Natural seabed gas leakage -- variability imposed by tidal cycles

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***Abstract*—The likelihood of leakage from sub-seabed Carbon Capture and Storage (CCS) sites has been debated since geological storage was proposed as an effective option to remove greenhouse gas emissions from the climate system. Within the marine environment, passive acoustics has been presented as a feasible way for detecting and quantifying any such leakage. When determining estimates of gas escape across the seabed, the influence of dynamic environments, introducing natural variations in seepage rates must be considered, including tidal cycles. Panarea, Sicily, is the location of a series of natural marine CO_2 gas seeps and provides an excellent test bed to investigate variations of natural seabed gas leakage across a tidal cycle. A multivariate statistical approach was used to recognize the relationship when gas leakage is dominated by natural forcing. We show that the tidal height correlates negatively with the bubble sound power spectral density, the gas flux, and the bubble size. The strength of the correlation can vary significantly for different investigated time periods of observation, showing sensitivity of tidal influence. Our results corroborate evidence that natural migration of CO_2 through the seabed is moderated by tidal cycles.**

***Index Terms*—Carbon Capture and Storage (CCS), gas leakage, tide, passive acoustics, greenhouse gas**

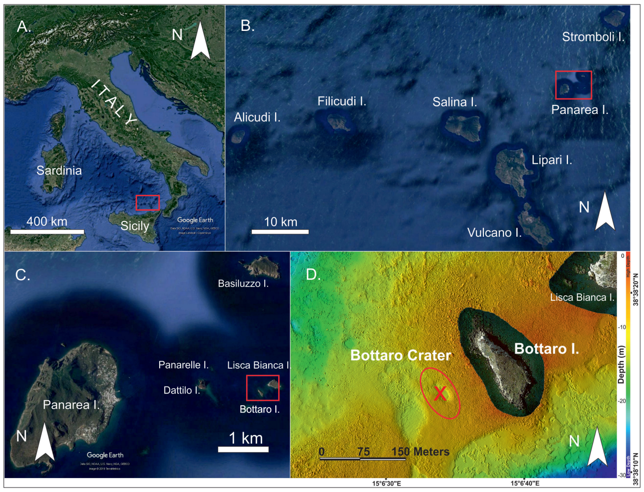

Fig. 1. Map of Panarea island and the surrounding islets. The deployment site (marked as a red star) is located northeast edge of the isolated islet Lisca Bianca along fracture ($38^\circ 38' 25''$N, $15^\circ 06' 56''$E). The seep site depth is 12.5 m below water surface. The sea state was primarily 2.

I. INTRODUCTION

In recent years, offshore Carbon Capture and Storage (CCS) has been proposed as an effective option for reducing greenhouse gas emission into the atmosphere [1]–[4]. However, the possibility of leakage from a CCS site is an ongoing concern, and multiple strategies for monitoring and quantification of such leaks have been presented [5]–[9]. Among these strategies, passive acoustic monitoring has been presented as one of the feasible techniques [6], [10]–[12].

Research on excess CO_2 in marine systems is frequently based on laboratory experiments and studies of natural CO_2 seeps [13]. Ideally, the area selected should have an element of tidal flushing, distributing CO_2 enriched sea water to facilitate investigations into techniques for tracing CO_2 leaks over wide area, but not so great a flushing rate that there would be no build-up of CO_2 concentrations in the area during the experiments. Controlled CO_2 release in the marine environment [11] has shown that seepage is tidally moderated.

Panarea, as shown in Fig. 1, is a small Aeolian island in the southern Tyrrhenian Sea, northeast of Sicily [14]–[19]. The island and its associated islets are the subaerial expression of a large submarine stratovolcano, originally formed by the subduction of the African continental plate below the Eurasian plate [16], [20], [21]. While there has been no evidence of volcanic activity on the island over the last 8000 years [22] the underlying silicic magma chamber is still present and has established a shallow hydrothermal system [23] resulting in dozens of natural CO_2 seeps in the area.

