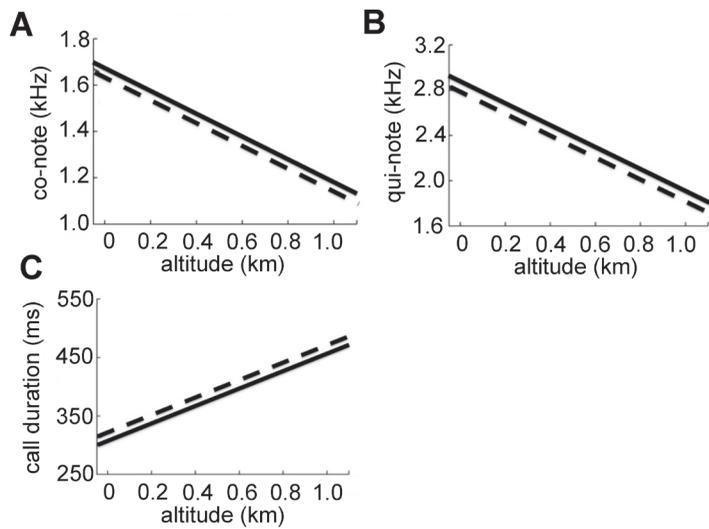


Figure 4: Relationship between acoustic parameters of the two note (co qui) advertisement call of male Puerto Rican coqui frogs and altitude at which the animals live, sampled in 1983-1984 (dashed lines) and again in 2006 (solid lines). Lines represent the best-fitting linear regression through the data for each time period. (A), the “co” note in the advertisement call decreases in frequency as altitude increases. (B), the “qui” note decreases in frequency as altitude increases. (C), total call duration (both notes together) increase as altitude increases. Regression lines for the two time periods are parallel, but shifted. Over the 23-year span, mean ambient temperatures increased by 0.37°C . Figure adapted from Narins and Meenderink (2014).

1912 and 1990-1999, four of six frog species acoustically censused in the area around Ithaca, New York, began calling earlier in the spring, by 10-13 days. This shift towards the earlier onset of advertisement calling was correlated with an average increase of $1\text{-}2.3^{\circ}\text{C}$ in the springtime mean daily temperatures. What effect this earlier breeding has on population size or viability is not known.

Changing environmental temperatures can also impact acoustic communication in tropical anurans. Narins and Meenderink (2014) compared advertisement calls of male Puerto Rican coqui recorded in 2006 to those recorded 23 years earlier, in 1983-84. These frogs are found at different altitudes in their natural habitat, and the acoustic parameters of their advertisement calls vary over this altitudinal gradient. At both time periods, the frequencies of the two notes in the advertisement call decreased with elevation (Figure 4), and the duration of the entire two note call increased with elevation, and at similar rates. That is, the best-fitting regression lines through the data from both time periods are parallel, but are offset. Note frequencies are higher in 2006 but call duration is shorter. These shifts are mirrored in an upward shift in mean local temperatures of 0.37°C (range $0.34\text{-}0.41^{\circ}\text{C}$) over this 23 year span. Although laboratory studies have shown that temperature affects the ability of some species of female frogs to discriminate adver-

tisement calls (Gerhardt and Huber, 2002), it is not known if the hearing sensitivity of female coqui frogs has shifted in a manner paralleling the shift in the male coqui’s call. Any disconnect between the male’s vocal output and the female’s hearing sensitivity would have severe negative consequences for species reproduction and survival.

Unlike ectotherms, endotherms (birds and mammals) regulate body temperature by internal physiological means. There are few data that address the question of how acoustic communication in endotherms is affected by global warming. This is a particularly important question in species such as songbirds, whose social and reproductive behaviors are largely regulated by vocal cues (song). Aside from the small influence of sound absorption on song bandwidth (Snell-Rood, 2012), it is not known if other acoustic parameters of song, like those of frog advertisement calls, vary with temperature over geographic gradients.

Increasing temperatures may affect acoustic communication in temperate zone songbirds indirectly, by advancing the breeding season (Torti and Dunn, 2005). Seasonal variability is an important component of the communication system in these animals. In some songbird species, the brain nuclei controlling song production and song perception are larger in the spring than in the fall (Tramontin and Brenowitz, 2000). These volume changes have been linked to changes in day length and levels of circulating hormones. The potential contributing factors of temperature or of precipitation, which also vary seasonally, on these volume changes have not been explicitly examined. It is not known if seasonal variations in the sizes of brain areas occur to the same extent in years where springtime comes earlier, due to global warming.

