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REVIEW ARTICLE

Infrasonic acoustic energy produced by offshore wind turbine energy generation may interfere with bird and cetacean navigation cues

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Abstract
Offshore wind turbine farms are being planned and installed throughout the coastal areas of the global ocean. Noise concerns from these activities are typically framed within frequency bands of concern defined by governmental regulatory agencies (NMFS – OPR, 2018). A less considered noise source are the various infrasonic noises generated by large rotating blades in a pressure-dynamic medium. These noises include the infrasonic "thumps" generated by the motion of the turbine blades as they intersect the "stagnate wind area" on the windward side of the mast (Clancy 1975). A second source of infrasonic energy is the collapse of tip vortices generated by the sudden air pressure gradient transitions across the turbine blades (Vermeer et al. Prog Aerospace Sci 39:467-510, 2003), and the associated "Blade-Vortex Interaction" (BVI) (Brentner and Farasat Prog Aerospace Sci 39(2–3), 2003). These infrasonic sources contain a lot of energy (Edwards 2015) and are in the perceptual range of migratory birds and baleen whales. Given that birds, and potentially whales use infrasonic sound and barometric pressure signals for navigation and migration cues, the installation of thousands of turbines globally may impose significant impacts on migratory birds along avian coastal migratory routes. Additionally, increasing anthropogenic infrasonic noise throughout the ocean may impact and compromise mysticete communication channels and potentially low frequency navigation cues used by these animals.

Keywords Offshore wind turbines · Wind farms · Infrasonic noise · Avian navigation cues · Mysticete navigation cues

Windfarms

The climate catastrophe facing us punctuates the global need to transition from hydrocarbon-based energy sources to "carbon neutral energy sources." This is driving the development and expansion of wind farms world-wide. Terrestrial wind farms have been part of this shift for a few decades by now, but have also been fraught by the variability of terrestrial weather conditions, impacts on terrestrial-oriented birds (Erickson et al. 2001), and noise impacts on people living near terrestrial situated turbines (Schomer et al. 2015).

Recent developments of offshore wind farms leverage the advantages of more dynamic barometric pressure gradients between the ocean and land, and thus more predictable wind conditions (Spiridonov and Ćurić 2021).

While there are a number of working offshore wind farms in Europe — including the North Sea, the Baltic, and Norwegian Sea, currently the largest offshore wind farm development plans are focused on the US Atlantic Coast (World

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Highlights

- Wind turbines generate high-energy infrasonic noise which has escaped consideration due to the frequency limitations of common acoustical instrumentation.
- This noise may interfere with navigation cues used by birds – such as barometric pressure fluctuations, and microbaroms generated by ocean swells, waves pulsing along beaches, and wind pressure instabilities caused by terrestrial features such as forests and geological characteristics.
- Due to the long wavelengths of infrasonic noise, it permeates the air/water boundary without much attenuation.
- Thus underwater infrasonic noise from offshore wind turbines will possibly interfere with low-frequency communication and navigation cues used by whales.

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Economic Forum 2021), the Chinese Pacific Coast, and the South China Sea (World Forum on Offshore Wind 2022).

These locations are in predominantly shallow water settings which have been, and will use sea-floor mounted turbines. There are many justified concerns about the noise impacts of these installations, which include noise impacts of pile driving required to anchor some of the turbine structures to the sea floor (Tsouvalas 2020), and the benthic propagation of dynamic noise down the turbine mast and into the substrate (Jianu et al. 2012; Solan et al. 2016).

Additional noise concerns come from the noises generated by the turbine blades as they harvest wind energy and convert it to electrical energy.These noises include blade turbulence, tip vortex shedding and consequent blade tip vortex collapse, blade vortex interactions (BVI) as following blades intersect vortices from the preceding blades (Brentner and Farassat 2003), and any pulse vibration transmitted onto the blades and supporting structure as the blades intersect the stagnate air piled up against the turbine mast (Van den Berg 2006).

