

MONITORING AIR-SEA EXCHANGE PROCESSES USING THE HIGH FREQUENCY AMBIENT SOUND FIELD

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LONG-TERM GOAL

Passive acoustic remote sensing of the marine environment has been developed to the point that we are able to make quantitative measurements of precipitation and wind speed. These processes are an important component of the ocean surface environment. Accurate sustained long-term time series of these processes from a variety of locations and environments are required for climate studies, model development and validation of other measurement techniques. This research seeks to build on the existing understanding of the sound generation mechanisms for wind, wave breaking and precipitation to improve the geophysical interpretation of the ambient sound field in the ocean. In turn, given environmental weather conditions, predictive Naval ocean ambient noise models will be improved. The long-term goal of this research is to make passive acoustic remote sensing of the marine environment an accepted standard measurement technique.

As a passive remote sensing technique, several advantages are inherent. The measurements are made from a simple and robust sensor, namely a hydrophone. It is remote from the process being measurements, and thus doesn't disrupt the process while making the measurement. It can be deployed from sub-surface locations, avoiding the generally higher cost of surface platforms, including the threat of vandalism or piracy. It can be used in environments where surface instruments do not survive, including severe storms and ice-covered locations or in remote regions that are difficult to monitor using more conventional methods. Finally, it is covert, introducing no acoustic disturbance into the environment, and poses no potential harm to marine mammals or other forms of life in the ocean.

The frequency range of interest is roughly 200 Hz to 50 kHz. In this frequency range, the dominant sources of sound are breaking wind waves and precipitation. The sound generated by these phenomena can be subsequently modified by ambient bubbles. Thus the ambient sound field contains information about precipitation, wave breaking, wind, bubbles and the interaction of these processes. Using sound to aid in the investigation of these processes will contribute to our understanding of ocean surface mixing, including heat, buoyancy and gas fluxes.

SCIENTIFIC OBJECTIVES

The scientific goal of this research is to develop an objective procedure for identifying and quantifying geophysical sources of ambient sound in the ocean. Nystuen and Selsor (1997) showed the

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14. ABSTRACT Passive acoustic remote sensing of the marine environment has been developed to the point that we are able to make quantitative measurements of precipitation and wind speed. These processes are an important component of the ocean surface environment. Accurate sustained long-term time series of these processes from a variety of locations and environments are required for climate studies, model development and validation of other measurement techniques. This research seeks to build on the existing understanding of the sound generation mechanisms for wind, wave breaking and precipitation to improve the geophysical interpretation of the ambient sound field in the ocean. In turn, given environmental weather conditions, predictive Naval ocean ambient noise models will be improved. The long-term goal of this research is to make passive acoustic remote sensing of the marine environment an accepted standard measurement technique.					
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identification of four ocean processes that produce distinctive features in the underwater sound spectrum. These are wind, drizzle, heavy rain and ambient bubbles present. In the ocean, there are sometimes other underwater sounds that can interfere with acoustical weather measurements. In order to make acoustical weather measurements, it is first necessary to identify the sound source. Figure 1 shows time series of oceanic underwater sound at 3 different frequencies. The different sources of sound are identified by comparing spectral intensity levels, spectral shapes and temporal variances of sound intensities. Sound spectra not consistent with known geophysical signals (wind, rain and drizzle) are assumed to be "noise" and can be identified and flagged in the data record. For example, shipping usually has higher sound levels at low frequencies relative to wind or rainfall generated sound and biological sources often have unique tonal characteristics. The process of identifying the sound source and then quantifying will facilitate the widespread use of passive monitoring of underwater sound to obtain geophysical measurements of wind, rain and bubbles.

In addition to the geophysical measurements, the distribution and identification of all noise sources in the ocean is of growing interest to society. Basic information about sound levels and their sources is generally not available in the marine environment. Yet these data are needed to assess the impact of anthropogenic activities on the marine environment. recorded from an Acoustical Rain Gauge (ARG) mounted on a deep ocean mooring at 40 meters

