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Connection between Ocean Acidification and Sound Propagation

Cem Gazioğlu[1*], A. Edip Müftüoğlu[1], Volkan Demir[1], Abdullah Aksu[2], Volkan Okutan[1]

[1]Istanbul University, Institute of Marine Sciences and Management, Department of Marine Environment, BERKARDA Remote Sensing and GIS Laboratory, 34134, ISTANBUL-TR
[2]Istanbul University, Institute of Marine Sciences and Management, Department of Chemical Oceanography, 34134, ISTANBUL-TR

Corresponding author*. Tel: +90 212 4400000-26004
E-mail: cemga@istanbul.edu.tr

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Abstract

Ocean Ambient Noise (OAN) results from both anthropogenic and natural sources. Varied noise sources are dominant in low (LFB: 10 to 500 Hz), medium (MFB: 500 Hz to 25 kHz) and high (HFB:>25 kHz) frequency bands. Mostly, LFB is dominated by anthropogenic sources. MFB that cannot spread over long ranges of sound sources contribute to the OAN. Ocean is an exceptionally noisy place.

Ocean acidification (OAc) from rising Carbon dioxide (CO_2) levels will result in decreased sound absorption and therefore, amplified levels of OAN. Carbon dioxide spewed into the atmosphere by burned fossil-fuel which dissolves in the seawater causes more acidic condition in oceans which has strong connection between chemical oceanography and sound propagation. As the ocean becomes more acidic, sound absorption at LFB decreases and acidic oceans would result in significant decreases in ocean sound absorption.

In the recent years, the acoustic environment of oceans has reacted to transformations in both natural and anthropogenic impacts. Greenhouse gases concentrations, especially CO_2, rises in atmosphere due to industrial revolution. CO_2 dissolved in the seawaters deposited in two major forms (carbonate and bicarbonate), which both lead to decrease pH of surface waters. Over the last 400 million years, pH of oceans has been stable around 8.2 globally. Latest investigations suggest that global pH is around 8.1 globally and various general oceanic circulation models (GOCM) calculate that, emissions could reduce ocean pH by a degree between 0.4 units (according to moderate approach) and 0.7 units (according to an aggressive one) by the end of this century.

This article discusses the CO_2 considerations both in the atmosphere and hydrosphere which are directly related with seawater pH and oceans noise levels.

Keywords: Ocean Acidification (OAc), pH, CO_2, sound propagation, carbonate or bicarbonate.

Introduction

Since the industrial revolution, the soundscape of the marine environment has responded to the changes in anthropogenic impacts. A soundscape is a combination of sounds that characterize and describe an ocean environment, as known as acoustic ecology. The idea of a soundscape covers the natural acoustic environment and anthropogenic sounds. The disruption of the natural acoustic environment which is categorized by spatial and temporal capriciousness will be caused by the anthropogenic noise pollution (Etter, 2012). Ocean ambient noise (OAN) is one of the important features of marine life forms (Richardson et al. 1995, Halpern et al. 2008). Sound is an extremely proficient way to propagate energy through the ocean and most marine life forms exploit this property. Fish utilize sound especially for navigation, surviving, procreation and communication (Bass and McKibben 2003, Simpson et al. 2005). Marine mammals use sound as a primary means for underwater navigation, communication, hunting and sensing (Ketten and Wartzok 1999; Hildebrand, 2009). In the last years, the acoustic environment of oceans has reacted to transformations in both natural and anthropogenic impacts. The climate change, which is mostly driven by

anthropogenic affects, influences the ocean soundscape.

Atmospheric concentration of CO_2 billowed 200-300 parts per million (ppm) over the last 400 000 years and by the middle of 1700's it has been approaching 397 ppm as a result of the anthropogenic factors (Fig 1). Since the beginning of the industrial revolution, the release of CO_2 from anthropogenic activities has resulted in an increase in atmospheric CO_2 concentrations from 280 to 397 ppm. Approximately 50% of this increase has been occurred since 1990's. Carbon dioxide concentration is now higher than it has ever been for more than 800,000 years (Luthi et al., 2008). Some aggressive climate and/or atmospheric models reports that atmospheric CO_2 levels could approach 800 ppm near the end of the century (Friedlingstein et al., 2006).

