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Research progress in artificial upwelling and its potential environmental effects

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Abstract Artificial upwelling, as a geoengineering tool, has received worldwide attention because it may actualize ocean fertilization in a sustainable way, which could potentially alleviate the pressures on the fish stocks and human-driven climate change in the ocean. We reviewed the current knowledge on the development of an artificial upwelling system and its potential environmental effects. Special attention was given to the research progress on the air-lift concept artificial upwelling by Zhejiang University. The research on artificial upwelling over the past few decades has generated a range of devices that have been successfully applied in the field for months. Based on field experiments and the associated modeling results, part of them reported positive effects on increasing primary production and enhancing CO_2 sequestration. However, as a significant disturbance to the environment, especially for large-scale applications, the uncertainties related to the potential effects on ecosystem remain unsolved. Zhejiang University has overcome the technical challenges in designing and fabricating a robust and high efficiency artificial upwelling device which has been examined in two field experiments in Qiandao Lake and one sea trial in the East China Sea. It was investigated that cold and hypoxic deep ocean water (DOW) could be uplifted to the euphotic layer, which could potentially change the nutrient distribution and adjust the N/P ratio. Both simulation and field experiments results confirmed that utilizing self-powered energy to inject compressed air to uplift DOW was a valid and efficient method. Therefore, further field-based research on artificial upwelling, especially for long-term field research is required to test the scientific hypothesis.

Keywords Artificial upwelling, Air-lifting, Self-powered, Environmental impacts, Research progress

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1. Introduction

The world's rapid population growth has increased the great pressures and concerns on ocean fish stocks and human-driven climate change. If large-scale ocean fertilization could be achieved in a sustainable way, the rate of photosynthesis would be stimulated which could probably alleviate both of problems (Lovelock and Rapley, 2007; Kirke, 2003).

In most oceans, primary production is limited by the availability of the macro-nutrients (e.g. N, P or Si) or essential micro-nutrients (e.g. Fe) (Sakka Hlaili et al., 2006; Arigo, 1999; Leinen, 2008). Artificial upwelling could bring cold, nutrient-rich, deep ocean water (DOW) to the euphotic zone, which could not only increase the total nutrient concentrations, but also adjust the N/P/Si/Fe ratio to a reasonable value. Thus, the rate of photosynthesis of phytoplankton could be stimulated, which may consequently increase the marine fish productivity and enhance the export of organic carbon to the deep ocean, via the biological pump, in a sus-

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*Corresponding author (email: ychen@zju.edu.cn) tainable way (Lovelock and Rapley, 2007; Kirke, 2003). Therefore, artificial upwelling is considered to be one of the promising geoengineering tools that could stimulate the Earth's capacity to cure itself (Lovelock and Rapley, 2007; Williamson et al., 2012). In addition, it was suggested to have the potential to reduce the hypoxia and cool the surface water, which on a large scale, could prevent the formation of typhoons, or at least reduce their severity (Kirke, 2003).

In light of the fuel shortages and rising fuel prices of the 1970s, ocean thermal energy conversion (OTEC), which is a method of turning solar energy into electricity using the temperature differences between cooler, deep water and warmer, shallow water, has become a research focus. Jacques Arsene d'Arsonval is the first to propose tapping the thermal energy of the ocean in 1881 (Day and McNeil, 2003). So far, there are many operating OTEC plants all over the world (Meyer et al., 2011). However, due to the low efficiency of power generation and the high capital and operational costs, the commercial application of OTEC has not yet been actualized. It was suggested by Liu and Jin (1995) that if the utilization of DOW to promote open ocean mariculture was successful, the feasibility of OTEC commercialization would be enhanced. However, the ocean mariculture may be a by-product of the OTEC project, the primary purpose of artificial upwelling is to pump nutrient-rich DOW to the surface to feed phytoplankton which differs from to generate continuously available energy proposed by OTEC. Therefore, the key technologies, the average investment sizes, the environmental assessments and the performance characteristics of the OTEC and artificial upwelling are distinct from one another.

Artificial upwelling attracts increasing attention worldwide due to its potentially positive effects. The severe challenges of artificial upwelling are the design and fabrication of a technologically robust device with structural longevity which can maintain the function in the variable and complex hydrodynamics of the upper ocean. Artificial upwelling research over the past few decades proposed a range of devices that were able to bring DOW up to the euphotic layer. The associated features, advantages and disadvantages of different types of artificial upwelling devices are summarized in Table 1. Some of these devices were potentially self-powered and have been successfully operated for months.

2. Overview of the artificial upwelling studies and experiments

Uplifting a large amount of DOW to the surface or near surface layer requires a massive energy supply, which partly causes its high costs. Therefore, research on artificial upwelling systems mainly focused on the following two aspects: increasing the uplifting efficiency and using renewable energy.

2.1 Study on artificial upwelling in the US

Isaacs et al. (1976) first proposed the use of wave energy to pump deep, nutrient-rich water to the euphotic layer. The

Table 1 Types of artificial upwelling

Type	Description	Advantages	Disadvantages
Wave-pump (Vershinskiy, 1987; Liu and Jin, 1995; White et al., 2010)	Extracts energy from the surface gravity waves to draw DOW	(1) Test in north of Oahu, Hawaii in June 2008; and (2) Self-powered	Pump fails after < 2 h
Electrical pump (Ouchi et al., 2005; Mizumukai et al., 2008; Masuda et al., 2011)	Uses a high power electrical pump to draw DOW	(1) Operated in Sagami Bay from 2003; (2) Robust technology and longevity structure; and (3) Large amount of uplifted DOW	Low efficiency and extremely high cost
Perpetual salt fountain (Tsubaki et al., 2007; Maruyama et al., 2011)	Uses salinity and temperature differences between layers of the DOW and the euphotic to draw DOW	(1) Test in the Mariana area of the tropical Pacific Ocean in 2002; (2) Higher Chl *a* was detected around the pipes; and (3) Self-powered	Low amount of uplifted DOW to support an ocean farming project
Brackish water uplift pump (Aure et al., 2007; McClimans, 2008; McClimans et al., 2010)	Pumps down low density brackish water to uplift DOW of the same depth	(1) Test in a western Norwegian fjord from May to September in 2004 and 2005; (2) Enhancing and adjusting the nutrient concentration and the N/P ratio; and (3) Chl *a* tripled, diatom biomass increased in a large extent within an influence area of 10 km^2	Lower efficiency compared to air-bubble and air-lift pump and limited applied region
Air-bubble pump (McClimans et al., 2010; Handå et al., 2013)	Pumps air through a horizontal pipe to uplift the DOW to a certain depth	(1) Tested in inner part of Arnafjord in September 2002; (2) High efficiency with an DOW to air supply of > 88[a]; and (3) Expected biological and biogeochemical responses of sea trials	Limited uplifting DOW depth
Air-lift pump (Liang and Peng, 2005)	Injects compressed gas in the pipe to uplift DOW from deeper depths	High efficiency with an DOW uplift to air supply approximately 100 m^3/min DOW	No sea trial data to date

a) An air supply of 1 m^3/min could uplift > 88 m^3/min.

