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Evaluation of the impact of brine discharge position on salinity in the Persian/Arabian Gulf's slow flushing zone

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ABSTRACT

The Persian/Arabian Gulf is the sink of hypersaline effluent (brine) for plants with about half of the world's seawater desalination capacity. Many of these plants discharge brine into the Gulf's southwestern region where the salt in brine accumulates because seawater there is not replaced often by the Gulf's residual circulation (i.e., the region is poorly flushed). This circulation flushes the whole Gulf and inhibits salt accumulation at the basin scale. But flushing is not effective in the southwestern region, which has been described as the "Gulf's slow flushing zone." Here, the impact of brine discharge position on salinity in this zone is evaluated by comparing two scenarios of brine discharge into the Gulf's residual circulation dynamics. In the first scenario, brine from the 24 largest seawater desalination plants in the Gulf is introduced into the residual circulation; and in the second scenario, the brine discharge position of one of these 24 plants is positioned away from the slow flushing zone. In the two scenarios, brine discharge caused salt buildup in the slow flushing zone. However, annual area-average salinity there is about 1.10–1.55 PSU smaller in scenario two compared to scenario one, indicating the influence of discharge position on salt buildup because of brine discharge. This study, accordingly, suggests a methodology for selecting brine discharge position in the Gulf's slow flushing zone.

Keywords: Seawater desalination; Marine brine disposal; Nearshore salt buildup; Flushing

1. Introduction

Marine disposal is a common strategy to manage brine, which contains salt, pretreatment biocides (e.g., chlorine), coagulants (cationic and anionic polyelectrolytes), antiscalants (e.g., H_2SO_4), antifoaming agents, and heavy metals (e.g., copper) from plant corrosion [1,2]. If the region surrounding the brine discharge position is not well-flushed (i.e., cleaned by ambient currents), then salt and other elements in brine will accumulate there indefinitely (hereafter "salt buildup") at a rate that depends on the regional flushing strength [3]. In enclosed seas with basin-scale residual circulation that dominate flushing at all spatial scales, such as the Gulf (Fig. 1), the circulation spatial structure is crucial for selecting brine discharge position that minimizes salt buildup [3,4]. Studies have reported Gulf basin and sub-region flushing times in the range 1.4–5 years [5–7]. Ibrahim and Eltahir [4], for the first time, quantified brine discharge and Gulf residual circulation interaction, which resulted in the division of the Gulf into two flushing zones corresponding mostly to the places where the circulation is strong and weak: (1) the fast flushing zone, which includes the northern and northwestern Gulf regions, and (2) the slow flushing zone, which includes the southern and southwestern Gulf regions (Fig. 1). This paper aims to evaluate the impact of brine discharge position on salinity in the Gulf's slow flushing zone.

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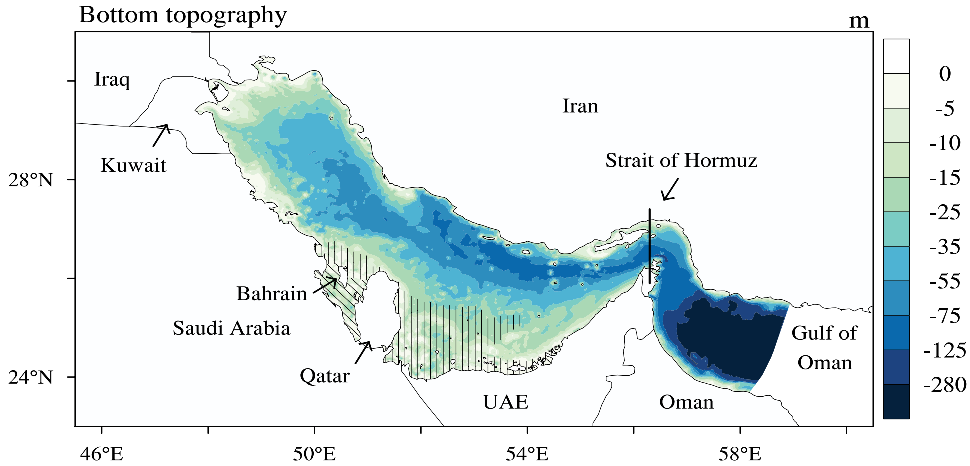

Fig. 1. Gulf depth profile, and the slow flushing zone. Mean depth is about 35 m and depth decreases from the northeast (Persian) coast to southwest (Arabian) coast, where most of the seawater desalination plants are located. The southwest region (shaded with lines) is the Gulf's slow flushing zone; the region shaded with horizontal lines has the largest salt buildup within this zone because of brine discharge [4].

Seawater desalination plants around the Gulf produce about 5 km^3/y of potable water and dispose about 7–10 km^3/y of brine into the Gulf, mostly through nearshore surface discharge [8–10]. This production capacity is projected to double by 2050 (i.e., 5 km^3/y increase above the current production capacity) because of rising freshwater demand in the region [11]. Most of the seawater desalination plants in the Gulf (and all the largest plants) are located near the Gulf's Arabian coast where nearshore topography is complex [12] and salt buildup occurs because flushing is not effective [4]. The various urgent environmental reasons for preventing salt buildup in the Gulf's marine environment have already been discussed [13–21]. Nearshore salt buildup, moreover, promotes corrosion of coastal infrastructure [22,23] and recirculation of brine into intake seawater for desalination plants, which decreases plant efficiency [24–26].

