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Acoustic Habitat Degradation Due to Shipping in the Indian Ocean Region

Arnab Das

Abstract

The Indian Ocean Region (IOR) is strategically emerging as the most important sea area in the twenty-first century and presents itself as a hub for maritime trade. The shipping traffic both due to merchant and naval vessels has increased manifold. The underwater radiated noise (URN) from marine vessels interferes with the perception of the marine ecosystem by the big whales, leading to acoustic habitat degradation. The global increase in the low-frequency ambient noise due to shipping is known to have doubled every decade, since the preindustrial era based on records available since the 1950s. The IOR has unique characteristics, in terms of geopolitical, socioeconomical, acoustical (tropical littoral waters) and more. The regulatory framework for managing the acoustic habitat degradation in the IOR will require understanding the unique challenges and opportunities. The frequent stranding of big whales in recent times is a manifestation of the severe acoustic habitat degradation in the region and demands urgent measures to be initiated. This chapter attempts to present the multiple dimensions of acoustic habitat degradation due to shipping in the IOR. Effective underwater domain awareness (UDA) framework proposed by the author could provide a comprehensive way forward to contain the noise pollution caused by increasing URN levels.

Keywords: acoustic capacity building, underwater radiated noise (URN), automated identification system (AIS), noise pollution, underwater domain awareness (UDA), sustainable blue economy, maritime capacity building

1. Introduction

Globally, there have been sustainability concerns due to the so-called development bogey which is slowly manifesting as a major cause of environmental degradation [1]. The oceans and other marine environments have been ignored so far because of perceived absence of direct impact on human well-being. However, in the recent times, we have been observing more and more attention being turned toward the oceans as it has been realized that marine ecosystems are a continuum of the universe and any disruptions there can impact human habitat on land as well [2].

The science and technology advances have made it more and more accessible to reach the deepest of the depths in the oceans, and we are realizing the challenges and opportunities that exist in the marine ecosystem. The vast undersea resources have significant potential for socioeconomic growth for mankind; however, the

exploration and exploitation should be done in a calibrated manner to address sustainability concerns. Blue economy has become a buzz word in strategic discussions and vision formulations; however, the environment impact assessment (EIA) at times lacks multiple dimensions of the marine eco-concern due to the human intervention with the undersea ecosystem. Acoustic habitat degradation always escapes attention of the scientific and political community due to high resource requirement and the relative inaccessibility of the undersea domain [3].

The stressed resource on land is encouraging us to look at the oceans for economic growth and prosperity. The blue economy has emerged as the new buzz word with significant potential to complement economic development using the oceans and its resources. The blue economy has multiple dimensions, and the emphasis is on sustainable growth; however, on ground, the unregulated and unscrupulous rush toward oceans for economic gains has made it a serious cause of concern. The traditional blue economic activities include shipping, ports, oil and gas exploration, fishing, deep sea mining, marine tourism and other marine industries. In the recent times, we are also seeing massive growth in emerging industries like aquaculture, carbon sequestration (or blue carbon) and renewable energy production such as wind, wave and tidal energy. **Figure 1** gives a broad pictorial representation of the multiple activities associated with the blue economy [4].

The availability of so-called modern science and technology tools has made the deepest of the oceans accessible, and thus, the humans are able to exploit and explore the vast resources of the undersea domain with ease. The uneven distribution of resources and know-how among the global powers coupled with the fragmented geopolitical approach toward regulating global commons are major obstacles for ensuring sustainability. There is vested interest among the global powers in ensuring complete lack of transparency and non-equitable extraction of the high-value resources available in the undersea domain. The environmental impact assessment (EIA) is skewed, and the real impact on the marine ecosystem never gets evaluated given the complex dimensions and dynamics of the marine ecosystem. Acoustic habitat degradation is one such issue that has escaped attention and attained monstrous proportion [5].

The ocean ambient noise or the background din in the seas has multiple sources both natural as well as anthropogenic. Theoretically, ambient noise cannot be directly linked to a specific identifiable source; however, it is attributable to general

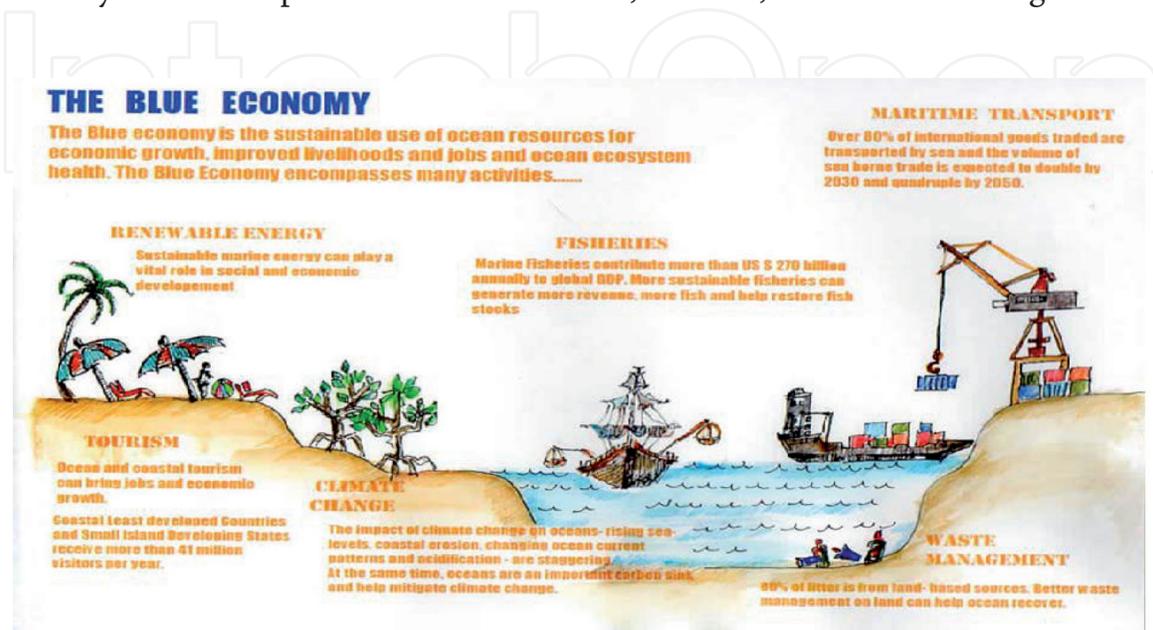


Figure 1. Multiple activities associated with blue economy.

types of sources. The natural sources include geophysical activities like wind-generated waves, earthquakes, precipitation, cracking of ice and many more as well as biological sources from marine species like whale songs, dolphin clicks and fish vocalizations. The anthropogenic noise originates from human-driven activities like shipping, geophysical surveys, oil and gas exploration, dredging and sonar transmissions. The classical ambient noise plot by Wenz GM, way back in the post Second World War period (valid even today), gives a clear segregation of the sources based on the frequency bands. The extreme low frequency (<1 KHz) is dominated by distant shipping followed by wind-generated noise up to 15 kHz [6]. **Figure 2** gives the Wenz curve with clear domination of the shipping noise in the low frequency region.

