Stoch Environ Res Risk Assess
DOI 10.1007/s00477-009-0357-4

ORIGINAL PAPER

Potential volume for CO_2 deep ocean sequestration: an assessment of the area located on western Pacific Ocean

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Abstract Captured CO_2 could be deliberately injected into the ocean at great depth, where most of it would remain isolated from the atmosphere for centuries. CO_2 can be transported via pipeline or ship for release in the ocean or on the sea floor. In Taiwan, CO_2 release is preliminarily projected from 2010 to 2030 in an average amount of 6.957 Gt within this duration. If deep sea sequestration for CO_2 can be the possible option in Taiwan, it seems to exists possible potential area delimited between 122.0°E to 122.5°E and 21.8°N to 22.3°N for CO_2 sequestration on account of its isolated and flat topography. Apparently, the area to the southeast of Taiwan is found to reach a depth deeper than −3,000 m and can be taken as a testing area for pilot studies. This study searches the area using the contours from the depth of −4,554 to −5,500 m with 1-m interval; the area, topographic volume, maximum mean height (volume/area), and ocean volume are reported. If the emission rate is kept constantly, for 20-year storage it needs 3 m of thickness reaching the sea ridge at the depth −4,554 m using top-down style; for 100 years of storage it needs 12 m. On the other hand, if it accounts for the bottom the sea floor is taken as the reference and the accumulated CO_2 is stored from the depth at −4,900 m using bottom-up style, it requires about 37 m for the 20-year storage and 61 m for one decade.

Keywords Carbon dioxide · Ocean sequestration · Regression analysis · Western Pacific Ocean

1 Introduction

Direct ocean injection of CO_2 is one of several approaches under consideration to sequester carbon dioxide in order to stabilize increased atmospheric CO_2. A potential CO_2 storage option is to inject captured CO_2 directly into the deep ocean at depths deeper than −1,000 m or more, where most of CO_2 would be isolated from the atmosphere for centuries. This can be achieved by transporting CO_2 via pipelines or ships to an ocean storage site, where CO_2 is injected into the water column of the ocean or at the sea floor. At typical pressures and temperatures, CO_2 exists as gas in the ocean at a depth of approximately −500 m and as a liquid below that depth. Between depths of about −500 and −2,700 m, liquid CO_2 is lighter than sea water (IPCC 2005). Deeper than −3,000 m, liquid CO_2 is denser than sea water. The buoyancy of CO_2 released into the ocean determines whether released CO_2 rises or falls in the ocean column. In the gas phase, CO_2 is lighter than sea water and rises. In the liquid phase CO_2 is a highly compressible fluid as compared to sea water. A fully formed crystalline CO_2 hydrate is denser than sea water and will form a sinking mass in mid-depth (Aya et al. 2003); hydrate formation can thus aid ocean CO_2 storage by more rapid transport to depth and by slowing dissolution. At the surface and intermediate depths, hydrate particles have negative buoyancy, and thus they will sink in the ocean (Teng and Yamasaki 1998). However, at a certain depth, called neutral depth, neutral buoyancy will be reached. Teng and Yamasaki (1998) indicate that neutral depth will be around −4,456 m. The hydrate density/seawater density

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ratio will be 1.00 to 0.992 (Fig. 1 of Teng and Yamasaki 1998) for the depth from −4,456 to −6,000 m. It means that the hydrate is lighter than seawater for the depth deeper than the neutral depth. In the future, CO_2 captured from the power plants can be designed and transported by a CO_2 tanker shipped to a single floating discharge platform for injection at a depth of −3,000 m. In some cases, the concept and technology for dilution type at medium depth (−1,500 m) or lake type at deep depth (or deeper than −3,000 m) for CO_2 ocean sequestration was conducted (Brewer et al. 2002; Nakashiki 1997; Ozaki 1997). Marine supporting system on the sea surface or at deep depths needs to be investigated drastically; it will be the most important works in the preliminary assessment stage.

