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Estimation of salinity, heat and buoyancy budgets of the inflow coastal current into the Persian Gulf from the Strait of Hormuz

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ABSTRACT: An analytical model for a coastal boundary current was used to investigate heat and salt budget of exchange flows in the Persian Gulf as a marginal sea. Coastal boundary currents exchange heat and freshwater with the atmosphere and the offshore waters. As heat and salinity fluxes caused by air-sea interaction and eddy activities, different temperature and salinity associated with boundary currents are adjusted on different length scales. Results obtained from the model show that the temperature and salinity length scales of coastal boundary current are 455 km and 914 km, for summer respectively for summer. In summer the inflow current density initially decreases to a local minimum and then increases, and finally flowing out the basin area with higher density than that of for the inflow. In winter, the estimated temperature and salinity length scales of coastal boundary current are 60 km and 64 km, respectively. In this season, density increases at the beginning with a steep slope and reaches a constant value and, finally the current flows out of the basin area.

Keywords: *Boundary current,; temperature and salinity length scale,; eddy transport, ; Ekman transport*

INTRODUCTION

Coastal boundary currents interacting with the atmosphere communicate heat, salinity and buoyancy with offshore water through ocean circulations. Concept known as large-scale thermohaline circulations taking place as horizontal circles on marginal seas has been studied by others as Mauritzen (1966). Based on his observations, Mauritzen showed that the dense waters feeding flows from the Strait of Denmark comprise of Atlantic surface waters. This dense waters play a key role in meridional reverse flows of the Atlantic, carrying heat to the north while keeping the climate in Europe adjusted (Mauritzen, 1966; Straneo, 2006). In this study, mass transport was assumed fixed across the seashore and along boundary current within the basin area. Bidokhti and Ezam (2009) used CTD data and an analytical model to determine outflow structure of the Persian Gulf. They showed that outflow from the Persian Gulf affects physical properties of waters coming from Oman Sea in different ways throughout the year. Then, by using a simple dynamic model based on a conservation of potential vorticity, they made an estimation of the outflow of the Persian Gulf. On this, the outflow discharge from the Persian Gulf was estimated to be about 0.4 Sv which is the highest of all values reported. It is likely due to the fact that friction effect has not been incorporated into the model used while the outflow is influenced by bottom friction (Bidokhti and Ezam, 2009).

Hasanzadeh and Khodabakhsh (2002) investigated the sea surface temperature (SST) and Ekman transport in the Persian Gulf. In this research, water motion caused by wind stress on the ocean surface has been explained by Ekman theory. Ekman transport across the Persian Gulf has been calculated using wind stress mean values and SST values, and mapped on a network grid covering the whole area.

Ezam *et al*. (2010) studied the outflow from the Persian Gulf into Oman Sea using a 3D model that included the analyses of water exchange through the Strait of Hormuz. They showed that the surface inflow, through

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the Strait of Hormuz moves along the Iranian sea shores into the Persian Gulf, while the outflow that is initiated from at least, two paths inside the Persian Gulf sinks and move out of the Gulf as a deep outflow. These outflows also show seasonal changes in the Oman Sea (Ezam *et al.*, 2010).

Using a method called balanced temperature, Abualnaja (2009) estimated heat budget of the Persian Gulf. It will be pointed out that surface temperature in this study is higher than the balanced temperature in the northern area of the Persian Gulf, indicating that this region loses heat; while, in the southern area, the process is reverse, indicating that this region absorbs heat at the sea surface.

Wahlin and Johnson (2009) presented an analytical model for heat and salinity budgets of an inflow coastal current moving into a semi-closed ocean basin. They showed that since heat and salinity fluxes caused by the air-sea interaction are different at the sea surface, temperature and salinity are adjusted on different length scales.

In this paper, the bases of the analytical model developed by Wahlin and Johnson (2009) for a marginal sea are explained first; then, processes affecting the changes in salinity, temperature and, accordingly, buoyancy of the coastal boundary current flowing into the Persian Gulf is estimated using this model. At the end, a comparison is made between inflow and outflow currents in terms of their properties.