Among the multiple activities under the blue economic umbrella, the shipping has some unique characteristics that merit attention while we want to analyze the sustainability concerns in the blue economy or the acoustic habitat degradation in the undersea domain [8]. These include the following:

- a. The shipping is the single ubiquitous source of noise in the ocean. It forms the basic low-frequency background ambient noise across the oceans.
- b. Shipping is directly linked to the global economic growth index, so there is minimal political motivation to regulate this sector.
- c. The shipping noise is low frequency, so it suffers minimal attenuation in the underwater medium. This results in maximum impact across a large area.
- d. The shipping noise is low intensity signal, however due to the well distributed nature of the shipping traffic the impact is wide spread across the entire global oceans.
- e. The shipping noise acts like slow poison and does not cause instant impact. But, it contributes to gradual degradation of the ecosystem where the marine animals suffer profound psychoacoustic degradation leading up to fatalities and drastic species depletion.
- f. The inability to establish direct linkages with the pollutant poses several regulatory challenges. Regulatory formulations demand clear cause and effect linkages.

The geostrategic relevance of the Indian Ocean Region (IOR) in the twenty-first century needs to be understood in a holistic manner. The economic development of any nation is closely linked to its trade and energy supply. The geostrategic location of the IOR ensures that it is the center of gravity for the sea lanes of communications (SLOCs) not only for the nations in the IOR but also for nations in the entire Indo-Pacific and beyond. The energy supplies from the middle-east, and the raw material from Africa to the growing economies in the South East Asia (China, Japan, Korea and others) and the return passage of finished goods from South East Asia to Africa and Europe put IOR in a very strategic position [9].

It is not only the commercial ships but also the naval ships that get deployed to protect the SLOCs given the volatile security situation in the region puts the number count of ships at an alarming level contributing to the high ambient noise. The socioeconomic conditions and also the socio-political situation of the nations in the IOR ensure poor design and manufacturing (with high radiated noise levels) of the ships in region and also limited regulatory provisions to be able to address the concerns of acoustic habitat degradation [10].

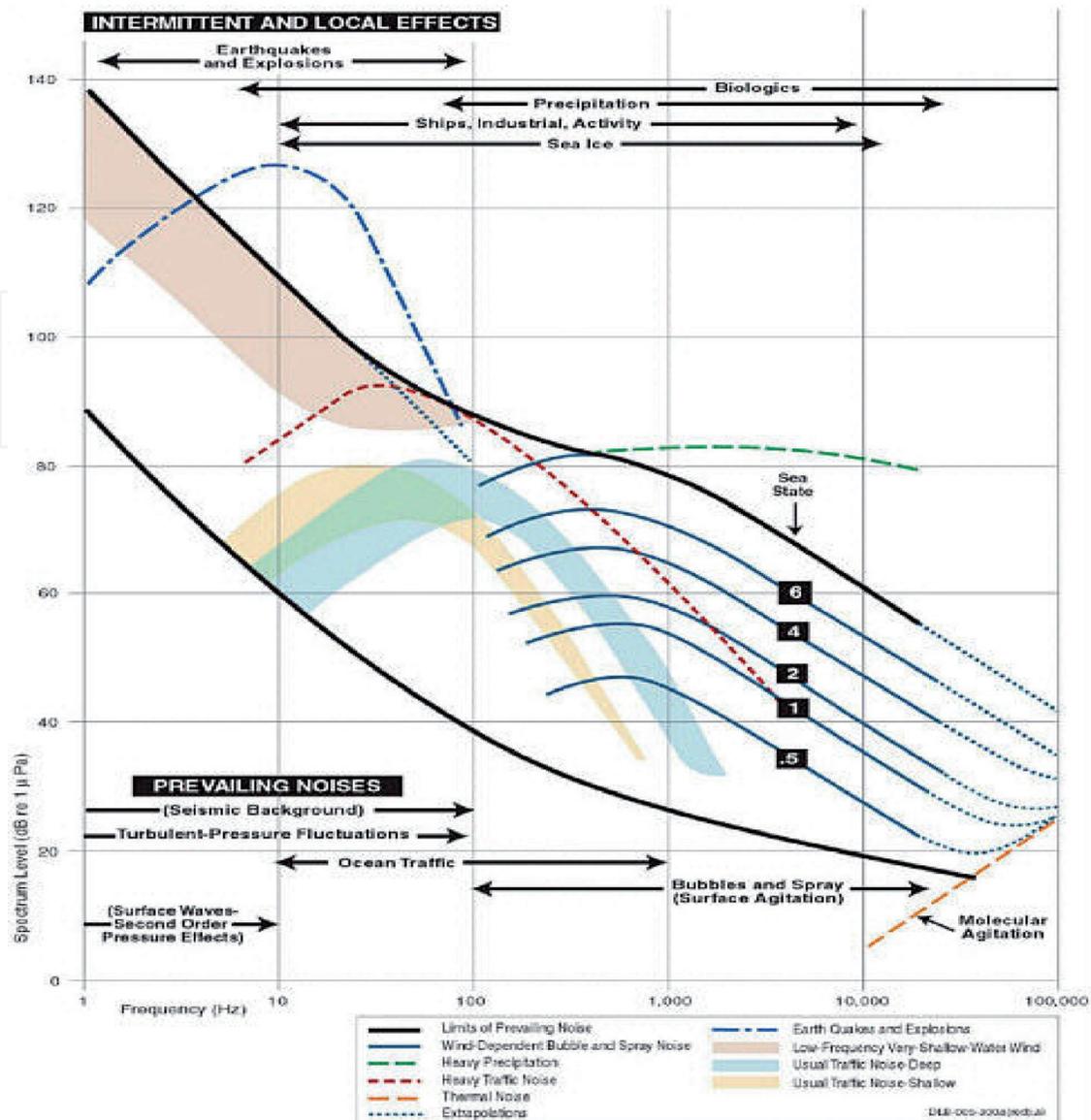


Figure 2. Wenz curve [7].

The subsequent sections in the chapter attempt to address the larger issue of acoustic habitat degradation in the IOR due to shipping. In Section 2, we present the basics of underwater radiated noise (URN), the mechanism of generation of URN, acoustic stealth requirements for the naval platforms, ship design and management issues include, e.g., to contain URN, measurement and analysis aspects and more. Section 3 brings the challenges and opportunities in the IOR at all levels, geostrategically, geopolitically and geophysically. In Section 4, we discuss the use of sound by the marine species and articulate the relevance of sound for these species. Section 5 elaborates on the acoustic habitat degradation due to shipping noise. Section 6 enumerates the regulatory provisions that exist globally and the specific limitations in the IOR. In Section 7, we conclude by giving some way ahead and leads for addressing this serious concern of acoustic habitat degradation in the IOR due to shipping noise.

2. Underwater radiated noise

The underwater radiated noise (URN) is the acoustic signal emitted out of a marine platform as a by-product of its operations. These operations include

propulsion, maintaining habitability on-board, any other mission specific activities and more. The platforms may be deployed in marine environment like the coastal waters or the high seas and the freshwater systems including rivers, lakes and reservoirs. Further, we could be looking at surface platforms like warships for naval deployments and merchant vessels for commercial deployments and also sub-surface platforms including submarines for naval deployments and other sub-sea submersibles for undersea explorations.

The URN emissions are broadly categorized into three components including propulsion systems (comprising of the propellers and other machinery associated with the propulsion of the platform). The second component is the auxiliary machineries required for maintaining habitability on-board, power supply and distribution, mission specific activities and more. The third component is the hydrodynamic noise associated with the flow of fluids within and outside the hull of the platform. The spectral characteristics of the URN can be defined as narrow band due to the reciprocating (corresponding to the cylinder firing rate) and rotating machineries (corresponding to the rotation rate) and broad band due to the cavitation effect in the propellers and the non-laminar flow of fluids within and outside the hull of the platform. The URN spectrum is largely low frequency with narrow band tonals seen up to 500 Hz; however, at higher propeller speed, the broadband cavitation spectrum masks the narrow band machinery tonals and is largely seen up to 1000 Hz [11].