In Taiwan, total CO_2 emissions from the energy sector are projected to increase from 266 Mt (million tons) of CO_2 in 2002 to 515 Mt in 2030 (Fig. 1). Such increase is mainly driven by the continual use of coal in electricity generation, despite the offset from decreasing oil utilization and increasing use of less carbon intensive natural gas, renewable and hydro (APERC 2006). For the actual capture capability of CO_2, the storage needs only for power generation and industry (Fig. 1) can be suggested in 0.2553, 0.3578, and 0.4205 Gt (Giga tons) for 2010, 2020, and 2030, respectively; the resultant average amount calculating the area of trapezoid of CO_2 emission versus year for the 2010∼2020 and 2020∼2030 will be 6.957 Gt in this duration.

Taiwan lies about 150 km to the east of the Fukien coast of the mainland China, separated by the Taiwan Strait (Fig. 2a). Geographically, Taiwan is represented by the main island with thirteen other islands and scattered islets. Taiwan is a member of the Ryukyu-Taiwan-Luzon arc chain rimming the western border of the Pacific Ocean

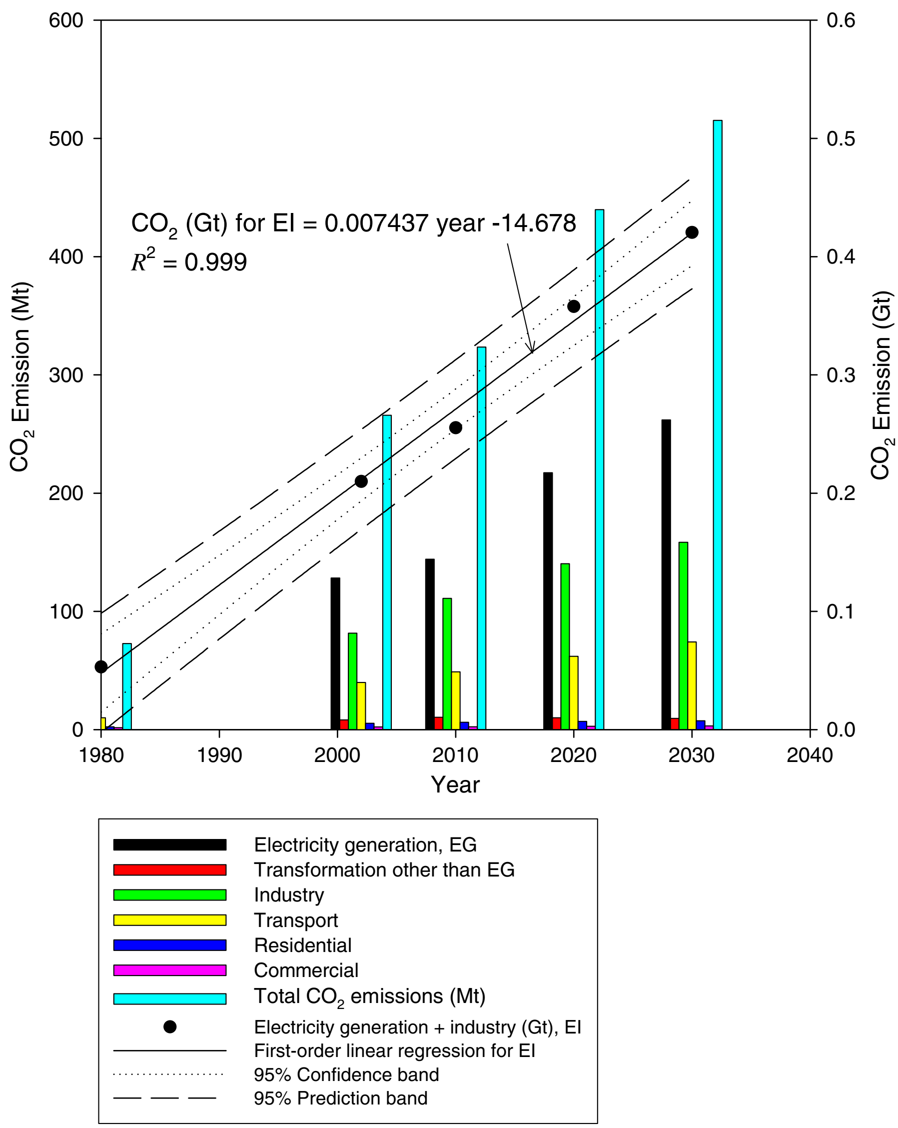

Fig. 1 Projected CO_2 emission in Taiwan (APERC 2006)