These concerns are substantiated by significant airborne (Baerwald et al. 2009), underwater (Stöber and Thomsen 2021), and benthic noise propagation studies (Dannheim et al. 2020). The preponderance of these studies bracket their acoustical bandwidth to noises perceivable to human hearing — 20 Hz and above. What has not been significantly examined are the noises which we term "infrasonic," which are sounds below human pitch perception. Nonetheless, wind turbines generate significant infrasonic noise, from predominantly two sources: the pressure "thump" as the turbine blades intersect the stagnate air build-up against the windward side of the turbine mast, and the collapse of the tip vortices as the wind unloads kinetic energy while passing through the turbine blades, and BVI (Uosukainen 2011) (See Fig. 1).

A preponderance of turbine noise generation has been evaluated in the context of human hearing paradigms — either using "A-weighed" filters, or high-pass filters set at 10 Hz or above (Downey and Parnell 2017). But a report by Geology Canada examined the acoustical energy, and seismic consequences of that energy produced by an array of four 3 MW turbines in a terrestrial setting. This study revealed that there is significant energy below 10 Hz (Brentner and Farassat 2003) For the sake of comparison, the acoustic spectrogram in Fig. 2 is in dB re: $1\text{Pa}^2/\text{Hz}$, which converted to the common in-air dB reference of $(20\mu\text{Pa})^2/\text{Hz}$ would raise the spectrogram y-axis index by 94.0 dB.

$$10\log_{10}\left(\left(10^6\mu\text{Pa}\right)^2/(20\mu\text{Pa})^2\right) \tag{1}$$

Based on the converted spectrogram values, in the human audible range of 20 Hz to 100 Hz humans may not be able to consciously "hear" this low frequency acoustic energy due to non-linearity in human auditory thresholds, although there is evidence of physiological impacts on humans from the infrasonic noise of terrestrial turbines (Schomer et al. 2015).[1] And while the low frequency cutoff of the study was 0.1 Hz, the trends indicated in the spectrograms suggests that acoustical energy continues to increase as the frequency decreases (Edwards 2015) (See Fig. 2).

There are no common human experience analogs to the "thumps" generated by the blade interruption of the stagnate air in front of the mast, but collapsing blade-tip vortices and Blade-Vortices Interaction (BVI) are evident to human perception — albeit at higher frequencies, with the "thwapping" noise generated by helicopter blades (Boucher et al. 2023). On larger wind turbines, these blade-vortex interactions occur at infrasonic frequencies due to the slower rotation speed of the turbine blades, but they nonetheless occur (Brentner and Farassat 2003) (See Fig. 3).

Bearing in mind that the noise levels from Edwards (2015) are a product of four × 3 MW turbines, there is nonetheless significant energy in these infrasonic noises from these turbines, which will be increased by the number of turbines deployed, and the increase in turbine size (offshore wind turbines currently range from 10 to 16 MW each).

These noises have largely been missed by studies that have been focused primarily on noises impacting human life quality, or intersect with regulatory agency noise exposure guidelines. This is accentuated by the difficulty in instrumenting and measuring infrasonic sounds (Kumar 1983). As a consequence, there is a paucity of environmental acoustical data which intersects the low-frequency perceptual regimes of other taxa.

In this report, we will examine infrasonic noise and the potential impact of this noise on migrating birds and mysticetes.

Defining "Infrasound"

The term "Infrasound" defines an acoustical niche (Krause 1993) inhabited by animals that can perceive acoustical energy at frequencies below human pitch perception. Some animals also produce infrasonic energy. This would include terrestrial mammals — elephants (Payne et al. 1986; O'Connell et al. 1987), horses (von Muggenthaler et al. 1999a), guinea pigs, (Salt et al. 2013), giraffes (von Muggenthaler et al. 1999b), rhinos (von Muggenthaler

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[1] The equipment and testing conditions in Edwards 2015 were not designed to resolve frequencies above 200 Hz, so while the infrasonic energy presented in these spectrograms may not be consciously audible by humans, higher frequency noise due to wind/blade turbulence and turbine mechanical noises are.

