MONITORING THE OCEAN USING HIGH FREQUENCY AMBIENT SOUND

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LONG-TERM GOAL

To make passive acoustic monitoring of the marine environment an accepted quantitative tool for measuring sea surface conditions (wind speed, rainfall and sea state), monitoring for the presence and identity of marine wildlife (especially whales), and monitoring anthropogenic activities including shipping, sonar and other industrial activities.

By establishing a methodology for describing the sound budget for a location, including the quasi-steady sound levels from the sea surface and the frequency and intensity of transient sounds from marine wildlife and human activities (close and distant shipping, sonar activities, etc.), a baseline of information for making decisions regarding additional human activities, in particular Naval operations using active sonars, will become available. This decision aid is needed to understand the perceived affect of sound-producing activities, in particular, Naval operations and research activities, on the marine environment.

SCIENTIFIC OBJECTIVES

This research has focused on the frequency band from 1-50 kHz. In this frequency band the primary sound sources are the sea surface, including breaking waves and rainfall, and various transient sources, including marine wildlife and human sources (ships, sonars, etc.). A particular emphasis has been on the sound generated by precipitation, especially drizzle and heavy rainfall under different wind and sea state conditions with the goal of being able to quantify wind speed, rainfall rate and sea state from passive acoustic monitoring. It is recognized that different marine environments are subject to different physical processes, biological and human activities. Consequently the ambient noise in these disparate environments is different, and distinctive, allowing "acoustic climate" to be established. Part of the goal of this research is to investigate and document the regional variation and potential universality of conclusions associated with passive acoustic monitoring measurements based on this acoustic climatology.

TECHNICAL APPROACH

The technical approach for this research has been to obtain long-term ambient sound data sets from a variety of locations worldwide. It is possible to find opportunities to deploy

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14. ABSTRACT
Passive acoustic monitoring of the underwater marine environment provides a quantitative description of the physical environment, including the detection and measurement of precipitation and the measurement of wind speed. Biological and anthropogenic sounds are also detected and quantified. Unique features of these sounds provide a basis to describe ocean acoustic climate.

15. SUBJECT TERMS
marine rainfall, sound budgets, passive acoustic monitoring, acoustic classification

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small acoustic listening packages on selected ocean moorings and then to share the data with the operators of those moorings. In turn, these moorings offer some ancillary data with which to evaluate the passive acoustic data, and thereby develop understanding of the data and to build algorithms using these data.

During this project three generations of a small acoustic recording instrument called a Passive Aquatic Listener (PAL), previously called an Acoustic Rain Gauge (ARG) have been designed and built at the Applied Physics Laboratory. PALs are autonomous acoustic recorders designed to be attached to ocean moorings. They consist of a broadband, low noise hydrophone, a signal processing board, a low-power microprocessor with a 100 kHz A/D digitizer, a memory card and a battery pack. They have variable and potentially very low duty cycle (~1%) so that the sampling strategy can be designed to allow autonomous operations for up to one year. Over 100 buoy-months of PAL data have been collected from deep ocean, continental shelf and coastal ocean moorings (Table 1). Recently PALs have been adapted for marine mammal monitoring to include a capacity to record a limited number of short time series to aid in the identification of the sound sources.

Table 1. Locations and times of PAL deployments

Location	depth	Period	Notes
8°N, 95°W	38m	1999-2004	ITCZ of Eastern Tropical Pacific Ocean
10°N, 95°W	38m	1999-2004	ITCZ of Eastern Tropical Pacific Ocean
12°N, 95°W	38m	1999-2004	ITCZ of Eastern Tropical Pacific Ocean
0°, 165°E	20-98m	2000-2002	Warm pool of the Western Tropical Pacific Ocean
20°S, 80°E	50 m	2001-2003	Stratus deck region of Eastern Pacific Ocean
Bering Sea	20 m	2004, 2008	High latitude coastal shelf, very little shipping
Haro Strait	100 m	2004, 2005	Inland waterway with heavy shipping traffic
Ionian Sea	60-2000 m	2004	Deep water near land, shipping traffic
Carr Inlet	10 m	2003	Inland waterway with minimal shipping traffic
50°N,145°W	50 m	2004-2008	North Pacific Ocean
Cape Flattery	50 m	2005-2008	Coastal Shelf, shipping and mammals present