Analysis of these seep have shown the gas content to be relatively stable composed of 98% CO_2, 1.7% H_2S and 0.3% other trace gases (N_2, He, H_2, CH_4) [17], [24]–[26], though the physical rate of gas flux can vary greatly from one seep to the next. This variety of natural CO_2-rich gas seeps make Panarea an excellent site to study variations in natural gas leakage in a dynamic marine environment. Indeed, gas leakage in offshore Panarea has been studied in depth since the 1980s [27], [28], with over 80 release sites mapped throughout the surveyed area [16]. There has even been continuous passive acoustic monitoring of bubble flux [29], focusing on the sensitivity of tidal activity on seabed gas leakage over different length of recording, though this has not yet been statistically investigated.

In this paper, we investigate the influence and acoustic sensitivity of tidal activity on natural sub-seabed CO_2 leakage over different time lengths of observation. We attempt to address the following questions: (1) how much does the tidal variation affect the power spectral density (PSD) and the standard deviation of the PSD; (2) how does the tidal cycle moderate gas flux and bubble size variation?

The paper is organized as follows. Sections II describes the methods. Section III gives the correlation relationship between measured and inverted values. Section IV summarizes the paper with conclusions and discussion.

II. METHODS

In this section, we describe methods of deployment, signal processing, passive inversion, and correlation.

A. Deployment

This study was centred in Bottaro Crater, a 1 m deep depression in the seabed formed by a gas eruption in 2002, 3.3 km to the east of Panarea (Fig. 1), which is in water depth of around 12 m depending on tidal height. CO_2-rich gas bubbles are continuously escaping from the body of the crater with more focused seeps located along the perimeter. A video survey prior to deployment was used to plan equipment deployment and provide an alternative estimate of bubble size and gas flux for later comparison.

A calibrated 'RS Orca' hydrophone was deployed in the center of the crater, 2 m away from the closest continuously active seep, to record the acoustic signature being emitted by gas bubbles escaping into the seabed. The hydrophone was calibrated with receive sensitivity of -164.5 dB re: 1 V/μPa, possessing a gain of 15 dB, and a sampling frequency of 96 kHz. The recording started at 13:45 on 14th May 2018 and lasted for 17 hours until 06:53 on 15th May 2018.

Tidal information and relevant weather data were obtained at 10-min interval. Recorded data of tidal oscillations was used for multivariate data analysis. The data set is applied to identify dependencies between the variables, i.e., tidal level, PSD parameters, and gas leakage quantifications.

B. Signal processing

The acoustic signature recorded from the channel is processed with 10-s observation windows. Relative statistics include PSD and standard deviation of the PSD. Based on the recorded data, a robust Least Square (RLS) regression model was used to identify parameters, which contributed significantly to tidal variations.

1) Power spectral density (PSD): A general quantitative description of the seafloor noise can be provided by the analysis of PSD. The noise PSD is estimated using the Welch's PSD estimate technique [30]. It works on the chosen noise period with $f_s/2$ points overlapping, to reduce the variance of the periodogram, breaks the time series into segments, and returns one-sided Welch PSD estimates [30]:

$$[\mathrm{PSD}_k] = pwelch(x_k(i)),\ k = 1, 2, \ldots, K, \qquad (1)$$

where the '$pwelch$' represents the Welch's technique [30], a hamming window of equal length f_s is used, and the NFFT size is chosen as $f_s/2$. The PSD_k [dB re μPa^2/Hz] for the kth fragment is finally computed with considering the gain and frequency dependent sensitivity of the hydrophone known from design specification. Thus, the estimate of the noise PSD would be the average at each time fragment.

2) PSD standard deviation: To find the acoustic sensitivity of the seafloor noise and the power variance of the signal as a function of frequency, the PSD standard deviation ρ is evaluated for each 2 min (J = 12 fragments). The mth min ρ_m is computed as:

$$\rho_m = \sqrt{\frac{1}{J-1}\sum_{j=1}^{J} |\mathrm{PSD}_m(j) - \mu_m|},\ j = 1, 2, \ldots, J, \qquad (2)$$

where μ_m is the mean of $\mathrm{PSD}_m(j)$.

