Assessing the Spatial and Temporal Capacity of a Semi-Enclosed Gulf to Absorb and Release CO_2 Using GIS and Remote Sensing

A. Shanableh, R. Al-Ruzouq and G. Al-Khayyat

Abstract The increasing CO_2 level in the atmosphere is threatening oceans' ecosystems due to increased CO_2 absorption and potential oceans' acidification. In this study, we used geographic information system (GIS) and remote sensing (RS) techniques, coupled with chemical–mathematical models to evaluate the water capacity of a semi-enclosed gulf to absorb and release CO_2. The water of the gulf exhibits a wide range of spatial and temporal salinity and temperature variations due to the gulf location in a hot, arid region, the high water evaporation rate, and the unique water circulation pattern. In this study, GIS and RS data were used to assess the spatial and temporal distributions of surface temperatures and salinity of the gulf, which, in turn, were used to assess the capacity of the gulf waters to absorb and release CO_2. The results confirmed the profound impact of salinity and temperature on the CO_2 absorption and release capacity of the gulf, which highly influences potential acidification of the gulf waters.

Keywords Geographic information systems · Remote sensing · CO_2 absorption and release · Surface temperature · Surface salinity · Seawater Semi-enclosed gulf

1 Introduction

Prior to the industrial revolution starting the 1950s, CO_2 level in the atmosphere was in the range of 200–300 ppmv for hundreds of thousands of years [1–4]. Since then, the level of CO_2 rapidly increased reaching approximately 400 ppmv at the present time, or the year 2017. The CO_2 increase is mainly attributed to burning fossil fuels. About 30% of the CO_2 released to the atmosphere during the 1980s and

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1990s was absorbed by the oceans, with about 50% remaining in the atmosphere and 20% removed on land by the biosphere [5]. Others [6] estimated that the oceans absorbed about 50% of the CO_2 released during the past 200 years. Absorption of atmospheric CO_2 acidifies oceans [7–10], threatening to reduce $CaCO_3$ supersaturation and posing risk to calcifying organisms [11]. Acidification of seawater can significantly impact the biogeochemical transformations [6, 7, 11–14] in the sea. Acidification scenarios indicate that a sixfold increase of the preindustrial CO_2 level can potentially reduce the pH of oceans by about 0.7 units [6]. Direct observation between 1991 and 2006 indicated a pH decline of about 0.06 in the upper 0.5 km of the water of the North Pacific Ocean [15].

The Arabian Gulf (also referred as the Persian Gulf) is located between latitudes 23.5°–30°N (Fig. 1). It is about 800 km long, 300 km wide and 40 m average depth, with a total surface area of approximately 240,000 km^2. Water enters and exits the Gulf through the Strait of Hormuz, which connects the Arabian Gulf to the

Fig. 1 Location of the Gulf obtained from national geographic, ESRI

Gulf of Oman, Arabian Sea, and the Indian Ocean. The Gulf receives limited freshwater supplies, with rain not exceeding 150 mm/year [16, 17], and experiences high evaporation rate that exceeds 2000 mm/year [17–19], which increases its salinity.

The capacity of the Gulf to absorb and release CO_2 is highly affected by water temperature and water salinity. The water in the Gulf is generally saltier than waters of open seas, and experiences wide spatial and seasonal variations in temperature and salinity [17, 20–25]. These variations are due to the geographical extent of the Gulf, unique water circulation and stagnation patterns, evaporation, and disposal of brines from desalination plants.

In this chapter, we used GIS and RS to assess the spatial and temporal distributions of surface temperatures and salinity of the Gulf, then used the temperature and salinity distributions to assess the capacity of the surface water to absorb and release CO_2. This capacity plays an important role in determining potential acidification and influences the carbonate chemistry of the water of the Gulf.