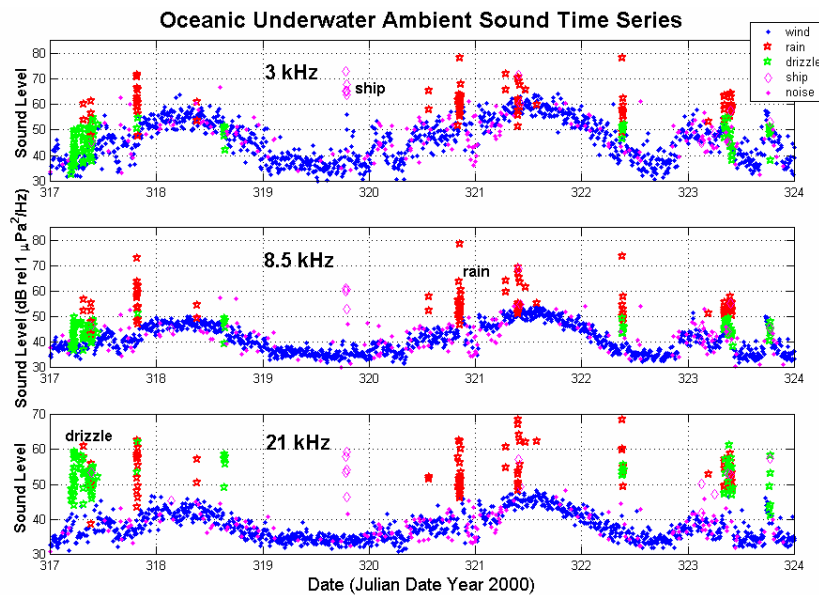


Figure 1. Time series of oceanic underwater sound at 3 different frequencies (3, 8.5 and 21 kHz) depth. Different sound sources can be identified based on spectral characteristics. In addition to quantifying geophysical quantities, the temporal duration and levels of the various noise sources in the marine environment are needed to assess the impact anthropogenic activities on the marine environment.

TECHNICAL APPROACH

Acoustic Rain Gauges (ARGs) have been designed and built at the Applied Physics Laboratory for autonomous deployment on ocean surface moorings. An ARG contains a hydrophone, signal pre-

amplifiers and a recording computer. The instrument is designed to record data for up to one year without servicing, and yet be able to record the short time scales associated with rainfall. In order to achieve this, the ARG is designed to enter a low power mode "sleep mode" between each data sample. Each data sample consists of a 1-50 kHz spectrum that is objectively evaluated to identify the sound source. If rainfall is detected, the sampling rate increases and stays at the higher sampling rate until rain is no longer detected.

Figure 2 shows the locations where ARGs have been deployed. Over 100 buoy-months of data are now available for analysis. Particularly long data sets are available from the Tropical Atmosphere Ocean (TAO) moorings in the ITCZ of the eastern Pacific Ocean at 8°, 10° and 12°N, 95°W and in the warm

pool (0°N, 165°E) of the western Pacific Ocean. These moorings have ancillary measurements of wind speed, rainfall and subsurface temperature and salinity profiles to help evaluate the geophysical measurements and identify the influence of rainfall on wave breaking, near-surface mixing, and the near-surface hydrological balance. Satellite data are also available for these locations. These data sets will be used to develop and evaluate an objective procedure for the detection and quantification of ambient sound sources in the ocean. An effort will be made to detect regional variations and limitations.

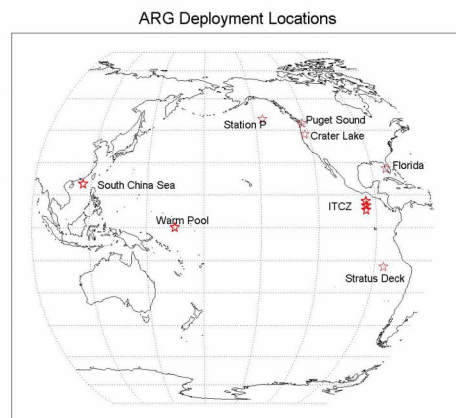


Figure 2. *Deployment locations for ARGs. Locations include coastal and deep water environments.*

RESULTS

Figure 3 shows a summary of spectra for wind and rain-generated ambient sound. The wind speed curves are shown for 3, 5 and 7 m/s conditions with no noise contamination. These spectra are characterized by a uniform spectral slope, and can be used to quantify the wind speed (Vagle et al., 1990). The acoustic wind speed algorithm is remarkably good and has actually been used to calibrate hydrophones.

