

A field study of the effects of CO₂ ocean disposal on mobile deep-sea animals

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Abstract

Before the feasibility of ocean sequestration of anthropogenic carbon dioxide can be evaluated completely, there is a clear need to better understand the potential biological impacts of CO₂-enriched (low pH and high *p*CO₂) seawater in regions of proposed disposal. We describe here the first empirical study directly examining animal responses to dissolving CO₂ hydrates on the deep-sea floor. Using a remotely operated vehicle (ROV) to conduct experiments within Monterey Canyon, CA, we found that several species (both invertebrate and vertebrate) did not avoid rapidly dissolving flocculent hydrates when attracted by the scent of food. Furthermore, while there were no apparent short-term effects of decreased pH, mobile animals appeared to suffer from respiratory distress due to increased *p*CO₂ when in close proximity to hydrates. Losses of higher organisms as a result of CO₂ disposal in the deep-sea may therefore be more extensive than previously predicted from toxicological models. However, the extent of changes to surrounding seawater chemistry, and thus biological impact, is largely dependent on CO₂ release method or the type of hydrate formed. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Ocean CO₂ disposal; Biological impact; Hydrate dissolution; Low pH; High *p*CO₂; Deep-sea animals

1. Introduction

Oceans represent the largest potential sink for man-made carbon dioxide. The sequestration of CO₂ in the sea has therefore been proposed as a measure to mitigate global warming (Marchetti, 1977; Handa and Ohsumi, 1995; Parson and Keith, 1998). However, direct ocean disposal of CO₂ will only be of

value if environmental impacts to marine systems are significantly less than the impacts avoided in atmospheric release.

While several CO₂ disposal scenarios have been proposed at various ocean depths and in different forms (gas, liquid, solid, and hydrate), almost nothing is known about impacts on marine organisms (Shirayama, 1995; Omori et al., 1996). To our knowledge, the few studies that directly considered the biological effects of ocean CO₂ sequestration have been toxicological models based on published values for mortality of shallow water animals (both

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fresh and marine) when exposed to low pH solutions (Auerbach et al., 1997; Caulfield et al., 1997).

These models make two basic assumptions about the impacts of CO₂ discharge on marine life: (1) the relevant perturbation is reduced pH and not increased carbon dioxide partial pressure ($p\text{CO}_2$) and (2) only passive or sessile organisms will be affected directly because mobile animals will avoid CO₂ discharge sites. While these studies are valuable in predicting the magnitude of potential losses for some organisms, controlled empirical tests are needed to both examine the appropriate species that may be at risk in the various disposal scenarios and to test the model assumptions.

Our study was designed to examine some of these issues and was a pioneering attempt to address specifically the biological effects of CO₂ disposal on the deep-sea floor. Using a remotely operated vehicle (ROV), we were able to conduct in situ experiments examining the behavior of mobile deep-sea animals in response to the formation and dissolution of CO₂ hydrates. Although industrial scale scenarios would involve much larger volumes of CO₂ than those studied here, our findings appear to be directly applicable.

2. Materials and methods

Experiments were conducted on the seafloor within Monterey Canyon (36° 44.75'N, 122° 02.91'W) at a depth of 625 m. The Monterey Bay Aquarium Research Institute's ROV *Ventana* (Robison, 1993) was used to deploy and regulate our experimental equipment, and to non-invasively video record the behavior of various benthic species. Because of the logistical difficulties in working at extreme depths and the time needed to carry out animal behavioral experiments in the wild, we were limited to two replicate trials during a single ROV dive.

Our experimental equipment included an odor/CO₂ release rig and a pH sensor. The release rig was comprised of a metal stand that held an inverted 4-l glass beaker (Fig. 1). Two tubes led from the ROV to inside the beaker, one for the delivery of an animal attractant solution and the other to release liquid CO₂.