RESULTS

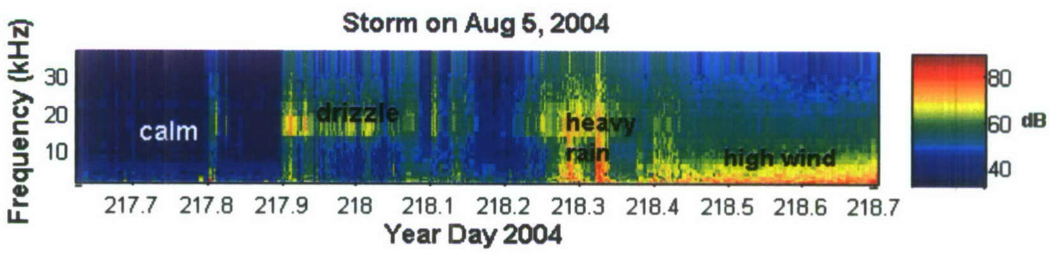

Figure 1. The underwater acoustic record of a storm passing on August 5, 2004 (Year Day 218) in the Bering Sea. A period of calm is followed by drizzle, heavy rainfall and finally high winds as a strong atmospheric front crosses over the mooring location. [The colorized units for sound intensity are in decibels (dB) relative to 1 $\mu Pa^2 Hz^{-1}$.]

Figure 1 shows the underwater acoustic record of a storm passing over a PAL deployed on the continental shelf in the Bering Sea (water depth 70 m). The ability to interpret the recorded sound as a physical description of the sea conditions is the overall goal of this research. Identifying the sound source is the first crucial step for reliability of using passive acoustic monitoring to describe the physical ocean environment. Different sound sources have distinctive acoustic signatures that can be identified in the spectral domain (Figure 2).

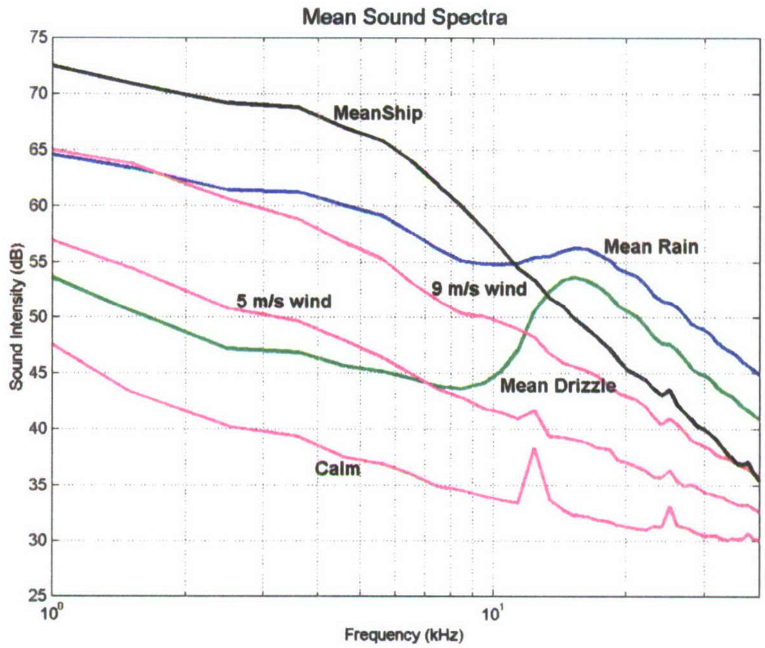

Figure 2. Different sound sources produce distinctive sound spectra underwater, allowing multivariate analysis to identify and then quantify the physical processes present.

Different features of the physical, biological and anthropogenic environment produce distinctive sounds that can be used to describe these components of the environment, often in a quantitative fashion. Examples of unique spectra include: wind generated breaking waves, drizzle, rain in moderate wind, heavy tropical (convective) downpour, very high sea state (the sound of spray), general shipping – close and distant, clanking and whale calls and clicking. These sound sources form the basis of the footprints of ocean acoustic climate (Figure 3). Changing patterns of acoustic footprints will be a basis for monitoring overall climate change.