The URN management comprises of three distinct communities. The first is the naval community for whom acoustic stealth is of paramount importance, and they are willing to deploy higher resources to achieve higher stealth standards. The second is the commercial merchant marine who need to maintain low levels of URN to comply with regulatory norms for acoustic habitat degradation. The third community comprises of the ship designers and shipbuilders who need to make sure that the newer marine platforms are compliant of the regulatory norms whether for acoustic stealth or for acoustic habitat degradation. They need to establish a direct link of every stage of the ship design and building activity to the overall URN value, at the end. The acoustic stealth has been a very well-developed area of science and technology for the naval community for a long time; however, it never percolated to the other communities as it remained a closely guarded secret for ensuring military supremacy [12].

The acoustic stealth requirement has multiple dimensions to it. The acoustic signature management as it is called comprises of three distinct stages—the first stage translates to measurement and analysis to be able to maintain enhanced levels of stealth or minimal levels of acoustic signatures to avoid detection. The second stage is the precise prediction of the acoustic signature of any platform (own or from the adversary) based on the available information in the open source regarding the design and machinery details. This can greatly enhance our tactical capabilities of initiating counter measures. The third is the deception, where we fake the actual signature of the platform and try to deceive the adversary given the advent of intelligent mines that can precisely target platforms. The acoustic signature management capabilities require high resource deployment right from infrastructure of an underwater range to measurement and analysis of hardware and software. The know-how is also highly specialized in terms of algorithm design for real-time implementation to advanced signal processing capabilities. The acoustic signature management will have similar corollary for the acoustic habitat degradation assessment as well. The measurement and analysis to minimize the URN is the first stage, and the second stage will be prediction that will be required for effective policy formulation and regulatory compliance. The third stage is the deception in some form, which will be required to ensure minimizing the acoustic habitat degradation for specific species [8, 12].

The second dimension of acoustic stealth management is impact on the performance of our own sensors. The self-noise of the platform that has its origin in the noise and vibration on-board (similar to the URN) impacts the performance of the own sensors. Thus, containing the self-noise is equally important to enhance the effectiveness of the platform. The third dimension is the condition-based preventive maintenance (CBPM) that has its implication on the health of the equipment and fatigue failure. Regular noise and vibration measurement and analysis on-board the platform is an integral part of the planned maintenance schedule to enhance operational efficiency and minimize failures of running machineries. Thus, noise and vibration is an important prerequisite for all the three dimensions with its origin remaining the same; however, the manifestation is different for all the three. There is a need to establish clear linkages of the noise and vibration measurement data for each of the three dimensions, while we undertake the analysis [13].

The URN management needs to be ensured right from the design stage and beyond. The naval warship design has evolved over several decades of effort, and now most of the advanced navies have very mature design and manufacturing capabilities to ensure very high acoustic stealth of its platforms. The stealth requirements for naval platforms are so stringent that it is not enough to have a good design, but also during the operations as well, the regimes of operations are so chosen that the platforms emit minimal URN. The naval platforms undergo regular stealth assessments, to evaluate the exact status of the acoustic signature under multiple machinery regimes and also to monitor any deterioration due to mechanical wear and tear. The redundancies on-board are used effectively toward ensuring enhanced stealth standards during operations based on the exact stealth assessment. The maintenance schedules and routines are planned based on diagnostic ranging to identify causes of poor stealth during operations. Post refit, the effectiveness of the maintenance schedules is evaluated based on the stealth assessment. Any mid-life upgradation of equipment and systems on-board has to undergo acoustic stealth assessment to evaluate its impact on the overall acoustic signature of the platform.

The URN measurement and analysis, normally referred as underwater ranging, is a very complex and involved process, with significant infrastructure requirement and also analysis capabilities. The NATO Standard STANAG 1136 is a framework defined by the NATO for undertaking underwater ranging of warships. The URN measurement of naval platforms is a highly classified activity, and navies have defined their own protocols of measurement and analysis that are not available in open source. The STANAG 1136 is just a broad guideline [14]. The underwater measurement has its own complexities in terms of deployment of the sensors to far field measurement requirements. The Acoustical Society of America (ASA) has its own standards for vertical sensor arrays and the measurement protocols [15]. The underwater ranges in earlier days were the fixed over-run ranges where sensors were laid horizontally, and the vessels were made to pass over them at certain depth and specified regimes of operations. The regime-wise recordings are subsequently analyzed, and inferences were drawn. The fixed sensors have their advantages of high accuracy and effective mitigation of environmental distortions; however, the infrastructure cost is prohibitive. Portable vertical ranges are being increasingly used with the advantage of low cost and reasonable deployment ease [16].

Figure 3 presents a detailed framework for URN management. The three stakeholders, namely the navy with their interest in acoustic stealth, the marine conservation community with their requirement to contain acoustic habitat degradation and the blue economic entities related to ship building and ship design, are represented by the three horizontal faces of the prism. Policy, Technology and Innovation and the Human Resource Development will remain the pillars of any

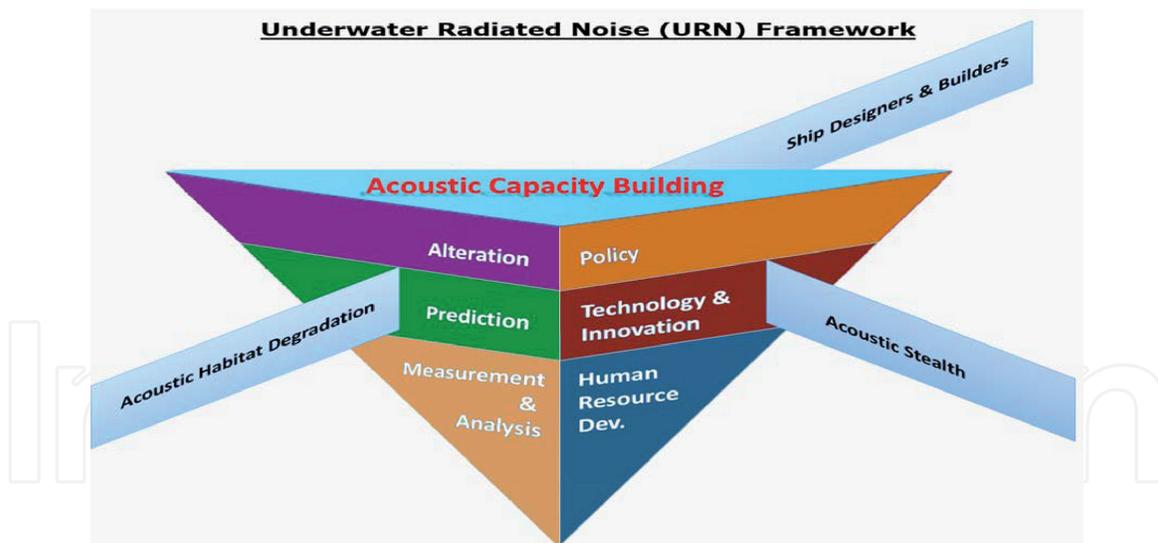


Figure 3.
URN management framework.

initiative toward URN management. The basic steps are measurement and analysis, prediction and alteration (naval community will call it deception as part of their acoustic signature management efforts). Acoustic capacity building will remain the core requirement.