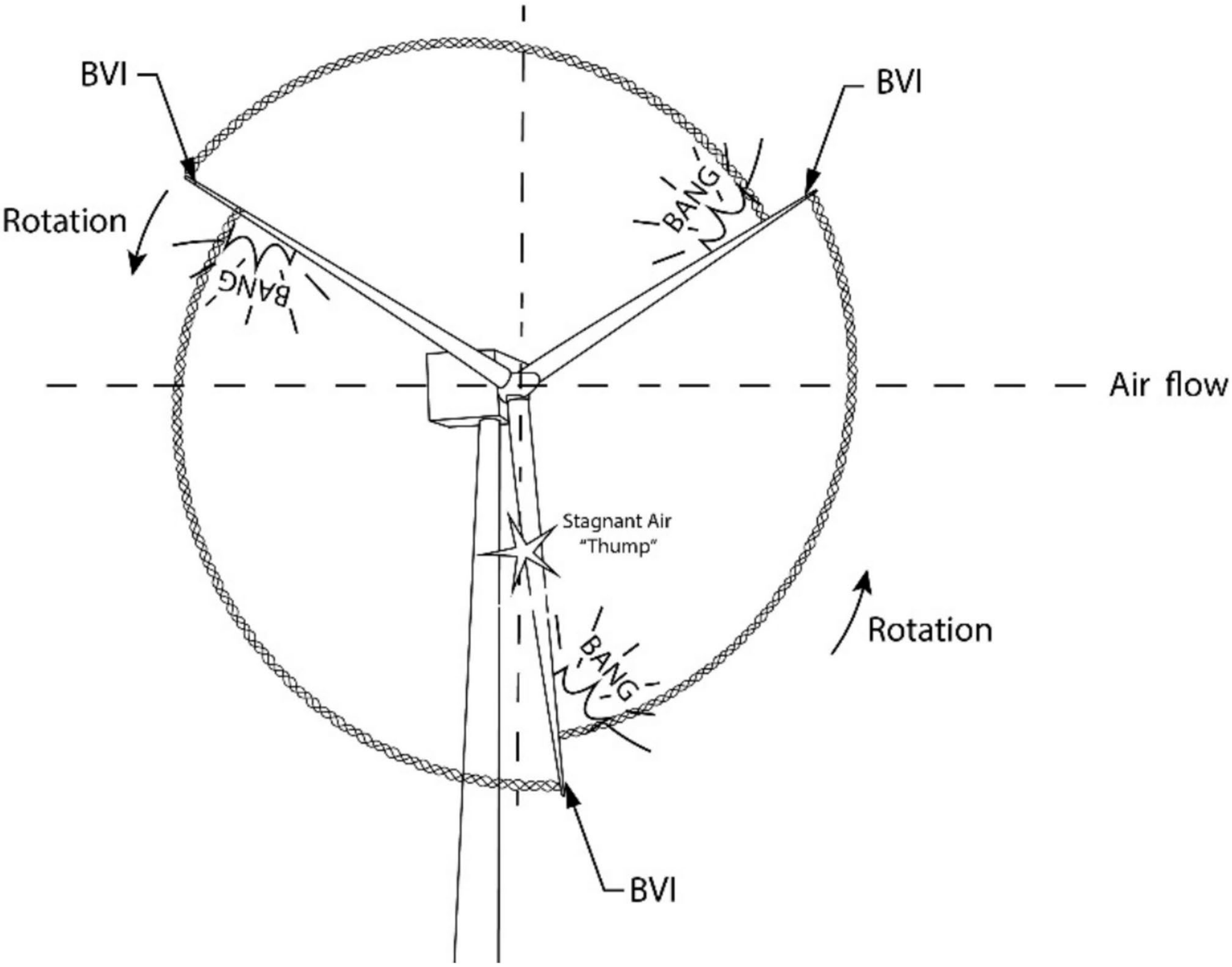


Fig. 1 Blade Vortex Interaction (BVI) (from Brentner and Farassat 2003). Vortices shedding off leading blades present pressure discontinuities that interact with the following blade. From the blade this would be a continuous noise, perceived as a pressure pulsing at the intersection frequency from a stationary position — which in the case of large turbines, occur in what is called the infrasonic band

et al. 1993), and tigers (von Muggenthaler et al. 2000) (among other terrestrial mammals), birds, (Boonman et al. 2020), and aquatic mammals — specifically baleen whales (Baumgartner et al. 2008), and a likely panoply of fishes and marine invertebrates which also inhabit an array of aquatic bioacoustic niches.