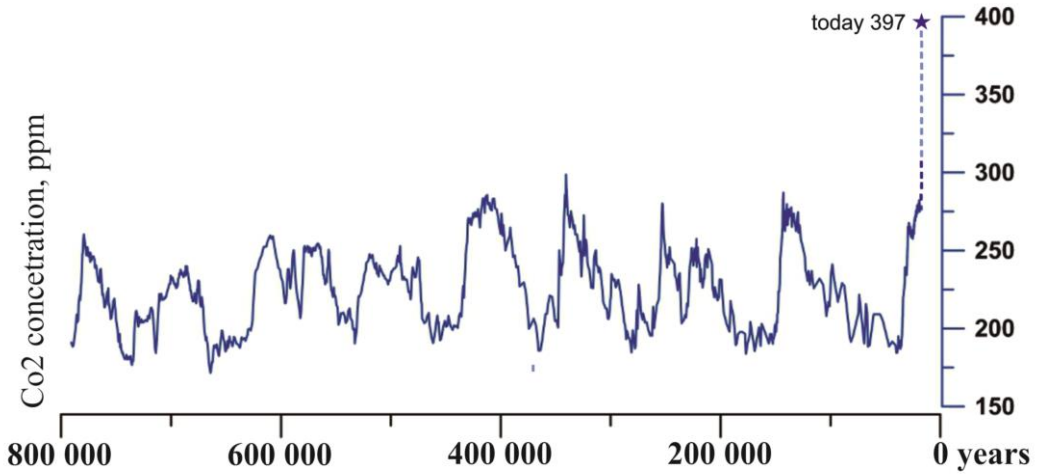

Fig.1. CO_2 concentration as measured in atmosphere (modified from Lüthi et al., 2008).

The oceans are a natural carbon sink, which absorbs CO_2 from the atmosphere. However anthropogenic CO_2 in the ocean could not be directly measured, but several approaches have been done (Wallace 2001; Lo Monaco et al., 2005; Waugh et al., 2006; Sabine and Felly, 2007). Concentration of rising greenhouse gases due to the industrial revolution has caused in atmosphere the greatest CO_2 concentration. Currently oceans absorbs %25 of human created CO_2 emissions. CO_2 mixes with the seawater, mainly either as carbonate (CO_3^{-2}) or bicarbonate (HCO_3^-) forms and both of them lead to higher acidity of surface waters. CO_2 will react with seawater and progress to CO_2 (aqua) 0.5%, bicarbonate 89.0% and carbonate 10.5%. The oceans get more acidic as excess CO_2 spewed into the atmosphere. The oceans have already become %30 more acidic than before the industrial revolution. Over the last 400 million years, pH of oceans has been stable around 8.2 ± 0.3 (local, regional and seasonal variations) globally. Latest investigations suggest that global pH is close about 8.1 globally and various general oceanic circulation model (GOCM) calculate that by the end of this century, emissions could reduce ocean pH by 0.4 units (moderate approach) or 0.7 units (aggressive one) globally (Fig.2) According to Henry's law, an increase in the atmospheric level of CO_2 increases the concentration of CO_2 in the surface water of the oceans.

Higher absorption will result in a smaller propagation gain which means that at a given distance from a source the sound level will be louder than it was. This article discusses the CO_2 considerations both in the atmosphere and hydrosphere which directly related with the seawater pH and oceans noise levels. Figure 2 indicates the past and the contemporary variability of pH. Future predictions are model derived values based on IPCC mean scenarios (Turley et al., 2006).