3) Smoothing technique: In practical, because the ambient noise (e.g., biological noise) has taken up a large portion of the acoustic recording, we firstly need to identify outliers and assign lower weight or zeros weight to these outliers. Thus, we process the collected tidal data and the estimated gas flux using a smoothing technique based on robust locally weighted regression presented by Cleveland [31]. The technique combines local fitting of polynomials [32] and robust estimation by adaptation of iterated weighted least squares [33], [34], which guards against deviant points distorting the smoothed points [31], i.e., it gives the most weight to the data points nearest the point of estimation and the least weight to the data points that are furthest away. It is preferable that the smoothed line is insensitive to these kinds of deviations. To compare and identify agreements between the time-variations of tides and the estimated gas flux, we have been setting different span (e.g., a certain percent of the whole data) for the moving average filter in the regression.

C. Passive inversion model

Acoustic inversion is used to quantify fluxes of gaseous CO_2 and determine bubble size and to assess associated impacts from ambient, e.g., tide [35]. For inversion of the gas flux from the bubble stream, we identify the dominant frequency range, $[f_{\min}, f_{\max}]$ over which the sound of the bubbles is evident above the ambient noise field. The radii of the bubbles whose resonant frequencies correspond to $f_{\min}$ and $f_{\max}$ are identified and are $R_{\max}$ and $R_{\min}$ respectively [36]. Then we create a bin vector of the radii R_0 with each bin equaling to $(R_{\max}$-$R_{\min})/M$, where M is the number of bins. For each bin, we integrate the measured power spectral density across the bin [35].

Based on the computed acoustic pressure, we estimate the bubble size distribution and population from the recorded passive acoustic data using the passive acoustic inversion (see details in [35]). Thus, the probability density function (PDF) of bubble equilibrium radius $p_{\mathrm{b}}^{R_0}$ as well as the number of bubbles for each size are obtained, and the gas flow rate F [L/min] is then computed. Due to the short distance from the hydrophone to the seep site (2 m), here we have not consider underwater multipath propagation [12], [37]–[40], e.g., sea surface reflection, and apply the spherical spreading of the bubble sound in the acoustic channel.

D. Correlation coefficient

Corrections between these values, i.e., tidal level, sound PSD, standard deviation of PSD, inverted seabed gas flux and bubble size, can vary over different length of recording. Here we present the cross-correlation of these values based on the field data. To show the strength of linear relationship between two variables, the Pearson correlation coefficient [38], [41] is used as

$$\xi = \frac{\sum_{k=1}^{K}(\varphi_1(k)-\bar{\varphi}_1)(\varphi_2(k)-\bar{\varphi}_2)}{\sqrt{\varepsilon_1^2}\sqrt{\varepsilon_2^2}}, \tag{3}$$

where

$$\varepsilon_1^2 = \sum_{k=1}^{K}(\varphi_1(k)-\bar{\varphi}_1)^2, \tag{4}$$

and

$$\varepsilon_2^2 = \sum_{k=1}^{K}(\varphi_2(k)-\bar{\varphi}_2)^2, \tag{5}$$

are covariance of the variables, $\varphi_1(k)$ and $\varphi_2(k)$ are the two variables, $\bar{\varphi}_1$ and $\bar{\varphi}_2$ are mean values of the two variables, respectively. Values between 0 and 0.3 (0 and -0.3) indicate a weak positive (negative) linear relationship via a shaky linear rule; values between 0.3 and 0.7 (-0.3 and -0.7) indicate a moderate positive (negative) linear relationship via a fuzzy-firm linear rule; and values between 0.7 and 1.0 (-0.7 and -1.0) indicate a strong positive (negative) linear relationship via a firm linear rule [41].

III. RESULTS

Fig. 2 shows the acoustic spectrum, tidal level, sound PSD, standard deviation of PSD, the inverted seabed gas flux and bubble mean radius. The tidal data covers 1.5 cycles. It can be observed that as the tidal height changes, the level of the PSD, hydrophone-determined gas flux and bubble size gently changes in an opposite direction. A strong correlation between peaks in gas flux and bubble size and low tide was observed in most cases, but some of them did not show correlation due to the surrounding and occasional noise, such as at around 19:30 and 21:45 on 14th May, 2018. Moreover, it is difficult to see tidal correlation in time period to gas flux and bubble radius only from this figure, thus we seek help from cross-correlation.