Bioacoustic Monitoring

In addition to understanding how climate change can impact the acoustic behavior of species, we can use acoustic techniques to monitor changes in the distribution and viability of species in different habitats. For example, birds are considered an indicator species for climate change since community-based bird watching datasets provide extensive historical data on the distribution and timing of behaviors. Bird species most vulnerable to climate change, however, are located in the tropics and are not as well observed as their temperate counterparts (Şekercioğlu et al., 2012). Acoustics can provide key information on these species and their habitats: by recording bird songs in critical habitats, species abundance and distribution can be monitored and

linked to environmental parameters to determine the impact of climate change in specific regions. Avian bioacoustic monitoring has been proven successful for identifying species and determining population density (Frommolt and Tauchert, 2014), as well as determining species richness in regions (Towsey et al., 2014). Bioacoustic monitoring can also be fruitful for examining the relationship between climate change and changing distribution of other species that rely on acoustic communication, including those living in aquatic and in terrestrial environments. Developing semi-automated approaches into fully automated approaches can provide rapid, real-time information on species identification, distribution, and behavior in habitats vulnerable to climate change.

Conclusions

This article has focused on the impact of climate change on the acoustics of individuals or species, but it is important to emphasize that an individual in any habitat is one link in a network of interactions with other individuals and species. This collective interaction of biological, geophysical, and anthropogenic sound, termed “soundscape ecology,” is studied to understand the dynamics of acoustics in environments across space and time (Pijanowski et al., 2011). We are only just beginning to understand how climate impacts the acoustic behavior of species. The evidence so far suggests that any acoustically communicating animal is at risk for climate-change induced modifications. For marine animals, ocean acidification may result in increased ambient noise, which can affect communication, foraging, and predator avoidance. For terrestrial animals, changes in precipitation and temperature can result in modifications to emitted vocalizations, modifications in the auditory system, and modifications to the balance between the sender and the receiver. Together with changes in species’ distribution due to environmental parameters, all these factors may result in changes to the entire soundscape of regions. New methods and approaches are allowing for rapid analysis of soundscapes in the marine (Denes et al., 2014; Parks et al., 2014), freshwater (Gage and Axel, 2014), and terrestrial environments (Farina and Pieretti, 2014; Rodriguez et al., 2014). As the planet continues to adapt to climate change, it is important that all bioacoustic studies document environmental parameters and climate conditions. With this information, we can begin to understand how the sounds of entire habitats and ecosystems will change in response to our changing climate and how this will impact bioacoustics on a global scale.

Biosketches



Laura N. Kloepper is a National Science Foundation Postdoctoral Fellow with dual appointments at Brown University and the University of Massachusetts Dartmouth. Her research focuses on the sensory and behavioral processes underlying echolocation in toothed whales and microchiropteran bats. She obtained her Ph.D. from the University of Hawaii, investigating the dynamics of echolocation in odontocetes using laboratory animals and hydrophone arrays. She currently uses new technological approaches and mathematical techniques to understand adaptive vocal-motor behavior in echolocating bats. She recently taught a course on climate change biology at Brown University, and is interested in linking bioacoustics and climate science.



Andrea Megela Simmons is Professor of Psychology, with a secondary appointment in Neuroscience, in the Department of Cognitive, Linguistics, and Psychological Sciences at Brown University. Her primary research interest is in analysis of the development of the octavolateralis (auditory, vestibular, lateral line) systems in developing anurans across the metamorphic transition. She also studies vocal interactions and dynamics in frog choruses using microphone array techniques. A new line of research concerns the impact of anthropogenic noise on communication in frogs and echolocation in bats.