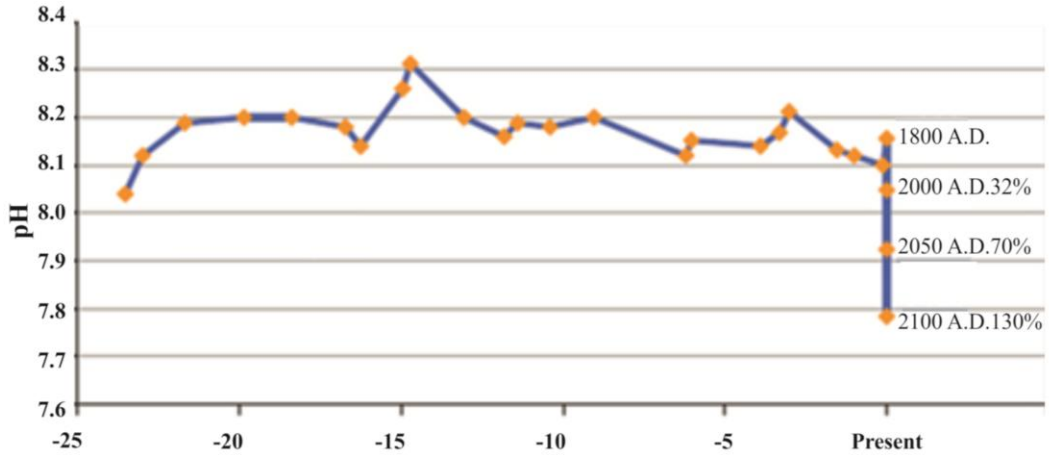

Fig. 2. Future calculations are derived values based on IPCC mean scenarios, date and % increase in H^+ ions (modified from Turley et al., 2006).

Ocean Acidification

Anthropogenic activities have led to a new flux of CO_2 into the atmosphere. Carbon dioxide in the atmosphere is a chemically unreactive gas but, when dissolved in seawater, becomes more reactive and takes part in several chemical, physical, biological and geological reactions, many of which are complex (Raven et al., 2005). According to Raven and Falkowski (1999) approximately %45 has remained in the atmosphere; most of the rest has been taken up by the oceans. According to Sabine and Feely (2007) and Canadell et al. (2007) over the industrial era, the ocean has absorbed about one-quarter of anthropogenic carbon emissions which is about 8.8 ± 1.35 billion metric tons/yr. This absorption has benefited humankind by significantly curtailing the growth of CO_2 levels in the atmosphere, thereby reducing the global warming which has been realized to date.

The carbon in the ocean is a mixture from both natural and anthropogenic sources. The anthropogenic fraction comes from human-induced emissions of CO_2 into the atmosphere that have continued at an increasing rate since the start of the industrial revolution and in 2007 was approaching $10x10^{15}$ grams CO_2, which is equal to 10^9 metric tons of C (Canadell, et al., 2007). It is estimated that 30% of total anthropogenic emissions annually are taken up from the atmosphere and sequestered by the ocean (Sabine and Feely, 2007). Regardless of source (natural or anthropogenic) the carbon in the ocean follows the ocean carbon cycle as described Fig. 3.

CO_2 dissolved in ocean occurs in three (aquatic CO_2, carbonate and bicarbonate) inorganic forms, with the contribution of each forms being dependent on pH. Bicarbonate is the most common inorganic carbon form in the ocean (see following equations [1]).

$$CO_{2(atmos)} \leftrightarrow CO_{2(aq)} + H_2O \leftrightarrow H_2CO_3 \leftrightarrow H^+ + HCO_3^- \leftrightarrow 2H^+ + CO_3^{-2} \quad [1]$$

Also carbon cycle could be described as the fluxes of CO_2 between the oceans, terrestrial, biosphere, lithosphere and the atmosphere in oceanography. The principal effect of adding fossil fuel CO_2 to sea water is a loss of carbonate ion to form bicarbonate and reduce pH [2].

$$CO_2 + H_2O + CO_3 \rightarrow 2HCO^-_3 \quad [2]$$

The addition of fossil fuel CO_2 alone could not change alkalinity of oceans. According to Redfield (1934) ratio (atomic ratio of C:N:P 106:16:1), the decline in dissolved oxygen that is simply associated with lower solubility of the gas in warmer water will not reduce pH; but by far the superior portion of the variations now being observed is from reduced ventilation respiration and this is necessarily accompanied by an increase in dissolved CO_2. The addition from the decomposition reaction of respiratory CO_2 at depth is accompanied by changes in the oxidation state of the nitrogen species, and this will change alkalinity and reduce ocean

buffering capacity (Brewer and Goldman, 1976), thus pH change over addition of CO_2 which is not only the result of fossil fuels but also deposition of reactive sulfur and nitrogen primarily affect the surface and coastal waters of ocean.

Oceans ecosystems play an important role in the global carbon cycle which involves both organic compounds and inorganic carbon compounds (CO_2 and carbonates). Inorganic compounds are in many forms of CO_2 present in oceans. CO_2 is soluble in water and it reacts with water and forms a balance of several ionic and non-ionic species which are dissolved as free CO_2, carbonic H_2CO_3, HCO_3^- and carbonate (CO_3^{2-}). These different forms of dissolved inorganic carbon are transferred from an ocean's surface. Basic describe of OAc could be explained as dissolving CO_2 in seawater caused acidification in oceans by decreasing ocean pH which driven by increasing the hydrogen ion (H+) concentration in it [3].