2 Methodology

2.1 Chemical Equilibrium Model

The methodology used in this article was based on models developed during earlier work [20, 21]. Simple chemical-mathematical models representing CO_2 equilibrium between seawater and the atmosphere were used. Such models were based on preserving initial alkalinity (Alk_0) regardless of increased CO_2 absorption. Seawater alkalinity (Alk_0), including the borate ion, is presented in Eq. 1, and its simplified version excluding borate is presented in Eq. 2.

$$\mathrm{Alk}_0 \cong [\mathrm{OH}^-] + [\mathrm{B(OH)}_4^-] + 2[\mathrm{CO}_3^{2-}] + [\mathrm{HCO}_3^-] - [\mathrm{H}^+] \quad (1)$$

$$\mathrm{Alk}_0 \cong [\mathrm{OH}^-] + [\mathrm{HCO}_3^-] + 2[\mathrm{CO}_3^{2-}] - [\mathrm{H}^+] \quad (2)$$

Using the pH-dependent carbonate speciation parameters $(\alpha_0, \alpha_1, \alpha_2)$, Henry's equation $([\mathrm{H_2CO_3}] = k_\mathrm{H} P_{\mathrm{CO_2}})$, which is expressed in terms of Henry's constant (k_H), CO_2 pressure in the atmosphere $(P_{\mathrm{CO_2}})$ and the water speciation constant (k_w), the initial alkalinity equation can be rewritten as

$$\mathrm{Alk}_0 \cong \frac{k_\mathrm{w}}{[\mathrm{H}]} + (\alpha_1 + 2\alpha_2)\frac{k_\mathrm{H} P_{\mathrm{CO_2}}}{\alpha_0} - [\mathrm{H}^+] \quad (3)$$

The water that enters the Gulf is subject to evaporation which concentrates the various water constituents. As such, a concentration factor R (i.e., $R = S/S_0$, where S = salinity, and S_0 = initial reference salinity) can be introduced in Eq. 3 to correct alkalinity as in Eq. 4.

$$R * \text{Alk}_0 \cong \frac{k_w}{[\text{H}]} + (\alpha_1 + 2\alpha_2)\frac{k_\text{H} P_{\text{CO}_2}}{\alpha_0} - [\text{H}^+] \tag{4}$$

Absorption and release of CO_2 can be evaluated from the concentration of total carbonates in water, C_T, noting that $[H_2CO_3] = \alpha_0 C_T$, $[HCO_3^-] = \alpha_1 C_T$, $[CO_3^{2-}] = \alpha_2 C_T$, then

$$C_T = [H_2CO_3] + [HCO_3^-] + [CO_3^{2-}] \tag{5}$$

The above equations rely on a number of constants, including the carbonate species dissociation constants, k_1, and k_2. The values of the various constants are dependent on water temperature and salinity as summarized in Table 1.

It should be stated that the suitability of the above models to predict pH and C_T was verified earlier [21] against [6] predictions relating to atmospheric CO_2 level of 280 ppmv up to sixfolds increase in CO_2 level to 1680 ppmv.

To estimate the pH and total carbonates (C_T) in the Gulf, the spatial and temporal distributions of salinity and water temperature were obtained from satellite images and an iterative procedure was used to estimate the pH and total carbonates for two CO_2 level in the atmosphere, 400 and 800 ppmv. The reference values required for solving Eq. 4 are provided in Table 2.

Table 1 Dependence[a] of the equilibrium constants (k_1, k_2, k_W, and k_H) on water salinity (psu) and temperature (k)

$\ln(k_w) = \frac{-13,847.26}{T} + 148.9652 - 23.6521 * \ln(T) + \left(\frac{118.67}{T} - 5.977 + 1.0495 * \ln(T)\right) * S^{0.5} - 0.01615 * S$
$\ln(k_H) = \frac{9345.17}{T} - 60.2409 + 23.3585 * \ln(\frac{T}{100}) + (0.023517 - 0.00023656 * T + 0.00000047036 * T^2) * S$
$pk_1 = \frac{3633.86}{T} - 61.2172 + 9.67770 * \ln(T) - 0.011555 * S + 0.0001152 * S^2$
$pk_2 = \frac{471.78}{T} + 25.9290 - 3.16967 * \ln(T) - 0.01781 * S + 0.0001122 * S^2$

[a] *Sources* [26–28]

Table 2 Initial values of parameters used in this study

Parameter	Value
Initial temperature (°C)	24
Reference salinity of surface water, S_0 (psu)	35
Initial alkalinity (eq/L)	0.0024
Reference (2016) CO_2 level in atmosphere (ppmv)	400[a]