major motivation behind the concept of the Isaacs wave pump is to extract energy from the surface gravity waves in the ocean. Theoretical performances of a wave pump for artificial upwelling were evaluated by Vershinskiy (1987) assuming the device operated following a sinusoidal ocean surface. It was suggested that the upwelling capacity of the wave pump was a function of the amplitude and frequency of waves, as well as the dimensions and efficiency of the individual pump. Liu and Jin (1995) described a similar wave-driven artificial upwelling device, which consisted of a buoy and a vertical long pipe with a one-way valve. The way it was hinged allowed the valve to open on the downslope of a wave and to close on the upslope, causing the DOW to rise up (Figure 1). The performance of the device was evaluated in both regular incident waves and random incident waves. Liu and Jin (1995) estimated that in the condition of 1.90 m wave height and 12 s a wave period, the flow rate would range from 0.45 to 0.95 m^3/s.

In June 2008, a commercially available wave pump (Atmocean) was tested in the north of Oahu, Hawaii by White et al. (2010) (Figure 2). In the experiment, the deployment methods and the durability of the equipment under open

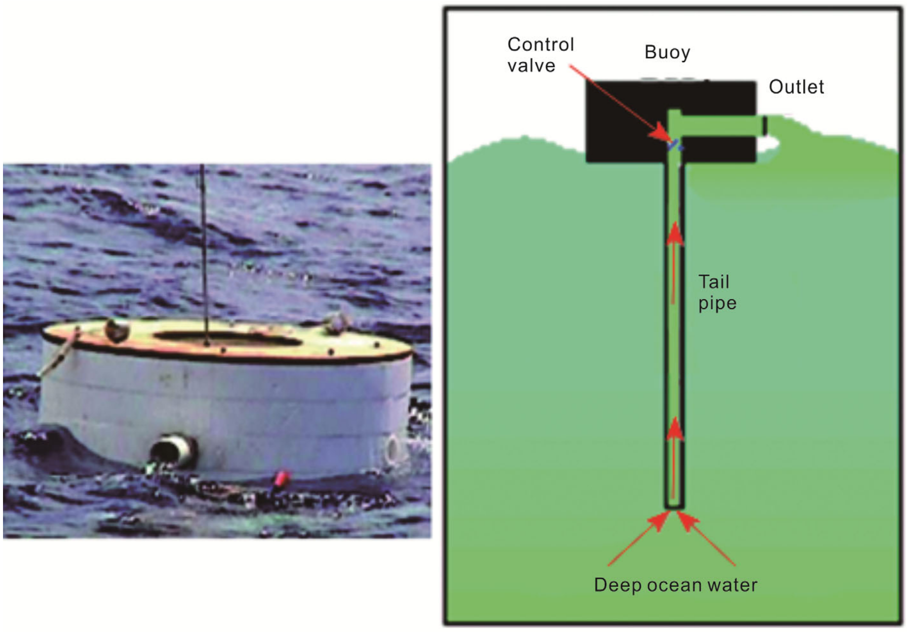


Figure 1 Diagram and sea trial picture of a wave-driven artificial upwelling device (Liu and Jin, 1995).

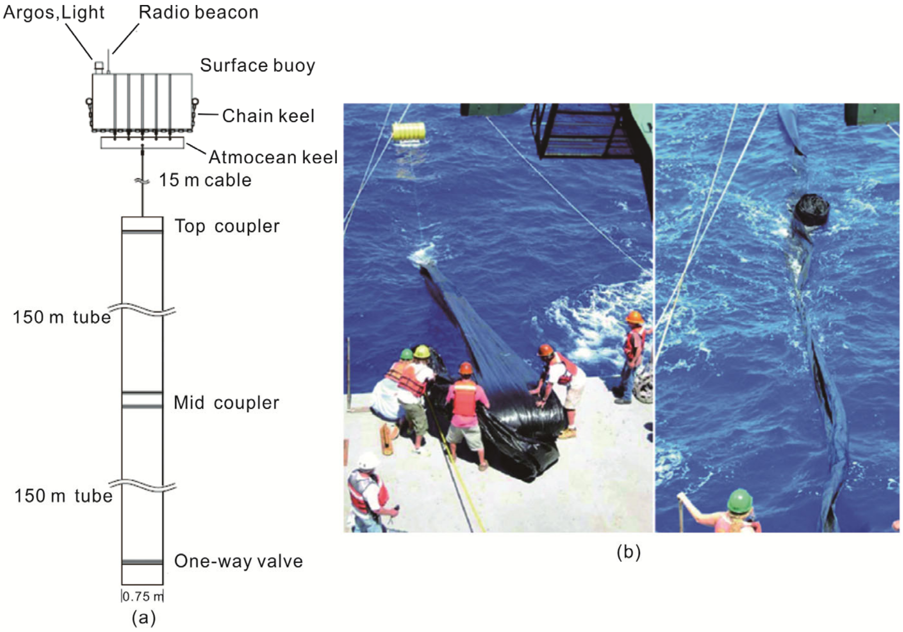


Figure 2 Diagram and sea trial pictures of Atmocean deployed in the north of Oahu, Hawaii. (a) The components and configuration of the wave pumps; (b) image of the deployment of the single pump (White et al., 2010).