The Gulf is a shallow basin (mean depth is about 35 m) in an arid region. Gulf evaporation (about 1.84 m/y) greatly exceeds freshwater inflow (about 0.28 m/y) from river runoff and precipitation [7,27]. To balance this freshwater deficit, Gulf residual circulation brings seawater from the Indian Ocean into the Gulf through the Strait of Hormuz (in upper layers). Evaporation, however, only removes freshwater and the salt in the seawater brought into the Gulf must be removed, or else salinity will increase indefinitely inside the Gulf. Thus, the salt left behind (after evaporation removes freshwater) is returned to the Indian Ocean as part of this same residual circulation (in bottom layers). The residual circulation spatial structure within the Gulf shows the spatial structure of flushing. Because the residual circulation inhibits salt buildup at the basin scale [4,8], salt buildup in every sub-region within the Gulf necessarily has a limit. But this limit is not the same for all Gulf sub-regions because of differences in regional conditions.

Here, using a coupled Gulf–atmosphere regional model (GARM), we evaluate the impact of brine discharge position on salinity in the Gulf's slow flushing zone by comparing two scenarios of brine discharge into the residual circulation dynamics: (1) a control scenario with brine discharge from the 24 largest seawater desalination plants in the Gulf, and (2) an impact scenario where the brine discharge point of one of the 24 plants is positioned away from the slow flushing zone to a region where flushing is effective. Comparison of the control and impact scenario showed that salt buildup reduced in the impact scenario, which decreased annual area-average salinity in the slow flushing zone by about 1.10–1.55 PSU. Our methodology is summarized next, followed by results, discussion, and conclusion.

2. Methodology

2.1. Model description

Only a brief description of GARM, as related to Gulf flushing, is given here. Descriptions of GARM setup and sensitivity analysis have already been given in great detail elsewhere [4,7]. GARM atmospheric component is the MIT regional climate model (MRCM). MRCM has been used to simulate different types of regional climate [28,29]. Because of the different spatial scales of atmospheric and Gulf circulations, GARM–MRCM is configured to cover a larger domain (29–61°E longitude and 12–40.5°N latitude) with 30 km resolution in 120 × 120 grids. The ocean component of GARM that simulates Gulf hydrodynamics is the finite volume community ocean model (FVCOM), which has been used widely because it has capability to geometrically fit complex topography [30]. GARM–FVCOM has high horizontal resolution (2–3 km nearshore, 5 km offshore, 10–15 km at the open ocean boundary), and high vertical resolution (<1 m nearshore and 1–2 m in most offshore regions). Consequently, GARM–FVCOM is able to simulate many time and space structures of Gulf flushing, especially in the shallow nearshore regions. GARM includes the two-way interaction between its atmosphere and ocean components, with a coupling frequency of 3 h. Recent estimate of Gulf flushing time (to exchange all Gulf waters with Indian Ocean waters) is only about 14 months, and diurnal and seasonal cycles dominate Gulf physical variables variability [7]. Accordingly, the simulation period for the two scenarios in this study is one decade (1981–1990), which is adequate to describe the long-term spatial structure of flushing within the Gulf.

At the open ocean boundary, GARM–FVCOM uses climatological monthly mean fields of temperature [31], salinity [32], and wind (from GARM–MRCM) to dynamically calculate mean flow velocity. Tigris and Euphrates Rivers runoff at the Shatt Al Arab, the main sources of freshwater into the Gulf, was specified based on streamflow statistics [33]. Although there are other smaller rivers from Iran that discharge into the Gulf's northeastern region, these freshwater inputs are order of magnitude smaller (than the Tigris and Euphrates) and are not considered in GARM. The control and impact scenarios in this study were initialized in GARM–FVCOM with the same constant initial salinity (40.1 PSU) and temperature (21.4°C) values.

2.2. Model validation and Gulf flushing spatial structure

First, we run GARM to simulate the circulation, temperature, and salinity of the Gulf. At the climatological monthly time scale, comparison of analysis [34] and simulated Gulf SST (Fig. 2a) shows that GARM reproduces Gulf seasonal heat balance. At this same time scale, comparison of satellite-derived [35] and simulated Gulf sea surface height (Fig. 2b) shows that GARM also reproduces Gulf water balance dynamics as given by seasonal variations of Gulf sea surface height (Fig. 2b): which reflects the seasonal variations of precipitation, evaporation, river runoff, lateral seawater inflow from the Indian Ocean (to balance freshwater deficit), and lateral hypersaline outflow to the Indian Ocean (to remove salt).

Annual basin-average salinity, which varies from a minimum in August to a maximum in December–January, is about 40.5 PSU (Fig. 2c). The largest regional salinity (42 PSU) is in the Gulf's slow flushing zone (Fig. 2d), which is very shallow (Fig. 1). Residual circulation lateral extent and flushing currents varies from a maximum in June to a minimum in November (Figs. 3a and b). Because the flushing currents are weak and do not vary seasonally in the Gulf's slow flushing zone (Figs. 2d and 3a and b), brine discharge into this zone causes large salt buildup there [4]. Guided by this previous work, two brine discharge scenarios were simulated in GARM to quantify impact of brine discharge position on salinity in this zone.

2.3. Method of simulating brine discharge

In seawater desalination, the primary objective is to produce potable water by separating salt from seawater. Introducing V_I (m^3), S_I (g/kg), and ρ_I (kg/m^3) for the volume, salinity, and density of intake seawater for a given plant; V_D