$CO_2+H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$ [3]

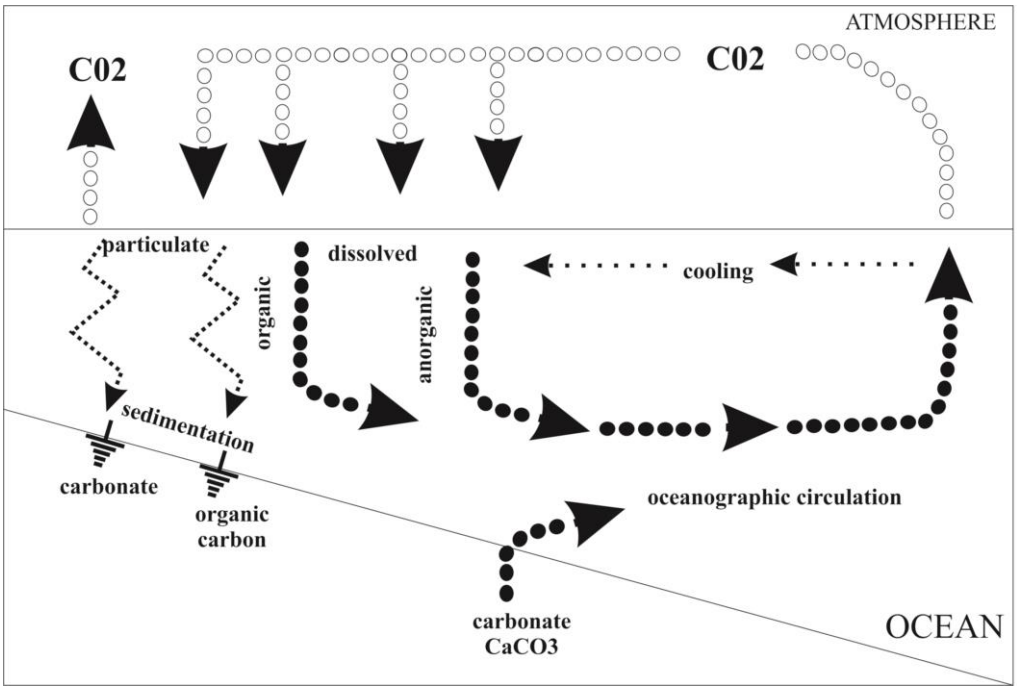

Fig. 3. Carbon circle.

These atmospheric additions of acids change ocean alkalinity and pH, and while there are offsetting reactions the net effect is acidification (Doney et al., 2007). Otherwise, CO_2 is absorbed by seawater, chemical reactions occur that reduce seawater pH, carbonate ion concentration and saturation states of the biologically important $CaCO_3$ minerals calcite and aragonite in a process commonly referred to as OAc (Broecker and Clarke, 2001; Caldeira and Wickett, 2003, 2005; Orr et al., 2005; Doney et al., 2009).

Earth's atmospheric concentration of CO_2 is expected to continue to rise at an accelerating rate, leading to significant temperature increases in the atmosphere and the surface ocean in the coming decades. Between middle of 1700's and 1994 globally surface ocean pH was estimated to have decreased from approximately 8.25 to 8.14 (Jacobson, 2005) on behalf of an increase of %30 in H^+ ion concentration in the oceans (Hall-Spencer, et al., 2008). Carbonate ion concentration declines, however, because of the increasing H^+ concentrations. Oceans are now undergoing an extraordinary transition in their fundamental chemical state and at a rate not seen since last 800 000 years. The belongings are being felt not only in biological impacts but also on ocean acoustics (Hester et al., 2008). The pH of seawater has decreased by 0.1 since the

beginning of the industrial era. The projected 0.3–0.4 ± %0.5 pH drop for the 21st century is equivalent to approximately a %150 ± %15 increase in H+ and %50 ± %5 decrease in CO3-2 concentrations (IPCC, 2005; Caldeira and Wickett, 2003, 2005; Orr et al., 2005), with a decrease approximately 0.0018 pH units/yr over the last quarter century (Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007; Dore et al., 2009). According to Friedlingstein et al., (2006) by the middle of this century, atmospheric CO2 levels could reach more than 500 ppm, and exceed 800 ppm by the end of the century. Additionally, burning of fossil fuels results not only in increasing CO_2 emissions but also in accumulating of reactive sulfur (0.8 Tmol/yr) and nitrogen (2.7 Tmol/yr) mainly in the surface waters of oceans (Doney et al., 2007). These chemical additions of strong acids change pH, and while there are counterbalancing feedbacks the net result is OAc.