[a] *Source* NOAA-ESRL

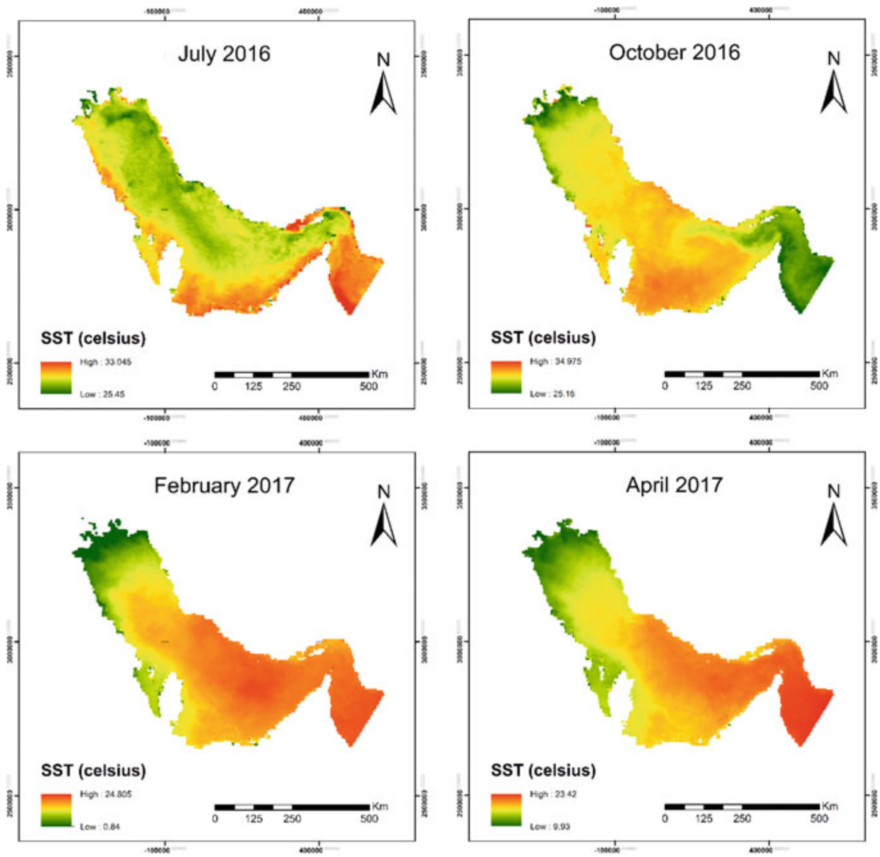

Fig. 2 Seasonal distribution of surface water temperature in the Gulf during 2017 as extracted from MODIS images by NASA

The spatial and seasonal distributions of temperature (Fig. 2) and salinity (Fig. 3) needed for estimating the various parameters in Table 1 were, respectively, extracted from the Moderate Resolution (4 km spatial resolution) Imaging Spectroradiometer (MODIS) on the Terra-satellite of NASA and from the Remote Sensing System (RSS) Company with 25 km resolution. For salinity, and as the obtained satellite images did not provide full coverage of the Gulf (Fig. 3), values in uncovered areas were estimated based on data available from a variety of other sources [17, 22–25].