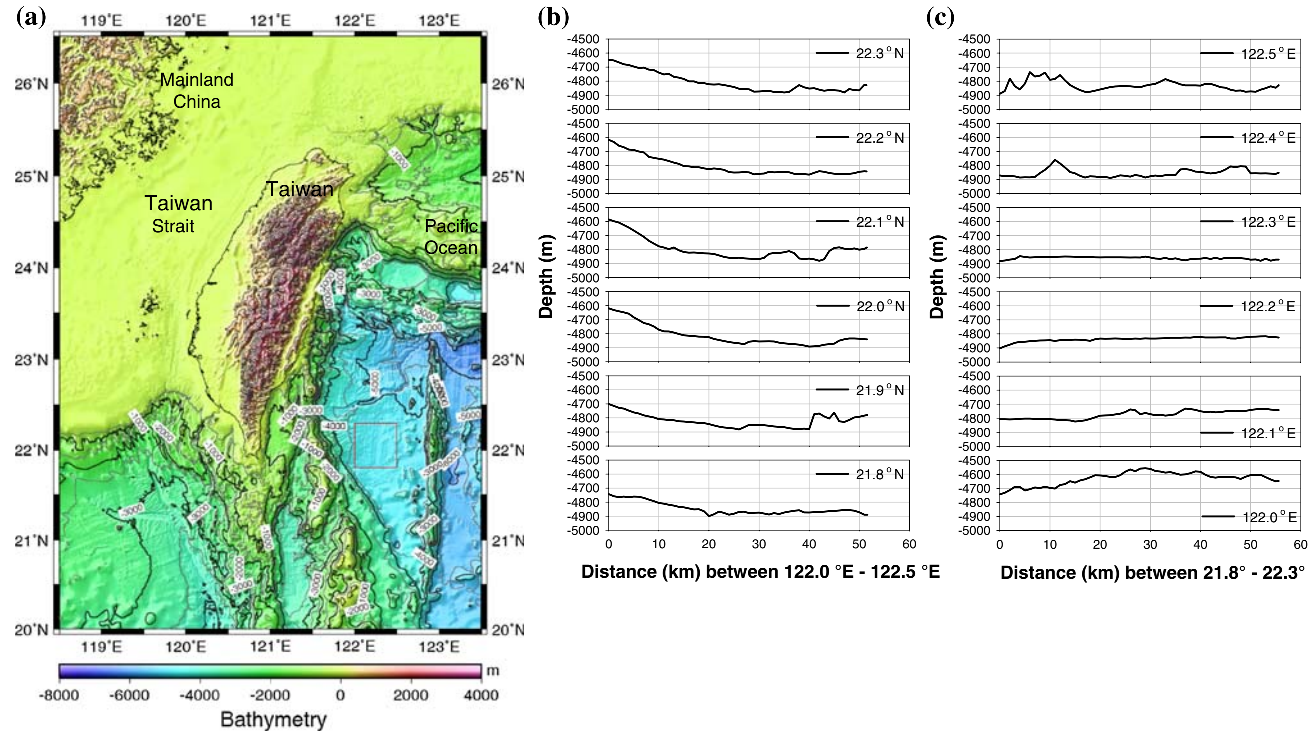

Fig. 2 **a** Map shows topography around Taiwan and west Pacific Ocean. Potential area for CO_2 sequestration is suggested and marked with *red line*, which located between 122.0°E ~ 122.5°E and 21.8°N ~ 22.3°N. **b** Topography profile between 122.0°E and 122.5°E with 0.1° increment from 21.8°N to 22.3°N. **c** Topography between 21.8°N and 22.3°N with 0.1° increment from 122.0°E to 122.5°N

(Shih et al. 2008). The tectonic evolution of Taiwan can be attributed either to the development of classic geosynclinal cycles or to the interaction of crustal plates. Taiwan is formed by a typical mobile or orogenic Cenozoic geosynclinal deposition on a pre-Tertiary metamorphic basement filled with Tertiary sediments to a thickness of more than 10,000 m. The main island of Taiwan is situated on the junction between the continental Eurasian Plate on the west and the oceanic Philippine Sea Plate on the east (Fig. 2 in Shih et al. 2008). The east coast of Taiwan apparently is located on the break of continental shelf of Eurasian Plate. It indicates that there exist potential areas at depths deeper than −3,000 m or more between 122°E to 122.5°E and 21.8°N to 22.3°N owing to its isolated and flat topography (Red rectangle in Fig. 2a). If deep sea sequestration for CO_2 is a feasible option for Taiwan, it is likely that a potential area nearby can be studied and tested for the pilot purpose.

