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Descriptive acoustic analysis of a newly-discovered marine seep

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NONTECHNICAL SUMMARY

Methane is a potent greenhouse gas that plays an important role in the global climate and has a warming potential that is twenty-five times greater than that of carbon dioxide. Natural fluxes of methane may be reaching the atmosphere from sources within marine sediment, forming features known as marine seeps. Marine seeps are associated with water column features known as “bubble plumes” or “flares” which contain the emitted gas from the seafloor. Marine seeps can be found on continental margins all over the world, but there was only one location previously known to be an active marine seep location on the Juan de Fuca Plate. This study discovered a new marine seep about fifty miles offshore Canada. Multibeam sonar was used to evaluate the spatial extent of the plume-like water column feature which held all the characteristics of a marine seep. Results from the acoustic analysis suggested a conservative estimate of the plume’s volume to be $3.00x10^6$ m^3. The plume was found among seafloor features known to be characteristic of marine seeps. Additionally, the sonar signature of the plume indicates that the seep may be at an unprecedented height in the water column. More long-term studying is needed before any conclusions can be made as to whether this seep is interacting with the atmosphere or not and how intermittent the seeping is at this location. If it is found upon further data collection that this seep is consistently reaching the upper water column, it is possible considerable amounts of methane are reaching the atmosphere before microbial oxidation occurs.

ABSTRACT

The effects of climate change on the environment and societal quality of life are already undeniable and show no signs of reversal by the end of the century. Methane contributes to climate forcing as an important greenhouse gas with both natural and anthropogenic sources. Natural contributions of methane may be reaching the atmosphere from marine seeps on continental margins around the world. Marine seeps are plumes of biogenic and thermogenic methane gas from deep sources in the sediment that form bubble plumes within the water column. The measurement of marine seeps by acoustic ocean surveying requires the acquisition of acoustic backscatter measurements from shipboard echo-sounders. Acoustic measurements of bubble plume shape and size are difficult to ground-truth but are critical to the interpretation of data. This project seeks to advance the current understanding of seeps by volumetrically characterizing a newly discovered natural seep offshore Canada with a ship-mounted sonar. The mid-water column backscatter data suggest a two-phase plume of approximately $3.00 \times 10^6 m^3$. It is important to understand the single-phase detrainment and dissolution of methane is likely not imaged on the sonar so acoustic surveying gives only a conservative estimate of the real plume field. Understanding and improving acoustic detection capabilities of bubble plumes will lead to improved bubble models, which will in turn help decipher the fate of marine seep methane and its influence on the global climate.

INTRODUCTION

Marine Seeps and Importance to Global Climate

Atmospheric methane absorbs outgoing infrared radiation from the earth which would otherwise pass into space, and contributes to the warming of the atmosphere. Although methane has a shorter residence time relative to other greenhouse gases, it has a powerful warming potential, ~25 times greater than that of CO_2

[Grant 2002, McGinnis 2006, von Deimling 2011].

Natural fluxes of methane around marine seeps may be one potential source of methane to the atmosphere [Solomon 2009]. Marine seeps on the seafloor are typically associated with gas hydrate deposits and are often locations where thermogenic and biogenic gases are seeping into the ocean, creating bubble plumes. Gas hydrate deposits are solid, crystalline structures of natural gas and water found in marine sediment and are stable within low temperatures and high pressures on continental margins.

Gas from biogenic sources in the sediment can be converted to hydrate if within the low-temperature, high-pressure hydrate stability field (HSF) zone; conversely, if gas is released from deep sources in the sediment outside the HSF free gas will form and dissolve in the water column [McGinnis 2006]. Various crystal structures of hydrate are possible and each crystal lattice behaves differently, depending on the constituents in the hydrate. For example, Structure I Hydrate has a narrower stability field than Structure II Hydrate, which may be important data to know about the seep discovered in this study, as it lies on the feather-edge of the HSF.

Fractures in the sediment can form conduits within the HSF that line with methane hydrate and lock the available water into crystal form, allowing free gas to flow through the conduits and into the water column. This forms what is known as “flares,” “seeps,” or “bubble plumes”; all terminology that is used interchangeably. As gas bubbles advect upward and entrain the surrounding water, they change in size due to changes in pressure and temperature. If methane from bubble plumes reaches the surface mixed layer of the ocean in a particular area, it will likely interact with the atmosphere via gas-exchange, which could be accelerated by a storm event.