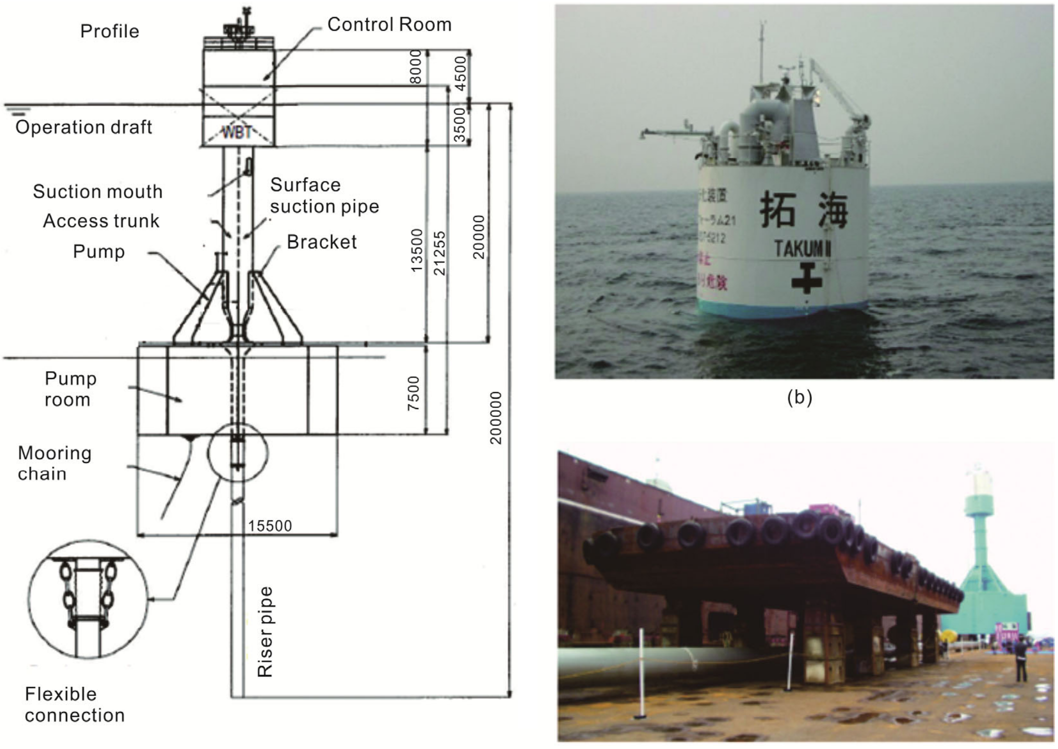
ocean conditions were tested. The scientific hypothesis that a two-phased, phytoplankton bloom would be generated by upwelling an excessive Redfield phosphate (P) to nitrogen (N) ratio in DOW, was also prepared to be evaluated. Unfortunately, the catastrophic failure of pump materials occurred within 2 h. During that period, it was estimated that total input of 765 m^3 of nutrient-enriched DOW was transported by wave-driven upwelling, and the cold water was documented for about 17 h after uplifting. Although the rapid delivery of DOW was transported to the surface ocean by 300 m pipes during the experiment, the end result was only partially successful.

2.2 Study on the artificial upwelling in Japan

The world first artificial upwelling experiment in the open ocean, named “HOYO”, was conducted in the Japan Sea in 1989 and 1990 (Ouchi et al., 2005). Approximately 26000 t/day DOW was reported to pump up from a depth of 220 m. However, due to the high density of the DOW, it easily sunk down and went out of the euphotic zone. Thus, a new prototype of an ocean nutrient enhancer, named “TAKUMI”, was developed with a density current generator to minimize the sinking problem. TAKUMI was installed in the Sagami Bay in May 2003 (Figure 3). It was designed as a huge floating device of 32 m in height and 16 m in width. The steel riser pipe is about 175 m in length and 1.0 m in diameter with an electrical pump of great power. TAKUMI was operated for more than 2 years without serious damage. Approximately 100000 t/day of 200 m DOW could be pumped up, which would be mixed with 200000 t/day of 5 m water before being discharged at 20 m depth.

Lagrangian observation was made by Masuda et al. (2011) using a drifting buoy to track a subsurface discharging plume. *In-situ* measurements and continuous water samplings were carried out following the buoy trajectory of the discharging water for 63.9 h. Micromolar concentrations of nutrients and high chlorophyll a (Chl *a*) were reported in the discharging layer. However, the active growth of picophytoplankton and nanophytoplankton, rather than diatoms, was observed in the subsurface, which was attributed to the low light availability. The main obstacles to prevent the large scale applications of TAKUMI are the low efficiency in energy consumption, and the high construction and maintenance expenses.

The other research interest in artificial upwelling in Japan is the perpetual salt fountain concept system, which utilizes salinity and temperature differences between the DOW layer and the euphotic layer to draw up DOW without an extra energy supply. The perpetual salt fountain concept was first proposed by Stommel et al. (1953), which only required long pipes with a buoy that could vertically floating between the euphotic layer and the intermediate low salinity layer. Because the drawn up DOW would be heated during its flow up through the pipe and become almost the



(a) (b) (c)

Figure 3 Ocean nutrient enhancer “TAKUMI”. (a) A schematic diagram of TAKUMI, the unit is mm; (b) photograph of TAKUMI in operation; (c) photograph of TAKUMI in final docking (Ouchi et al., 2005).

same temperature as the surrounding water, it could remain on the discharging layer. Buoyancy would be created in the pipe and the upwelling flow would continue as long as the differences of the temperature and salinity existed. Thus, the nutrient-rich DOW could be drawn up continuously and energy free after the initial filling of DOW in the pipes by a pump (Tsubaki et al., 2007).

To verify the feasibility of the concept, the Laputa project was tested by Maruyama et al. (2004) in the Mariana area of the tropical Pacific Ocean in 2002, using a flexible plastic pipe that was 280 m in length and 0.3 m in diameter (Figure 4). Another open sea experiment was also conducted in 2005, with a pipe of 300 m in length and 0.5 m in diameter (Maruyama et al., 2011). The flow rate with a single pipe was estimated to increase from 2.5 to 7 mm/s. Maruyama et al. (2011) reported that the Chl *a* concentration observed was much higher than that in the surrounding seawater, and it was measured by both an *in-situ* Chl *a* sensor and the color sensors via satellite over 30 days. The results of the sea trials indicated that the salt fountain concept artificial upwelling could be energy free, which made it one of the ideal ways to enhance the nutrient concentration in the euphotic layer. However, according to the simulation results by Zhang et al. (2004) and Williamson et al. (2009), the transport of nutrient-rich DOW from an artificial upwelling pipe would be maintained at approximately 0.1% of their inlet concentration in a 6 m diameter plume. The amount of uplifted DOW seemed to be too small to sustain the minimum nutrient concentration requirements of an ocean farming project.

2.3 Study on the artificial upwelling in Norway

Fjords of western Norway are thought to have a large potential for growing blue mussels. However, from June to September, the water in the fjords is strongly stratified and the brackish surface waters become depleted of nutrients. Subsequently, toxic dinoflagellates were increased to kill the mussels via food web. Artificial upwelling is proposed as one of the promising methods that could create a non-toxic algae favoring environment by enhancing the nutrient concentration and adjusting the N/P ratio during the summer season (McClimans et al., 2010).