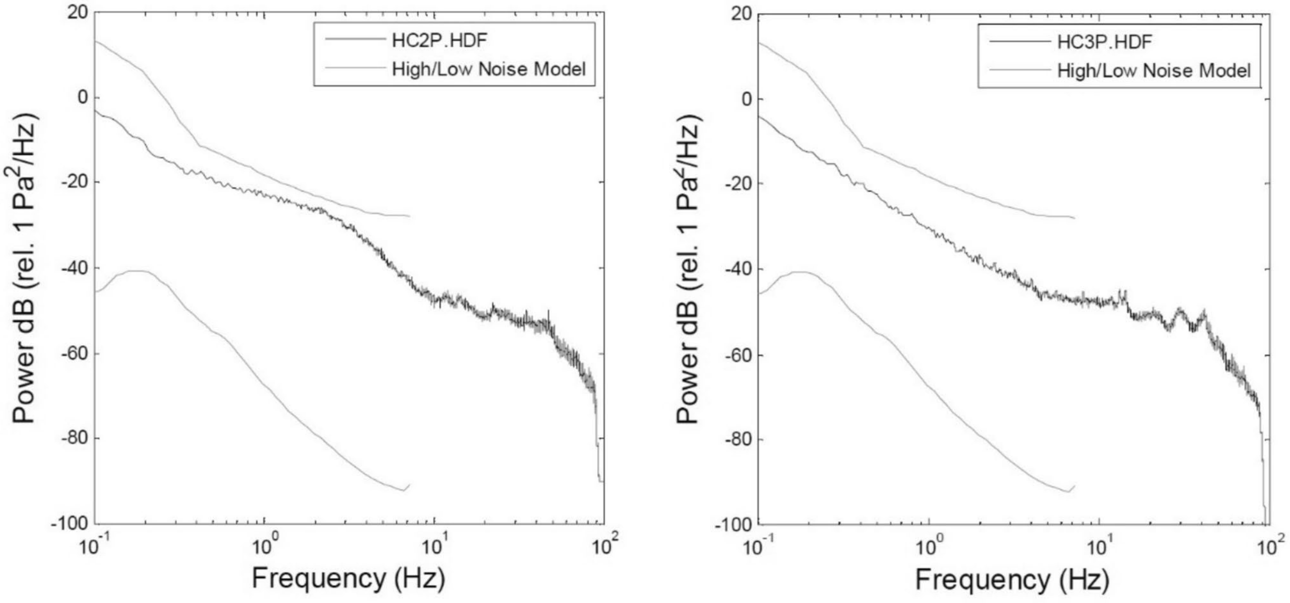
The use of this infrasonic acoustical, barometric, and seismic energy (Roberts and Elliott 2016) in nature is diverse, reflecting the complex adaptations which various animals have evolved to establish their acoustical relationships with their circumstances and surroundings. Behavioral adaptations may include acoustical community binding, breeding fitness announcement, mother/offspring communications, predator/prey relationships, and small and large-scale navigation cues within their surroundings (Stocker 2013).

While it is not common to define barometric fluctuations as "sound," under the definition of acoustical energy being "pressure gradient energy fluctuations in air over time," these fluctuations — perceivable by birds, would constitute "sound" to humans if recorded and "sped up" to come into the range of human frequency discrimination.

Avian use of infrasound and barometric cues

Due to the exceedingly long wavelengths of infrasonic signals, most of their various biological functions remain largely outside of our ability to evaluate, because whatever information environmental infrasonic energy conifers, clear uses of this energy are difficult to simulate in controlled settings (Zeyl et al. 2020).

One exception has been studies in how homing pigeons may use infrasound for navigation. The infrasonic perceptions of pigeons had already been established in 1979



HC2P - 2.5km from array

HC4P - 10km from array

Fig. 2 (from Edwards 2015) Power spectral density of initial 30 min of data acquisition at station located ~ 2.5 km (HC2P) and ~ 10 km (HC4P) from the base of the nearest turbine of a 4 × 3 MW turbine array. Ambient High/Low noise models of ambient atmospheric infrasound (figures from Bowman et al. 2005)

(Quine and Kreithen 1979). These studies revealed that pigeons could perceive fluctuations in barometric pressure down to at least 0.05 Hz (the low frequency limits of the equipment).