3. Indian Ocean region

The Indian ocean region had become the strategic heartland of the 21st century, dislodging Europe and North East Asia which adorned this position in the 20th century ... the developments in the Indian Ocean region were contributing to the advent of a less Western centric and a more multi-polar world. [17]

—Donald L. Berlin, Head of Security Studies, Asia Pacific Centre for Security Studies, Honolulu, Hawaii

The twenty-first century is seeing massive strategic build up in the IOR, not just from the nations within the region but also from extra-regional powers to safeguard their strategic interests. These strategic interests range from political to economic and also militarily as a theater for great power rivalry being played out in the region. The IOR is the locus of important international SLOC for varied reasons and thus has a very unique strategic relevance [17].

Militarily, SLOC is a major maritime instrument of power, and the maritime geography dictates deployment of maritime forces. The security vulnerabilities in the IOR coupled with the strategic relevance of the SLOC ensures high deployment of maritime forces not just from the nations in the region but also by the extra-regional powers. The political interests originate from the fact that the SLOC signifies the state of relation with the nations along the sea route traversed. The choke points that govern the entry of SLOC into the region have a significant role in shaping the geopolitics of the region. Economically, the shortest route is the most important aspect for SLOC, and any disruption may call for strategic action. The socioeconomic status of nations in the region facilitates large-scale interference by the extra-regional powers, and thus rule-based regional framework is a big causality. The piracy and maritime terrorism in the region being on the rise has ensured huge presence of maritime forces to escort the SLOC, making it a high density

shipping traffic zone. Anti-piracy measures also dictate rerouting of the SLOC, at times against the shortest route logic [17, 10].

The unique geography of India in the IOR and its position with respect to the international shipping lanes carrying bulk of the SLOC have not translated to having even a single transshipment hub in India. This is a major cause of suboptimal routing of shipping in the Indian subcontinent. The bulk of the seaborne trade to or from India, to or from America, East Asia, Africa, Europe and more passes through the Indian territorial waters. The ships carrying this cargo break their bulk in Colombo or in Singapore/Hong Kong. Further, the poor maritime infrastructure in terms of ports and shipyards has a significant impact on the shipping traffic in the region. The poor management of the shipping traffic is a serious cause of concern, in terms of distribution of the traffic that has a major impact on the crowding of the shipping lanes [18].

The shipbuilding industry in the Indian subcontinent has been a nonstarter for various reasons, in spite of having all the inputs necessary for a flourishing industry. Lack of strategic vision probably is the major cause of such a non-starter. Although India boasts of a glorious maritime past, but in the modern era, India has been termed as Sea Blind and has not displayed substantial maritime intent since Independence. The maritime infrastructure has been working in progress, and a huge potential is waiting to be explored and exploited. Right from specialized human resource to conducive policy framework has been a major cause of concern, and thus the contribution of the maritime sector to the GDP is in single digits. The sector not doing well also manifests as minimal investments on R&D and strategic thinking [19].

The Indian shipbuilding industry currently accounts for only 1% of the global shipbuilding market. There are 27 shipyards in the country presently, and out of these, 19 are in the private sector. The current cumulative shipbuilding capacity of Indian shipyards is around 0.5 million deadweight tonnage. The order books of the public sector undertakings (PSUs) are completely skewed owing to high government protection enjoyed by them, whereas the private sector has been struggling due to lack of level playing field. Our shipyards are not competitive in the global market due to high cost and time overrun and archaic infrastructure and technology used. Some of the highly specialized components like the propellers and engines are still being imported at very high cost. Although we are in the major shipping routes, internationally, our shipbuilding and also ship repair industry has not been able to attract much business due to cost and quality concerns. There is serious gap in brand building and marketing as part of the national policy. As a nation, we were late in recognizing our maritime potential, and thus there is total absence of strategic vision [20].

The twenty-first century is certainly seeing a sea change in the maritime outlook for the IOR, both domestically and globally. The Indo-Pacific strategic construct is a recognition of the importance of the IOR in the global strategic space. More and more nations are deploying strategic assets in the region both militarily as well as for economic and political interests. India is being seen as a strategic partner for the global powers, specifically for the Indo part of the Indo-Pacific strategic construct. Domestically, as well, there is substantial strategic intent being displayed by successive governments. The Security And Growth for All in the Region (SAGAR) vision, announced by the Indian prime minister in May 2015, and the earlier mega initiative, named Sagarmala, are some of the critical policy announcements and affirmative action being aggressively pursued by the Indian establishment. Massive maritime capability and capacity building initiative are being given high priority including transshipment hubs, seamless multi-model connectivity and inland water transport across the river systems [21].

The tropical littoral waters in the IOR ensure significant challenges in the acoustic monitoring of the underwater domain. The sonars deployed for any attempt at underwater survey for effective underwater domain awareness (UDA) is grossly limited due to the sub-optimal performance. The tropical waters manifest as higher depth for the sound axis synonymous with the SOFAR channel that dictates the interaction of the acoustic propagation with the surface and the bottom. The depth of the sound axis at the equator is close to 2000 m, in contrast to 50 m at the poles. Acoustically, the littoral waters are defined based on interactions with the surface and bottom boundaries; thus in the tropical waters even in water depths of 3000 m, the underwater domain behaves like shallow waters. This means that the entire IOR is likely to be behaving like littoral waters acoustically due to tropical conditions. To top it all the tropical conditions also ensure higher surface and bottom fluctuations, and thus, the multipath propagation further translates to higher acoustic signal distortions. Thus, any attempt at acoustic habitat assessment to ascertain acoustic habitat degradation will be subject to the tropical littoral limitations in the IOR [22].

The regional dynamics in the IOR has a profound impact on the geopolitical outcomes. The lack of synergy among the nations in the region and large-scale interference by the extra-regional powers have facilitated total absence of rule-based governance. The regulatory framework to manage acoustic habitat degradation and R&D efforts to facilitate realistic acoustic habitat assessment have been a non-starter. The socioeconomic status of the nations in the region makes it politically unviable to bring regulatory frameworks to manage the marine environment effectively [23].

4. Acoustic habitat

The marine species use sound or acoustic signals for numerous biologically critical functions, and thus they can safely be said to possess acoustic vision as they perceive the world around them through sound. These biologically critical functions include communication (for group cohesion and coordination), navigation and exploration (for sensing the environment around), echolocation (for foraging and detection of prey), survival (avoiding predators) and many more. They may generate (vocalization) and receive (listen) sound, based on the soundscape of their habitat. Thus, acoustic habitat is critical for their well-being and survival. The vocalization and hearing is species specific and thus needs deeper understanding. The vocalization is relatively possible to monitor for varied range of species. However, the hearing of species is near impossible to monitor as the psychoacoustic study cannot be undertaken in the natural environment as the sound stimulus and its impact cannot be studied, without taking the animal into captivity. The auditory systems of smaller species that can be taken in captivity have been studied to some extent, but these animals in captivity may not respond in the same manner as in their natural habitat. Thus, such studies will have their own biases and may not reflect the true animal behavior. The vocalization in the large species like the big whales has been studied in their natural environment in a limited sense as their habitats are spread across the vast expanses of the oceans and also inaccessible in many cases. Out of the 126 sub-species of the whales (including dolphins and porpoises), only 25 have been studied for their acoustic characteristics, and most of them have only been studied for their vocalization as these are extremely large in size so cannot be taken in captivity in a lab environment [Chapters 2, 8].

Typically, it is assumed that the vocalization and the hearing have to be overlapping, with the hearing frequency band being much larger than the vocalization range. Further, it is interesting to note that some species may require hearing

sensitivity far beyond their own vocalization to be able to detect any predatory threat through their vocalization. For example, a harbor seal may need to be able to detect the vocalization of a killer whale, though it may not vocalize in the same band. Thus, significant study is required to understand the acoustic habitat in the marine environment, both in terms of vocalization and auditory system (perception of sound) for varied marine species. The sound scape in their natural habitat will play a critical role in this study as these animals are known to adapt to their natural settings [Chapters 2, 8].