Large-scale artificial upwelling experiments were conducted in the western Norwegian fjord from May to September in 2004 and 2005 (Aure et al., 2007). Surface brackish water was pumped down through a vertically mounted pipe of 1.25 m in diameter. An outflow of 2 m^3/s was produced from a depth of 30 m, transporting N, Si, P at the rate of 450, 760 and 75 kg/day, respectively. During the experiment, the mean Chl *a* concentration tripled within an influence area of 10 km^2 near the head of the fjord and the diatom biomass increased from approximately 4% of the total phytoplankton biovolume to 85%.

Another technique used in Norway was the air-bubble screen. A bubble curtain experiment was conducted in the inner part of Arnafjord in September 2002 (McClimans, 2008; McClimans et al., 2010), with three parallel, perforated air pipes (100 m in length) at depth of 40 m (Figure 5). Approximately 44 m^3/min air at normal pressure was pressed and popped through 300 holes to produce the buoyancy flux. During the 21 day experimental period, nutrient-rich DOW was transported up to the near surface layer of 4–17 m in depth. Although the concentrations of N and P remained low in the surface layer, the dissolved Si concentration increased in a large scale. A local reduction in the stratification close to the upwelling zone was generated, where the biomass of non-toxic algae increased significantly and the growth of the toxic algae reduced completely (McClimans et al. 2010; Handå et al., 2013).

2.4 Study on the artificial upwelling in Taiwan

An air-lift pump for upwelling DOW with high efficiency

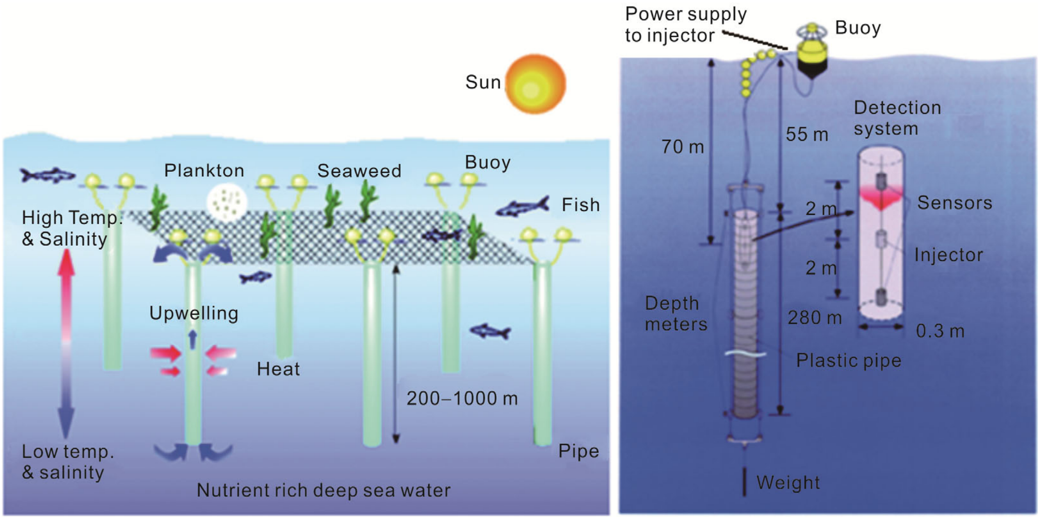


Figure 4 Diagram of the Laputa project and its experiment apparatus (Maruyama et al., 2004).

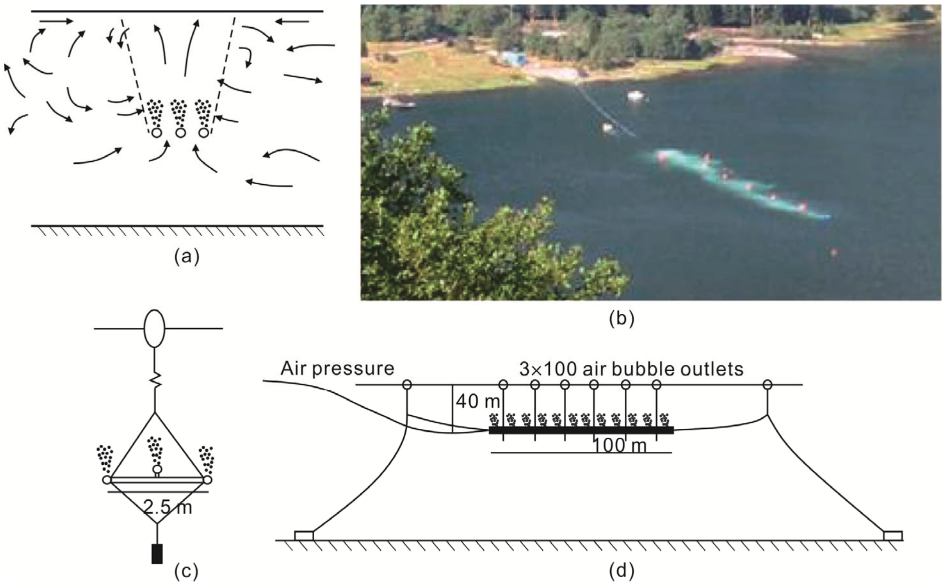


Figure 5 Diagrams of bubble curtain artificial upwelling in Arnefjord. (a) Cross-section of the induced circulation; (b) view from the mountain side; (c) cross-section of the construction; (d) suspension scheme (McClimans et al., 2010).

was first proposed by Liang and Peng (2005) in Taiwan. The air-lift pump is a simple pump that is powered by compressed gas, usually air. After injecting the compressed gas in the lower part of a pipe, the gas bubbles are suspended in the water, which makes the average density of the two-phase mixture in the pipe less than the surrounding fluid. Thus, by fluid pressure, the liquid would be taken into the ascendant air flow and moved in the same direction as the air. Modeling results suggested that the seawater flow rate could be a hundred times higher when compared to the air flow rate. However, no open sea experimental data of the air-lift artificial upwelling were found in the literatures.

3. Potential environmental effects

3.1 Nutrient supply and marine production

The transport of nutrients and the increase of phytoplankton production were reported in some of the successful artificial upwelling sea trials. It seems that the life-time of artificial device in operation is the key to determine whether the expected biological and biogeochemical responses could be observed. No obvious increase in nutrients or Chl *a* was observed in the open sea trial of a commercially available wave pump (Atmocean) in 2008, which collapsed after 2 h of continuous work (White et al., 2010). In the sea trial of TAKUMI, nutrient concentrations of the discharging water mass increased to a micromolar magnitude and Chl *a* doubled after about 34 h (Masuda et al., 2011). The enhancement of nutrients and Chl *a* in the euphotic layer sometimes could not always be observed simultaneously in some successful open sea experiments. In the open sea trial of the perpetual salt fountain driven artificial upwelling in the Philippines Sea, high Chl *a* was observed at the outlet of a 300 m pipe over 30 days. Due to the extremely low flow rate of the upward pumping, the enhancement of nutrient concentrations in the discharging layer could not be achieved and was not observed (Maruyama et al., 2011).