Although methane bubble plumes from seeps have only recently been recognized as an important mechanism for methane transfer from the seafloor to sea surface, unconstrained estimates indicate bubble plumes may be contributing ~20-40 Tg yr^{-1} of methane to the atmosphere [Kvenvolden 2005], which is approximately half the annual fossil fuel budget [Solomon 2007]. Better estimates of this flux will help constrain the importance of methane bubble plumes as a source of methane to the ocean and atmosphere.

Understanding plume dynamics can also serve as a proxy for modeling the outcomes of possible gas hydrate dissociation in the future with a changing climate. The amount of methane that reaches the atmosphere from plume transport depends on an accurate understanding of bubble size, rise velocity, surfactants, bubble-bubble interactions and bubble-fluid interactions, which have not been well-constrained in the past [Leifer 2002, McGinnis 2006]. As a result, current bubble models are oversimplified and do not adequately reflect the natural system [Grant 2002].

Importance of Acoustic Surveying to Marine Seep Science

Acoustic surveying can be used to estimate both two-phase (gas bubbles and water) and single-phase (dissolved methane) plume fluxes from marine seeps by use of echo-sounders on a ship or submersible [Linke 2010]. Sound has variable velocity in different density mediums, which can arise from thermal and saline gradients [Ostashev 1994] and from the differences in density between gas and water [Linke 2010]. Plume detection takes advantage of the velocity difference of sound traveling through water versus a gas bubble.

Acoustic echo-sounders operate as multibeam sonar systems with a transducer array, which record the travel time and intensity of acoustic backscatter from active ensonification of the water-column. Backscatter return can either be interpreted as an estimate of seafloor depth or as acoustic reflection within the water column; therefore, bubble plumes can be detected on sonar [Linke 2010, Trevorrow 2003]. Acoustic scattering additionally depends on physical parameters of the scattering agent, such as size and density [Di Iorio 2012]. Hydroacoustic surveying has the benefit of overcoming the limitations of light in water [Ostashev 1994]. Light attenuates quickly in water, but ensonification can penetrate great distances as well as give return descriptive of both water column scattering and the surface properties of the seafloor. Sonar has been a common technique in previous plume studies, but hydroacoustics have been used much longer by biological oceanographers and fisheries scientists to detect moving aggregates or animals in the water column.

When a potential marine seep is first detected, preliminary questions researchers want to answer about the potential seep are: What is the spatial extent of the plume and a rough volume estimate? Where does the HSF lie given the water column properties? More in-depth subjects, such as entrainment and detrainment of the plume, and chemical composition require additional studying. Temporal characterization is also needed to determine how often and how long a seep is venting.

A water-column feature suggestive of a marine seep was discovered and surveyed for the first time by this study, fifty miles outside of the Strait of Juan de Fuca (Fig. 1).

This study seeks to answer the first of those preliminary questions about the spatial extent of a new seep that can be quantified upon doing an initial survey. Using hydroacoustics and hydrographic software, inferences about the identity of the detected water column feature as a marine seep are given, as well as the shape and rough volume of the proposed plume.

Implications of the data lead to more technical research directions such as whether or not the seep is reaching the surface mixed layer and how much it is exchanging with the atmosphere. Future research will need to determine why this seep is actively venting and whether it is passive or active dissociation of gas hydrate. Given the water column properties there is evidence to believe that this seep may be actively dissociating, which has never been seen outside of the Arctic before. This raises the question of whether anthropogenic activities are influencing long-term temperature trends on the seafloor. If that connection can be established with further research, this seep may become an icon of anthropogenic climate change and lead to questions about the impacts of other undiscovered seeps around the world. Marine seeps studies and acoustic water column detection are both new and developing fields, so most of these implication questions will require many more decades of research to answer. This study seeks to contribute to the current knowledge of marine seeps by quantitatively and qualitatively describing the newly discovered seep and make supported conjectures about the implications of these data to worldwide seeps.

Figure 1. Location of interest. The potential seep was located on a continental margin about 50 miles outside of the Strait of Juan de Fuca.