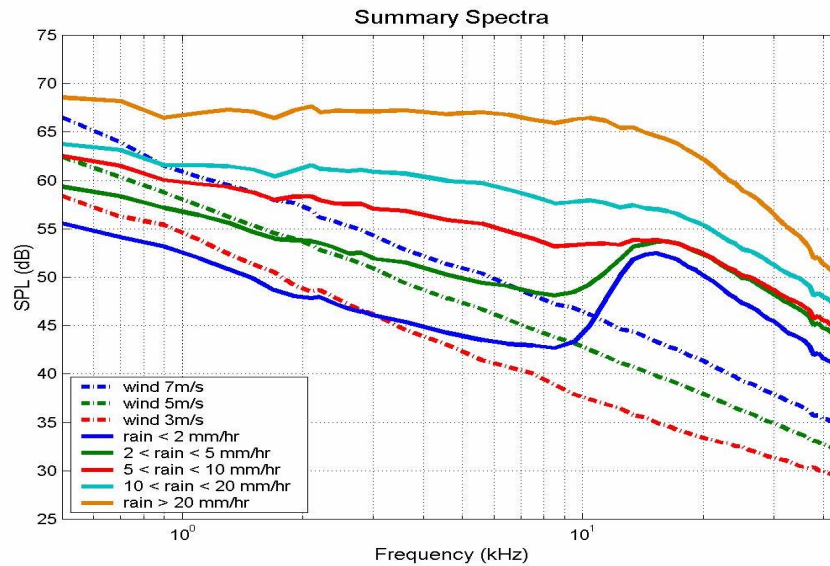


Figure 3. Mean underwater sound spectra from wind and rain. The sound generated by wind is distinctive but relatively quiet when compared to the sound from drizzle or rain. A peak in the spectrum due to bubbles produced by small raindrop splashes is the distinctive sound of drizzle. In contrast, the sound from heavy rain is very loud and has a nearly white spectrum to 20 kHz. The effect of ambient bubbles is to depress the observed sound levels at high frequency.

When rainfall is present, it is usually the dominant sound source. The specific sound sources for rain are the impacts of individual raindrops onto the water surface and bubbles trapped underwater during the splashes of the raindrops (Medwin et al., 1992, Nystuen 2001). For all but the largest raindrop sizes, it is the sound of bubbles trapped underwater during the splash that is the dominant sound source. And it turns out that a small droplet size (1 mm), commonly present in light rain or drizzle, is particularly efficient at producing sound from 13-25 kHz. This feature, a peak in the spectrum between 13-25 kHz, is the sound of drizzle and is particularly apparent when the rain contains few large raindrops and the wind speed isn't too high. If large raindrops are present in the rain, then a loud, broad, nearly white spectrum is measured for frequencies below 20 kHz. Above 20 kHz, ambient bubbles produced by the rain itself form a layer just below the ocean surface. This layer of bubbles attenuates the new sound produced at the surface by subsequent raindrop splashes. As the rainfall rate increases, injecting more bubbles into the surface, this distortion becomes more apparent.

The influence of wind on the sound spectra generated by rainfall is examined in Figure 4. Here the data have been partitioned by rainfall rate and wind speed. Two influences of wind on the rain spectra are apparent. As wind speed increases, the amplitude of the drizzle peak decreases. This is because the sound production mechanism, a bubble formation, depends on the angle of impact (Medwin et al., 1990). As wind speed increases, this sound production mechanism is suppressed (Nystuen, 1993). The second influence is observed at very high frequencies and high rainfall rates. As wind speed increases, the sound levels above 30 kHz decrease. This is due to sound absorption by small bubbles that have been mixed downward by wind-induced turbulence. The absorption of sound by bubbles is mostly at the resonant frequency for the bubbles. Small bubbles, with high resonant frequencies, are more easily mixed down into the ocean surface layer and so this phenomenon is most apparent at very high frequencies and at high rainfall rates when the rain is producing a lot of bubbles.

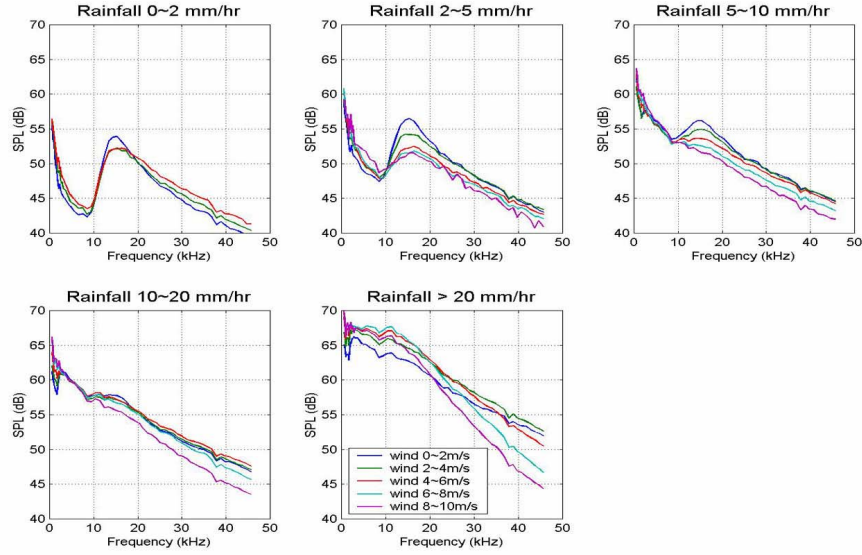


Figure 4. The influence of wind on the sound spectra generated by rainfall for different rainfall rates.