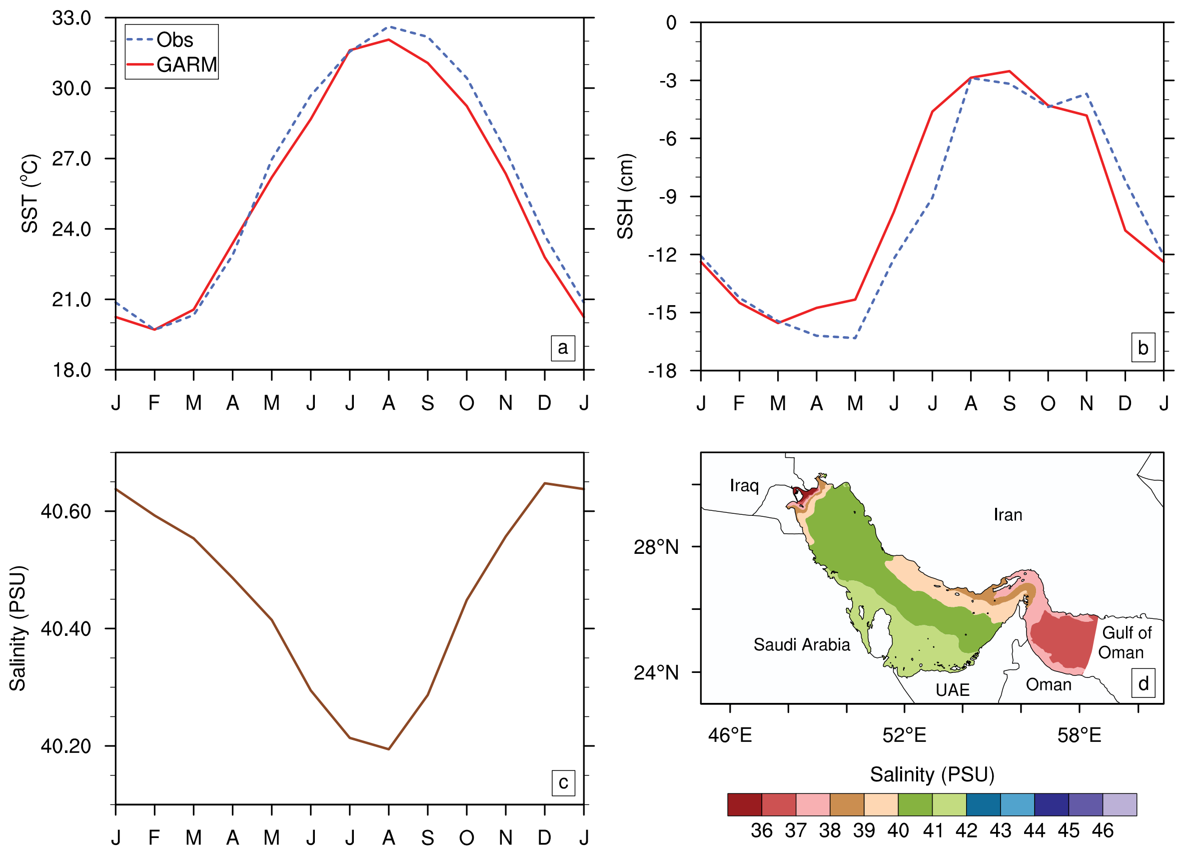

Fig. 2. Gulf residual circulation (RS) dynamical properties [4]. (a) Simulated vs. satellite-derived Gulf sea surface temperature (SST), (b) simulated vs. satellite-derived Gulf sea surface height (SSH), (c) simulated basin-average salinity, and (d) simulated basin-average salinity spatial distribution.

(m^3), S_D (g/kg), and ρ_D (kg/m^3) for the volume, salinity, and density of brine discharged; V_P (m^3) and ρ_P (m^3) for the volume and density of produced potable water; assuming negligible salt content in the produced potable water, the mass of salt in brine discharged into the sea is the same as the mass of salt in the intake seawater, that is, $\rho_I V_I S_I = \rho_D V_D S_D$. But the mass of freshwater in brine is the difference of the mass of freshwater in the intake seawater and mass of produced potable water [4], that is, $\rho_D V_D = \rho_I V_I - \rho_P V_P$. Therefore, regardless of the particular technique employed, the mass exchange cycle between a seawater desalination plant and the oceanic basin where seawater is removed can be described as a freshwater mass sink to that basin (Fig. 4). Because the focus in this study is on long-term flushing dynamics when the Gulf is fully mixed, seawater desalination plants' brine discharges are simulated in GARM as freshwater sinks.

Defined as plants with potable water production capacity ≥10,000 m^3/d, there are 24 large seawater desalination plants in the Gulf: these large plants are all located near the shallow (≤15 m) Arabian coast [37,8]. For practical reasons, and since small seawater desalination plants are assumed here to have negligible impact, only brine discharge from these 24 large plants are considered in this study (Table 1).

2.4. Design of brine discharge scenarios

Two brine discharge scenarios are simulated in GARM. In the first scenario (control scenario), hereafter Experiment 1 (Exp1), brine from the 24 largest seawater desalination plants in the Gulf is introduced into the Gulf's residual circulation dynamics at approximately 2 km offshore (Fig. 5a), based on available design parameters. In the second scenario (impact scenario), hereafter Experiment 2 (Exp2), the brine discharge point of Plant 15 (Table 1) is positioned approximately 77 km offshore (Fig. 5b). Evidently, because local conditions (topography, tide wind,