In situ experiments concerning the sensitivity of deep and shallow-living marine biota to elevated carbon dioxide levels have been limited in scope. Significant CO_2 effects have been observed in experiments, consistent with the mechanisms of CO_2 action have been reported (IPCC 2005). Some animals resist CO_2 plumes, others do not. Studies evaluating the behavior and survival of deep sea animals exposed to liquid CO_2 or to CO_2-rich sea water have been performed on the continental slope and rise off the California coast. Experiments in which about 20–70 kg of liquid CO_2 were released in small corrals on the sea floor at −3,600 m depth were used to evaluate the response of animals that came in contact with liquid CO_2, and with the dissolution plume emanating from CO_2 pools (Barry et al. 2004). Liquid CO_2 released at −3,600 m initially forms a liquid CO_2 pool on the sea floor in a small deep ocean experiment has been conducted (Brewer et al. 2004). Long-term storage of carbon dioxide might be more effective if CO_2 were stored on the sea floor in liquid or hydrate form below −3,000 m, where CO_2 is denser than sea water (Ohsumi 1995; Shindo et al. 1995). Liquid carbon dioxide could be introduced at depth to form a lake of CO_2 on the sea floor (Ohsumi 1993). Alternatively, CO_2 hydrate could be created in an apparatus designed to produce a hydrate pile or pool on the sea floor (Saji et al. 1992). Simulation of CO_2 storage in a deep trench (Kobayashi 2003) indicates that the bottom topography can weaken vertical momentum and mass transfer, slowing the CO_2 dissolution rate. This study evaluates the ocean volume for possible CO_2 storage using ocean topography data with depth deeper than −3,600 m in the target area. It expects that the potential quantity of CO_2 sequestration in the target area can be well modeled and predicted. However, dynamic condition, e.g. deep current and possible mass transfer of hydrate, is out of scope in this study.

2 Conceptual model and data manipulation

The east coast of Taiwan locates exactly on the break of continental shelf on the southeast of Eurasian Plate (Fig. 2a). Topographically, depth change is drastically down to −5,000 m for the distance nearly about 60 km off the southeastern coast of Taiwan. The suggested potential area for CO_2 sequestration is preliminarily focused on the area ranging from 122.0°E to 122.5°E and from 21.8°N to 22.3°N, which area is represented about 3,000 km^2. Gridded topography is collected from marine geophysics database of National Marine Science Center, Taiwan. Grid data is manipulated as 1,094 × 1,422 points from 118.497°E to 123.503°E and 19.9959°N to 26.501°N with resolution of 0.00457928° and 0.00457782°, respectively. The depth reaches about −6,360 m in maximum and reach the sea bed ridge at −4,554 m of depth. It searches the area using the contours from the depth at −4,554 to −5,500 m with an interval of 1 m using the GMT utilities (Wessel and Smith 2007); the area, topographic volume (called volume), maximum mean height (volume/area) are substantially reported; resultant sea volume is then calculated. The area is measured in the plane of the contour.

3 Result and discussion

It shows topography section between 122.0°E and 122.5°E and demonstrated with 0.1° increment of the array from 21.8°N to 22.3°N (Fig. 2b). The slope is gradually decreased from the west side towards the east side of the target area. This can also be seen in the profile between 21.8°N and 22.3°N with 0.1° increment of the array from 122.0°E to 122.5°E (Fig. 2c). A conceptual model (Fig. 3a) illustrates the representative volume used in this study, ocean volume can be calculated by the difference from the volume of the rectangular parallelepiped and topographic volume at the targeted depth. Topographic volume, plane area, and maximum mean height is then derived (Fig. 3b). The volume is accumulated using all contours from the depth at −4,554 to −5,000 m with an interval of 1 m.