The cross-correlation results are shown in Fig. 3, from which the tidal dependency can be observed. In short period corresponding to small smooth span $< 0.1\%$, the tidal level is modest positively correlated with the PSD standard deviation (Std), modest negatively correlated with the PSD, and weak correlated with the gas flux and bubble radius. While in the long period corresponding to large smooth span $> 10\%$, the tidal level is strong positively correlated with the PSD Std, and strong negatively correlated with the PSD, the gas flux and bubble radius. The PSD is modest positively correlated with its Std in short period while strong negatively correlated with its Std in long period. As the smooth span increases, the positive correlation between gas flux and bubble radius becomes stronger. The short period correlation shows instant changes, while the long period correlation shows the influence of tidal cycles on CO_2 gas seepage. The PSD value and the standard deviation of it possess negative correlation in short period (instant agitation) and positive correlation in long period (daily tidal cycle). The size of the leakage bubbles have stronger negative correlation with the tide than with the seabed gas flux.

Fig. 4 shows the seabed gas seep related variables correlating with tidal circulation of $\sim$12 hours, showing a negative correlation between tidal level and PSD, gas flux, as well as bubble size. It is shown that in dynamic water areas like offshore Panarea, natural variability is comparable in its levels of gas seep variation with the effects of tidal variation. Natural forcing, such as tide, may be a strong factor in the gas seepage from the seabed. In general, the circulation offshore Panarea is tidally driven and the influence of tidal circulation was significant on all the measured seep variables.

IV. CONCLUSIONS AND DISCUSSION

Multivariate analysis of tidal and acoustic data using cross-correlation is an efficient tool in identifying correlations for different time periods of observation. During the acoustic recording, the strongest positive dependence was found between gas flow rate and bubble size, and the strongest negative correlation was found between high tidal height and small bubble size (due to greater hydrostatic pressure reducing bubble size). We show that the tidal activity correlates significantly with the gas seep related sound PSD, the standard deviation of PSD, the inverted seabed gas flux and bubble radius. Our results corroborate evidence that natural migration of CO_2 through the seabed is moderated by tidal activities with strong negative correlation.

Gaseous CO_2 flow rates estimated from acoustic inversion varied significantly with tidally induced changed in hydrostatic pressure. Impact is indicated not by change per second, but by deviations from well-established normal tidal cycles. Intermittently the high gas flux in the water column was advected increased owing to tidal circulation, inducing bubble sound strength change. Bubble streams, when present, are easily recorded, but we observed that these are sensitive to hydrostatic pressure and may represent a fraction of released CO_2. While as only 18 hours data were observed and analysed here, the results on the gas leakage variability due to tidal cycles are limited. Longer measurement, e.g., more than tidal cycles, could be useful to provide more information on the correlation between environmental parameters (e.g., tidal level) and measured acoustic data characteristics.