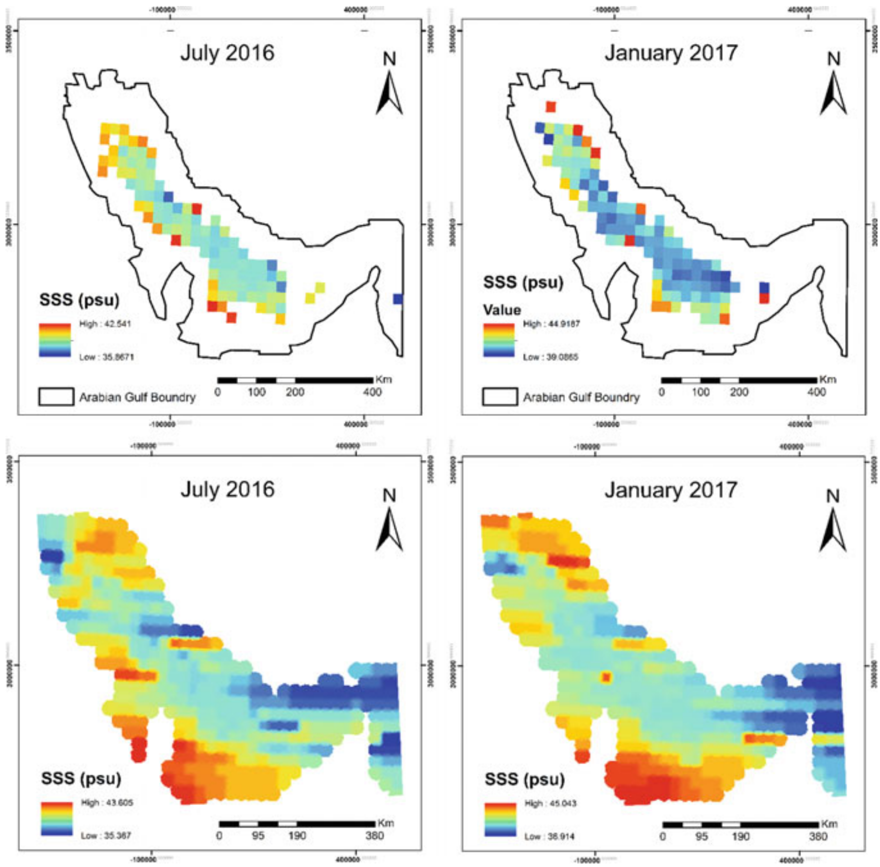

Fig. 3 Example seasonal distribution of surface water salinity in the Gulf during 2017 extracted from RSS by NASA

3 Results and Discussion

3.1 Spatial and Seasonal Distributions of Temperature and Salinity

The water temperature in July (summer) was in the range of 24–33 °C (Fig. 2), 25–35 °C in October (fall), 1–25 °C in February (winter) and 10–23 °C in April (spring). The water along the southern parts of the Gulf was the warmest in July and October and relatively warm in February and April. In February and April, warm waters entering from the Hurmuz straight kept the water along the northern coastline of the Gulf warmest. The February and April warm water entering the Gulf pushes northwest along the northern coastline of the Gulf but does not reach

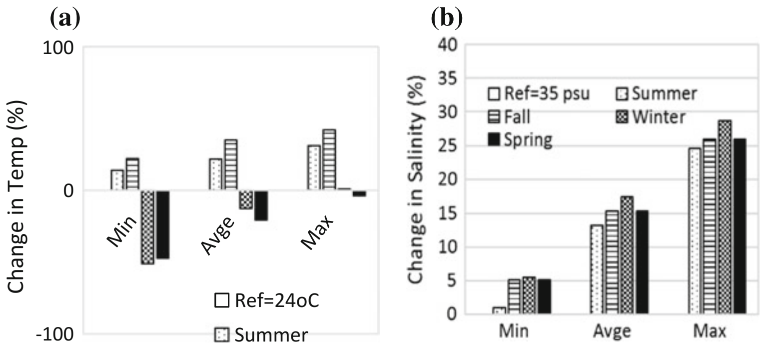

Fig. 4 Projected distribution of salinity and temperature in the Gulf compared to reference values (24 °C and 35 psu)

the northwestern part, opposite Iraq and Kuwait, which remains the coldest area in the Gulf during all seasons.

Although the satellite salinity data are incomplete, the general salinity distribution is generally affected by the water that enters from the Gulf of Oman, which generally has lower salinity than the water that exists the Gulf. The salinity is also affected by water circulation and evaporation in the Gulf. In general, the northern parts along the Iranian coast maintain the lowest salinity values while the southern parts along the coasts of the UAE and Qatar maintain the highest salinity values (Fig. 3).

A statistical summary of salinity and temperature variations in the Gulf compared to the reference values stated in Table 2 (i.e., 24 °C and 35 psu) is presented in Fig. 4. The data show that depending on the season, the temperature in some parts of the Gulf declined up to 50% or increased up to 42%. On the other hand, the salinity increased between 5 to about 27%, with an average increase of approximately 15%.

3.2 *Capacity of the Gulf to Absorb/Release CO_2*

The data in Fig. 5 show the impact of temperature and salinity on surface water alkalinity (Alk), total carbonates (C_T) and pH according to Eq. 4. At constant salinity, the Alk remains constant and C_T declines, as the water loses capacity to dissolve CO_2 with increasing temperature. As expected, the pH increases as the temperature increases up to 21°C, but then unexpectedly declines apparently due to the differences in the impact of salinity on the various constants in Table 1. On the other hand, both Alk and C_T increase as salinity increases at constant temperature due to concentration of constituents. The increase in alkalinity is equivalent to adding a strong base, which helps the water absorb more CO_2 but also results in increasing the pH.