METHODS

Multibeam sonar serves as an effective tool for surveying marine seeps because bubbles are efficient acoustic scattering agents. On 26 January 2013, following a location tip by a fisherman, the *R/V Thompson* surveyed a flare-like water column feature with a Kongsberg Maritime EM302 multibeam sonar system, at a speed of four knots. The sonar was operating at a frequency of 30 kHz. The EM302 transducer offers 1-cm resolution over a swath angle of 70 degrees. Sound velocity profiles were obtained from SeaBird 911 CTD casts.

The water column (WC) across track display was monitored and the acoustic signature of the plume was unambiguously evident above background noise (Fig. 2). A total of 8 survey lines were conducted; however, only two lines yielded useable data as the other lines were small and involved the ship turning for the majority of the line. The two lines where data was gathered from to estimate the spatial envelope of the plume were perpendicular to each other, which is important for maximizing acoustic coverage.

The acquisition software, Kongsberg Seafloor Information Systems, continuously records estimations of depths by the ping return and corrects for geographic space, which turns pings into soundings. Onboard sensors automatically correct for the pitch, heave, and yaw of the ship.

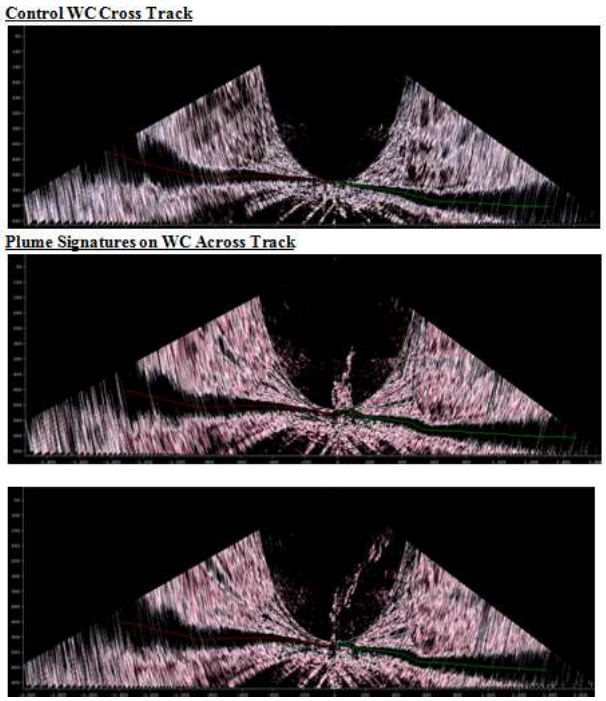


Figure 2. The top panel shows, for reference, WC data with min/max dB intensity filtering of -39 and -29 and without a water column feature. The bottom two panels are the plume signature that was seen on the sonar during the survey.

The data were post-processed the hydrographic data-processing software, CARIS HIPS and SIPS 7.1 (Computer Aided Resource Information System). The raw data was converted and corrections for sound velocity and tide were made, according to the day of the survey. Total propagated uncertainty (TPU) was calculated on the data and integrated into a CUBE algorithm which produced a BASE surface. Water column editing and visualization were then done with Swath Editor and Subset Editor. Subset Editor was used for estimations of height, width, and length with verification in Swath Editor. The coordinates of the box used in Subset Editor for the volume estimates are (Fig. 3):

1. 47-55-49.22N, 125-38-31.63W
2. 47-55-44.32N, 125-38-21.30W
3. 47-55-45.20N, 125-38-35.78W
4. 47-55-40.25N, 125-38-25.33W

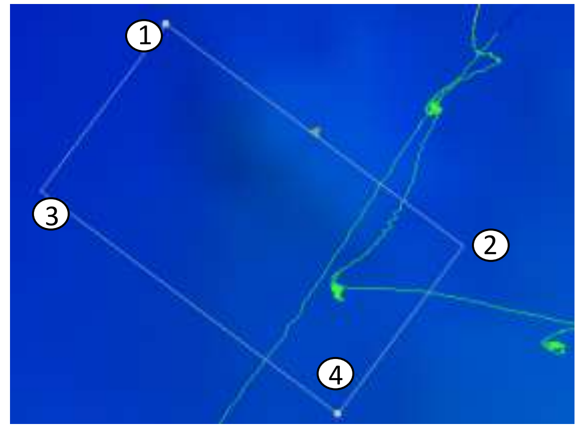


Figure 3. Area used in Subset Editor for volume estimation. In the top center the depression is visible.

Both along and across tracks were evaluated; the along track display is a "side view" from the perspective of the ship, whereas the across track display shows one full sounding perpendicular to the centerline of the ship (Fig. 4).