Nowadays, pH is around 8.1. Oceanic General Circulation Model (OGCM) shows that by the end of this century, emissions would reduce ocean pH by another 0.5 units dramatically. As a result of increasing anthropogenic loads, it is estimated to drop by a further minimum 0.3 todays units, 0.4 from pre-industrial, by 2100, which represents an increase in the ocean's hydrogen ion (H+) concentration by approximately 2.5 times relative to the beginning of the industrial era. It is estimated to drop by a further minimum 0.4 and 0.7 maximum pH units (Fig.4.).

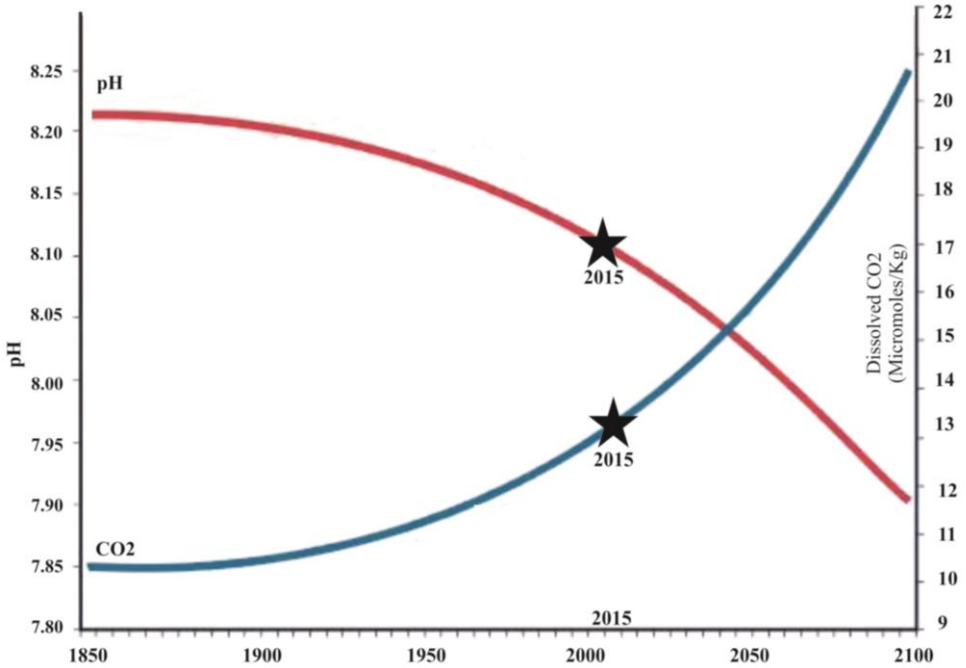

Fig. 4. Historical and Projected pH and Dissolved CO2 (modified from Feely, et al. 2006)

Results from CO_2 surveys and time-series studies over the past two decades show that OAc is a predictable consequence of rising atmospheric CO_2 (Feely et al., 2004; Bates and Peters, 2007; Santana-Casiano et al., 2007; Dore et al., 2009; Takahashi et al., 2009) that is independent of the uncertainties and outcomes of climate change. Seawater carbonate chemistry is governed by a series of abiotic chemical reactions (CO_2 dissolution, acid/base chemistry) and biologically mediated reactions (photosynthesis, respiration, and $CaCO_3$ precipitation and dissolution). The first key reaction occurs when CO_2 gas from the atmosphere dissolves into seawater

Ocean Ambient Noise (OAN)

Carbon dioxide, which is directly anthropogenic activities by the global ocean, induces major changes in oceans chemistry that could have dramatic impacts on both biological ecosystems in the ocean surface and it will be the cause of the increased OAN (Felly, et al., 2009). According to Intergovernmental Panel on Climate Change (IPCC) reports further compounding the problem is the globally observed change in ocean surface temperatures. It is estimated that the ocean surface is now about approximately 0.7°C. The effects of rising temperatures do not only affect the ocean surface, but these higher temperatures propagate through new stratification which is investigated in detailed and the effects of these phenomena in underwater environments which are explained and understood. Ocean acidification is located on a secondary emphasis for marine acoustic environment. Underwater sound propagation is much more complex; mainly it depends on spatial distribution of sound sources and environmental parameters. However, increasing pH and temperature are not the main factors and only responsible for changes in the absorption mechanism, but they are also contributing to increase OAN.