To examine the effects of CO₂-enriched seawater (as might be found near dissolving hydrates) on the behavior of mobile deep-sea animals, benthic macrofauna were first drawn to the release rig with a fish

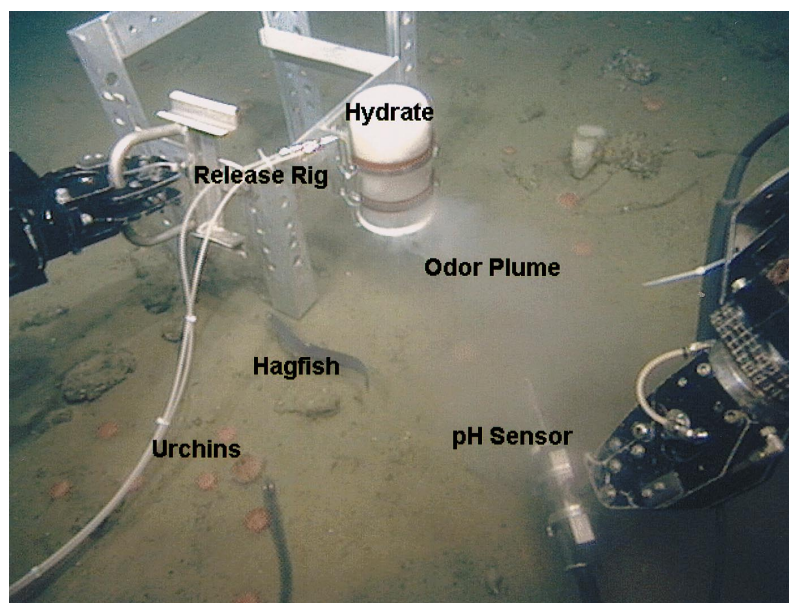


Fig. 1. Image of the odor/CO₂ release rig, CO₂ hydrate formed in the inverted beaker, pH sensor, and benthic animals attracted by the odor plume.

odor solution. The solution was prepared by blending 4 kg of rockfish flesh (*Sebastes* sp.) into 40 l of seawater and filtering the homogenate to 1 mm. A peristaltic pump forced the homogenate solution from a collapsible container on the ROV into the beaker, out the bottom opening, and down stream with the current. The odor solution alone was released until animals accumulated near the release rig (30–60 min). The numbers and behavior of different species attracted by the solution were noted.

After several animals gathered near the release rig, a buoyant CO₂ hydrate mass was formed in the inverted beaker as the odor solutions continued to be discharged. The flocculent hydrate was created by vigorous injection of liquid CO₂ by means of piston expulsion from an accumulator attached to the ROV (see Brewer et al., 1999; Brewer et al., 2000, for a more detailed description of the CO₂ release system). The odor solution flowed through the porous hydrate, which filled approximately half the beaker (Fig. 1). Again, the numbers and behaviors of different species near the release rig were noted for an additional 30 min.

Throughout the experiments, a pH sensor (Sea-Bird SBE 18 with a pressure-balanced glass-electrode Ag/AgCl-reference probe modified to be deployed at depth) was attached to a robotic arm of the ROV (see Brewer et al., 2000, for a more detailed description of the in situ pH measuring system). This allowed pH measurements of ambient seawater at the 625-m site, at the beaker opening when the odor solution alone was released, and at the beaker opening when the attractant solution was expelled through the CO₂ hydrate.

The above procedure was repeated at the second study site without measurements of pH. To avoid attracting the same animals, the replicate experiment was conducted after the ROV and release rig were moved approximately 100 m from the first site in a cross-current direction.

3. Results and discussion

Seawater at the 625-m study sites in Monterey Canyon had pH values of 7.6. The pH at the opening of the inverted beaker dropped to 7.2 due to release

of the fish odor solution alone (Fig. 2). A pH of 7.2 is however well above the levels known to influence aquatic organisms (Morris et al., 1989). During both experiments, several animals moved towards and accumulated near the odor source (Fig. 3). Various species of fish (Sablefish, *Anoplopoma fimbria*; Hagfish, *Eptatretus stouti*; Dover Sole *Microstomus pacificus*) and invertebrates (urchin, *Allocentrotus fragilis*; gastropod, *Neptunea amianta*) were seen following the odor plumes to the release rig.