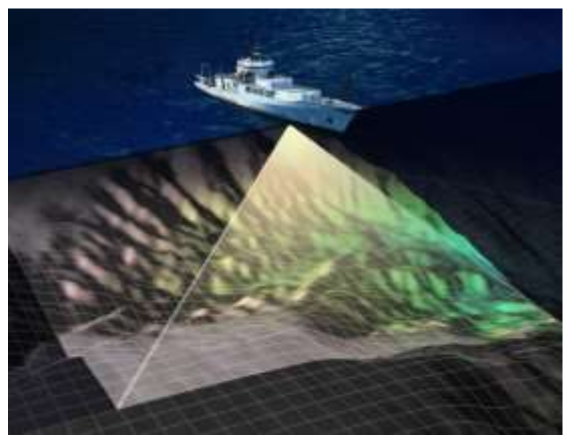


Figure 4. Diagram of a sounding. Highlighted portion in the foreground shows the across track. Along track would be a side view of the sounding shown. Picture credit: OOI.

RESULTS

The flare-like feature seen in the WC across track data is an acoustic signature that is typical for marine seeps [Di Iorio 2012]. The plume was located near a depression occupying about 100 square meters with a relief of about 10 meters, at a depth of 526 meters which is also characteristic of marine seeps [Leifer 2006]. The dimensions of the depression were estimated using Subset Editor (Fig. 5).

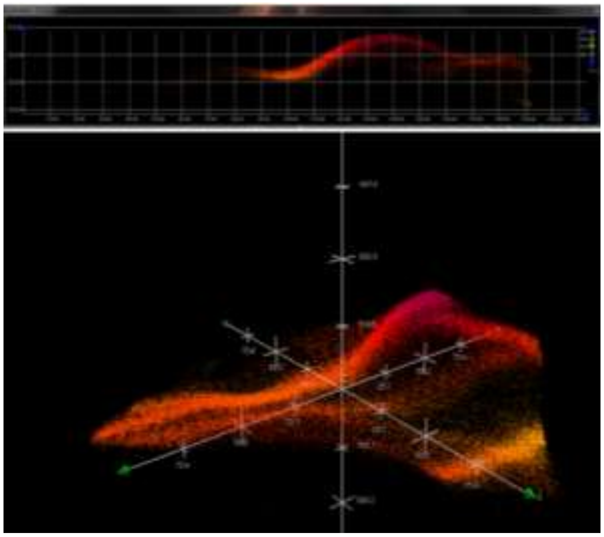


Figure 5. Seafloor bathymetry showing the depression in which the seep was found (WC data not shown) in both 2D and 3D.

The top tail of the plume was clearly being advected NW by the current, as seen in both the sonar across track and in the 2D and 3D visualization, and noticeably extends outside the swath angle of 70 degrees (Fig. 6). Acoustic shadowing is evident, even after heavy filtering of min/max dB intensity (-33, -31). Shadowing occurs when a feature blocks the acoustic path to the regions behind the feature, which is why multiple survey lines are important. Delayed return from beams traveling through the plume can give artificial height to the acoustic noise. However, despite the acoustic artifacts, the plume is plainly distinguishable from background acoustic feedback.

Using the Subset Editor for 3D visualization in CARIS HIPS and SIPS 7.1, the spatial envelope of the plume could be estimated after very aggressive filtering based again on min/max dB intensities of (-33, -31) (Fig. 7). Water column backscatter was imaged by intensity of the return; therefore filtering by intensity removes certain ranges of intensities that are considered acoustic noise. The main plume was approximately 200 meters high, 100 meters wide and 150 meters long giving a rough volume estimate of 3.00×10^6 m^3. The height and width of the plume was estimated in Subset Editor 2D, with verification in 3D, and the length was estimated using the along track WC data. The tail of the plume was not included in volume estimations due to the difficulty of verifying the dimensions.