Pigeon use of infrasonic or barometric navigation cues was further inferred with the unusual disturbances of four separate pigeon races in Europe and the USA. In all cases birds arrived late, and many were lost altogether. The only common variable in all races were that the routes intersected the sonic boom ‘swath’ created by the over-flights of the Concord Supersonic Transport (SST) (Hagstrum 2000), suggesting that the high-energy infrasonic pulses compromised or destroyed the pigeon’s low frequency perception mechanisms — and thus their ability to use infrasonic cues to navigate.

Adaptations to avian infrasonic perception would include synchronization with localized pressure oscillations generated by wingbeats from adjacent flocking neighbors. Flocking cues are critical to prevent collisions with conspecifics in tight flocking assemblies found in the murmurations of starlings, and the tight flocking formations of various shorebirds, and of course, flocking pigeons (Stocker 2013 p.150).

Avian infrasonic perception could also include long wavelength navigation cues from fluctuating pressure patterns off of geological features, such as waves crashing on beaches, pressure fluctuations created by ocean swells (Waxler and Gilbert 2006), wind blowing across mountain ridges, through forests, and across plains (Patrick et al. 2021).

These localized, or geographical pressure fluctuations are termed “microbaromes,” and ride above regional barometric pressure variations (den Ouden et al. 2021), which are the larger barometric fluctuations induced by oncoming weather fronts. These larger barometric conditions inform flight strategies of migrating birds (Breuner et al. 2013) that would want to avoid dynamically fluctuating macro-barometric cues indicating unstable weather fronts, but exploit stable, steadily decreasing barometric pressures of a stable oncoming front — which would indicate tailwind advantages of a predictable oncoming weather system (Breuner et al. 2013). Further studies indicate that pigeons can follow pressure gradients by way of tracing wavelength variables through Doppler shifts perceived while weaving their flight patterns through the long wavelength pressure gradients, which, at flight velocities of 20 m/s, would yield Doppler frequency fluctuations of 5% at 5 Hz — possibly enough for dynamic directional discrimination and may account for the circling behavior of pigeons as they flock toward their particular destinations (Quine and Kreithen 1981).

The ability to read these infrasonic soundscapes would confer detailed temporal-spatial maps to birds using them for navigation cues.