While the invertebrates crawled slowly to the odor source, all fish species swam quickly up the plume center or zigzagged and cast through plume edges as they moved up stream. These patterns of turning and movement up stream were identical to the odor tracking behavior of other flying and swimming animals, which has been characterized as longitudinal klinotaxis (Vickers and Baker, 1994; Finelli et al., 1999; Tamburri et al., in preparation).

After the CO₂ hydrate was formed, pH at the beaker opening decreased to 5.6 (Fig. 2). Surprisingly, however, the total number of animals near the release rig increased in both experiments (Fig. 3). Rather than the dissolving hydrates repelling mobile animals, individuals continued to accumulate near the odor source at a fairly constant rate (approximately one animal every 5–10 min) without any noticeable change in search behavior. These results resemble the anecdotal observation by Brewer et al. (1999) that animals at depth of 3627 m swam, apparently unharmed, within several centimeters of liquefied CO₂ pooled on the seafloor.

The dissolving CO₂ hydrate did, however, dramatically lower the pH of the odor solution exiting the inverted beaker. Although the acidic solution was mixed by turbulence and diluted with the ambient seawater, small distinct patches or eddies were likely encountered by individuals following the odor plume. Turbulent diffusion does not produce smooth concentration gradients at the spatial scales of macroscopic organisms (Zimmer-Faust et al., 1988; Moore et al., 1992). In fact, some animals gain information about the location of an odor source from pulses or filaments of concentrated chemical signals (Moore and Atema, 1991; Vickers and Baker, 1992). It is therefore likely that animals drawn to the release rig after hydrates were formed responded to strong, low pH odor signals.

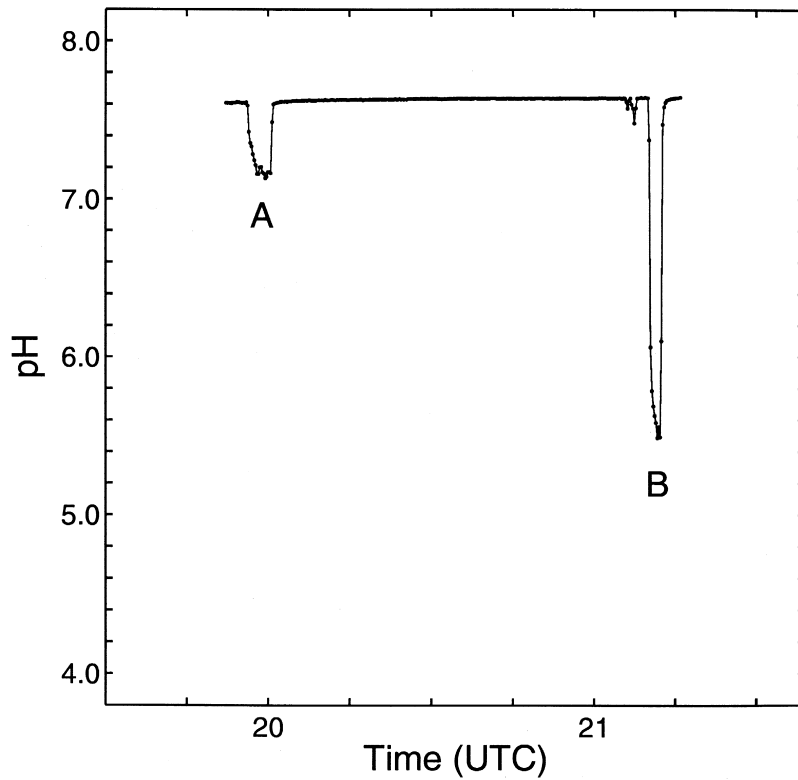


Fig. 2. pH profiles of seawater, at 625-m depth within Monterey Canyon, obtained from the ROV mounted pH electrode. (A) Designates when the electrode was placed at the opening of the inverted beaker as the odor solution was being released. (B) Designates when the electrode was placed at the beaker opening as the odor solution was being released through the flocculent CO_2 hydrate.