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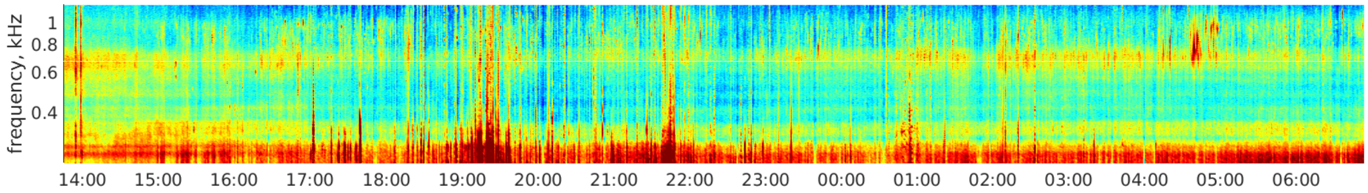
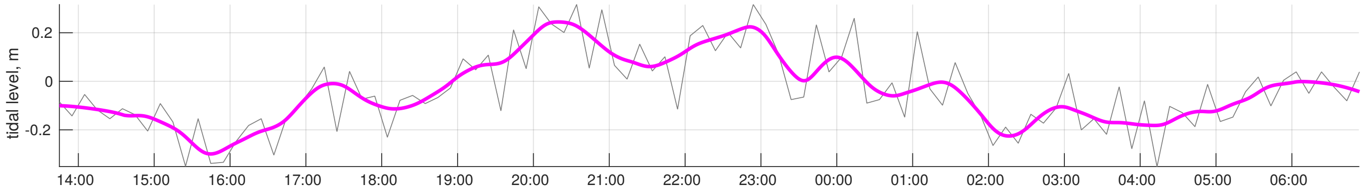
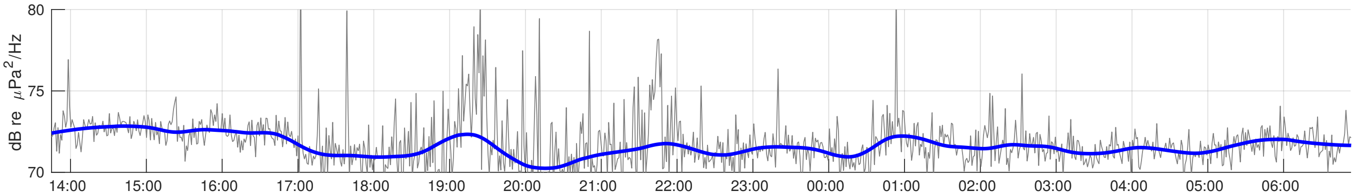


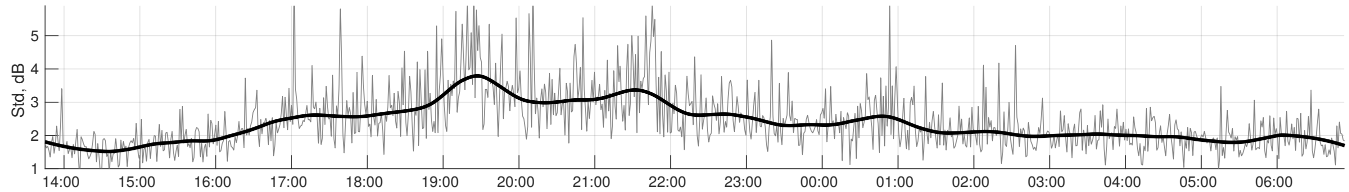
(a) power spectral density (PSD)



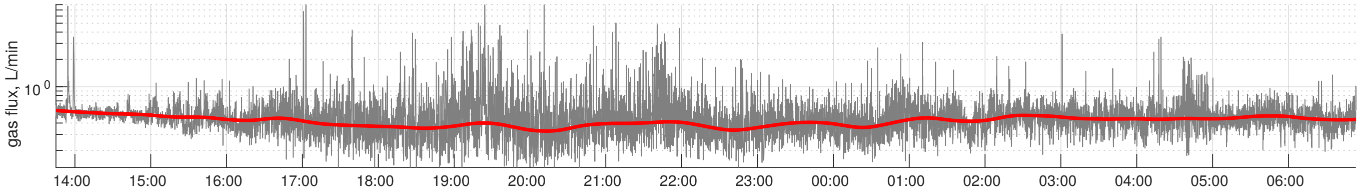
(b) tide over average level (10% span smoothed - purple line)