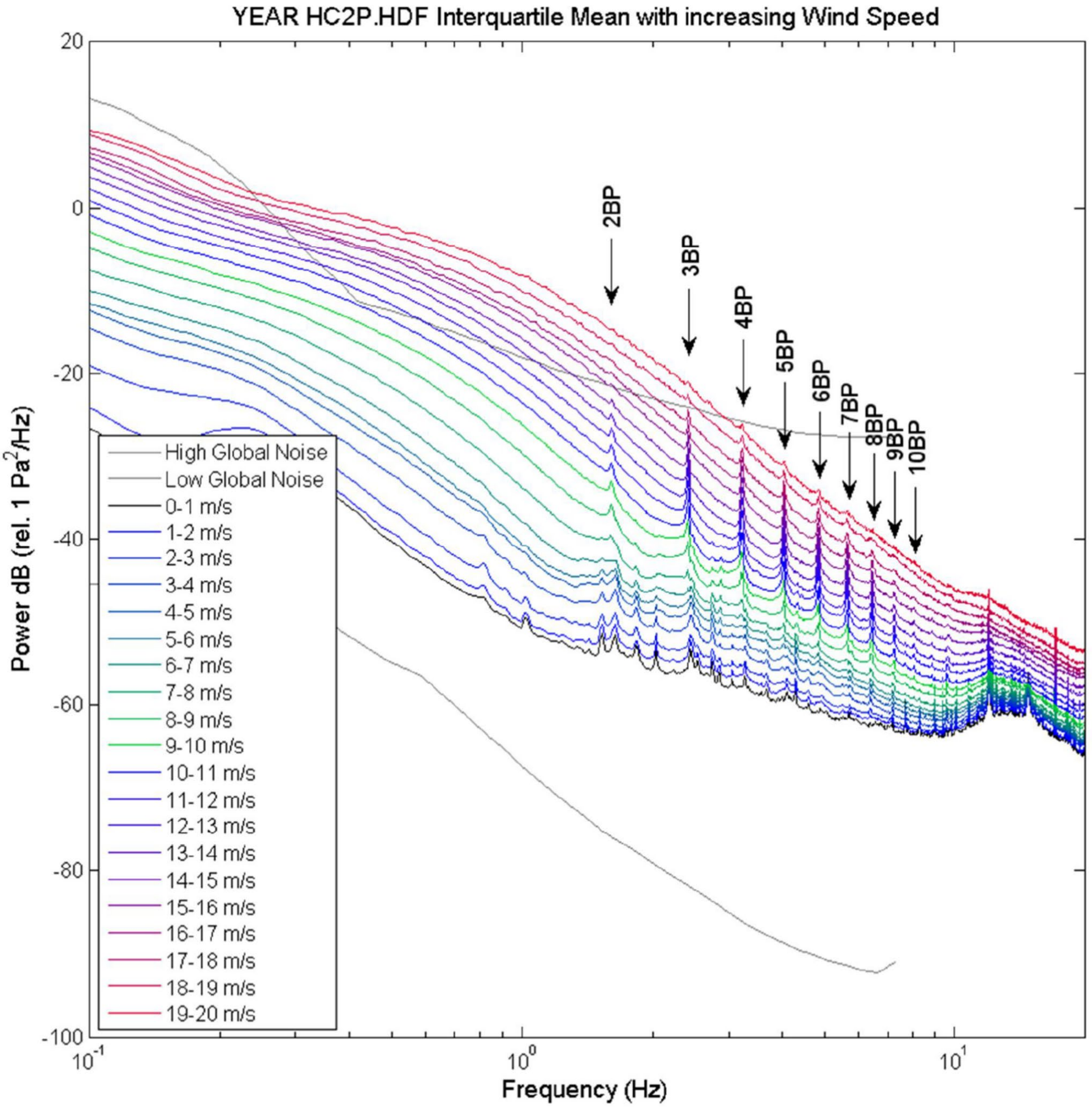


Fig. 3 Inner-quartile means for a range of wind speeds as observed infrasonically at monitoring station located ~ 2.5 km from the base of the closest turbine in an array of four × 3 MW turbines. Observed noise source is primarily that of the turbine blade-pass harmonics. A more rapid increase in ambient background levels between 0.03 and 4 Hz resulted in a near-burial of the turbine harmonics at high wind speeds. This is likely due to the greater exposure of the monitoring station to wind turbulence as compared to the other three monitoring stations presented in Edwards 2015

Mysticete use of infrasound

The evidentiary question remains as to whether mysticetes use low frequency acoustical energy for navigation cues as well — given that they navigate across vast distances. As underwater visual input is limited by turbidity and marine light conditions, low frequency acoustical energy remains the best candidate for mysticete navigation cues (Clark and Gagnon 2022).

Infrasonic navigation cues could be derived from waves crashing along coastlines, tectonic and geothermal activity, tidal and current flows around marine geological formations, underwater pressure oscillations caused by (weather induced) ocean swell patterns, and possible acoustical reflections of low frequency, long wavelength mysticete phonations off of marine geological formations — somewhat in the way that odontocetes echolocate off of their surroundings with high frequency short wavelength sounds (Burnham 2020).

Unlike teasing out how birds perceive and use infrasonic sounds in enclosed pressure chambers (Quine and Kreithen 1979), determining if, what, and how Mysticetes engage with infrasonic acoustic energy remains outside of the lab, and largely up to informed speculation, expert elicitation (Slottje et al. 2008), and modeling (Ketten et al. 2007; Cranford and Krysl 2015).

There are a few studies verifying that Mysticetes can track and localize low frequency sound sources — involving the whales spatially responding to seismic surveys. One involved tracking of fin whale migrations in the Mediterranean in which their annual migration course was disrupted by a 285-km-distant seismic survey in the Mediterranean Sea (Castellote et al. 2012), and seismic surveys causing group course deviations of as much as 40 degrees in Australian Humpback whales (Dunlop et al. 2017), confirming that they can localize (to avoid) long wavelength sound sources.