How to keep the high density DOW within the biologically productive area in the open ocean without the occurrence of significant dilution has become another research interest in artificial upwelling. To prevent the quick sinking phenomena, TAKUMI added a density current generator that could help adjust the density by mixing the high-density DOW with low-density surface seawater before discharging (Ouchi et al., 2005). Numerical models that predicted the distribution of uplifted flow in the pipe and the trajectory after it left the pipe suggested that the discharge parameters could be controlled with proper engineering designs (Liu and Jin, 1995). Zhang et al. (2004) developed a model to predict the induced flow in upwelling DOW using a perpetual salt fountain. Williamson et al. (2009) simulated the transport of nutrient-rich DOW from an artificial upwelling pipe and found that the nutrient levels would be maintained at approximately 0.1% of their inlet concentration in a 6 m diameter plume initiated about 10 m downstream of the pipe outlet, which was too small to sustain the minimum nutrient concentration requirements of an ocean farming project. A mathematical model to simulate the discharging DOW's trajectory and concentration distribution was reported by Fan et al. (2015). It was suggested that to make the plume trapped at the density interface and form the concentration of DOW at the far-field up to 22%, an optical discharge nozzle height could be calculated according to the regional surface current speed, pumped water flow rate and pipe diameter using a newly deduced mathematical model.

3.2 Carbon sequestration and hypoxia reduction

The most important reason why artificial upwelling is treated as one of the geoengineering tools and attracts increasing scientific and policy interests is its potential to counteract the accumulation of anthropogenic CO_2. It was proposed that nutrient-rich DOW brought to the euphotic layer could stimulate the growth of phytoplankton on a scale large enough to significantly increase the uptake of atmospheric CO_2 by the ocean. Therefore, the portion of the organic carbon that sinks out of the surface layer into the deep ocean, where it can be kept long enough to provide a climatic benefit, would be greatly increased. However, the uplifted DOW also contains a high concentration of inorganic carbon, which directly enhances the surface partial pressure of CO_2 ($p$$CO_2$). Balance between these two opposite effects should be taken into account when investigating the carbon dynamics of an artificial upwelling area (Chung et al., 2012).

Acquiring the CO_2 sequestration effect by artificial upwelling is important, but difficult. Reliable estimates of the CO_2 sequestration effect need to account not only for the amount of carbon initially fixed by the phytoplankton growth but also for the CO_2 time-series variation from long-term monitoring, which may require measurements at the scale of thousands of square kilometers in the open sea and over several months. No *in-situ* measurements of the carbonate parameters have been reported to date that can tell whether the contribution of artificial upwelling on carbon sequestration is negative or positive.

Model-based estimates of the CO_2 sequestration effect showed major uncertainties on whether net CO_2 drawdown is achievable (e.g., Yool et al., 2009; Lenton and Vaughan, 2009; Williamson et al., 2012; Bauman et al., 2014; Keller et al., 2014). There are major doubts concerning the extremely small proportion of upper ocean production reaching the deep sea. As the high CO_2 concentration DOW is pumped up, it would release CO_2 from previous cycles of production/export and sinking/decomposition (Schiermeier, 2007). Under the most optimistic assumptions, artificial upwelling estimated by Oschlies et al. (2010) had the potential to sequester atmospheric CO_2 at a rate of approximately 0.9 PgC/yr, which was almost half of the CO_2 uptake rate of the global open ocean (Takahashi et al., 2009). However, 90% of the sequestered atmospheric CO_2 was stored terrestrially, due to lower global temperatures and decreased respiration. Dutreuil et al. (2009) reported a large increase in the amount of organic carbon exported from surface waters by artificial upwelling; however, the total ocean to atmosphere CO_2 flux was estimated to increase. Yool et al. (2009) examined the consequences of deploying a large number of floating "pipes" in the ocean and suggested that, although the primary production would be generally enhanced as expected, the effect on the uptake of CO_2 from the atmosphere was much smaller and even negative. Keller et al. (2014) indicated that the atmospheric CO_2 concentration could be slightly reduced by artificial upwelling; however, the amount was too small to be compared with the expected, business-as-usual anthropogenic emissions. In addition, the effect on carbon sequestration showed considerable spatiotemporal variability. Similar spatiotemporal variation of CO_2 sequestration was also reported by Pan et al. (2015). It was also indicated that the appropriate technical parameters of the artificial upwelling device that suit the applied region and season would greatly affect the CO_2 sequestration efficiency (Pan et al., 2015).

Reducing the hypoxia is another potential positive impact of artificial upwelling, although, simulation results based on different models conflict with each other. In a semi-enclosed bay, the simulation results indicated a reduction of up to 70% of oxygen-deficient water could be achieved (Mizumukai et al., 2008). It was reported by Keller et al. (2014) that the volume of the oxygen minimum zones would be reduced by the application of large-scale artificial upwelling, but the mean ocean oxygen concentration would also be decreased. However, Moore et al. (2013) suggested that while the mean ocean oxygen concentration declined, the volume of the oxygen minimum zones also increased, which attributed to deoxygenation, another undesirable and potential side effect of artificial upwelling. Theoretically, pumping DOW to the surface layer could break the stratification phenomena and increase the convection effect, which help increase the oxygen levels in deep water. Meanwhile, fertilization induced organic matter demands more oxygen to decompose, which would decrease the oxygen level in water column. There is no *in-situ* data that could tell whether the oxygen level was increased or decreased by artificial upwelling, or to provide information regarding the dynamic patterns of oxygen in the applied sea.

3.3 Side effects of artificial upwelling

Concerns about undesirable or uncertain impacts caused by the large-scale application of artificial upwelling are discussed with its potentially positive effects, including aggravation of acidification and the disturbance of upper and seafloor ocean ecosystems. The acidification of oceanic environments due to the increase of atmospheric CO_2 is already a serious threat to ocean life. Because decreased pH can alter the carbonate chemistry by reducing the concentration of carbonate ions and the associated saturation states, marine invertebrates that build calcium carbonate structures, such as shells and skeletons, will face critical survival threats (Gao et al., 2009; Gaylord et al., 2011; Bechmann et al., 2011). As the low pH value of DOW is uplifted and mixed with surface seawater, the surface acidification problem would likely be exacerbated. Keller et al. (2014) indicated that artificial upwelling would decrease pH up to 0.15

units beyond the present trajectory, which may cause potentially negative impacts on calcium carbonate structure dependent marine organisms.