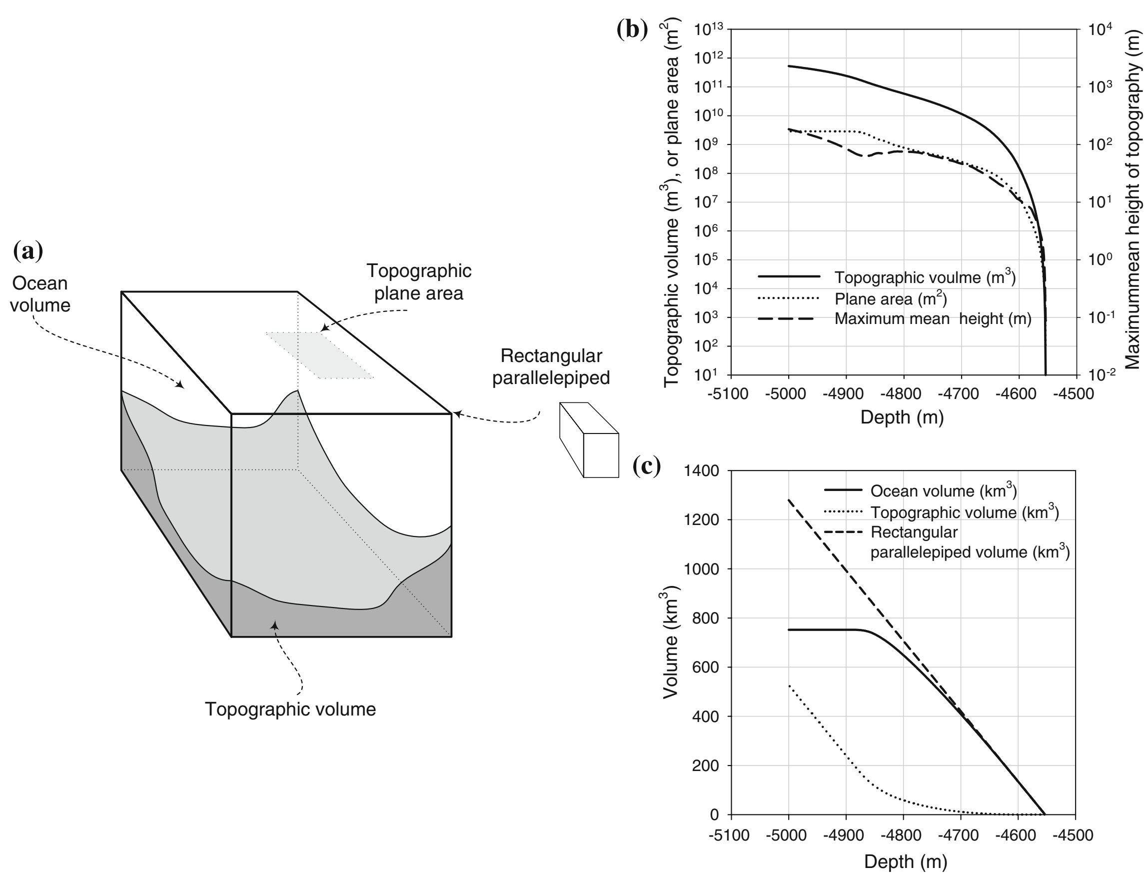

Fig. 3 **a** Conceptual model for volume calculation. **b** Topographic volume, plane area and maximum mean height. **c** Ocean volume versus depth

Maximum mean height is calculated by the volume/area; the area is measured in the plane of the contour. It shows that accumulated volume of topographic sea bed changes drastically from the depth of −4,554 to −4,700 m. The depth at −4,554 m is a level reaching the underwater ridge using the top-down style. Ocean volume versus depth is calculated using the difference of volume of rectangular parallelepiped and topographic volume (Fig. 3c). Note that the ocean volume has a limited bound and will not increase at the depth of −4,860 m. Ocean volume and CO_2 storage quantities versus depth for every 1 m of thickness have been analyzed (Fig. 4a and b). Non-linear regression for Sigmoidal Weibull 4 parameters demonstrates highly correlated match for the predicted and the observed volume at depth from −4,554 to −5,000 m. The 95% confidence band indicates significant acceptance in such regression. Prediction of targeted layer for CO_2 sequestration can be conducted for volume or quantity subjected to the above regression in no doubt.