Echolocation—bio-sonar, has been well established in smaller vertebrates such as bats (Griffin 1958), birds (Brinkløv et al. 2013), and odontocetes (Schevill and Lawrence 1953). These signals have been easily associated with hunting strategies, but are hard to confirm in long-range navigation strategies such as home-finding. Nonetheless Microchiroptera (without the visual faculties of the Megachiropterans) are able to return to their roosts after long foraging journeys.

It is clear that cetaceans also know where they are — from the smaller odontocetes to the larger mysticetes, and can navigate to where they need to be. The use of sound would be obvious — with signal wavelength being correlated to the dimensions and extents of their maps.

Noise interference with biologically important signals

Noise pollution impacts on marine taxa has been an advancing field as a consequence of increasing anthropogenic noise from the mechanization and industrialization of the ocean (Kusku et al. 2018). While the introduction and increase of anthropogenic noise tracks the introduction and expanding use of internal combustion engines (Stocker and Reuterdahl 2012), it has only been in the last few decades that noise regulations have been applied to inform noise mitigation in marine habitats (Guan et al. 2018). But the regulated frequency band of the “Low Frequency Cetaceans” “rolls off” before falling into the infrasonic band of concern in this paper (NOAA 2024).

This may be due to the fact that the development of the Marine Mammal Noise Exposure Thresholds was initially developed around “temporary” and “permanent” auditory threshold shifts, and only secondarily concerned about behavioral disruption (NOAA 2024). Infrasonic noise has not been integrated into the exposure metrics because with the exception of explosions infrasonic noise rarely exceeds levels likely to cause auditory threshold shifts.

A second reason may be that infrasonic noise is more complex to measure than higher frequencies, requiring microbarometers or seismometers in above-water environments, and infrasound-adapted hydrophones or seismometers underwater (Grimmett et al. 2019). This may be the reason that wind turbine noise data rarely includes frequencies below 10 Hz (Tougaard et al. 2020; Stöber and Thomsen 2021).

So while there is clear evidence that birds perceive infrasonic pressure oscillations in the atmosphere in Quine and Kreithen (1979), and that it can disrupt their way-finding (Hagstrum 2000), infrasonic hearing in cetaceans currently rests on circumstantial evidence (Clark and Ellison 2004), and physiological modeling (Tubelli and Ketten 2019). Evidence.

In birds there are clear examples of windfarm avoidance (Fig. 4). There is a visual component to this, as birds entering the windfarm increases at night (13.8% of the flocks vs. 6.5% during the day). At night 6.5% of those flew closer than 50 m to the turbines, whereas12.3% did during the day (Desholm and Kahlert 2005). It would be difficult to determine if any of this avoidance was due to infrasonic noise,

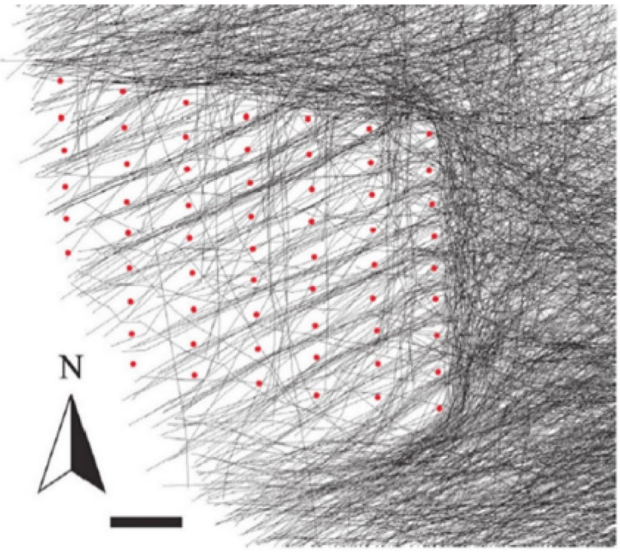


Fig. 4 Graphic of eider ducks and geese windfarm avoidance from Desholm & Kahlert (2005). Black lines indicate bird flight paths and red dots are turbines. The thick black line represents 1000 m to show scale

as the dimensions of the variables (the distribution of the turbines, wavelengths of the infrasonic noise, and sizes of the flocks) are large.