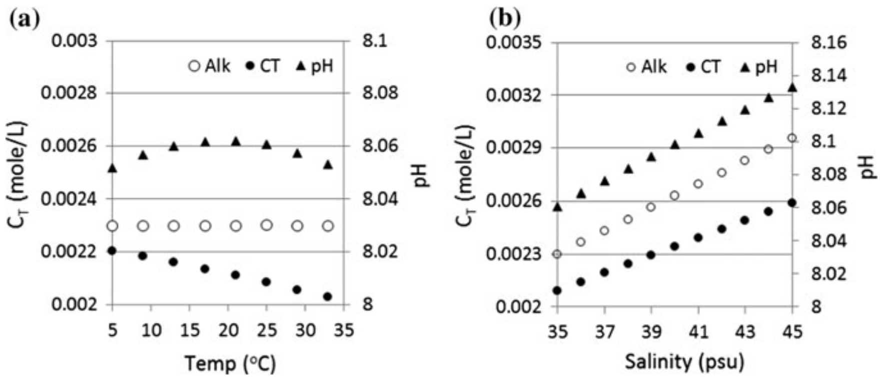

Fig. 5 Impact of temperature (at constant salinity of 35 psu) and salinity (at constant temperature of 24 °C) on pH and total carbonates (C_T) at atmospheric CO_2 = 400 ppmv

Clearly, the model suggests that lower temperatures and increased salinity increase the capacity of seawater to absorb CO_2 from the atmosphere. In terms of pH, the model suggests that increased salinity increases the pH despite absorption of additional quantities of CO_2 into the water. Therefore, the model predicts that increased salinity helps in absorbing excess atmospheric CO_2 and combating acidification of seawater.

The data suggest that water in the Gulf acted as a sink for CO_2 compared to water entering from the Gulf of Oman due to increased salinity. Furthermore, salinity was more important than temperature in deciding the level of CO_2 absorption as indicated by C_T. Therefore, the southern parts of the Gulf with high salinity achieved the highest CO_2 absorption levels followed by the somewhat saline and cold northern parts of the Gulf (Fig. 6). In general, the northern parts of the Gulf receiving water entering the Gulf from the Strait of Hurmuz showed lower CO_2 absorption levels than the saltier southern parts regardless of temperature.

Projected absorption of CO_2 into the surface water of the Gulf at double the current atmospheric CO_2 level (i.e., 800 ppmv) followed similar trends as absorption at 400 ppmv, except that the absorbed C_T quantities increased significantly (Fig. 7). The southern parts of the Gulf, which have the highest salinity are projected to experience the highest CO_2 absorption levels followed by the somewhat saline and colder northern parts.

The data in Fig. 8 present a statistical summary of the C_T variations in the Gulf compared to a chosen reference value (i.e., C_T = 0.00209 mol/L) defined at temperature of 24 °C and salinity of 35 psu. The data show that at atmospheric CO_2 level of 400 ppmv, C_T increased in the Gulf from 5 to about 25% above the reference C_T value, with an average increase of approximately 12%. The increase in C_T was consistent with increase in salinity shown in Fig. 4. At atmospheric CO_2 level of 800 ppmv, the data in Fig. 8 show projected C_T increase above the reference value between about 7 and 30%, with an average increase of approximately