Ocean Ambient Noise is the result of both natural and anthropogenic sources. Natural sources are well known as earthquakes, waves, rainfall, bio-acoustic sound generation, etc. Anthropogenic noise is produced by different activities (shipping; oil and gas exploration, naval operations, fishing, research, construction, icebreaking, boating, military and civil sonars, etc.) (Hildebrand, 2009). According to Ross (1993), OAN increased by about ten decibels between 1950 and 1975. Additionally, according to Kuperman (1988) ocean environmental factors that are important for acoustic propagation and thereby influence OAN are; the sound speed structure of the ocean for long range propagation, the acoustic attenuation of seawater, the water depth and the geo-acoustic properties of the ocean bottom. Sound velocity in the ocean is accepted 1500 m/sec., it is actually dependent on many parameters such as ambient temperature, salinity and depth (1400 ≤Velocidity of Sound ≤1700 m/sec.) (Fig.5.)

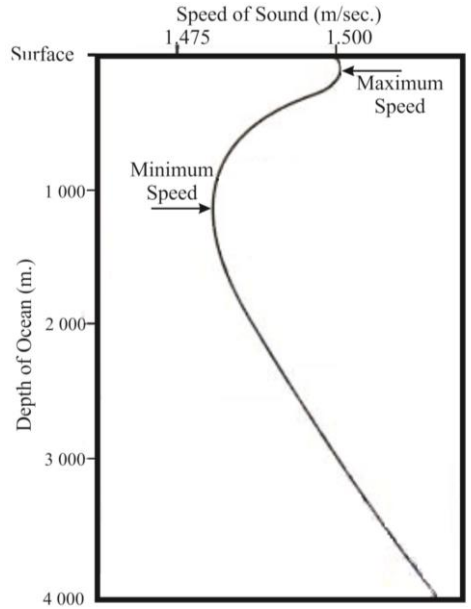

Fig. 5. Sound speed varies as a function of water depth. The speed of sound in water increases with increasing water temperature, increasing salinity and increasing pressure (related with depth).

Alkalinity dependence of sound absorption in the ocean has been drawn attention by Fisher and Simmons (1977) and has been linked to ocean geochemical and carbon cycles by Brewer et al. (1995). The emerging impacts of the fossil fuel CO_2 and climate-induced changes on sound absorption in the ocean are studied to understand by oceanographers. Sound absorption depending on the ocean alkalinity which will drop by another 0.6 pH units, the absorption of 200 Hz sound would decrease by up to %70 already during this century considering the atmospheric composition, gases from the atmosphere to the oceans and anthropogenic activities.

Specifically CO_2 spewed into the atmosphere by burning of the fossil-fuel dissolves into the sea causes more acidic condition in oceans which as a strong connection between chemical oceanography and sound propagation. An acoustic environment is a mixture of sounds that characterizes, or arises from, an ocean environment. One of the most important effects of the obscured effects of climate change is OAc from which fossil fuel CO_2 invasion and reduced ventilation will result in significant

decreases in ocean sound absorption for frequencies lower than about 10 kHz (Herster, et al., 2008). More acidic seawater will cause increasing noise level in ocean and low-frequency sounds will propagate farther, making the ocean noisier. The major changes are projected and expected to happen in the ocean surface waters. Obviously ocean surface will be affected more strongly than the rest of ocean.

Sound could travel farther at depth of about 1000 m than at the surface. Although most of the anthropogenic and natural sources of sounds are scattered from ocean surface, they also could reach the depth of oceans and travel over thousands of kilometers in the ocean. The speed of sound depends on the temperature of water, salinity and the pressure which is related column height (Fig 5). Sound that does not hit the ocean surface or seafloor will still lose energy to absorption which increases as the frequency of the sound increases and higher frequency sounds are therefore only detectable at shorter distances. The distances at which sounds can be detected depend on the frequency, how loud the source is, and how loud the OAN is.