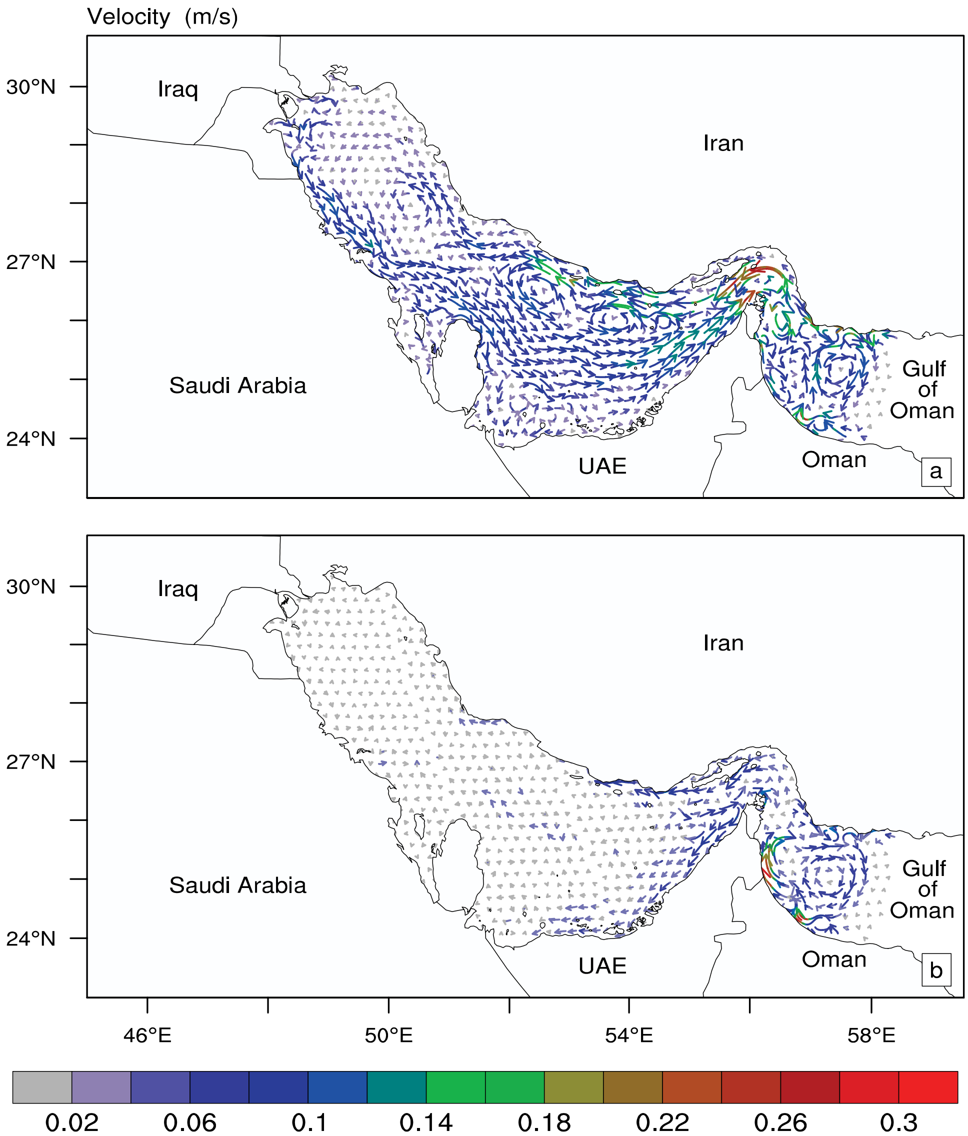

Fig. 3. Gulf residual circulation (RS) horizontal velocity spatial and temporal variation [4]. (a) Depth-average horizontal velocity when RS lateral extent is maximum in June and (b) depth-average horizontal velocity when RS lateral extent is minimum in November.

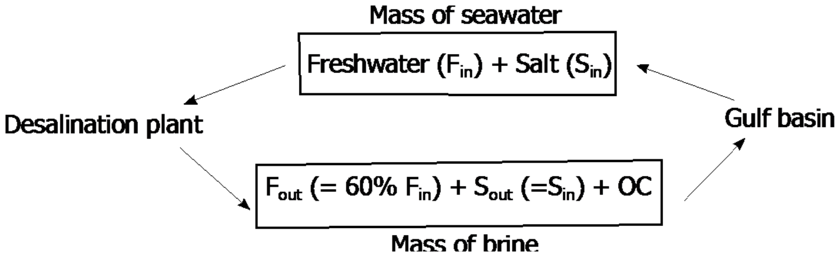

Fig. 4. Schematic of mass exchange cycle between a seawater desalination plant and an oceanic basin. From the point of view of the desalination plant: F_{in}, freshwater mass in the intake seawater; F_{out}, freshwater mass in brine discharged; S_{in}, salt mass in intake seawater; S_{out}, salt mass in brine discharged; OC, mass of other constituents (of brine); 60% is the proportion of F_{in} that remains in brine, based on a plant potable water recovery ratio of 40% [36].

Table 1
Largest (capacity ≥1,00,000 m^3/d 24 seawater desalination plants in the Gulf [4]

Plant ID	Country	Plant Latitude/Longitude (°)	Capacity (m^3/d)	Status
1	Bahrain	26.25/50.61	2,72,760	O
2	Bahrain	25.96/50.65	2,18,000	O
3	Bahrain	26.24/50.65	1,36,380	O
4	Kuwait	28.74/48.39	6,22,400	O+C
5	Kuwait	29.64/48.15	4,54,600	O
6	Kuwait	29.36/47.97	2,27,300	C
7	Kuwait	29.04/48.13	2,04,390	O
8	Kuwait	29.34/47.94	1,36,260	O
9	Kuwait	28.70/48.37	2,61,840	O
10	Qatar	25.92/51.54	7,41,160	O
11	Qatar	25.28/51.53	5,45,250	C
12	Qatar	25.19/51.61	6,54,606	O
13	Saudi Arabia	26.89/49.77	1,011,814	O+C
14	Saudi Arabia	27.53/49.14	1,025,000	O+C
15	Saudi Arabia	26.17/50.20	4,32,580	O
16	UAE	25.05/55.11	6,36,440	O
17	UAE	24.16/52.56	9,13,346	O
18	UAE	25.30/56.35	8,74,460	O
19	UAE	24.81/54.74	1,226,950	O
20	UAE	24.43/54.51	5,03,061	O
21	UAE	25.32/56.37	3,06,500	O
22	UAE	24.09/53.49	1,40,000	C
23	UAE	24.12/53.43	1,02,144	O
24	UAE	25.79/55.94	1,00,000	C

O, plant is online; C, plant is under construction; O+C, plant is being expanded; and UAE, United Arab Emirates.

bathymetry, etc.) modify flushing currents, brine outfall length in practice will vary from place to place. For a given plant in the Gulf, the "best" brine discharge position is in the region closest to the plant where salt buildup capacity is smallest: this region must exist because the Gulf's residual circulation imposes a limit on basin (and therefore regional) salt buildup. The choice of D2 is intended here only to emphasize differences in flushing effectiveness within the Gulf.