MATERIALS AND METHODS

2-1-1. Heat, Freshwater and Buoyancy Budgets

A schematic presentation of a coastal boundary current moving into a semi-closed sea basin with a mass transport along the seashore of Q, that could be changed by wind, river flow, precipitation and eddy mixing from the offshore water is shown in figure Fig. 1.A. throughout the basin the mass transport is assumed independent of buoyancy, and the width and length of the boundary current are, R and LB respectively. The boundary current exchanges heat and moisture with the atmosphere and with the interior water of basin until it is fully adjusted. Exchanges with the atmosphere are considered as being direct, while those with the interior of the area as sum of eddy and Ekman transports (Whalin and Johnson, 2009).

2-1-1-1.1. Freshwater Budget

Figure Fig. 1.B depicts a scheme of the coastal boundary current and processes affecting its salinity. Freshwater with a constant F rate (m^2s^{-1}) per unit length of the boundary current is added to each unit of length for the boundary current which shows the effects of rainfall and currents with low salinity (runoff) running into the basin. Also, the total exchange of the current with the water contained in the basin is defined as $M=M_{EDDY}+M_{EK}$, where M_{EDDY} is the mass transport per unit length of the boundary current caused by eddy transport, M_{EK} is wind-driven Ekman exchange, and S_{INT} is the salinity of water inside the basin influenced by evaporation;, hence the salinity budget of the current as a one dimensional bulk model, is:(Wahlin and Johnson, (2009))

$$Q\frac{ds}{dy} = -M(S - S_{INT}) - FS \qquad (1)$$

which Q is the boundary current transport, y is the coordinate along the current, S is the average salinity of the boundary current and $S_0=S$ is the salinity associated with the inflow; that is, where $y=0$. Equation Eq. (1) can also be formulated as below:

$$\frac{ds}{dy} = \frac{-S}{L_s} + \frac{S_{INT}}{L_E} \qquad (2)$$

in which:

$$L_S = \frac{Q}{F+M} \quad , \quad L_E = \frac{Q}{M} \qquad (3)$$

are proper length scales of for the problem; and (2) is solved as follows:

$$\delta\, S(y) = \delta S_0\, e^{-\frac{y}{Ls}} \qquad (4)$$

in which:

$$\delta S = S - S_{EQ} \; and \; \delta S_0 = S_0 - S_{EQ} \qquad (5)$$
$$S_{EQ} = S_{INT}\frac{L_S}{L_E} = S_{INT}\left(\frac{1}{1+\frac{F}{M}}\right)$$

Equation Eq. (5) reveals that if F/M is small, $S_{EQ}=S_{INT}$, i.e., equilibrium salinity equals the inside salinity of the basin; for great values of F/M, however, S_{EQ} will be lower than the inside salinity of the basin. Q being increased and/or M and F being decreased giving rise to salinity length scale, L_S. So, it can be concluded that the major boundary current with low exchange within the basin or with the atmosphere need more time to achieve equilibrium salinity. So the approximate salinity S_{EQ} (equilibrium salinity) is tied with the relative value of L_S (salinity length scale) and L_B (boundary current length). When $L_B/L_S >> 1$, the basin will be well adjusted at some distance along the coast to the value of that of inside the basin so that $S_{EQ}=S_{out}$, i.e, equilibrium salinity will be equal to the salinity of the outflow current.

When $L_B/L_S < 1$, however, the outflow salinity does not attain the equilibrium value. When adjusted, the salinity associated with the coastal boundary current may increase or decrease depending on y. If boundary currents are initially more fresh than the water inside the basin; that is, $S_0 < S_{INT}$ (inflow salinity is lower than that of the interior), exchange with the interior will increase the salinity of the boundary current. When $S_0 < S_{EQ}$, i.e. inflow salinity is lower than equilibrium salinity, the net salinity of the current will increase. When $S_0 = S_{EQ}$, i.e. the input salinity is equal to equilibrium salinity, and then the salinity associated with boundary currents will not change.