In autumn, the waterbirds featured in the paper (common eider *Somateria mollissima* and Geese) flock with coordinated, or sequential wingbeats, so observing whether this coordination becomes more erratic closer to the turbines would point to infrasonic noise interfering with their flight patterns. The authors were using radar to track the flocks, which is not granular enough to track wingbeats, but the fact that 13.8% (night) and 6.5% (day) pulled away from their flock formations may point to this sort of disruption.

While there is much concern with, and thus studies on turbine blades colliding with birds in flight, much of this concern comes from terrestrial turbines, which interfere with raptor habitat use (Diffendorfer et al. 2021). Offshore turbines are significantly taller, with the rotor sweep commonly being 30 m or more above the waterline, which is just within the upper altitude reach of many oceanic birds (Schatz 2025).

On a local–regional level, avian avoidance of windfarms due to infrasonic disturbance may pose significant habitat loss for birds that feed on ocean life. On a geographic level, infrasonic noise may interfere with navigation cues used by many migrating birds. This will be of particular concern with the rash of proposed windfarms along the US Atlantic coast, along which many passerine birds migrate, and is called "The Atlantic Flyway" by ornithologists.

As mysticetes use of infrasonic sounds is based on informed speculation, pre-determining the impacts of wind turbine infrasonic noise on them would be difficult. But as there is a correlation between frequency and transmission loss across the air/water boundary such that:

$$TL^{dB} = 20\log_{10}(k^{a}h) \tag{2}$$

where "TL_{dB}" is Transmission loss in decibels, "k_a" = $2\pi/\lambda$ (the acoustic wave number), and "h" is the height of the sound source,[2] so that the air/water boundary becomes much more permeable to acoustical energy at lower frequencies. "Wave number" is used here, also called "repetency," because it expresses the spatial frequency of a wave in radians. At the wavelengths we are speaking about here (1 Hz = 343 m in air and 1500 m in water), the sources of infrasonic noise — the blade-vortex interaction, and the blade intersection of the stagnate air in front of the mast, the whole turbine assembly acts as a monopole source. So the common concern about the soundwave angle of incidence intersecting the air/water boundary that would otherwise be considered at higher frequencies is superfluous (Godin 2006). Additionally, Oleg A. Godin found that "the [water-to-air] interface becomes anomalously transparent and the power flux in the wave transmitted into air increases dramatically when a compact underwater sound source approaches the interface within a fraction of wavelength" (Godin 2008a). A similar property exists in air-to-water transmission (Godin 2008b).

Given the high level of acoustic energy in the four × 3 MW turbines from Edwards (2015), we can anticipate significant levels of marine infrasonic noise to be generated by hundreds to thousands of 10 MW to 16 MW turbines.

Conclusion

Given the geographical and temporal scale (e.g. gradual construction of wind farms over years) of this inquiry, it would be hard to assume a null hypothesis. This is exacerbated by the assumption offered under the National Environmental Policy Act (NEPA) required Environmental Impact Statements on these large project's inclusion of "Adaptive Management" strategies — implying that if the projects are found to be compromising habitat and wildlife, strategies will be applied to mitigate the problem.

At present, we can only speculate about the impacts that the turbine-generated infrasonic noise will have on avian migration and navigation cues, and mysticetes communication and navigation signals, but as the windfarms are constructed, we will surely find out.

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Declarations

Competing interests Not applicable.

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[2] Given the wavelengths at 1 Hz and below, the height variable "h" is also somewhat arbitrary.

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The work advances the mission of our 501(c)(3) “Not for profit, public benefit organization” Ocean Conservation Research which is: “focused on understanding the energy and noise impacts of the industrialization of the ocean, and its consequences on marine life.

“We engage in marine biological and technological research based on conservation priorities. We use the products of this research to inform the policies and practice of the public, industry, and lawmakers so that we may all become stewards of the sea.”.

As such there is no “competing interests.”.

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