Based on analysis of Exp1 results, and to account for upstream contribution of brine, Plant 15 was chosen to test the sensitivity of the Gulf's slow flushing zone to brine discharge position because this plant is immediately upstream of the slow flushing zone. The choice of Plant 15 discharge position in Exp2 is based on three reasons: (1) compared to Plant 15 discharge position in Exp1 (D1), Plant 15 discharge position in Exp2 (D2) is in a deeper Gulf region (Fig. 5c), and (2) although D1 and D2 are both in the Gulf's slow flushing zone (Figs. 1 and 2d), seasonal flushing is stronger in D2 area compared to D1 area (Fig. 3a). Starting in 1983, Plant 15 produced freshwater at a rate of 191,780 m^3/d, but after expansion in 2002, freshwater is produced now at a rate of 432,580 m³/d. Plant 15 uses a multi-stage flash distillation desalination technique, which produces brine at about 2–3 times the potable water production rate [36].

2.5. Methods of brine discharge impact analysis

Because salinity may be viewed as a conservative tracer indicating the time and space structure of Gulf residual circulation and because the focus here is on regional salt buildup, Exp1 and Exp2 results are compared by analyzing time series of area-average salinity for three Gulf areas: (1) entire Gulf basin up to the Strait of Hormuz (Fig. 1), hereafter "basin"; (2) Gulf slow flushing zone area with the largest salinity, the region between the coasts of Saudi Arabia, Bahrain and Qatar, hereafter "Reg1" (Fig. 1); and (3) Gulf region 20 km offshore the Arabian coast where the largest 24 seawater desalination plants in the Gulf discharge brine, hereafter "Reg2." Because the only factor that differentiates Exp1 and Exp2 is Plant 15 discharge position, a one-way analysis of variance (ANOVA) is performed to compare impact of brine discharge position on area-average salinity in Exp1 and Exp2, for each of the three areas chosen for impact analysis. Thus, the ANOVA statistical analysis tests the null hypotheses given in Eqs. (1)–(3):

$$H_{0,\text{basin}} : \mu_1 = \mu_2 \quad (1)$$

$$H_{0,\text{Reg1}} : \mu_1 = \mu_2 \quad (2)$$

$$H_{0,\text{Reg2}} : \mu_1 = \mu_2 \quad (3)$$

where μ is area-average salinity in Exp1 and Exp2 for the three areas, respectively.

3. Results

Because of brine discharge in Exp1, salinity increased in the Gulf's slow flushing zone in a spatially non-uniform manner (Figs. 2d and 6a). Change in Plant 15 discharge position in Exp2 does not significantly affect basin-average salinity (Fig. 6b): compared to Exp1, only in the last six years of Exp2 simulation did the difference between annual maximum and minimum basin-average salinity (salinity seasonal cycle amplitude) decrease by only 0.07 PSU.

Comparison of Exp1 and Exp2 shows that change in Plant 15 brine discharge position caused salt buildup to decrease in the Gulf's slow flushing zone, mostly in Reg1 (Figs. 6c and d). Annual area-average Reg1 (Fig. 7a) salinity decreased by about 1.3 PSU (Fig. 7b) in Exp2, and Reg1 salinity seasonal cycle amplitude is significantly smaller compared to Exp1 (Fig. 7b).

The smallest change in Reg1 salinity (about 1.05 PSU) occurred in May–June (Fig. 7c), when residual circulation flushing is strongest (Fig. 3a), while the largest change in Reg1 salinity (about 1.55 PSU) occurred in November–December (Fig. 7c), when residual circulation flushing is weakest (Fig. 3b). Reg2 (Fig. 7d) annual area-average salinity decreased by about 0.3 PSU (Fig. 7e) in Exp2, and Reg2 salinity seasonal cycle amplitude is similar to Exp1 (Fig. 7e). Like Reg1, the smallest change in Reg2 salinity (about 0.26 PSU) is in May–June, while the largest change in Reg2 salinity (about 0.39 PSU) is in November–December (Fig. 7f).