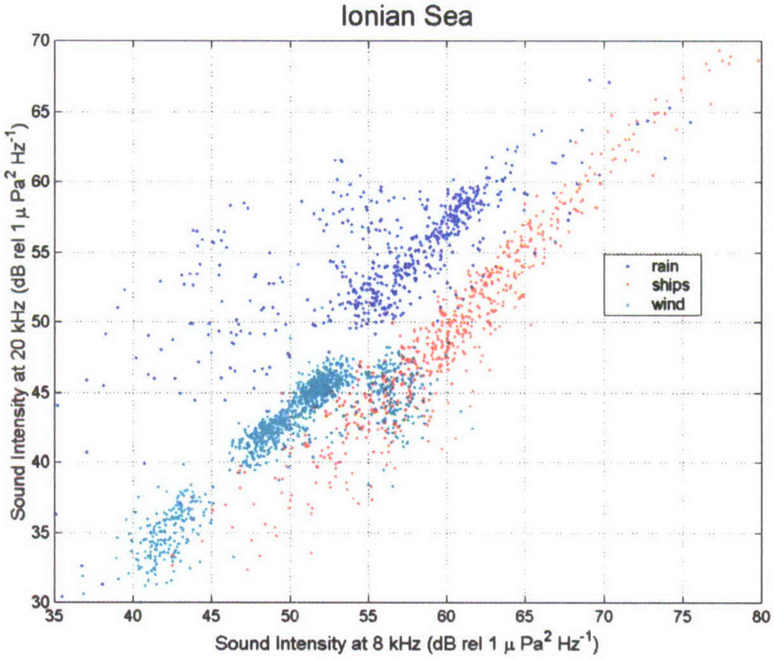

Figure 3. The two-dimensional scatter diagram or acoustic "footprint" for the Ionian Sea. Shown are distinct clusters of points for wind, rain and shipping.

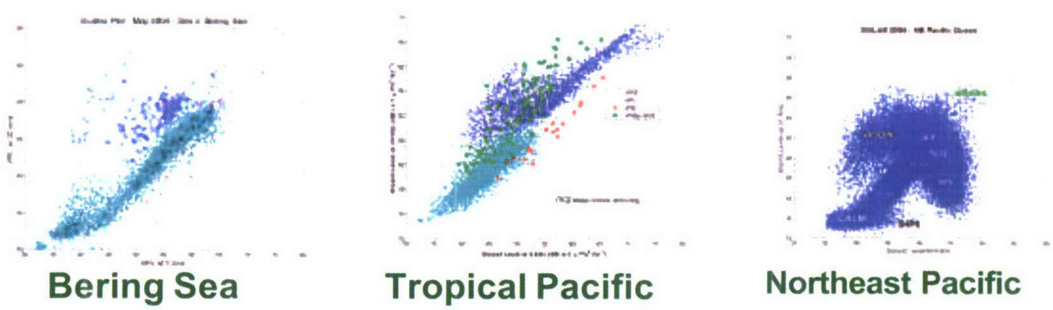

Figure 4. Acoustic climate footprints for three different marine environments. Each region has a combination of sounds present that produce a pattern of sound that can be used to describe the physical, biological activity and human activity of that location. These patterns represent acoustic footprints of climate.

Quantification of wind speed (Vagle et al., 1992), rainfall rate (Nystuen, 1996; 2001) and integrated ambient bubble populations are possible using ambient sound. However, there is a contamination issue that must be addressed (Ma and Nystuen, 2005). Classification of the sound source is an important quality control that needs to be further developed. In particular, platform self-noise is clearly "noise", and must be minimized or suppressed (banging, pumps, etc…). Other noises such as biological activity or shipping, might be a signal for some applications. The low-duty cycle recorder is capable of providing a sampling strategy to monitor these noises (animal detection or human activity), or to detect and analyze the background physical environment (wind, rain and sea state) (Nystuen et al., 2008b).

Specifically, rainfall is a robust signal that can be detected with a high level of confidence (Ma and Nystuen, 2005; Nystuen et al., 2008a). Drizzle has a unique signal that allows it to be acoustically identified (Nystuen, 2001). There is a clear signal of bubble injection during heavy rain or high sea state. There is a contamination of the rainfall rate measurement by the present of wind. There is a contamination of the wind speed measurement by the present of rain. There is an extremely high correlation between wind speed and sound levels (r ˜ 0.95) provided that the sound source is properly identified. The wind speed measurement is potentially contaminated by rainfall, shipping (close), and during calm conditions by distant shipping.

Under calm conditions, the acoustic wind measurement is limited. There are two components of this limitation: First, there are no wind-generated breaking waves/wavelets to produce sound. This means that there is no acoustic signal for wind conditions less than 2.2 m/s, the onset of wind-induced wavelet breaking. Second, the acoustic propagation conditions are excellent because surface reflection (mirror-like) allows mid-frequency (2-8 kHz) sound to propagate unusually long distances. If these frequencies are being used to quantify wind speed, then there will be a potential contamination from, for example, distant shipping. As wind begins to roughen the surface the sound levels at 2-8 kHz can actually drop, suggesting changing sea surface roughness has altered propagation (reduced) in this frequency band.