References

- Aguilar Soto, N., Johnson, M., Madsen, P. T., Tyack, P. L., Bocconcelli, A., and Fabrizio Borsani, J. (2006). “Does intense ship noise disrupt foraging in deep-diving Cuvier’s beaked whales (*Ziphius cavirostris*)?” *Marine Mammal Science*, 22, 690–699.
- Au, W. W. L., Carder, D. A., Penner, R. H., and Scronce, B. L. (1985). “Demonstration of adaptation in beluga whale echolocation signals,” *Journal of the Acoustical Society of America* 77, 726–730.
- Blair, W. F. (1961). “Calling and spawning seasons in a mixed population of anurans,” *Ecology*, 42, 99–110.
- Bradbury, J.W., and Vehrencamp, S.L. (1998). *Principles of Animal Communication* (Sinauer Associates, Sunderland, MA).
- Brewer, P. G., and Hester, K. C. (2009). “Ocean acidification and the increasing transparency of the ocean to low-frequency sound,” *Oceanography* 22, 86–93.

- Cox, T. M., Ragen, T. J., and Read, A. J. (2006). "Understanding the impacts of anthropogenic sound on beaked whales," *Journal of Cetacean Research Management* 7, 177-187.
- Denes, S. L., Miksis-Olds, J. L., Mellinger, D. K., and Nystuen, J. A. (2014). "Assessing the cross platform performance of marine mammal indicators between two collocated acoustic recorders," *Ecological Informatics* 21: 74-80.
- Deutsch, C. A., Tewksbury, J. J., Huey, R. B., Sheldon, K. S., Ghalambor, C. K., Haak, D. C., and Martin, P. R. (2008). "Impacts of climate warming on terrestrial ectotherms across latitude," *Proceedings of the National Academy of Sciences* 105, 6668-6672.
- Farina, A. and Pieretti, N. (2014). "Sonic environment and vegetation structure: A methodological approach for a soundscape analysis of a Mediterranean maqui," *Ecological Informatics* 21, 120-132.
- Foote, A. D., Osborne, R. W., and Rus Hoelzel, A. (2004). "Whale-call response to masking boat noise," *Nature* 428, 910.
- Frommolt, K.-H. and Tauchert, K.-H. (2014). "Applying bioacoustic methods for long-term monitoring of a nocturnal wetland bird," *Ecological Informatics* 21, 4-12.
- Gage, S. H. and Axel, A. C. (2014). "Visualization of temporal change in soundscape power of a Michigan lake habitat over a 4-year period," *Ecological Informatics* 21, 100-109.
- Gerhardt, H.C., and Huber, F. (2002). *Acoustic Communication in Insects and Anurans*. (The University of Chicago Press, Chicago, IL).
- Gibbs, J. P., and Breisch, A. R. (2001). "Climate warming and calling phenology of frogs near Ithaca, New York, 1900-1999," *Conservation Biology* 15, 1175-1178.
- Hester, K. C., Peltzer, E. T., Kirkwood, W. J., and Brewer, P. G. (2008). "Unanticipated consequences of ocean acidification: A noisier ocean at lower pH," *Geophysical Research Letters* 35, L19601.
- Hobday, A. J. and Lough, J. M. (2011). "Projected climate change in Australian marine and freshwater environments," *Marine and Freshwater Research* 62, 1000-1014.
- IPCC (2013). "Summary for Policymakers," In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. (Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA), pp.1-28.
- Joseph, J. E., and Chiu, C.-S. (2010). "A computational assessment of the sensitivity of ambient noise level to ocean acidification," *Journal of the Acoustical Society of America* 128, EL144.
- Lengagne, T., and Slater, P. J. B. (2002). "The effects of rain on acoustic communication: tawny owls have good reason for calling less in wet weather," *Proceedings of the Royal Society of London B: Biological Sciences* 269, 2121-2125.
- Llusia, D., Márquez, R., Beltrán, J. F., Benítez, M., and do Amaral, J. P. (2013). "Calling behaviour under climate change: geographical and seasonal variation of calling temperatures in ectotherms," *Global Change Biology* 19, 2655-2674.
- Meenderink, S.W.F., and van Dijk, P. (2006). "Temperature dependence of anuran distortion product otoacoustic emissions," *Journal of the Association for Research in Otolaryngology* 7, 246-252.
- Miller, J. H., Klopper, L. N., Potty, G. R., Spivack, A. J., D'Hondt, S., and Turner, C. (2014). "The effects of pH on acoustic transmission loss in an estuary," *JASA Express Letters*, in preparation.