One part of the rain generated sound spectra that is relatively insensitive to variations in wind speed is between 5-10 kHz. Thus, a single frequency inversion algorithm for open ocean conditions has been developed using this frequency band and is given by:

$$R = 10^{(SPL - 42)/15.4}$$

where R is rainfall rate and SPL is the sound pressure at 5 kHz. This algorithm has been validated through comparisons with buoy-mounted rain gauges and satellite rainfall measurements.

In addition to the single frequency inversion, a multi-frequency inversion algorithm has been developed to measure the actual drop size distribution (DSD) in the rain (Nystuen, 2001). This multi-frequency inversion is based on the unique sound characteristics generated by the different raindrop sizes. Measuring DSD directly has the advantage that rainfall type (convective or stratiform) can be acoustically identified, and other rainfall quantities, such as equivalent reflectivity, can be calculated (Nystuen and Amitai, 2003). Figure 5 shows the acoustic inversion of the ambient sound field to obtain DSD during a strong oceanic rainfall event that lasted several hours and included both convective and stratiform components. The full inversion provides a better estimate of rainfall rate during the stratiform component of the rain.

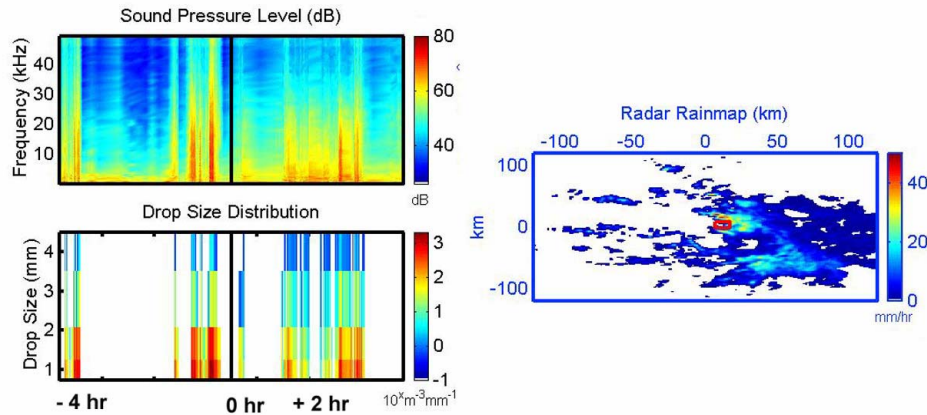


Figure 5. *An acoustic inversion of the sound field to measure drop size distribution in the rain is shown for a heavy oceanic rain event at 10°N,95°W on 23 September 2001. The radar image is centered at 1500Z and shows that a convective cell has just passed over the ARG. Two hours later, stratiform rainfall is detected by the ARG and the radar.*

IMPACT/APPLICATIONS

Analysis of the ambient sound field to provide important air-sea exchange measurements is a technology that should lead to important advances in our understanding of the physics of the air-sea interface. The measurement is simple, robust and covert. It can be made from small, autonomous drifters, or larger surface moorings. The measurements of wind, precipitation and bubbles are difficult to make by more conventional means, and are critical components of the air-sea fluxes of heat, water, momentum and gas that drive the interaction of the atmosphere and the ocean. These data are needed to develop and verify numerical models that analyze and forecast environmental (weather) conditions on small, regional and global scales. Through this effort we will be better able to interpret and monitor the underwater sound field. In addition to geophysical measurements of wind, rain and bubbles, the ARGs can be used to monitor biological activities and anthropogenic activities including shipping and active sonar activities.

TRANSITIONS

The Tactical Oceanography Warfare Support (TOWS) program at NRL has sponsored the development of air-deployable autonomous drifters (Selsor, 1993). Navocean and NOAA are now deploying these sensors on a regular, but limited, basis (about 20 per year). The NOAA National Data Buoy Center is interested in “no-moving-parts” sensors for wind and precipitation. As part of the NOAA Pan-American Climate Studies (PACS) program, ARGs are to be mounted on some of the NOAA Tropical Atmosphere Ocean (TAO) array moorings. It is proposed that the acoustic sensors become a regular component of the NOAA TAO tropical ocean mooring array, and be regularly deployed as part of other large oceanic field experiments.