A new application of the PALs has been to detect and identify specific cetacean species, in particular, the different populations of killer whales in the NE Pacific Ocean. This has been accomplished by detecting transient sounds with short 4.5 second data samples (Figure 5). These short time series are sufficient to identify different killer whale types (transient versus resident) and to even identify specific groups within the resident killer whale type (Puget Sound Southern Resident pods J, K and L) because these groups have distinctive calls that human experts have learned to identify. This ability to detect and identify specific groups of whales has vastly increased knowledge of the whereabouts of these animals during the winter when visual observations are difficult or impossible (Nystuen et al. 2007).

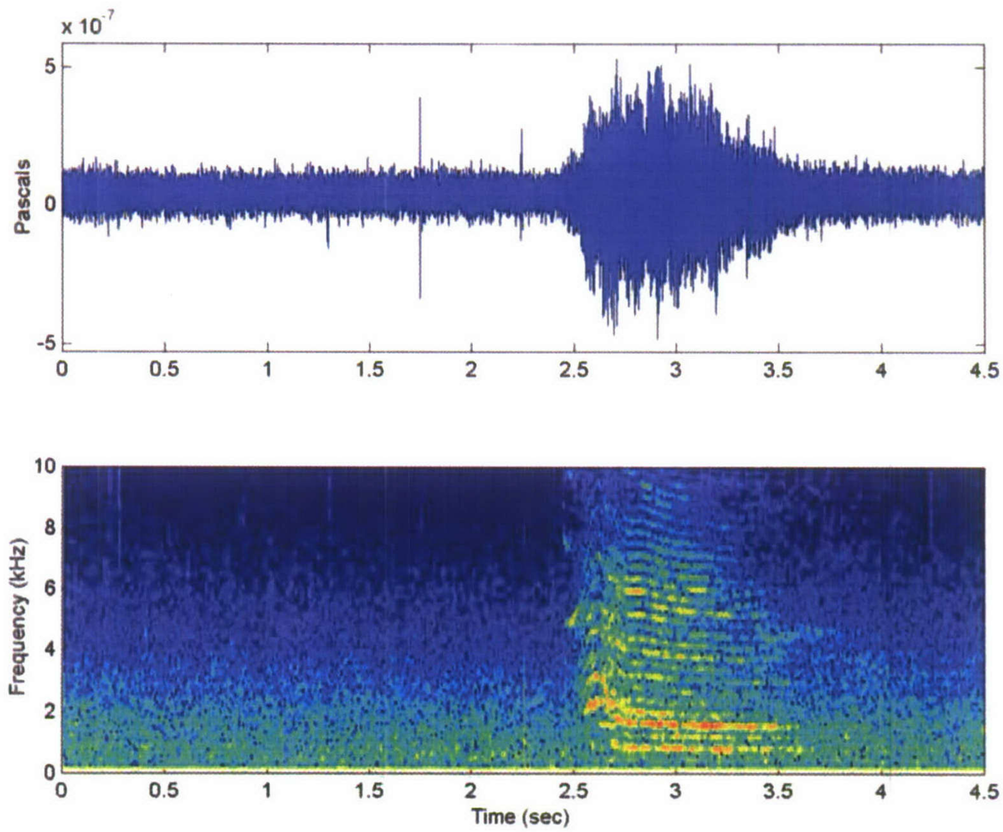

Figure 5. The acoustic signal (call) from a Transient-type Killer Whale near Cape Flattery, WA. The top panel shows the recorded pressure signal, sampled at 100,000 Hz. The bottom panel shows the related sonogram (spectral time series). When presented to a human expert whale listener, this record was immediately identified to killer whale type (NE Pacific Ocean Transient-type Killer Whale, pers. comm.).

How low can the duty cycle of a recorder be and still be adequate for the task demanded of it? This depends on the characteristics of the sound source. Geophysically generated sounds usually have time scales that change slowly. For example, the wind speed changes on a scale of tens of minutes, and so one sample every ten minutes is adequate to describe it. On the other hand, rainfall changes on the scale of minutes, and so it needs to be sampled much more frequently. This time scale continues on down to the time scale of banging on the mooring (self-noise) and calls and clicking of marine mammals. Modification of the sampling strategy by PALs shows that a low-duty cycle instrument can adequately sample the sound field, accounting for multiple scales of different sound sources, even at the same time (Nystuen et al., 2008).