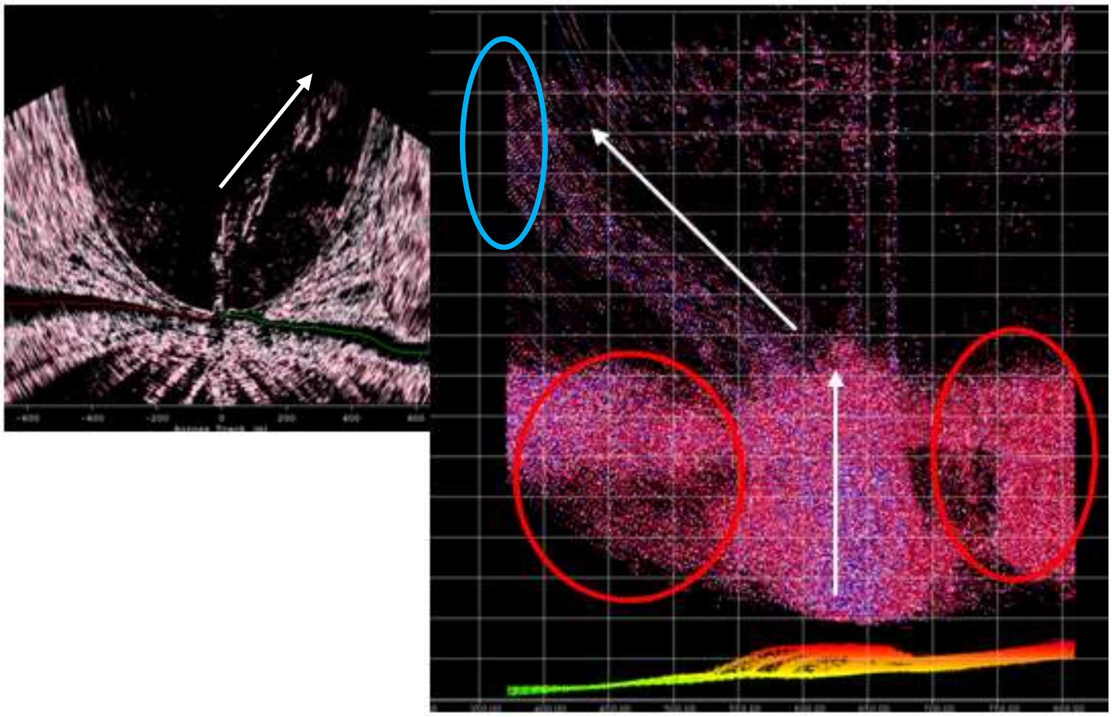
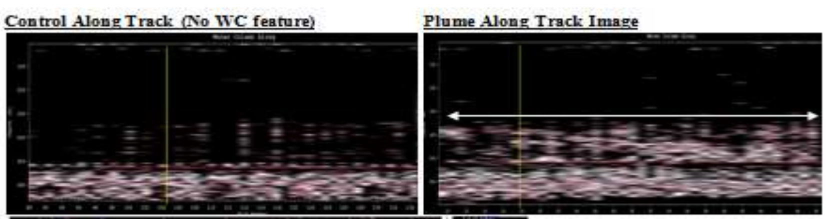


Figure 6. Image on left is WC across track data, image on right in view in Subset Editor 3D. White arrows show travel path of plume and advection by current. Red circles are most likely acoustic shadowing and delayed return due to the plume itself. The blue circle indicates where the plume extends outside of the beam angle. Filtering intensities were (-39, -29) and (-33, -31), respectively.



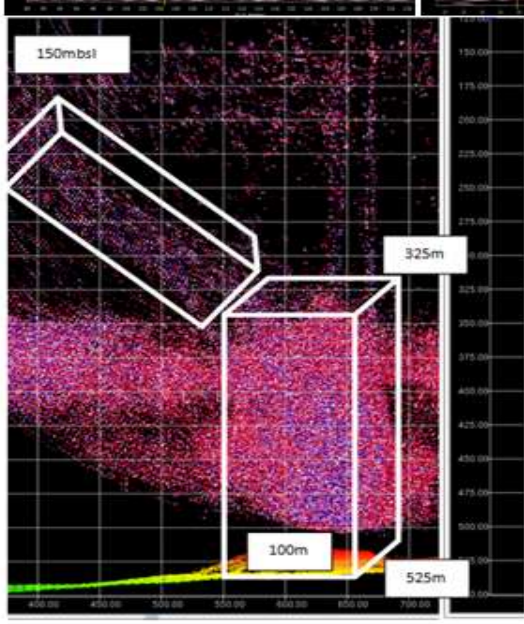


Figure 7. Top panel shows WC along track without a WC feature on the left then with the plume on the right, for comparison. The along track was used for length estimation. The red line is the seafloor. The bottom image shows volume estimation in 2D Subset Editor. Verification was done in 3D Subset Editor (not shown). The tail of the plume was unverifiable in three dimensions so was therefore not included in the volume estimate.