- Miller, P. J.O., Biassoni, N., Samuels, A., and Tyack, P. (2000). "Whale songs lengthen in response to sonar," *Nature* 405, 903.
- Moller, A. P. (2011). "When climate change affects where birds sing," *Behavioral Ecology* 22, 212-217.
- Morton, E.S. (1975). "Ecological sources of selection on avian sounds," *American Naturalist* 109, 17-34.
- Narins, P.M., and Capranica, R.R. (1976). "Sexual differences in the auditory system of the tree frog *Eleutherodactylus coqui*," *Science* 192, 378-380.
- Narins, P. M., and Meenderink, S. W. F. (2014). "Climate change and frog calls: long-term correlations along a tropical altitudinal gradient," *Proceedings of the Royal Society of London B: Biological Sciences* 281, 20140401.
- Navas, C. A. (1996). "The effect of temperature on the vocal activity of tropical anurans: A comparison of high and low-elevation species," *Journal of Herpetology* 30, 488-497.
- Orr, J. C., Fabry, V. J., Aumont, O., Bopp, L., Doney, S. C., Feely, R. A., Gnanadesikan, A., et al. (2005). "Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms," *Nature* 437, 681-686.
- Paaijmans, K. P., Heinig, R. L., Seliga, R. A., Blanford, J. I., Blanford, S., Murdock, C. C., and Thomas, M. B. (2013). "Temperature variation makes ectotherms more sensitive to climate change," *Global Change Biology* 19, 2373-2380.
- Parks, S. E., Johnson, M., Nowacek, D., and Tyack, P. L. (2011). "Individual right whales call louder in increased environmental noise," *Biology Letters* 7, 33-35.
- Parks, S. E., Miksis-Olds, J. L., and Denes, S. L. (2014). "Assessing marine ecosystem acoustic diversity across ocean basins," *Ecological Informatics* 21: 81-88.
- Payne, R., and Webb, D. (1971). "Orientation by means of long range acoustic signaling in baleen whales," *Annals of the New York Academy of Sciences* 188, 110-141.
- Pijanowski, B.C., Farina, A., Gage, S. H., Dumyahn, S.L., and Krause, B.L. (2011). "What is soundscape ecology? An introduction and overview of an emerging science," *Landscape Ecology* 26, 1213-1232.
- Rodriguez, A., Gasc, A., Pavoine, S., Grandcolas, P., Gaucher, P., and Sueur, J. (2014). "Temporal and spatial variability of animal sound within a neotropical forest," *Ecological Informatics* 21, 133-143.
- Şekercioğlu, Ç. H., Primack, R. B., and Wormworth, J. (2012). "The effects of climate change on tropical birds," *Biological Conservation* 148, 1-18.
- Simpson, S. D., Munday, P. L., Wittenrich, M. L., Manassa, R., Dixon, D. L., Gagliano, M., and Yan, H. Y. (2011). "Ocean acidification erodes crucial auditory behaviour in a marine fish," *Biology Letters* 7, 917-920.
- Snell-Rood, E. C. (2012). "The effect of climate on acoustic signals: Does atmospheric sound absorption matter for bird song and bat echolocation?" *Journal of the Acoustical Society of America* 131, 1650-1658.
- Stiebler, I. B., and Narins, P. M. (1990). "Temperature-dependence of auditory nerve response properties in the frog," *Hearing Research* 46, 63-82.
- Torti, V.M., and Dunn, P.O. (2005). "Variable effects of climate change on six species of North American birds," *Oecologia* 145, 486-495.
- Towsey, M., Wimmer, J., Williamson, I. and Roe, P. (2014). "The use of acoustic indices to determine avian species richness in audio-recordings of the environment," *Ecological Informatics* 21, 110-119.
- Tramontin, A.D., and Brenowitz, E.A. (2000). "Seasonal plasticity in the adult brain," *Trends in Neuroscience* 23, 251-258.
- Wiley, R.H., and Richards, D.B. (1978). "Physical constraints on acoustic communication in the atmosphere: implications for the evolution of animal vocalizations," *Behavioral Ecology and Sociobiology* 3, 69-94.
- Wysocki, L.E., Montey, K., and Popper, A.N. (2009). "The influence of ambient temperature and thermal acclimation on hearing in a eurythermal and a stenothermal otophysan fish," *The Journal of Experimental Biology* 212, 3091-3099.