Marine animals have adapted to their acoustic habitat by developing specialized vocalization and hearing organs. The sound generated by fish is largely low frequency up to 1 kHz that use multiple mechanisms for the same. These include [Chapters 2, 8] the following:

- *Drumming* that uses sonic muscles located on or near the swim bladder.
- *Stridulation* that uses striking or rubbing together of skeletal components.
- *Hydrodynamics* that uses quickly changing speed and direction while swimming.

The cetaceans have two major suborders namely Odontoceti (toothed whales) and the Mysticeti (Baleen whales) with a distinct and complex mechanism to generate and receive sound. The Odontocetes generate a variety of sounds using a complex system of air sacs and specialized soft tissues that vibrate as air moves through the nasal passage. The Mysticetes use the larynx (without the vocal cords) for sound generation. Marine vertebrates generate sound by closing their enlarged claws to create a bubble that cavitates. Snapping shrimps are known to generate sound with very high intensity using the cavitation process. Crabs are known to generate sound by drumming on the substrate with both their claws. Marine invertebrates use stridulation and rapid muscle contraction for sound generation like the spiny lobster [Chapters 2, 8].

The auditory system for acoustic perception of sound varies based on the fact that the particular marine species is exclusive water dweller or mixed. Cetaceans (exclusive water dwellers) and pinnipeds (seals, sea lions and walruses are mixed dwellers) show significant differences as the cetaceans have no external pinnae, and their ear canals are nonfunctional and narrow that are clogged with debris and dense wax. The narrow ear canal is not attached to the tympanic membrane (ear drum), thus not connected to the middle ear. In toothed whales, the lower jaw is surrounded by specialized fats which along with a thin bony area called the pan bone is known to play a critical role in channelizing the sound to the middle ear. The middle and inner ears of cetaceans are encashed in bones that are located in a cavity outside the skull. The complexity of the inner ear determines the sophistication of the auditory process [Chapters 2, 8].

In pinnipeds, the external ear flaps, or the pinnae are reduced or absent. Muscles and cartilage valve along the external ear canal function to close the ear canal to water. In general, the middle and inner ears in pinnipeds, polar bears and otters are similar to those of terrestrial mammals, and the mechanism for perception of sound is also similar. Depending on their lifestyles, some species hear best in air, whereas others hear better underwater.

The fishes have developed a unique mechanosensory (lateral line) system that senses vibration and water flow. The fish body is considered to be acoustically transparent as the density is approximately the same. The fish's body moves in concert with the traveling sound wave, and the sound gets picked up by bones in the inner ear called otoliths that are denser. The displacement/bend of the otoliths deforms

the cilia on the hair cells located in the inner ear that is picked up by the brain as sound. Otoliths are the species-specific sensory organs, made of calcium carbonate, whose shape and size determine the acoustic characteristics of the sensed signal. The proximity of the swim bladder and the inner ear significantly determines the sensitivity to sound by the fish species. The density of the gas inside the swim bladder being lower than the fish's body and that of the seawater allows the swim bladder to deform due to sound pressure waves [Chapters 2, 8].

The acoustic characteristics of the vocalization by the marine animals that contribute to the soundscape in the underwater domain are highly species specific based on their intensity, frequency and time duration. The purpose for vocalization could vary from one-way communication signals to two-way echolocation signals for active sensing. The size of the animal also has a bearing on the acoustic characteristics, as bigger animals tend to generate low-frequency signals, whereas smaller animals tend to produce high frequency, sensitive to the mechanism of sound generation; size being comparable to the wavelength of the signal.

The large size Mysticetes produces sounds for communication over long ranges and senses the environment at low-frequency band ranging from 10 to 2000 Hz. These large animals migrate over large areas and need to communicate over large ranges, thus use low frequency that attenuate far less. These signals are categorized as tonal calls, frequency-modulated sweeps, pulsed tonals for echolocation and broadband grunts. They use echolocation to sense the environment around them rather than for foraging. The Odontocetes use mid-to-high frequency sound in the frequency band of 1–200 kHz. These signals are categorized as broadband clicks with species-specific peak energy between 5 and 150 kHz, burst pulse click trains for echolocation used for foraging and other active sensing requirements and tonal and FM whistles for communication ranging from 1 to 25 kHz. Pinnipeds that are semi-aquatic breed produce a limited array of barks and clicks in the frequency range of 1–4 kHz [Chapters 2, 8].

The non-toothed cetaceans have been found to be incapable of echolocation. The Odontocetes have very sophisticated sonar processing abilities with directed beams in space to locate, track and intercept prey. The fatty melon in the forehead acts as an acoustic lens to focus the acoustic beam. The freshwater dolphins like the Ganga river dolphins and harbor porpoises have been known to have very specialized clicks in the frequency range of above 100 kHz for foraging. These animals have long beaks that form narrow beams to be able to direct high energy in the front for locating small fish for food. The sperm whales generate sonar pulses with intensity of the order of 223 dB underwater, which is equivalent to 160 dB in air, louder than a jet during take-off [Chapters 2, 8].

The marine animals have evolved their vocalization and auditory system to be able to exploit the acoustic potential of the undersea domain, in spite of the severe limitation of the propagation conditions and low SNR. The natural sound from the animals is also complemented by the noise due to wind and others due to human intervention [Chapters 2, 8].

5. Acoustic habitat degradation

The sound scape in the marine environment is composed of two main sources. The natural source comprising of the physical activities like wind, wave, ice, rain and others and the biological sources as discussed above. The alternate source is the anthropogenic or manmade sources that primarily comprise of distant shipping, seismic surveys for oil and gas sector and the sonar transmissions for military and commercial applications. Additionally, there are industrial activities like deep sea

mining, pile driving, dredging and many more that also contribute significantly to anthropogenic sources in the ocean [24].

The acoustic signals are the only signals that propagate effectively and efficiently underwater, so any disruption of the soundscape causes serious acoustic habitat degradation for the marine species. The marine species adapt very well to the natural sources of the soundscape in their habitat; however, the anthropogenic noise associated with the so-called human development index directly abets the acoustic habitat degradation. The rapid rise in the maritime activities has resulted in massive increase in the ambient noise having serious impact on the marine species' ability to adapt to the changes. The impact varies from minor discomfort to serious injuries and even fatalities and long-term species degradation [8].

The stressors impact the marine animal based on the acoustic characteristics of the noise ranging from the intensity, spectral content, duration, duty cycle and more. The sound propagation characteristics of the underwater medium also have a profound impact on the acoustic characteristics of the signal projected on the animal. The most important of all is the acoustic characteristics of the receptor (the marine animal likely to be impacted). Thus, a comprehensive source-path receiver model needs to be studied for a realistic assessment of the precise acoustic habitat degradation of any stressor on the marine environment. The IOR with its tropical littoral characteristics will have significant influence on the sound propagation. Certain marine species may be directly impacted, while others may get influenced through the ecosystem changes. Most of the conservation studies are species specific and have limited impact due to the dynamic interaction between the multiple components of the ecosystem and the stressors [12].