These results demonstrate that mobile animals may not necessarily avoid regions of low pH and high $p\text{CO}_2$. The assumptions made in previous models of the biological effect of CO_2 ocean disposal (Auerbach et al., 1997; Caulfield et al., 1997) were based on published work that many aquatic animals are unwilling to enter acidic waters (e.g., Jones, 1948; Portmann, 1970). However, to our knowledge, none of these previous studies attempted to attract animals to pH environments that may cause harm. Thus, a potentially large impact of ocean CO_2 disposal may have been overlooked in these earlier estimates of mortality.

Most animals associated with the deep-sea floor exploit carrion or detritus for at least part of their nutritional needs and contribute significantly to the rapid clean up and processing of organic material (Issacs and Schwartzlose, 1975; Jumars and Gallagher, 1982; Priede et al., 1991). Deep-sea scav-

engers, in particular, are well adapted to quickly locate food falls using chemical signals (Tamburri and Barry, 1999) and may thus be attracted to dis-

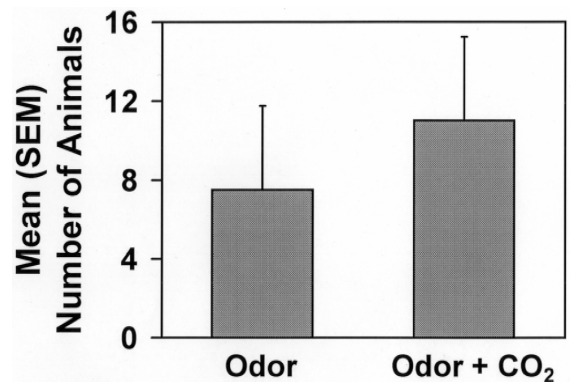


Fig. 3. Mean and standard error of the total number of animals attracted to the release rig by the odor solution alone and by the odor solution with a CO_2 hydrate present.

positional sites if detritus and carrion collects from above or if passive and sessile organisms are killed once disposal begins. It is conceivable that biological losses can extend far beyond initial impact on immobile organisms if scavengers attracted from outside disposal sites (by the scent of recently deceased organisms) are themselves adversely affected.

Both low pH and high $p\text{CO}_2$ can have detrimental effects on many aquatic animals. In addition to behavioral changes, stress, and mortality (e.g., Knutzen, 1981; Morris et al., 1989; Lorenz and Taylor, 1992), low pH solutions (commonly ≤ 5.8) can also destroy chemosensory systems (Hara, 1976; Allison et al., 1992). Whereas, hypercapnic conditions often lead to acidosis in the blood of animals that can cause increased susceptibility to infections (Dwyer and Burnett, 1996), reductions in growth rates and an overall decrease in population sizes (see review by Burnett, 1997).

Although our field study was unable to address the consequences of chronic exposure to low pH and high $p\text{CO}_2$ on mobile deep-sea animals, we did gain valuable insight on an important short-term effect after one hagfish entered the beaker containing a CO_2 hydrate. The animal quickly (< 5 s) lost consciousness, sank to the bottom, and rolled over on its dorsal side. After approximately 20 s, the hagfish recovered and resumed tracking the odor plume back to the release rig. Twice more the same individual approached and entered the beaker, then lost consciousness. In all instances, the hagfish appeared to recover and resumed swimming only after it rolled down stream, away from the dissolving hydrate. Presumably, more animals did not enter the inverted beaker because the opening was elevated approximately 25 cm above the substrate. All species seen in our study were either restricted to crawling on the bottom or are known to explore the seafloor exclusively (strongly geotactic) when searching for food (Tamburri and Barry, 1999; Tamburri, et al., in preparation).