In LFB and MFB sound absorption has already decreased by %15 ± %5 as OAc increase (decrease of pH). This means that sound travels %15 ± %5 further, with the effect that OAN levels rise as the cumulative noise in any one place contains source noise from a larger area. The most dramatic impact is in sound below 1kHz, with significant effects up to 10kHz (Hester et al., 2008).

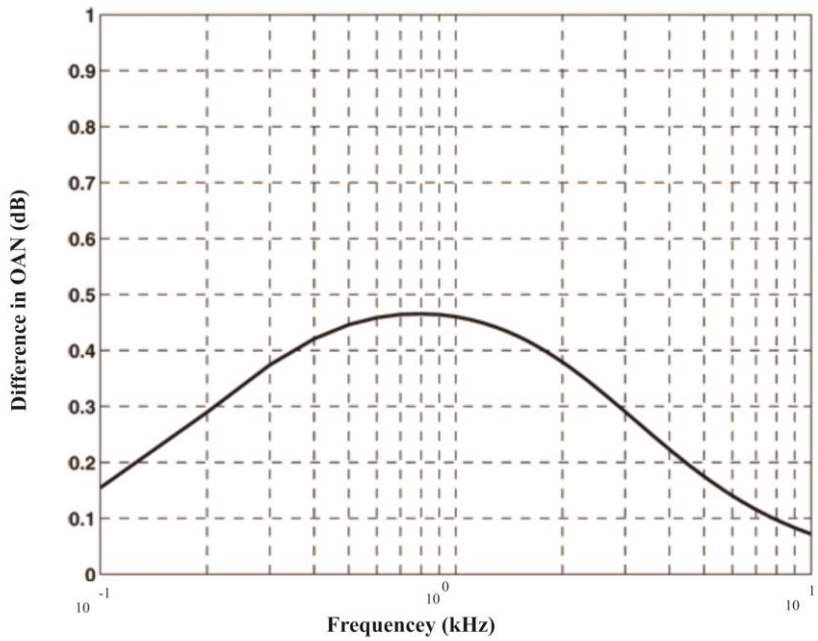

Fig.6. Expected variance in average ambient noise level (dB) for the deep water case using the historical pH profile from the 1960's (Browning et al., 1988) and a predicted pH profile for the year 2250 (Caldiera and Wickett, 2003). An increase of 0.5 dB is a statistically minor change associated to the critical unpredictability of OAN associated with shipping and anthropogenic activities (Reeder and Chiu, 2010).

Anthropogenic CO_2 enters into the deep ocean; the changes in sound absorption will also propagate well underneath the deep sound channel axis. Sound absorption will continue to decrease even after reductions in CO_2 emissions because ocean pH will continue to decrease. Sound absorption will continue to decrease even after reductions in CO_2 emissions because

ocean pH will continue to decrease (Ilyina, et al., 2009). A decrease in pH by about 0.45 units results in a decrease in sound absorption by about %50 for frequencies below about 1 kHz. As a result, sound could have to travel at least twice as far to lose the same amount of energy to absorption in LFB.

The scale of surface ocean pH change today from the +105 ppmv change in atmospheric CO_2 is about -0.12 pH units, sound absorption will be more than %12 ± %3. Under reasonable projections of future fossil fuel CO_2 emissions, pH change of 0.4 units or more could be expected by mid-century, resulting in a decrease by approximately 40% (Herster, et al., 2008). Other investigations modelled that effect of the increasing acidity of the ocean would have OAN levels in shallow water where the internal waves are exist. (Rouseff and Tang, 2010). The pH units decreased from 8.0 to 7.4 caused increasing about one decibel OAN. (Fig. 6). These results are representative of other contemporaneous investigations dealing this subject (Rouseff and Tang, 2010; Etter, 2012). A insignificant variation in OAN in the deep waters for all frequencies well known acoustic features.

Physicochemical and mathematical calculations show us a drop of 0.1 of pH of seawater, acidity is estimated to have increased by 27% (Barry, 20110). Rendering to introduction to oceanography, global pH is 8.2 globally which is the first obtained knowledge of chemical oceanography over the last decades. The average pH of seawater has declined from 8.19 to 8.05.