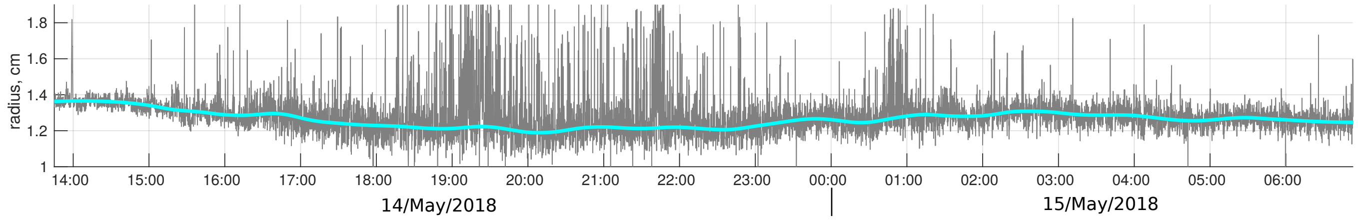
(c) PSD at 700 Hz (10% span smoothed - blue line)



(d) standard deviation (Std) of PSD at 700 Hz (10% span smoothed - black line)



(e) estimate of gas flux (10% span smoothed - red line)



(f) bubble mean radius (10% span smoothed - cyan line)

Fig. 2. Acoustic sound power spectral density (PSD), standard deviation (Std) of PSD, hydrophone-determined seabed flux and bubble size variations in the water column over 17 hours (approximately 1.5 tidal cycles). Seabed gas flux and bubble mean radius inversely correlate with the tidal cycle, with low gas flux and small bubble size at high tide. (a) PSD; (b) tide over average level; (c) PSD at 700 Hz; (d) standard deviation (Std) of PSD at 700 Hz; (e) estimate of gas flux; (f) bubble mean radius at the seabed from inversion of hydrophone data with 50th percentile of confidence interval.

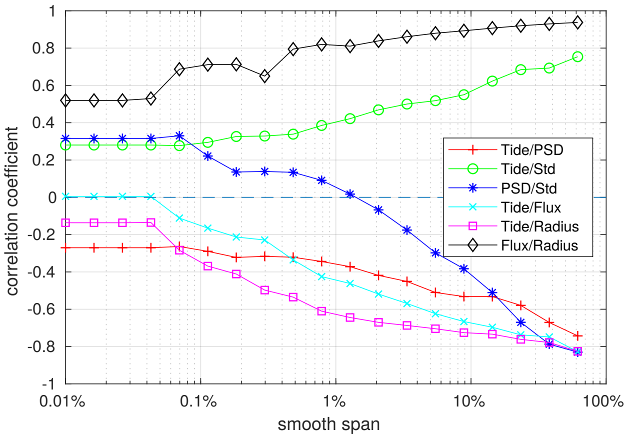
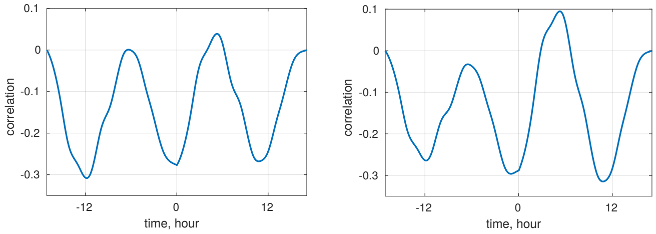
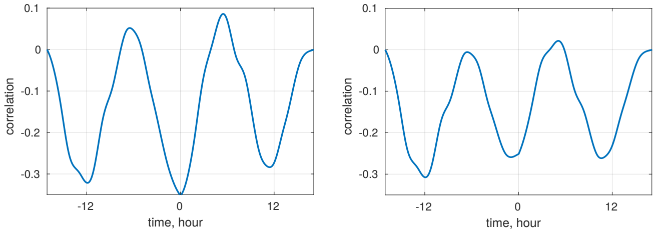


Fig. 3. Multivariate analysis of the collected data: correlation coefficient between different variable pairs. Negative points and distanced far away from 0 indicate strong negative correlation between the variables. Points that are closer to 0 have weaker influence on the model.



(a) tide vs. power spectral density (PSD)

(b) tide vs. standard deviation (Std) of PSD



(c) tide vs. gas flux

(d) tide vs. bubble mean radii

Fig. 4. Cross-correlation between the 10% span smoothed tide from the Panarea seepage site for the 17-hour observation period with (a) the power spectral density (PSD); (b) the standard deviation (Std) of PSD; (c) the calculated gas flux; and (d) the bubble mean size recorded.

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