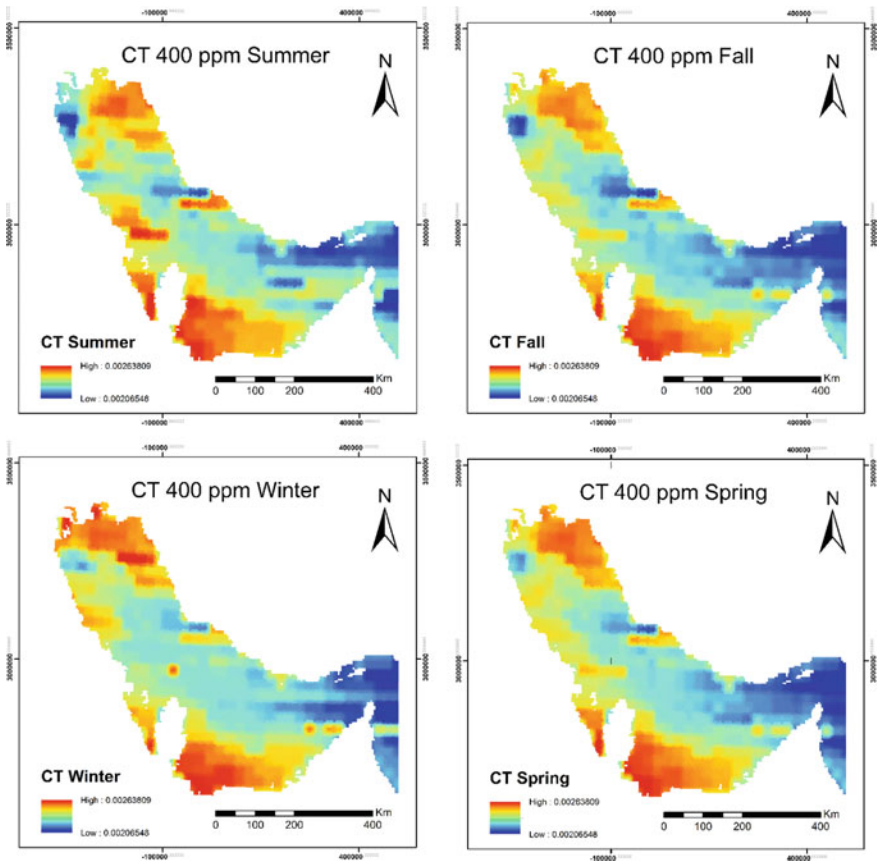

Fig. 6 Projected seasonal distribution of total carbonates (C_T) in the surface water of the Gulf at atmospheric CO_2 = 400 ppmv based on the salinity and temperature distributions in Figs. 2 and 3

20%. The data suggest significant increase in capacity of the Gulf water to absorb CO_2, which is mainly due to increased salinity.

3.3 Acidification of Surface Water

Absorption of CO_2 in the surface water of the Gulf increases as salinity and CO_2 in the atmosphere increase and declines as the temperature increases. Therefore, the temperature and salinity distributions in the Gulf have a significant impact on water acidification. In Fig. 5, it was shown that higher salinity resulted in higher alkalinity and more C_T absorption, which translated into pH increase. The data in Fig. 9 show that compared to the reference pH value of 8.061 at atmospheric CO_2 level of