It suggests that CO_2 storage for power generation and industry required in an average amount of 6.957 Gt in this duration (Fig. 1). If the emission release rate is kept constant, for a 20-year period started from 2010, it needs 3 m of thickness at the depth from −4,554 m down to −4,556 m using top-down style and 12 m for 100 year (Fig. 4c). On the contrary, if CO_2 storage can be initiated

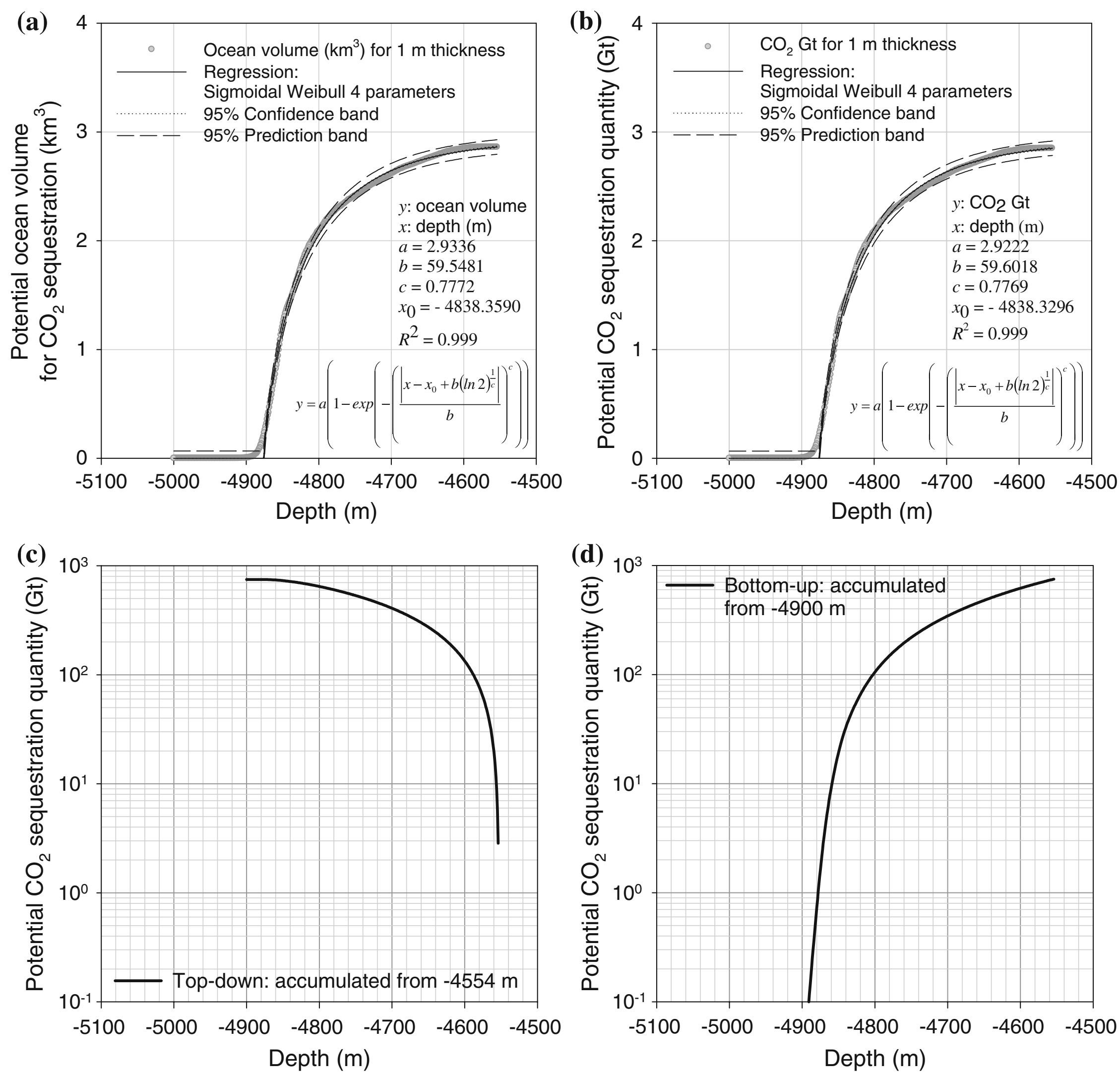

Fig. 4 **a** Ocean volume for 1 m thickness versus depth. Non-linear regression for Sigmoidal Weibull with 4 parameters demonstrates a highly correlated match for the predicted and the observed. **b** CO_2 storage potential quantities (Gt) versus depth for the volume of 1 m thickness. Non-linear regression for Sigmoidal Weibull with 4 parameters demonstrates a highly correlated match for the predicted and the observed. **c** Potential CO_2 storage quantity accumulated from the reference depth reaching sea bed ridge at the depth −4,554 m using top-down style. **d** Potential CO_2 storage quantity accumulated from the sea floor bottom at the reference depth −4,900 m using bottom-up style

from the bottom of sea floor the accumulated quantity from the reference depth at −4,900 m using bottom-up style will require 37 m for the storage of 20-year duration and 61 m for one decade (Fig. 4d). Although it demonstrates the current condition of topographic volume in the proposed area; environmental impacts must be reviewed at two different scales. On a global scale, direct injection of CO_2 to the ocean can be considered environmentally beneficial as compared to the acceptable level. On a local scale, the most significant environmental impact is derived from lowered pH as a result of the reaction of CO_2 with seawater (Magnesen and Wahl 1993; Auerbach et al. 1997). Impacts would occur principally to non-swimming marine organisms (e.g., zooplankton, bacteria and benthos) residing at depths of about −1,000 m or deeper; their magnitude will depend on both the level of pH changes and the duration of exposure (Auerbach et al. 1997). In the future, chemical and physical impacts must be strongly addressed and studied before disposal of CO_2 in the target area. If the far field is defined as the region in which the concentration of added CO_2 is low enough such that the resulting density increase does not significantly