In addition, to increasing the total primary production and the biomass, the abundance of different species would be inevitably changed, although some of these species are considered to be the aim of the artificial upwelling (Aure et al., 2007; McClimans et al., 2010). As the nutrient fluxes are brought up by artificial upwelling, communities that favor oligotrophic environment would change to eutrophic, and the phytoplankton community would shift toward larger cells. When a larger proportion of the carbon flux reaches the seafloor, it is likely to increase the amount of seafloor biomass and change the balance among different organisms. It is still uncertain whether the effect on the seafloor biodiversity is positive or negative. In addition, the uplifted nutrient rich DOW may significantly alter the concentration and composition of settled organic matters on the seafloor, which would either cause the suppressed development of marine organisms, due to the limited nutrients, or the stimulation of metabolism activities, due to fresh organic matter input and the dissolved organic material exchange (Weikert, 1977; Aspetsberger et al., 2007).

Therefore, artificial upwelling that may probably cause a measurable reduction in atmospheric CO_2 would surely be a major disturbance to the structure of the regional ocean ecosystems, affecting the seafloor, the ocean interior and the upper ocean. Such risks must be thoroughly assessed prior to engaging in large-scale geoengineering application, which requires more efforts due to the complexity of ocean dynamics (Williamson et al., 2012; Bauman et al., 2014; Keller et al., 2014).

4. Focus on the artificial upwelling research by Zhejiang University, China

Research on the air-lift concept artificial upwelling driven by self-powered energy was conducted by Zhejiang University since 2010. This research mainly focused on designing a robust and high efficiency artificial upwelling system. The aim of this project was to utilize the high efficiency air-lift upwelling to uplift deep-sea water to the euphotic layer and keep it in a relatively high concentration plume without an external power supply. Gas collection and compression were achieved by employing renewable energy. The compressed gas was then injected into the upwelling tubes at certain depths. Research on the theoretical analysis of build-up models, considering the flow characteristics of air-lift artificial upwelling, suggested that the pump capacity and efficiency were functions of the geometrical parameters of the upwelling pipe, air volume flow rate, air injection method and vertical distribution of water density (Meng et al., 2013; Fan et al., 2013, 2015). The experimental results confirmed that the upwelling efficiency increased with the increase of the pipe diameter and the water volume flow rate vs. air volume flow rate could reach 40, which was close to the simulation results (Figure 6) (Fan et al., 2013).

Because self-powered technology makes it possible to apply an artificial upwelling system far away from the shore, the energy demand to assure the feasibility and sustainability of an artificial upwelling system was also studied at Zhejiang University. Wave energy conversion is a quite feasible way to supply the power for air-lift artificial upwelling. A 1/64th scale prototype of multi-axis wave energy converter (WEC) and a 1/64th scale prototype of single-axis point absorber WEC were tested in the sea trail, and the overall concept was verified. Zhang et al. (2013) suggested that when multiple directions of motion were involved, the multi-axis WEC was proven to be able to supply more power generation than a single axis WEC (Figure 7). Moreover, a distributed generation system composed of a photovoltaic array, wind turbines, a wave energy converter array and a conventional diesel generator were constructed, installed and deployed as the power supply for air-lift artificial upwelling. With the distributed generation system, it was feasible to keep an artificial upwelling system working for a long duration, without the restrictions of

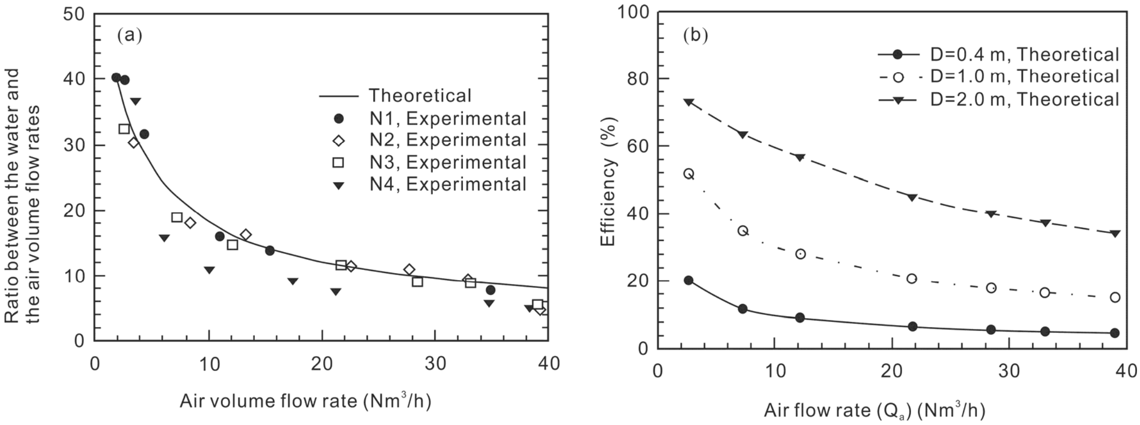
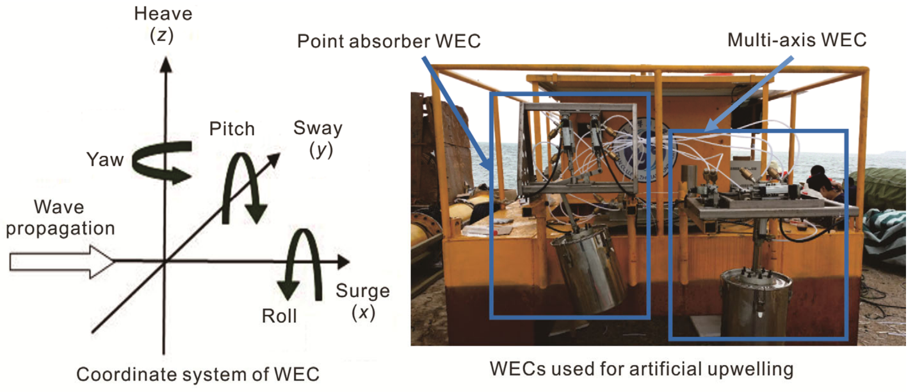


Figure 6 Comparison between the theoretical and experimental results (a) and variations of theoretical upwelling efficiency with air flow rate for different pipe diameters (b).



Coordinate system of WEC

WECs used for artificial upwelling

Figure 7 WECs used for artificial upwelling (Zhang et al., 2013).

time or place, even in an unmanned station. From that point of view, the distributed generation system was better than the single energy supply system such as the wave energy conversion.