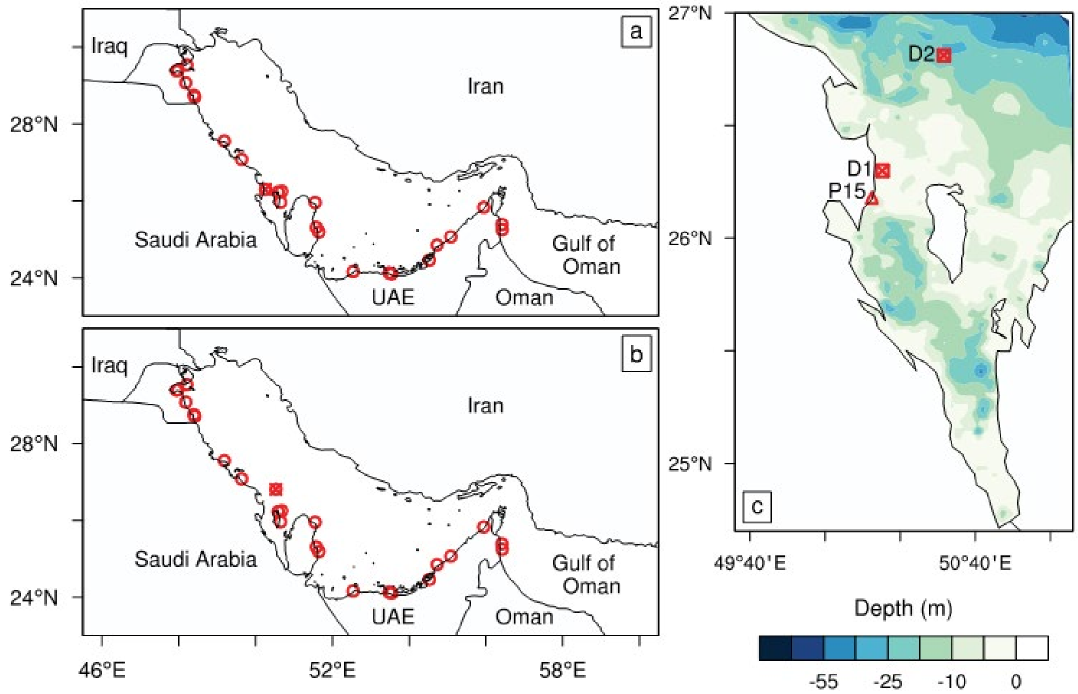

Fig. 5. Design of brine discharge scenarios. (a) Exp1: brine discharge points for the 24 largest plants in the Gulf are positioned approximately 2 km offshore, (b) Exp2: brine discharge point of Plant 15 (square marker) is positioned approximately 77 km offshore where water depth is up to 25 m and flushing is strong, and (c) Plant 15 depth at first discharge position (D1) and second discharge position (D2).

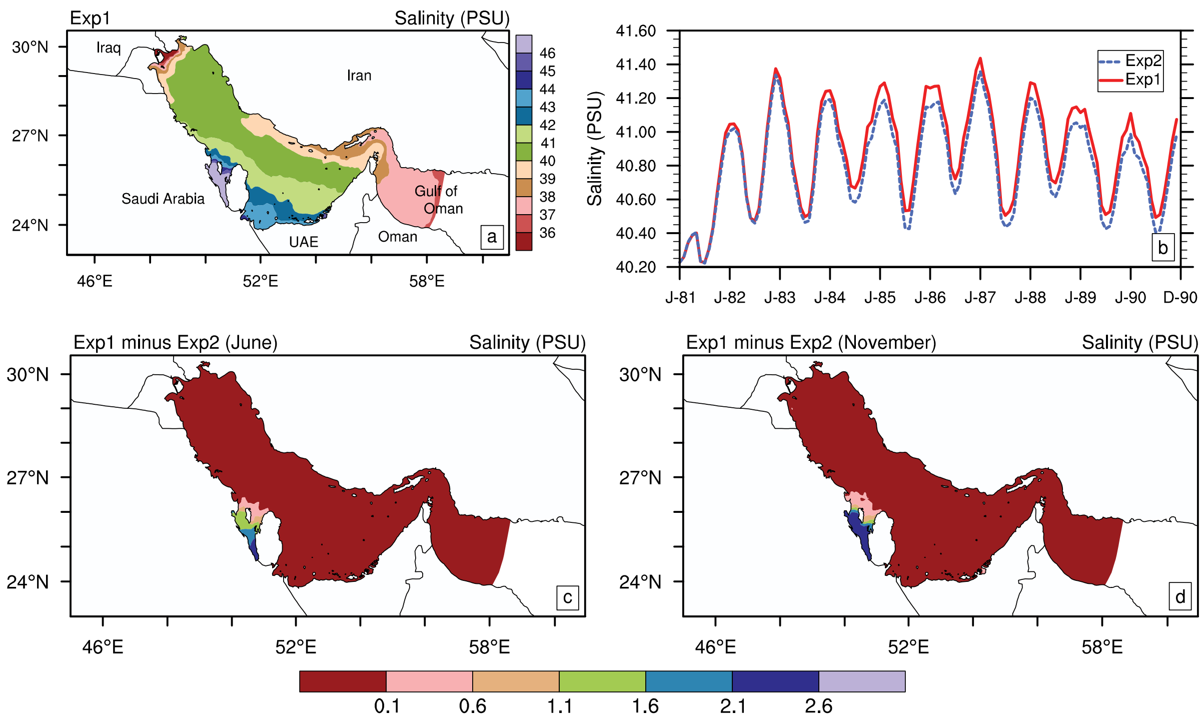

Fig. 6. Gulf salinity characteristics in Exp1 and Exp2. (a) Depth-and-time average salinity in Exp1, as in [4], (b) monthly time series of Gulf basin-average salinity in Exp1 and Exp2 (J = January; D = December), (c) depth-and-time average difference of salinity (Exp1 minus Exp2) in June when flushing by RS is strongest (Fig. 3a), and (d) same as (c), but in November when flushing by RS is weakest (Fig. 3b).

But most of decrease in salt buildup that caused Reg2 salinity to decrease occurred in Reg1 (Figs. 6c and d).

4. Discussion

The two main reasons for salt buildup in the Gulf's slow flushing zone are [4], (1) this region has several deep depressions of up to 25 m deep that are surrounded by shallow waters of only 5 m deep (Fig. 1 and 5c), which promotes salt trapping in the deep depressions and (2) these deep depressions are separated from the east-bound flushing currents of the Gulf's residual circulation by shallow waters that prevent interaction between brine discharge into the Gulf's slow flushing zone and the residual circulation (Figs. 1 and 3a and b). One-way ANOVA does not reject the null hypothesis in Eq. (1): impact of brine discharge position on basin salinity was not significant, $F(2,238) = 3.69$, $p = 0.055$ (Table 2). But one-way ANOVA rejects the null hypothesis in Eqs. (2) and (3): impact of brine discharge position on salinity was significant in Reg1, $F(2,238) = 89.37$, $p = 0.000$; and Reg2, $F(2,238) = 34.36$, $p = 0.000$ (Table 2). Thus, brine discharge position determines whether and to what extent salt buildup occurs in the Gulf's slow flushing zone.