Among the stressors, the distant shipping, seismic activities due to the oil and gas industry and the sonar transmissions are considered among the primary sources of underwater noise that impact large-scale acoustic habitat degradation. Among these, the distant shipping is the single ubiquitous source of noise source that has widespread implications on the acoustic habitat degradation. The others are transient and localized in nature so can be managed to some extent. The distant shipping has the following characteristics that make it extremely complex, when we look at the management of the stressor:

- a. The shipping traffic is extremely spread out to have a larger influence across multiple geographical regions and a very widespread impact as well.
- b. The low frequency characteristics of the underwater-radiated noise from marine vessels suffer least attenuation while propagating in the underwater medium. Thus, the impact is spread over a large area covering thousands of kilometers. Coupled with the shipping traffic distribution, the influence is across the entire globe.
- c. The shipping is directly linked to the economic growth index as over 90% of trade by volume and 70% of trade by value are carried by them. Thus, it is politically unviable for governments across the third world developing nations to bring regulations to limit underwater radiated noise (URN) from marine platforms.
- d. The URN from shipping is like a slow poison that does not have any dramatic demonstration of catastrophic impact unlike the other transient sources. The increase in low-frequency ambient noise in the world oceans due to shipping has been recorded to have increased by 3.3 dB per decade since the 1950s. The

so-called focusing event very essential for bringing regulatory provisions driven by strong public outcry does not get created due to the slow rise in the low-frequency ambient noise caused by URN [25, 26].

e. It is interesting to note that the acoustic stealth requirements for the naval vessels drives the same technologies and techniques required for managing acoustics habitat degradation. However, the absence of any regulatory provisions the profit hungry merchant marine has avoided implementing any such provisions. The humans being terrestrial animals do not see a direct impact of acoustic habitat degradation of the marine ecosystem on their well-being.

The global merchant marine fleet is directly connected to the economic engines, and so the enhanced global economic growth has translated to rise in the shipping traffic. The term “Noiseconomics” has been coined by Frisk to describe the relationship between ambient noise levels in the sea and global economic trends. His work is based on the assumption that distant shipping is the single ubiquitous source of ambient noise in the ocean, and these assumptions lead to the following hypothesis [27].

A. *Hypothesis 1:* Gross tonnage of the world fleet is directly correlated with low-frequency ambient noise.

B. *Hypothesis 2:* The world GDP is directly proportional to the gross tonnage of the commercial shipping fleet.

C. *Corollary:* Ambient noise in the oceans is directly correlated with the world GDP.

The plots in **Figure 4**, as given by Frisk in his work, confirm that the rate of growth in all the three parameters, namely the world GDP, world fleet gross tonnage and the low-frequency ambient noise in the oceans. This closely matches with actual underwater recordings presented by Ross given above.

“Measurements of ambient noise levels, world fleet gross tonnage, and world gross domestic product are plotted as decibel (dB) quantities for the period 1950-2007. Linear fits to the data for all three quantities show similar slopes of 3.3 dB per decade with high goodness of fit (R^2) factors.”

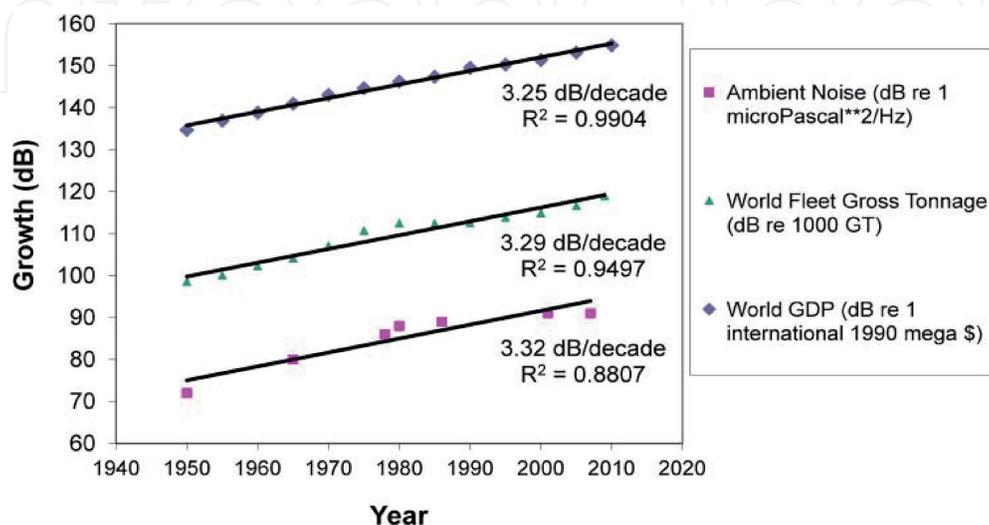


Figure 4. Long-term trends in ambient noise levels, gross tonnage of the world fleet, and world gross domestic product [27].



Figure 5. Recent marine mammal stranding along the Indian coast [10]. Top left: 42 ft. Blue whale stranding off the Alibag coast in June 2015. Top right: 50 ft. Bryde whale stranding off the Mumbai coast in January 2016. Below: Over 90 short-finned pilot whales stranding off Tuticorin beach in January 2016.

The massive maritime infrastructure push in the IOR is creating unregulated activities both within and also on a regional level, thereby causing sustainability concerns in the IOR. The growing global consciousness on environmental degradation is bringing uniform regulatory frameworks across regions, and now India being a signatory to global norms may get constrained by these regulations. Acoustic habitat degradation is a major fallout of the rising maritime activities without comprehensive regulatory framework. The increasing maritime activities are also accompanied by higher noise levels in the ocean. The frequent stranding of marine mammals along the Indian coast is a manifestation of the catastrophic acoustic habitat degradation. **Figure 5** presents recent incidents of stranding that is a manifestation of the severe acoustic habitat degradation. Such stranding is attributable to the navigation failure due to high ambient noise leading to disorientation [10].

6. Regulatory framework

The transboundary nature of the underwater noise and its variability across time and space and across the species have profound impact on any attempt at managing the acoustic habitat degradation in the underwater domain. Any attempt at regulation demands that we have precise information on the “cause and effect.” While many stressors like seismic activities and sonar transmissions may

be reasonably quantifiable to establish the cause and effect, but the URN from shipping is very complicated to establish this direct connect. The low-frequency ambient noise due to URN for distant shipping is spread across the entire ocean basin, so it is near impossible to define the jurisdiction of a nation or a region. The regional or global regulatory framework will require political consensus among all the stakeholders, which is a very difficult task given the diverse socioeconomic and geopolitical realities [28].

The URN has been recognized as a pollutant way back in 1982 under the United Nations Convention on the Laws of the Seas (UNCLOS). The substance vs. energy debate has also been put to rest under the UNCLOS that is ratified by 168 countries by now. The UNCLOS did declare the hazards of noise on the marine mammals and stated that it had a deleterious effect on them. However, even today, it has failed to announce regulatory framework on tackling noise in the ocean. The complexities of URN measurement and the infrastructure requirement for the same are extremely prohibitive for the developing world to accept it particularly when the shipping industry is going through a global down-turn [12].

The Marine Strategy Framework Document (MSFD) proposed by the European Union is by far the most forward looking international agreement to manage the acoustic habitat degradation issue so far. It considers multiple anthropogenic stressors and their potentially cumulative effect, giving more stress on ecosystem-based approach toward managing maritime activities. The stated objective is to achieve and maintain “Good Environmental Status” by 2020, measured by 11 descriptors, out of which the 11th one refers to underwater noise. URN management is getting far more attention under the MSFD, and more R&D-based regulatory aspects are being encouraged. There are multiple other regional initiatives originating in Europe like the Helsinki Commission (HELCOM), OSPAR Convention, ASCOBANS, ACCOBAMS, etc., that do address the issue of noise in the oceans. However, it is important to recognize the trans-boundary nature of noise and the limited effect in the absence of larger regional and global initiatives [28].