Two field experiments in Qiandao Lake (29°33′51″N, 119°11′9″E) and one sea trial in the East China Sea (30°8′14″N, 122°44′59″E) were performed in September 2011, December 2012 and September 2014, respectively. Figure 8 shows the schematic diagram of the experimental set-up with the air-lift pumping system. The Qiandao Lake test area was 100 m^2, with an average depth of 50 m. It provided pier side mooring, storage and a ship based crane for loading the air-lift pumping system. The upwelling tubing used in the first experiment was a plastic hose. It was replaced by a tensional cloth with steel supporting rings inside for the second experiment. The experimental apparatus is depicted in Figure 9. It was composed of a water suction pipe (h_d=20 m) and a gas injection section pipe (h_u=8 m), with a vertical upwelling pipe of 28.3 m in length and different internal diameters (0.4, 0.5, 1.0, 1.5 and 2.0 m). The pipe was totally submerged vertically in the water, and the submerged depth of the pipe outlet was h_o=2.1 m. Air went from the air compressor through a 15 mm diameter tube to point B, and the air was controlled in the range of 1.2–3.2 Bar.

According to the experimental results of the two lake trials, deep water from approximately 30 m depth could be uplifted to the upper layer. With the mixing ratio at approximately 300 m^3/h deep water with ~1200 m^3/h upper layer water, a nutrient-enhanced plume could be formed at about 18 m (Fan et al., 2013). In addition, the efficiency of the air-lift artificial upwelling was shown to be strongly dependent on the geometrical parameters of the upwelling pipe, type of air injection nozzle, air volume flow rate and the material related tubing structure. Based on a theoretical analysis, the lifting efficiency increased with the increase of the pipe diameter, which was due to a reduction of the friction in the upwelling pipe. When comparing the efficiencies between the two lake field trials with the different tube materials, the plastic hose upwelling flow had a higher water flow vs. air flow ratio than that of the upwelling tube with the supporting rings, which was likely due to the quick shrinkage deformation of the tubes during the pumping. However, due to the advantages of the flexible tubing for storage, transportation, release and recovery, the flexible tube with supporting rings may be the development direction. Thus, efforts on optimizing the arrangement of the supporting rings inside of the upwelling tube must be made to reduce the inward shrinkage of the upwelling tube that resulted from the up-flowing of the gas-water mixture.

Thus, it was confirmed by the experimental results that the air-lift pump was feasible and effective to uplift DOW into the euphotic zone. The challenges in designing and fabricating a technologically robust artificial upwelling device for structural longevity were basically overcome.

In September 2014, a sea trial was performed in the East China Sea (30°8′14″N, 122°44′59″E) (Figure 10). The aim of the sea trial was to examine the structural robustness of the devices in the variable and complex hydrodynamics of the ocean and evaluate its potential environmental impacts, including the effects on the nutrient distribution, enhancement of marine primary production, the carbon cycle and the hypoxic condition. Cold and hypoxic DOW at about 30 m was measured to be uplifted to the euphotic layer, which was assumed to potentially change the nutrient distribution and adjust the N/P ratio. The results of the experiments will be summarized and submitted to related scientific journals.

In addition, the simulation works and laboratory experiments on the efficiency of wave and/or current induced artificial upwelling, the relationship among the plume trajectory after it was discharged out of the pipe (Fan et al., 2015), the technique parameters (Leng et al., 2014) and the relevant carbon sequestration ability were also conducted (Pan et al., 2015). In the research on the wave pump, the contributions of wave-induced and current-induced upwelling were extracted and simulated. It was suggested that the pump capacity and efficiency were the functions of the wave amplitude and frequency, the geometrical parameters of the pipe and the vertical distribution of water density. In the research on the plume trajectory and its related carbon sequestration ability, the simulation results indicated that the significant impacts of the technique parameters on

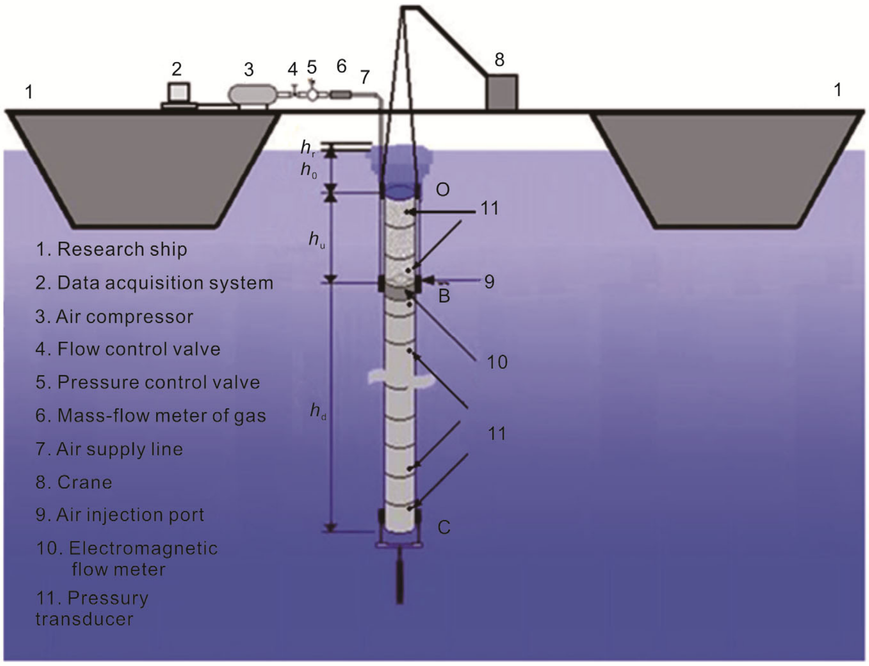
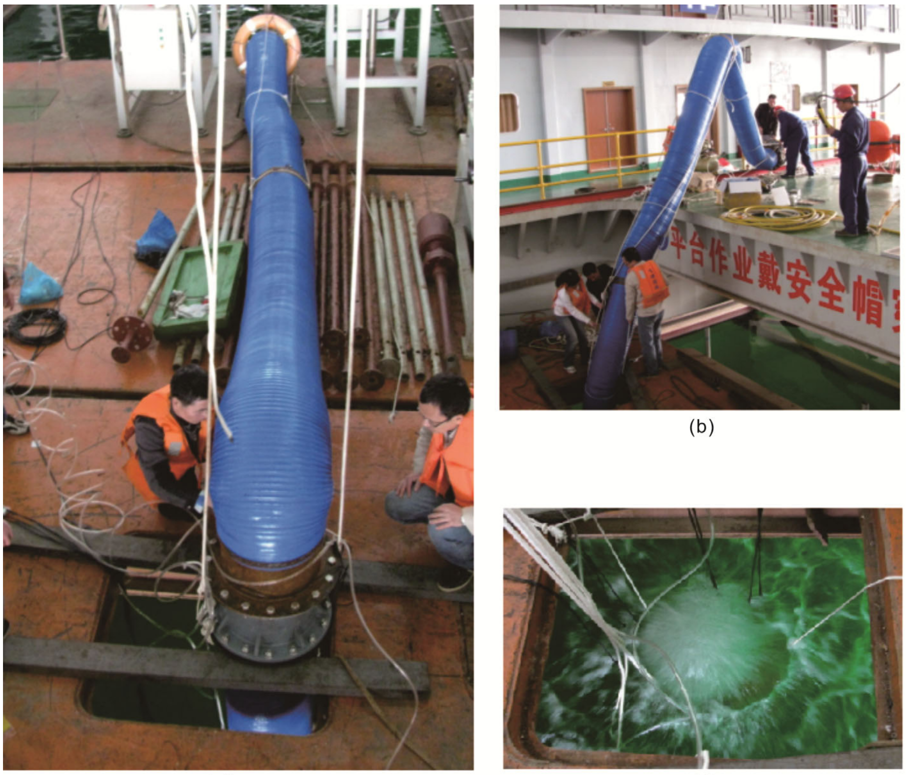