2-1-2-1.2. Heat Budget

Figure Fig. 2 illustrates side view and top view plan of a boundary current along with the heat-affected processes thereof. A stable mode of heat budget of the current can be formulated again as:

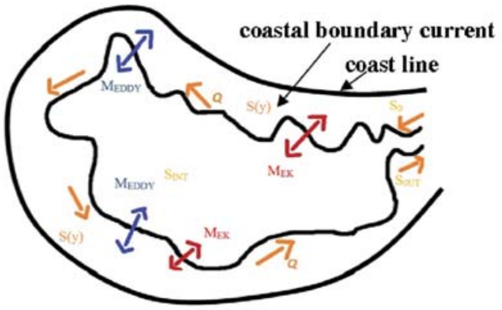

Fig. 1: Processes affecting the salt budget along of a coastal the boundary current.

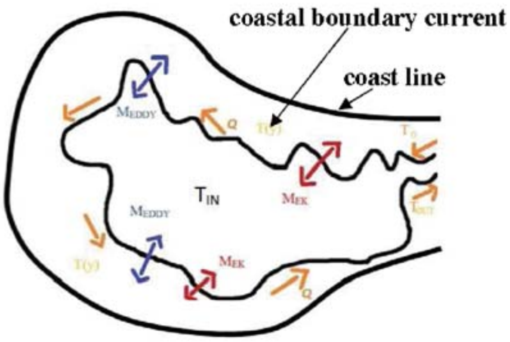

Fig. 2: Processes affecting the heat budget along of a coastalthe boundary current.

$$Q\frac{dT}{dy} = -R\gamma_A(T-T_{air}) - M(T-T_{\text{int}}) \tag{6}$$

where R and γ_A *(m/S)* are the width of the boundary current and heat temperature relaxationexchange coefficient, respectively.

T_{AIR} is the air temperature that can be different from the temperature of boundary current, TINT is the temperature inside basin, and $T=T_0$ (where $y=0$) is the inflow temperature. Equation Eq.(6) is also expressed as:

$$\frac{dT}{dy} = -\frac{T-T_{AIR}}{L_A} - \frac{T-T_{INT}}{L_E} \tag{7}$$

in which:

$$L_A = \frac{Q}{R\gamma_A} \tag{8}$$

As before, $L_E=Q/M$, which is the length scale of the interior, and L_A is caused by atmospheric forcing. Equation Eq. (7) is solved as:

$$\delta T_{(Y)} = \delta T_0 e^{\frac{-y}{L_T}} \tag{9}$$

in which:

$$\delta T = T - T_{eq}$$
$$\delta T_0 = T_0 - T_{eq} \tag{10}$$

$$T_{eq} = \frac{L_E T_{AIR} + L_A T_{INT}}{L_E + L_A} = \frac{T_{AIR} + T_{INT}\dfrac{M}{R\tilde{a}_A}}{1+\dfrac{M}{R\tilde{a}_A}} \tag{11}$$

Like salinity, Equation Eq. (9) gives an exponential adjustment of the inflow temperature to length scale LT proportional to the equilibrium temperature T_{eq}.

2-1-3-1.3. Buoyancy Budget

Buoyancy of the boundary current is defined by the equationEq :

$$\rho(S,T) = \rho_o(1+\beta S - \alpha T) \tag{12}$$

Where $\alpha = 2\times10^{-4}{}^{\circ}C^{-1}$, $\beta = 8\times10^{-4}\ psu^{-1}\alpha$

in which $\rho_0 = 1000\,kg/m^3$ is the density reference of water, α is coefficient of thermal expansion, and β is coefficient of salinity. Normal density difference is formulated using (4) and (9) as below:

$$B(y)=\frac{\rho(y)-\rho_0}{\rho_0}=\beta(S_{EQ}+\delta S_0\, e^{\frac{-y}{LS}})-\alpha(T_{EQ}+\delta T_0 e^{-y/L_T}) \quad (13)$$

$$\Delta B(y)=B(y)-B(0)=B\delta S_0(e^{-\frac{y}{L_s}}-1)-B\delta T_0(e^{-\frac{y}{L_T}}-1) \quad (14)$$