Comparison of Exp1 and Exp2 shows that seasonal Reg1 flushing by the Gulf's residual circulation, as reflected in the large Reg1 salinity seasonal cycle amplitude, is effective only in Exp1 (Fig. 7b). In other words, annual Reg1 salinity reached an upper limit of about 46.5 PSU in Exp1 before the residual circulation flushing prevents additional salt buildup. Therefore, because the effectiveness of flushing by the Gulf's residual circulation can be inferred from the salinity seasonal cycle amplitude, the results here highlight the importance of collecting salinity samples to establish this seasonal cycle before selecting a brine discharge position.

The main contribution of this study is a practical methodology for selecting brine discharge position that minimizes salt buildup in the Gulf's slow flushing zone. To facilitate illustration of this methodology, the slow flushing zone is partitioned into four critical zones of decreasing sensitivity to brine discharge from the Arabian coastline (Fig. 8): in Exp1 D1 is in zone 4, and in Exp2 D2 is in zone 1 (Figs. 5a–c and 8). Consider Qatar, for example, with borders adjacent to critical zones 1–4. Because the northern Qatar region is adjacent to critical zone 1, which is least sensitive to brine discharge (Fig. 8), this region is the best location to discharge brine from seawater desalination plants in Qatar. Moreover, Bahrain, Saudi Arabia, and the UAE also have access to more than one critical zone, which suggests the best locations to discharge brine from plants in these countries.

For any number of possible brine discharge positions under consideration, a two-step methodology can be applied to identify the best of all the possible discharge positions: (1) obtain salinity samples and establish the salinity seasonal cycle at each position and (2) select the position with the largest salinity seasonal cycle amplitude, which corresponds to the position with the strongest seasonal flushing by the Gulf's residual circulation. This methodology is more suitable for new seawater desalination plants because modifying the brine discharge position of an existing plant is difficult

Table 2
ANOVA summary: impact of brine discharge position on salinity

Gulf region	Scenarios		Mean difference	95% Confidence interval		*P*-value
				Lower bound	Upper bound	
Basin	Exp1	Exp2	0.0720	–0.0014	0.1455	0.055
Reg1	Exp1	Exp2	1.2803	1.0149	1.5457	0.000
Reg2	Exp1	Exp2	0.3200	0.2130	0.4270	0.000