RELATED PROJECTS

“Long-term Measurements of Air-Sea Processes: Rainfall, stratiform drizzle, ambient bubbles, and wind speed” is sponsored by the NOAA Pan-American Climate Studies (PACS) program. Its goal is to

apply the acoustical weather analysis technology to obtain climatic rainfall data. This project has allowed ARG instruments to be deployed on the Tropical Ocean Atmosphere (TAO) deep ocean mooring array in the eastern tropical Pacific Ocean as part of the Eastern Pacific Intercomparison of Climate (EPIC) program.

“Ionian Sea Rainfall Experiment”, is a new effort sponsored by the Ocean Sciences Division of the National Science Foundation. The goal is investigate the optimal depth for deployment of ARGs to monitor oceanic rainfall. Spatial averaging of the acoustic signal is a function of depth of deployment. Polarametric radar coverage will be used to identify the spatial distribution of rainfall within the listening area of vertically positioned ARGs.

REFERENCES

Medwin, H., A. Kurgan and J.A. Nystuen, 1990: Impact and Bubble Sound from Raindrops at Normal and Oblique Incidence, *J. Acoust. Soc. Am.* **88**, 413-418.

Medwin, H., J.A. Nystuen, P.W. Jacobus, L.H. Ostwald and D.E. Synder, 1992: The anatomy of underwater rain noise. *J. Acoust. Soc. Am.* **92**, 1613-1623.

Nystuen, J.A., 1993: An Explanation of the Sound Generated by Light Rain in the Presence of Wind, in Natural Physical Sources of Underwater Sound, ed. B.R. Kerman, Kluwer Academic Publishers, 659-668.

Nystuen, J.A., 2001: Listening to Raindrops from Underwater: An Acoustic Disdrometer. *J. Atmos. and Oceanic Tech.* **18**, 1640-1657.

Nystuen, J.A. and E. Amitai, “High Temporal Resolution of Extreme Rainfall Rate Variability and the Acoustic Classification of Rainfall”, *J. Geophys. Res.*, **108** Number D8, 8378, doi:10.1029/2001JD001481, 2003.

Nystuen, J.A. and H.D. Selsor, 1997: Weather Classification using Passive Acoustic Drifters. *J. Atmos. and Oceanic Tech.*, **14**, 656-666.

Selsor, H.D., 1993: Data from the sea: Navy Drifting Buoy Program. *Sea Technology* **34**, 53-58.

Vagle, S., W.G. Large and D.M. Farmer, 1990: An evaluation of the WOTAN technique for inferring oceanic wind from underwater sound. *J. Atmos. and Ocean. Tech.* **7**, 576-595.

PUBLICATIONS

Nystuen, J.A., 1997: Validation of Acoustic Measurements of Wind and Precipitation using Expendable Ambient Noise Sensor (ANS) Drifters, AN/WSQ-6 (XAN-2). Final Technical Report, Grant #N00014-94-1-G906, Naval Research Laboratory, via Defense Technical Information Center, Alexandria, VA 22304-6145, 21 p.

Nystuen, J.A. and H.D. Selsor, 1997: Weather Classification using Passive Acoustic Drifters. *J. Atmos. and Oceanic Tech.*, **14**, 656-666.

Nystuen, J.A., 1999: Relative Performance of Automatic Rain Gauges under Different Rainfall Conditions. *J. Atmos. and Oceanic Tech.*, **16**, 1025-1043.

Nystuen, J.A., 1999: Listening to Raindrops, *Solstice* **10**, Number 2,
<http://www.csfn.net.org/image/solstice/win99/janystuen/listen.html>

Nystuen, J.A., M.J. McPhaden and H.P. Freitag, 2000: Surface Measurements of Precipitation from an Ocean Mooring: The Underwater Acoustic Log from the South China Sea”, *J. Applied Meteor.* **39**, 2182-2197.

Nystuen, J.A., 2001: Listening to Raindrops from Underwater: An Acoustic Disdrometer. *J. Atmos. and Oceanic Tech.* **18**, 1640-1657.

Nystuen, J.A. and E. Amitai, 2003: High Temporal Resolution of Extreme Rainfall Rate Variability and the Acoustic Classification of Rainfall”, *J. Geophys. Res.*, **108** Number D8, 8378,
doi:10.1029/2001JD001481.

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