Conclusion

The oceans are now undergoing extreme conditions in their fundamental chemical state and at a proportion not observed before and the effects are being converted not only biological, physical and geological oceanography but also ocean acoustics. The oceans are known as significant carbon reservoir. Scientific knowledge of interactions between changes of the oceans pH and concentration of CO_2 in atmosphere and their effects are currently limited. Both OAc and climate change result from increasing atmospheric CO_2 emissions. Effects of climate change, mainly increases in ocean temperature, will directly impact on marine ecosystems. According to calculation and estimation it is currently taking up about 1 ton anthropogenic CO_2 per year for each human by oceans. A half of the CO_2 produced has been absorbed by the oceans since industrial revolution. Calculations based on measurements of the surface oceans and according to scientific knowledge of ocean chemistry, indicate that this uptake of CO_2 has reduced surface seawater pH by approximately 0.1±0.001 units, which corresponds to an increase of approximately %30 in the concentration of H ions. Nowadays, pH of ocean is 8.1 (over the last 400 million years, pH is stable 8.2) which shows us that the dramatic changes have been taking place in oceans globally. Environmental condition of the oceans has high rate of acceleration than any change in acidity of seawater known last period of Earth's life hosting. More than the estimated marine life forms it is estimated that, quickly adaptions to changes occurred in the oceans acidity. Although in danger of assuming the OAc, oceans would not become acidic. Additionally, OAc likely will affect the biogeochemical dynamics of ocean (calcium carbonate, organic carbon, nitrogen, and phosphorus) as well as the seawater chemical, physical and biological features.

Carbon dissolves which into the ocean is caused more acidic condition in oceans which has a strong connection between ocean chemistry and sound propagation. Declining sound absorption due to changes in ocean chemical composition is obvious. As the ocean becomes more acidic, sound absorption at 10 to 500 Hz (low frequency bands) decreases and acidic oceans would result in significant decreases in ocean sound absorption and sounds would propagate farther, making the ocean noisier, and it would have to travel at least twice as far to lose the same amount of energy to absorption at 10 to 500 Hz.

Trends show us noise pollution has been getting worse, CO_2 has been rising; and this results an additional increase of OAN. However decreasing sound absorption, underwater sound could travel farther and this could generate OAN. Low-frequency sounds could also enable

marine mammals to communicate over longer distances. More knowledge about impacts of pH and sound relation in ocean acoustics need to be further investigations. Some investigation suggested (Joseph and Chiu, 2010; Reeder and Chiu, 2010) that OAN levels in the ocean are very insensitive to the OAc. However the sounds of the sea have less mysterious than they had a few years ago, but also underwater acoustic knowledge is still limited to learn and sense which sounds different underwater creatures could actually hear.

Salinity has a much smaller effect on sound speed than temperature or pressure at most locations in the ocean, anthropogenic influences are changing the oceans chemistry which affects the sound propagation in oceans. As a result of the decline in attenuation by absorption due to OAc which is the significant factor for temperature increase and pH decrease, the OAN levels are expected to increase in the surface and shallow ocean layers (>500m). According to calculation and estimation, OAN seems to be growing by about 3 to 5 decibels per decade in the band occupied by activity and effects of OAc in deep waters of oceans. Rising OAN is going to influence marine life forms by interfering with their ability to detect sounds, also might cause comprehensive stress and affect developmental, reproductive, or immune functions. Effects on marine life due to these changes are expected and dynamically investigated. Biological processes such as calcification and respiration of deep-sea animals are already expected to be negatively affected. Ocean acidification is leading to changes in the geophysical properties of the ocean as well. Ocean acidification needs a detailed investigation (such as carbonate chemistry, etc.). Underwater acoustic is one of the most important features and should be investigated in the area under the pressure of OAc. Underwater acoustic is not only important for fish and mammals but also important for humanity who works in underwater engineering, wireless network and naval forces, etc. Briefly summarize; more CO2 in the atmosphere means a noisier ocean and increases in OAc are already assisting sound to travel further.

Elevation of ocean alkalinity and OAN are global environmental problem which is strongly responsible from the global climate change and the ratio of CO_2 concentration of atmosphere. International organizations have begun to address the problem of sound propagation due to OAc, urging that nations work together. The recent years it has seen a remarkable increase in awareness of OAN as an issue that must be addressed multilaterally. The understanding of OAc and its impacts needs to be investigated by the international scientific institutions (IPCC, IOC, IMO, etc.) which must be supported long-term records and measurements in diverse marine environments. This will help to document the past changes in OAN besides to provide a baseline for future changes.

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