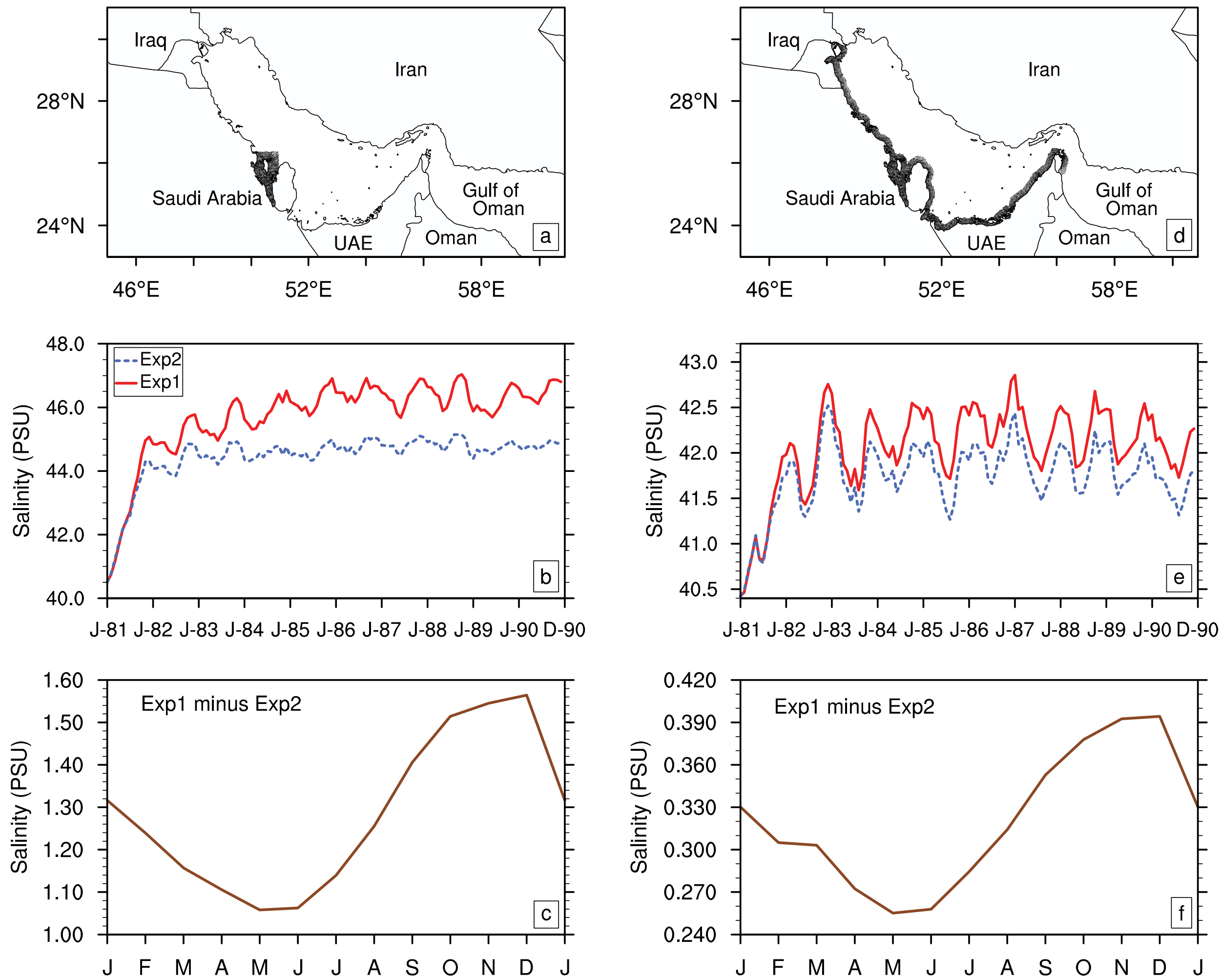

Fig. 7. Gulf Arabian coast nearshore salinity characteristics in Exp1 and Exp2. (a) Reg1 (shaded), where salinity and salt buildup is largest, (b) monthly Reg1 salinity, (c) seasonal Reg1 salinity difference between Exp1 and Exp2, (d) Reg2 (shaded), region 20 km offshore from the Arabian coast, (e) monthly Reg2 salinity, and (f) seasonal Reg2 salinity difference between Exp1 and Exp2.

and expensive. However, an environmental monitoring program is vital to assess environmental performance of a marine outfall [38–42], and relocation of marine outfall farther offshore in order to reduce nearshore effluent buildup is sometimes necessary, as was the case for Boston's sewage outfall [41]. Consequently, the methodology given here can be used iteratively [42–44]; first to select initial brine discharge position, and second, to evaluate and modify (if necessary) this initial discharge position.

Brine discharge position that is far from shore has a higher capital (fixed) cost. But it is sometimes necessary to put brine farther offshore in order to avoid recirculation of brine into intake seawater [44,45]. No two-seawater desalination plant are alike, and the optimal brine discharge position depends on a variety of site-specific factors [25,46]. The energy (electrical power in kilowatt-hour) required to desalinate seawater is an operating cost. Accordingly, only a plant-specific life-cycle cost analysis will establish the fixed

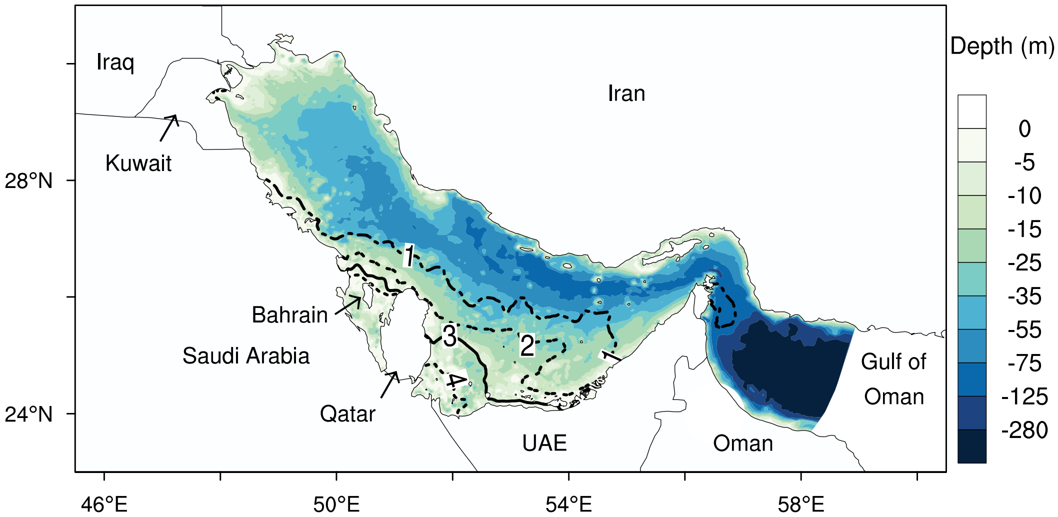

Fig. 8. Gulf critical zones of decreasing sensitivity to brine discharge (derived by subtracting Fig. 2d from Fig. 6a). Black lines are salinity contour lines enclosing Gulf slow flushing zone subregions in decreasing order of sensitivity to brne discharge, from high (4 PSU) to low (1 PSU) sensitivity; in Exp1, Plant 15 discharge position (D1) is zone 4, while in Exp2, the discharge position (D2) is in zone 1.

and operating cost differential between putting brine farther offshore and the additional energy required to desalinate high-salinity seawater resulting from brine recirculation.

Based on 20 existing seawater reverse osmosis desalination plants, constructed between 2005 and 2010, with potable water production capacity of 40,000 m^3/d or more, the industry average energy use for producing potable water is 3.1 kWh/m^3; and by using lower-salinity intake seawater the potential for energy savings is over 50% [25]. For these same types of plants, the fixed cost, operating cost, and energy cost/operating cost breakdowns are 35%, 65%, and 54%, respectively [47]. Because brine outfall is only one of the numerous facilities associated with the fixed cost, the additional expense to increase brine outfall length is unlikely to significantly affect unit product cost of potable water. Hence, for both existing and future seawater desalination plants in the Gulf, application of the methodology given here for selecting brine discharge position can yield considerable energy cost savings for desalination of Gulf seawater.

5. Conclusion

Impact of brine discharge position on salinity in the Gulf's slow flushing zone was evaluated using control and impact scenarios of brine discharge into the Gulf's residual circulation dynamics. Salt buildup in this zone is sensitive to brine discharge position only up to a limit, after which the Gulf's residual circulation flushing prevents further salt buildup. A practical methodology for selecting brine discharge position that minimizes salt buildup in this zone is investigated. Unlike salt, other brine constituents are foreign to the marine environment. Accordingly, in addition to energy cost savings resulting from avoiding brine recirculation into intake seawater, selecting brine discharge positions that minimize buildup of salt and other brine constituents is vital for preventing costly environmental problems to Gulf marine life.

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