FUTURE NEEDS:

The acoustic classification of sound sources will need to be continually improved. We will never learn to identify all noises present, but the ability to identify specific sound sources will continually improve. Important physical sounds will be the combined sound of wind and precipitation. This is a critical need as electromagnetic remote sensing from satellites or radars fails when wind is present with precipitation. It is likely that this difficult situation can be sorted out using ambient sound.

Passive and active acoustic instruments can be used to census populations of whales and other sound-producing marine animals (Moore et al. 2006). A basic component of this technique is to learn to identify the acoustic signatures of different marine animal populations. This is a major effort in the biological community (e.g. Johnson et al., 2004; Mellinger et al.,2004; Moore et al., 2006). One of the obstacles of continuous recorders is the massive amounts of data generated by these instruments and the subsequent need for extensive post-deployment processing. Low duty cycle recorders will adequately sample the acoustic environment (Nystuen et al., 2007), but require real-time onboard processing to achieve this goal. This ability is being developed and will allow real-time reporting of the environment, including the presence of marine animal populations at specific locations.

IMPACTS/APPLICATIONS

Ambient sound measurements are made from robust instruments at sub-surface locations. This implies a relative safe and covert method for obtaining useful sea surface condition measurements where surface moorings are unavailable or cannot survive. This includes ice-covered locations and other extreme weather conditions. The technology can be transferred to many other platforms including drifters, profilers, sea gliders, cabled systems and bottom moorings.

Knowledge of the presence and identity of marine animals, especially whales, is important for monitoring their populations, but also will allow potential harmful human activities, in particular, the use of active mid-frequency sonars, to be mitigated in an informed way when animals are present. And having a baseline of sound budgets from a wide variety of marine environments will allow future decisions regarding the impact of proposed human activities, including Naval operations and research efforts, on those environments.

TRANSITIONS

An improved ambient noise prediction model for wind and rain has been published (Ma et al. 2005) and is available for incorporation into operational ambient noise models. Ambient noise is one of the basic components of predicting the performance of various Naval systems, including sonars, communications and weapon systems underwater.

The PAL technology has been installed on two different ocean instrumentation platforms: ARGO floats and Mixed Layer Floats. The ARGO project (NOPP sponsor) is demonstrated acoustic wind speed and rainfall measurements from a deep ocean float. The MLF application (ONR CBLAST sponsor) provides ambient sound measurements under extreme hurricane sea state conditions.

The PAL technology has recently been used to describe the physical environment from several moorings where no surface signature of the mooring is present. This is the ultimate goal of this research – to provide physical measurements of the marine environment from passive acoustic recorders when other means of measurement are unavailable.

RELATED PROJECTS

"Spatial Averaging of Oceanic Rainfall Variability using Underwater Sound" sponsored by the National Science Foundation (NSF) Physical Oceanography Division. This project investigated the inherent spatial averaging of the underwater acoustic rainfall signal associated with the depth of the measurements. Co-located high resolution coastal radar data are being compared to acoustical rainfall data collected at 60, 200, 1000 and 2000 m depths. This demonstrated that PAL technology can be used on instrument platforms that are deployed at depth including deep-going ARGO floats and bottom-mounted systems. (Nystuen et al., 2008a).

"Marine Mammal Monitoring for NW Fisheries" sponsored by NOAA NW Fisheries Science Center (NWFSC). This project monitored the ambient sound field at highly active and noisy locations where marine mammals are present. The goal was to quantify the sound field and to demonstrate detection of specific marine mammals (Fig. 5). It has allowed a modification to the PAL operating software to enhance identification of underwater sound sources. (Nystuen et al., 2007)

"Bering Sea Acoustic Report" sponsored by NOAA. This project analyzed passive acoustic data from a continental shelf mooring in the Bering Sea to report physical conditions and to demonstrate the efficacy of a low duty cycle recorder (a PAL) to make such measurements. (Nystuen et al., 2008b).

"Detection of Killer Whale predation at Stellar Sea Lion Rookeries", sponsored by NOAA National Marine Mammal Lab (NMML). This project uses PALs to detect and identify killer whale predation on Stellar Sea Lions in the Bering Sea. The physical environment is monitored using PALs. (ongoing)

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AWARDS and PRIZES

2003 Medwin Prize for Acoustical Oceanography by the Acoustical Society of America
"for the development of the theory for the acoustic detection and measurement of rainfall at sea"

2003 Elected Fellow, Acoustical Society of America