DISCUSSION

The plume appeared on the WC cross track while surveying (Fig. 2) as a visual anomaly in relation to background noise in the water column. The WC feature was considered distinguishable after heavy filtering in the post-processing software, but its identity as a marine seep was unconfirmed until it met further standards set forth by seep researchers. Bubble plumes may be considered distinguishable from other water column features such as schools of fish if (1) the ratio of the height to the horizontal width of a plume is larger than two, as schools of fish have a lower height to length ratio and (2) the bubble plume is seen to have contact with the seafloor [von Deimling 2011]. These criteria are met in the data gathered from the location studied. The height:width ratio of the plume is exactly 2:1 from the preliminary estimations and contact with the seafloor is clearly evident (Fig. 5). Therefore, until proven otherwise, this feature can be considered a marine seep, given the evidence.

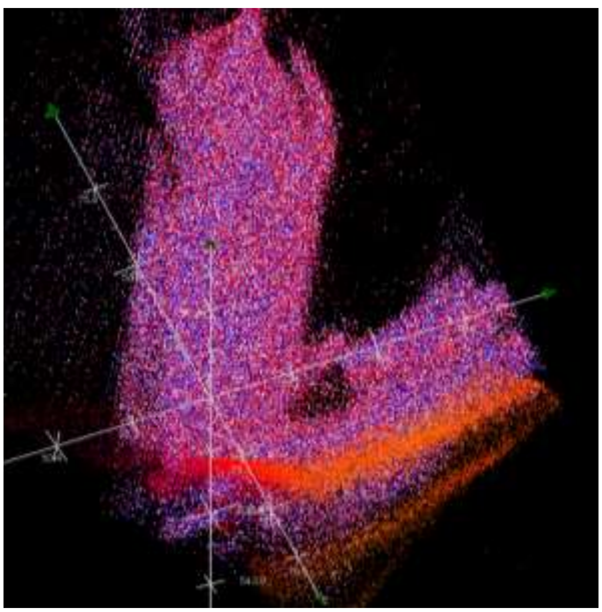


Figure 5. 3D view in Subset Editor of plume; looking from the underside. The red/orange colors are the seafloor; acoustic shadowing is evident at the right. Plume is seen to be in contact with the seafloor.

Because the manual volume estimation methodology is different from previous seep studies, direct relation to other volume estimates is not possible without more information. Only a small area was surveyed; therefore, it is difficult to say whether this seep is a large-scale seep and if it is isolated or in a vent field. More than likely, this seep is a part of a vent field and is among other active seeps along the same isotherm and isobar.

The goals of this study were to determine the identity of the WC feature and to get an idea of the spatial extent of the seep to help direct future research in the area and make supported speculations about the importance of this seep on local air-sea gas exchange. Because the initial location tip was given by a fisherman, the seep has become known as Fisherman's Seep.

The goals of this study were met; a rough volume estimate was accomplished, but it proved to be somewhat cumbersome in the software and very conservative. Also, quantitative comparison to literature values was difficult, but in an approximate sense, Fisherman's Seep lies at the largest extreme of known individual seep sizes.

Although the data in this study are preliminary, some important implications still arose. It was not expected or common to see the plume as high in the water column as it appeared to be on the across track sonar. This increases the priority of this location for future studies. If the plume is consistently found as high in the water column as 150 meters, it is very likely that methane-saturated water is interacting with the atmosphere. What does this in turn imply about other undiscovered seeps around the world? It is not unreasonable to think the same phenomenon is occurring at other locations in similar environments and that seeps are possibly affecting the atmosphere in a considerable way. More than likely it is only technological and methodological limitations that have prevented marine seeps from being recognized as one of the most significant climate change drivers in both geologic and modern history. Considering the massive reservoir of carbon stored in gas hydrate, which surpasses that of fossil fuel reservoirs, the atmospheric impact of marine seeps will be an important player in future climate regimes, especially in the Arctic. Polar amplification in the Arctic and Antarctic leave the high latitudes more susceptible to changes in climate. In the meantime, acoustic surveying the known locations of marine seeps and continued monitoring will help build time-series data to answer address some of these issues.