This observation suggests that the hagfish was affected by a large increase in $p\text{CO}_2$ rather than a low pH. Low pH solutions, in the range studied (5–6), can clearly influence most aquatic organisms but the effects are seen as avoidance in the short term (e.g. Portmann, 1970) or toxic ionic imbalances after long-term exposure (see review by Morris et

al., 1989). The narcotic effect we observed appears most likely to be a result of respiratory distress (reduced O_2 carrying capacity of blood) caused by elevated seawater $p\text{CO}_2$ (Burnett, 1997). It has long been known that aquatic organisms can be anaesthetized by raising CO_2 concentrations of surrounding water (Fish, 1942; Post, 1979). However, if individuals are not removed from the high $p\text{CO}_2$ conditions, low blood oxygen levels will eventually lead to death. Because it is unlikely that animals will be swept to safety after entering extensive regions of high $p\text{CO}_2$ under some industrial scale disposal scenarios, the risk of mortality may be very high.

The extent of changes to surrounding seawater chemistry, and thus biological impact, is largely dependent on the method of CO_2 release. As described in Brewer et al. (2000), there are different types of hydrate that can be formed when disposing of CO_2 on the deep-sea floor. One type is when liquid CO_2 is pushed rapidly into the seawater. In this case, the turbulence caused by rapid injection results in the so-called flocculent hydrate that is not pure hydrate but the mixture of hydrate and liquid CO_2 . Due to the very large interfacial area per unit volume or high chemical activity, this mixture dissolves rapidly, which dramatically lowers the pH of surrounding seawater. Another type is the plane hydrate membrane that appears on the interface between liquid CO_2 and seawater. This occurs when liquid CO_2 is introduced into seawater slowly or introduced into a large CO_2 mass (e.g., a stored CO_2 lake). In this case, the dissolution rate may be so slow that the pH of the seawater close to the hydrate membrane is almost the same as the ambient level (Brewer et al., 2000; Yamane et al., in preparation). While losses of some marine life are unavoidable in all disposal scenarios, it is likely that the slow release of liquid CO_2 will have less impact on benthic deep-sea organisms than the flocculent hydrates studied here. Similarly, Adams et al. (1997) suggested that zooplankton mortality would be minimized in midwater disposal scenarios if the CO_2 were released in dilute concentrations and over large areas.

4. Conclusion

Our knowledge of deep-sea ecosystems is, in general, limited. However, benthic communities have

been identified as a critical component in the decomposition of organic matter and in the production of nutrients necessary for the growth of primary producers (Gage and Tyler, 1991; Smith, 1992). Destruction of deep-sea benthic environments by the disposal of CO₂ might therefore lead to declines in primary production, causing an overall reduction in the biomass of higher organisms (Shirayama, 1995). The results of our current study also suggest that CO₂ disposal as hydrates on the seafloor may significantly reduce abundances of higher organisms directly.

The deep sea is high in diversity with species uniquely adapted to little or no light, low temperatures, and high pressures (Rex, 1983; Gage and Tyler, 1991). Therefore, many organisms not only grow and reproduce slowly but are also endemic to these extreme environments. Removal of such organisms can result in delayed recovery or collapse of many populations and potentially the loss of distinct genetic information.

Oceans are clearly an integral component in global processes. However, we still do not understand completely all the complex physical, chemical, and biological factors that regulate marine systems and how they interact. Any dramatic, large-scale changes made to these systems must therefore be done with extreme caution. While many questions still remain on the biological effects of CO₂ disposal in the sea, we can conclude that: (1) mobile deep-sea animals do not necessarily avoid discharge sites, (2) both low pH and high pCO₂ can adversely affect deep-sea animals, and (3) the depth and method of CO₂ release (fast versus slow injection) is important in determining the extent of detrimental changes to marine environments.

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