Figure 8 Schematic diagram of the air-lift pump for artificial upwelling of DOW (Fan et al., 2013).



(a)

(b)

(c)

Figure 9 Photos of the apparatus setting and the research ship. (a) The upwelling pipe on the deck; (b) installation of the gas injection section of the upwelling pipe; (c) water rising to the surface under internal hydraulic pressure (Fan et al., 2013).

the pumping efficiency, the plume trajectory and the carbon source or sinks characteristics of the artificial upwelling in the local area could also be significantly influenced.

Further work on artificial upwelling will mainly focus on measuring the environmental impacts in different coastal regions, where problems of eutrophication and the imbal-

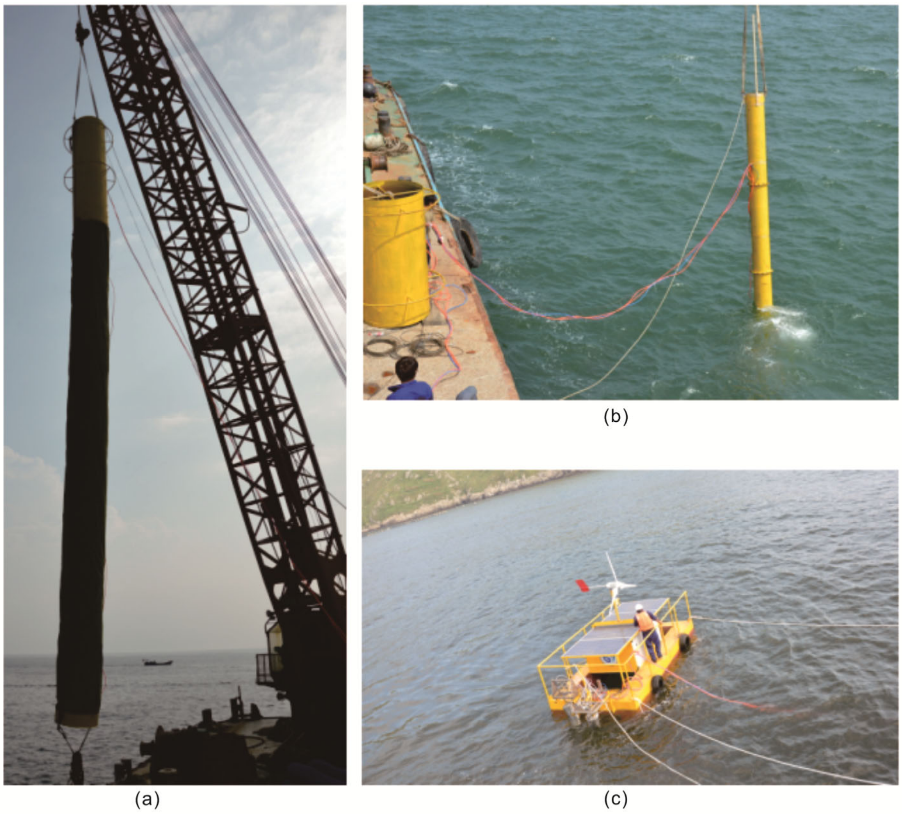


Figure 10 Photos of the sea trials for an air-lift system for artificial upwelling. (a) The upwelling pipe on the deck; (b) installation of the upwelling pipe; (c) floating platform of energy supply.

ance among the macro-nutrients are non-negligible. Methods combining the cultivation of high economic value seaweeds and sea grasses with artificial upwelling to repair highly polluted regions, such as lakes, rivers and coastal regions are planned. Designing a scheme to monitor the environmental disturbances of artificial upwelling especially in the long-term range, are further research interests, although the high variability of oceanic environments makes it much harder to achieve a unified description of the potential effects.

5. Conclusions

Using artificial upwelling to bring up DOW to fertilize the ocean and enhance the flux of organic carbon downflow is an attractive geoengineering tool. Scientific studies and sea trials on artificial upwelling will greatly improve our understanding of the biological and physico-chemical processes involved. However, artificial upwelling is a significant disturbance to the environment, and there are uncertainties relevant to the potential effects of the technique, especially for large-scale application. The high variability of oceanic environments makes it extremely hard to achieve a unified description of the potential effects. Most of the research results to date, including the simulation work and open sea experiments, supported the idea that, in a short time, artificial upwelling could help fertilize the nutrient-depleted euphotic layer and adjust its N/P ratio. However, more data are necessary to indicate the regional carbon source or sink characteristics caused by the artificial upwelling, especially data from field experiments. Thus, artificial upwelling as an available geoengineering tool needs more research before its large-scale application.

Research on the air-lift concept artificial upwelling was conducted by Zhejiang University, with two lake trials and one sea trial. The technical challenges in designing and fabricating a robust and high efficiency artificial upwelling device were generally overcome. The simulation and field experiments confirmed that utilizing self-powered energy to inject compressed air into a certain depth through upwelling tubes was a valid and efficient method for uplifting DOW. Besides, with the optimized technical parameters that fit the applied regions and seasons, the carbon source or sink characteristics of the artificial upwelling in the applied ocean could also be significantly influenced. According to the simulation and field experimental results, cold and hypoxic DOW could be uplifted to the euphotic layer, which was assumed to potentially change the nutrient distribution and adjust the N/P ratio. Further works will mainly focus on combining the cultivation of high economic value phytoplankton and sea grasses with artificial upwelling to repair highly polluted regions, where the problems of eutrophication and imbalance among the macro-nutrients are considerable.

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