Some of the methodological limitations in seep studies derives from the fact hydrographic software has not caught up with the field of seep science as of yet. The newest version of CARIS, CARIS 8.0, has improved water column capabilities than 7.1, but still needs further development. In particular, better tools for eliminating acoustic noise, automatically calculating spatial extent, and estimating bubble size would vastly improve on what is currently available. Better post-processing tools will assist researchers in more quickly and effectively characterizing water column data.

It is additionally important to understand echo-sounding at a specific frequency, such as 30kHz, provides a discrete and not continuous spatial representation of a bubble plume. Only the features that send a backscatter return at a given frequency appear as density anomalies in the mid-water-column data. Therefore, complete spatial representation of a plume is difficult and not comprehensive with a single frequency. High-frequency sonar (>10kHz), however, has been shown to have the best success for imaging the water column and seafloor at depths shallower than 5000m [Trevorrow 2003], but for purposes of volumetric analyses of plumes, it is important to realize only an approximation can be done at one frequency without further temporal and spectral imaging. Hydrographic surveying is not a temporal analysis especially considering the dynamic behavior of seeps, unless a monitoring station is installed on the seafloor, which has been done recently by some studies. It is also important to understand much of the single-phase detrainment and dissolution of methane cannot be imaged with sonar so acoustic surveying gives only a conservative estimate of the real plume field. As gas bubbles travel upward, they change in size due to changes in pressure and temperature, which additionally affects backscatter intensities. Although these uncertainties exist, they only serve to reinforce this seep as a focal point of future study due to the fact the unknown variables in this study have likely only lead to an overly conservative estimate of the bubble field.

Future research endeavors at this location should seek to improve on various aspects of this study. Specifically, a more logical and organized grid structure for the survey is important. After adequate surveying is complete, ideally water samples would be taken with greater care and in the right bottles for later gas chromatography analyses. Water samples would be taken preferably about every 10-20 meters from seafloor to surface, following the advection of the plume. A more in depth and more expensive approach would be to take the acoustic data and water samples from a remotely operated vehicle (ROV), as was done by a few studies on Hydrate Ridge, offshore Oregon. ROVs can achieve greater precision and resolution than shipboard casts and sonar. In the most ideal case, a monitoring station would be installed along the lines of the nodes in Neptune and the Ocean Observatories Initiative to provide temporal data and a more accurate characterization of the plume.

Error Analysis

Possible sources of error in hydrographic data are primarily the heave, pitch, yaw and roll of the ship during data collection, tide error, and possible sensor offset error. Qualitatively, the largest source of error in this analysis is the non-grid-like structure of the survey lines, which did not give the most ideal coverage of the seep. Instead, after discovering the seep, attention was focused on collecting water samples following the plume tail in the current; however, attention should have stayed focused first on doing a quality survey. Additional error is involved in making rough calculations on the spatial occupancy of the plume. Intensity filtering, while necessary to discern the plume, may give a falsely smaller spatial representation of the plume. It is likely even the unfiltered plume representation is conservative and does not fully image the extent of the dissolved methane. Additional post-processing is needed to “clean” the acoustic shadowing out of the data. Regardless of these potential sources of error, the large observed extent of the seep is enough to warrant further investigation.

CONCLUSION

The current bubble models which are feeding climate models are very unrealistic. Bubble-bubble and bubble-fluid interactions are not currently included in these gas transfer models due to the complexity of the interactions. Very little has yet been quantified on the flux of methane to the atmosphere from marine seeps. Although more studies are emerging that improve on knowledge of bubble dynamics, plume characteristics, and gas transfer, increased focus is still needed in this field on quantifying bubble plume behavior to build more realistic bubble models. More realistic bubble models in turn will produce a more believable picture of how marine seeps could influence climate in the future or how they have in the past.

Ignorance in the past of the possible influence of the massive reservoir of carbon stored in gas hydrates now has researchers scrambling to catch up and quantify this missing piece to the carbon cycle. Gas hydrates and marine seeps are complex systems and are a new field of study. This study has proposed an important new location for future research and has attempted to give an estimation of the volume and the big-picture importance of the new seep found.

The data collected on Fisherman's Seep suggests unprecedented seep dynamics and is volumetrically on the larger end of detected seeps. A manual approach to volume estimation was done and the implications of the data were evaluated and considered to be of high priority.

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