affect transport, and thus CO_2 may be considered a passive tracer in the ocean (IPCC 2005). Typically, this would apply within a few kilometers of an injection point in mid-water, but if CO_2 is released at the sea floor and guided along topography, concentration may remain high and influence transport for several tens of kilometers. CO_2 is transported by ocean currents and undergoes further mixing and dilution with other water masses (Alendal and Drange 2001). Most of this mixing and transport occurs along surfaces at nearly constant density, because buoyancy forces inhibit vertical mixing in a stratified fluid. Over time, a release of CO_2 becomes increasingly diluted but affects ever greater volumes of water. Therefore, it requires a thoroughgoing investigation of the relevant physical and chemical oceanography in deep sea environments in the future.

4 Conclusions

Direct ocean injection of CO_2 is one of several options to sequester carbon dioxide in order to stabilize increased atmospheric CO_2. In Taiwan, CO_2 release for power generation and industry is preliminarily suggested in an average amount of 6.957 Gt from the year of 2010 to 2030. If deep sea sequestration for CO_2 can be the possible option in Taiwan, it shows that potential areas with isolated and flat topography at depths deeper than −4,554 m between 122°E to 122.5°E and 21.8°N to 22.3°N is suitable for such purpose. This study searches the area using all contours from the depth at −4,554 to −5,000 m by 1-m interval; the area, topographic volume, maximum mean height (volume/area), and ocean volume are substantially analyzed. If the emission rate is kept constantly, it indicates that for the storage of 20-year duration it needs 3 m of thickness reaching the sea bed ridge from the depth −4,554 down to −4,556 m using top-down style and 12 m for 100 year. On the other hand, if CO_2 storage can be conducted from the sea bottom using bottom-up style at the reference depth −4,900 m, it requires 37 m for the storage of 20 year and 61 m for one decade.

Acknowledgments The authors thank the Department of Geosciences, National Taiwan University, Taiwan, for providing useful tool and related map source of this study. The support from Institute of Nuclear Energy Research, Taiwan is also greatly appreciated.

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