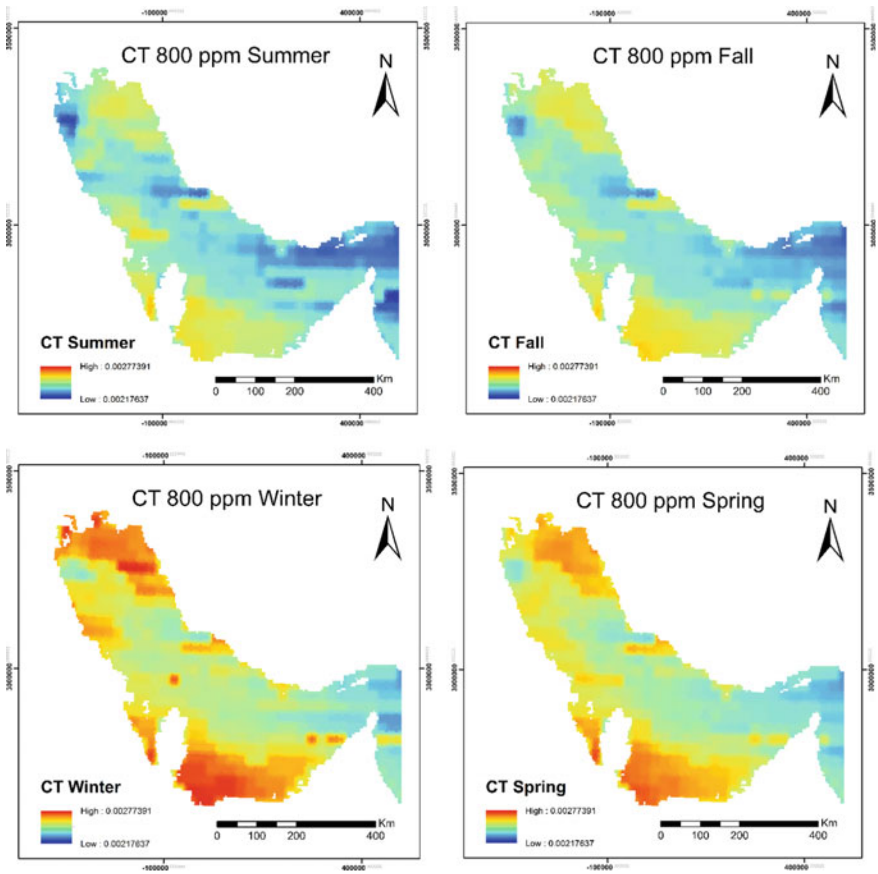

Fig. 7 Projected seasonal distribution of total carbonates (C_T) in the surface water at atmospheric CO_2 = 800 ppmv based on the salinity and temperature distributions in Figs. 2 and 3

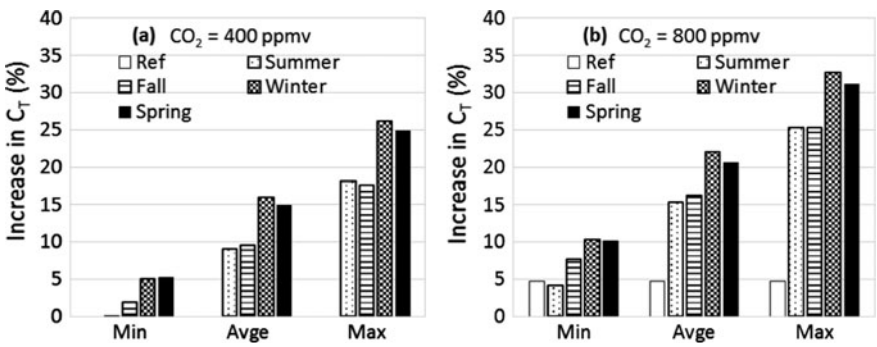

Fig. 8 Projected distribution of C_T in the Gulf compared to reference C_T value defined at 24 °C and 35 psu

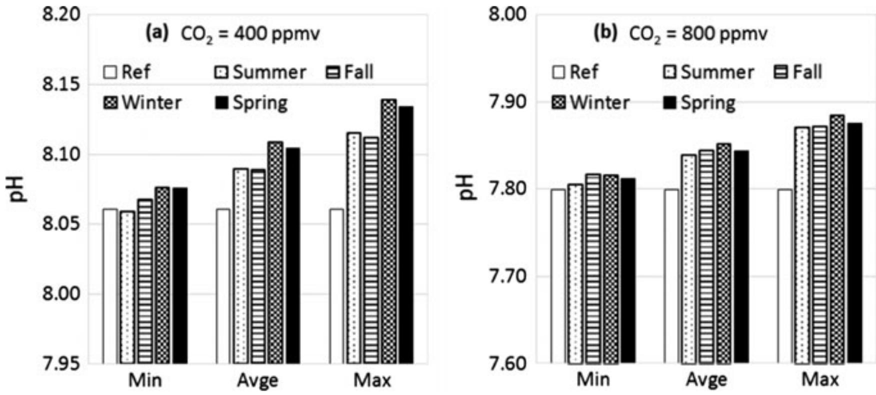

Fig. 9 Projected distribution of pH in the Gulf

400 ppmv and temperature and salinity values of 24 °C and 35 psu, the pH distribution in the Gulf ranged between 8.06 and 8.14 and average is 8.1, with more saline regions associated with the higher pH values. Similarly, compared to the reference pH value of 7.80, projected at atmospheric CO_2 level of 800 ppmv and temperature and salinity values of 24 °C and 35 psu, the pH distribution in the Gulf ranged between 7.80 and 7.89 (average of 7.84).

4 Summary and Conclusions

A simple mathematical–chemical equilibrium evaporation model was developed and used to assess the capacity of the surface water of the Arabian Gulf to absorb and release CO_2. The capacity of the surface water was found to be determined mostly by the salinization of the Gulf due to evaporation and other causes. Salinization increases the alkalinity of the water, which allows it to absorb more CO_2 and simultaneously increases the pH. As such, the salinization of the Gulf acts as a buffer that helps reduce projected acidification of the Gulf due to increasing atmospheric CO_2. The Gulf capacity thus to absorb and release atmospheric CO_2 is highly influenced by the distributions of the salinity and temperature in the Gulf waters, with the water releasing or absorbing CO_2 depending on its salinity and temperature levels.

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