The Marine Mammal Protection Act (MMPA) was probably the first regulation to recognize and implement the precautionary principle for the marine environment. In 1972, the MMPA in the United States recognized the harm caused by noise to marine mammals and mandated that activities in the oceans have to contain their energy (acoustic) emission into the water. The International Maritime Organization (IMO) in its protocol of 1978 (MARPOL) addresses the aspect of marine pollution from ships through its six annexures. The MARPOL fails to recognize noise as a pollutant being in energy form and only defines substance pollution (oil, noxious liquid substances, harmful packaged substances, sewage, garbage and air pollution). More recently, it has declared certain vulnerable areas as particularly sensitive sea areas (PSSA), where noise from the ships is recognized as a hazard and bars the ships from these areas in order to protect the acoustic habitat. However, in the open ocean, IMO fails to regulate the noise from the growing shipping traffic. The International Whaling Commission (IWC) does recognize the adverse impact of noise on the whales from the whale watching vessels and others. However, it fails to formulate an effective policy for protecting the whales from noise in the ocean [12].

The challenge of environmental conservation, rather management of the commons, has far greater complexities particularly in the developing world due to what we refer as the “Tyranny of Small Decisions.” This concept was first explored in the context of economics by Alfred E Kahn, who highlighted the fact that a number of small decisions, individually small in size and time perspective, cumulatively generate an outcome that is neither optimal nor desired. He brought out that market economies commonly commit this, leading to market failure. The findings were extended to other areas like environmental degradation, political elections and

health by many other scholars. The underwater environment more specifically the acoustic habitat degradation, a late entrant to the entire environmental debate, is a very fit case to apply these concepts for holistic management of the entire issue [8].

The ocean noise regulation has significant scientific uncertainties, management limitations and regulatory complexities. The Marine Mammal Protection Act (MMPA) 1972 was one of the most progressive regulations of its times with the precautionary principle as the guiding environmental framework. The MMPA covered whales, dolphins, porpoises and other marine mammal species; however, even after so many decades, over 20 species from the great blue whale to the Hawaiian monk seal are still considered endangered and threatened. The failure of any regulatory provision has multiple political, economic, social, scientific and management-related attributes [Chapters 5, 8].

The first and foremost issue that made the act meaningless was the exemptions, as the *Defense Authorization Act* gave far too many exemptions for multiple military deployments related to sonars and numerous other use of underwater sound in the name of national security. The peak of the Cold War ensured that the US Navy had numerous operational naval deployments and also research and training projects with heavy use of underwater transmissions for Anti-Submarine Missions against their adversary namely the Soviets. The second aspect was the noise criterion itself that could not cover the large number of marine species with very unique auditory features. The regulatory provisions necessitate robust noise criterion; however, the diverse marine species are very hard to map in terms of their hearing characteristics. Further, in the absence of detailed psycho-acoustic study across the species, the precise cause and effect cannot be established. The absence of firm noise criterion also makes it open to exemptions in the court of law even for commercial activities, especially in the developing nations with least political will for environmental concerns against the socioeconomic demands. The tropical littoral water in the IOR makes the medium impact far more severe to establish the source-path receiver model for formalizing the noise criterion. The resource limitations ensure that field experiments are too few and far in-between to be able to establish the noise criterion for the indigenous species in the local water. Ecosystem approach has always been a causality, as it is highly resource intensive and also requires high-end and sustained research efforts. Species-specific conservation efforts can never map the cause and effect in a complex and high biodiversity habitat with very intricate interplay of exchange among the species [Chapters 5, 8].

The regulatory provisions that exist so far have been able to address the instantaneous noise sources like seismic surveys, sonar transmissions, underwater explosions and others. However, the transboundary nature and the slow manifestation of the shipping noise have very unique challenges to establish the precise cause and effect and also the noise criterion. The cumulative impact is not only hard to prove but also impossible to implement. The time and resource constraint on the regulatory authority to undertake a scientifically logical experiment to establish biologically significant and population level impact is never enough. Further, in the absence of a credible noise criterion that addresses all species and all sources, it is a non-starter. The transboundary and the widespread impact (due to low frequency of the URN) brings complications of legal jurisdiction on regulatory provisions. National authorities cannot unilaterally bring regulations, and regional cooperation involves geopolitical challenges of diplomacy and international relations. Socioeconomic diversity, political factors, extra-regional power play and others complicate regional cooperation. The IOR is a mix of all kinds of physical, economic, political and geo-strategic factors making it a fragmented regional dynamics with significant interference by the extra-regional powers [Chapters 5, 8].

7. Way ahead

The formulation of way ahead for any crisis is the precise assessment of the degradation. In this case, we may refer as the environmental impact assessment (EIA) for the shipping in the IOR. The author has undertaken two critical works to establish the EIA, specific to this requirement. The first work pertains to the spatiotemporal low-frequency ambient noise mapping in the IOR using automatic identification system (AIS) data for shipping. The spatiotemporal low-frequency ambient noise map provides the precise levels of the anthropogenic noise due to shipping in the IOR. This is the first comprehensive assessment of the noise levels with a qualitative and quantitative description. The quantitative assessment provides the dB levels of anthropogenic noise in the IOR, based on the shipping traffic in the region and also keeping the medium fluctuations into account to make it an authentic in-situ assessment. The qualitative assessment pertains to the spatiotemporal changes based on the varying shipping traffic and the medium fluctuations across the entire region. The dB levels can be updated real time for any applications ranging from policy formulation, local management of the conservation efforts and more. The **Figure 6** provides the spatiotemporal low-frequency ambient noise map for the IOR as discussed [12].

The second work pertains to the real impact assessment of the shipping traffic and some policy decisions pertaining to the security concerns namely the anti-piracy measures. The on-ground assessment of the increase in the low-frequency ambient noise levels and the manifestation on the big whales have been presented in the work. The real recordings have been compared with previously reported work to present the precise ground situation and also correlation with the recent stranding incidents in the IOR. A detailed cause and effect assessment along with in-depth analysis has been presented to give a sense of the actual seriousness of the concern. **Figure 7** above gives the recent hike in the stranding in the IOR and how it can be attributed to the increased shipping traffic in the region [10].

The two works above make it amply clear that all is not well, and very urgent steps are required to be initiated, to contain the crisis and manage the larger acoustic habitat degradation issue in the IOR. Given the specific challenges of the IOR—politically, socioeconomically, scientifically and otherwise—it is extremely important that we bring in a framework that addresses the entire issue very comprehensively. The author has been progressing a unique underwater domain awareness

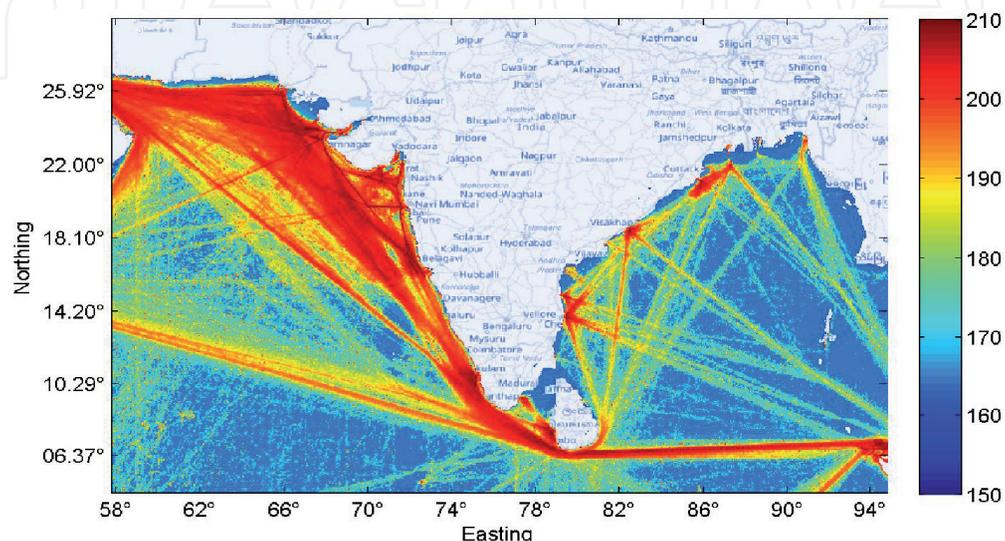


Figure 6.
Spatial noise mapping for IOR (noise in dB re 1 μPa^2) [12].

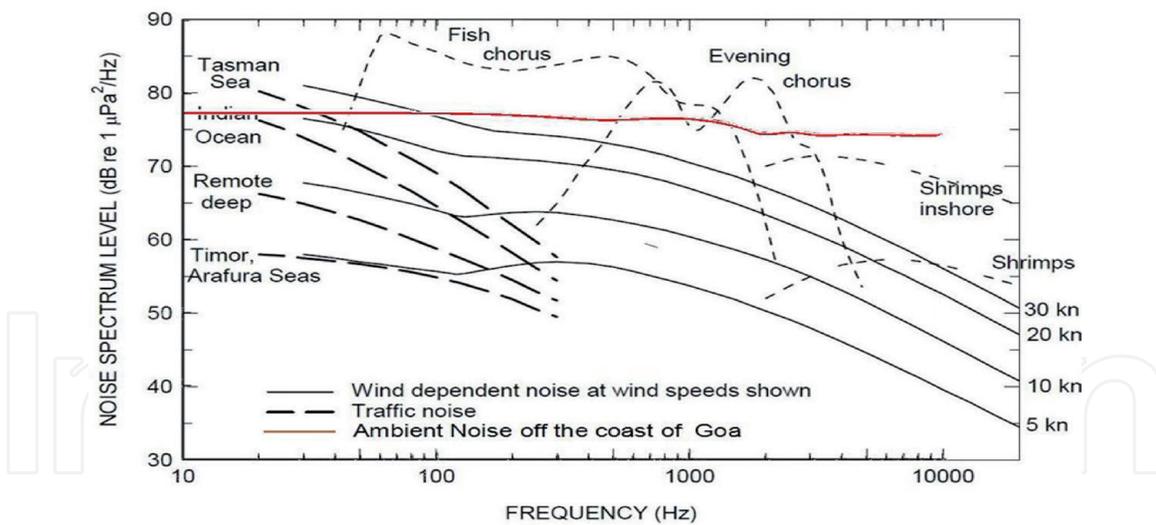


Figure 7. Ambient noise comparison across different sea and Indian Ocean recordings over a decade. Recent data (in red) recorded off the west coast of India closer to the stranding area in 2010 post the anti-piracy measures is compared with recordings a decade earlier [10].

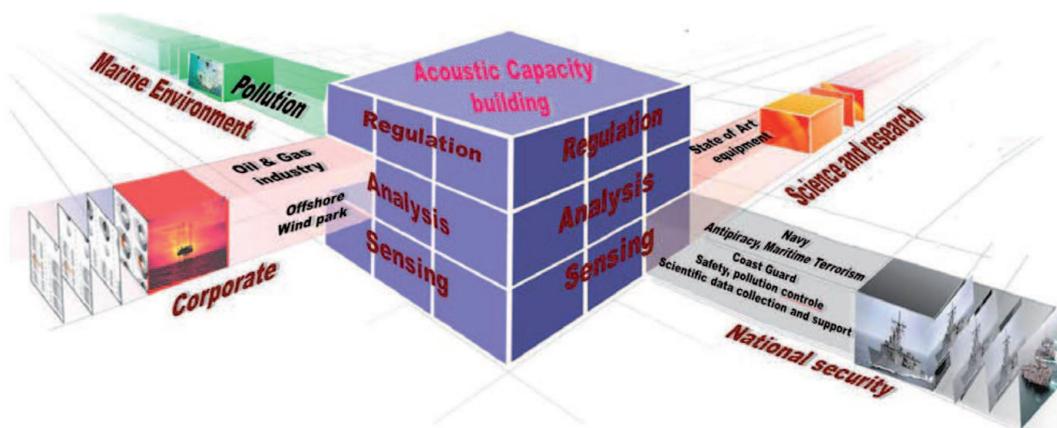


Figure 8. Comprehensive perspective of undersea domain awareness [29].

(UDA) framework that could potentially address all the challenges mentioned above. The UDA framework largely addresses the critical issues of pooling of resources and synergizing of efforts across stakeholders to take care of the resource limitations in the developing world and also bring in efficiency and effectiveness. It is completely aligned with the local challenges and strategic vision of the dominant local authorities. **Figure 8** gives a broad overview of the UDA framework as proposed by the author [29].

More specifically, there is a need to initiate an effective URN management plan that comprehensively takes care of all issues pertaining to the problem at large and also the local challenges of the IOR. It is ironical that the acoustic stealth is such a critical component of the military deployment in the underwater domain; however, the same has not percolated to the merchant marine for narrow commercial interests. The stealth technology has seen quantum jump during the Cold War era, and thus the know-how to undertake effective URN management does exist. However, in the absence of statutory regulatory provisions, the commercial shipping industry has managed to avoid these measures. Such actions (aptly described by the “Tyranny of Small Decisions”) have brought us to a very critical state of affairs, and urgent measures are now required to save even the human kind. Acoustic habitat

degradation has reached monstrous proportions. Hazards of underwater noise, though recognized way back in 1972, however concrete steps are still awaited more than 4 decades later. While we want to formulate the way forward, the following aspects merit attention:

- a. Massive awareness drive is required across the stakeholders and policy makers. The humans being terrestrial animals feel that there is no direct impact on their well-being. However, it may be known that acoustic habitat degradation has grown in monstrous proportion to impact sustainable maritime growth for all.
- b. URN management across the military community for stealth as well as the merchant marine community for acoustic habitat degradation in the IOR requires a very strategic approach. Synergizing technology development and human resource development for the two communities may have rich dividends. A national and regional URN policy is required to be formulated for India and the IOR. India being a dominant power in the region should take the lead and bring cogent regulatory framework to address the issue of URN management in a comprehensive manner.
- c. The UDA framework as discussed could be the overarching concept to address the specific IOR challenges. The IOR has become a geo-strategic space not just for the nations in the region but also for global powers far removed geographically. Pooling of resources and synergizing of efforts as proposed in the UDA framework is the only way forward.
- d. All three aspects of policy, technology and innovation and human resource development will require massive efforts to be able to address the serious concern of acoustic habitat degradation in the IOR. The massive maritime infrastructure development push for harnessing the blue economic potential needs to be equally backed by the efforts to manage the acoustic habitat degradation concerns, to facilitate sustainable growth.
- e. Significant research efforts to understand the local characteristics in the IOR will be required to establish the source-path receiver model more accurately to be able to precisely ascertain the EIA due to the ever increasing shipping in the region.
- f. The precautionary principle has to be the driving concept, as it is not possible to directly establish the cause and effect. Shipping, being the only ubiquitous source of ambient noise source in the ocean and being low frequency, has its own challenges and needs to be addressed accordingly.

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