Divided by $B\delta S_0$, it will be as follows:

$$\Delta\hat{B}=e^{-\hat{y}}-1-E(e^{-\frac{\hat{y}}{\eta}}-1) \quad (15)$$

where:

$$\Delta\hat{B}=\frac{B(y)-B(0)}{\beta\,\delta S_0} \qquad E=\frac{\alpha\delta T_0}{\beta\delta S_0} \quad (16)$$
$$\eta=\frac{L_T}{L_S}=\frac{F+M}{R\gamma_A+M} \quad \hat{y}=\frac{y}{L_S},L_B=\frac{L_B}{L_S}$$

Dimensionless density difference $\Delta\hat{B}$ is a function of parameters E and . E describes temperature and salinity adjustment, and the value assigned to E indicates how important adjusting temperature to salinity adjustment for density is. If $|E|>1$, the deviation of primary temperature from equilibrium condition will have a greater impact than that of primary salinity, on the density. But if $|E|>1$, the deviation of primary salinity will have a greater impact than temperature on density.

Parameter η is the ratio of two scales, i.e. L_T and L_S, that is simply tied with the relative force of the transport through exchange with the atmosphere or inside the basin. If there is no exchange inside, then, $\eta = F / R\gamma_A$, $M = 0$. But if there is exchange with the interior, then:

$\eta \to 1,\ M > R\gamma_A,\ M > F$;

as a result, when atmospheric forcing is missing, temperature and salinity both will be adjusted on the same length scale. If $F / R\gamma_A < 1$ ($0<\eta<1$), i.e. when only atmospheric forcing is present, the temperature of boundary current is adjusted faster than salinity.

3-2. The Region of Study

Region under study covers some area of the Persian Gulf located between latitude 24-28˚ *N* and longitude 51-56˚ *E* (Figure Fig. 3). the northern part of the Persian Gulf is separated from the south by the front extending to Qatar, which is usually high under the extreme hot condition in summer and low under the cold condition in spring and winter (at least in terms of surface temperature). This front, separates the incoming inflow currents from the Strait of Hormuz, from the inside water of the Persian Gulf and can be spotted by climate hydrology and SST remote sensing data.

Evidences indicate a counter-clockwise inflow current (a cyclonic current) in the eastern area of the central front of the Persian Gulf and also an outflow current at the head of Musanden peninsula in the eastern area of the front located on the northern Oman Gulf. High levels of evaporation create a reverse delta circulation in the Gulf, with the outflow leaving the Persian Gulf through deep waters of the Strait of Hormuz. According to salinity and SST background data, the main source of outflow waters of the Persian Gulf lies on a region of salt waters extending from eastern Qatar to shores of UEA (Sadrinasab and Kampf, 2004).

Based on the studies by Johns *et al*. (1999) and other research performed on an existing salinity front extending from the floor of the Persian Gulf towards Oman Sea throughout the year, a boundary current could be assumed in the south (eastern) half of the Persian Gulf, and, applying the hypotheses below, a study could be conducted using the same analytical model developed by Wahlin and Johnson (2009).

1.Length of the boundary current will be set equal to the length of the region under study.

2.To measure the fresh inflow waters, the whole basin area (all rivers and total rainfall) of the Persian Gulf will be concerned.

As the total length of the Persian Gulf has been estimated to be 3000 km and as the southern part is under question here (due to the existing salinity front), the length of the outgoing boundary current can be set to about half length of the Persian Gulf and equal to 1500 km*: LB*=1500 *km*.

RESULTS AND DISCUSSION

To use this analytical model for estimating the heat, salinity and buoyancy budgets of coastal boundary current, the parameters required for the model have been gathered and estimated according to previous studies and several field measurements already taken. Briefly speaking, values obtained from these parameters in winter and in summer as well as references related thereto have been shown in Table 1.

After applying the required parameters in accordance with Table 1, appropriate length scales for adjusting temperature and salinity of the inflow boundary current in the Persian Gulf in winter and in summer can be estimated (Equ.s 4, 9 and 15); the calculated parameters have been given in Table 2.

4.1-3.1. Changes of Salinity in the Coastal Boundary Current

To estimate changes of salinity in boundary current, first S_{EQ} (equilibrium salinity) and then $\delta\ S_0$ is

Table 1: Selected parameters for the Persian Gulf including the relevant references

Parameter	Summer	Winter	References
$L_B(m)$	1.5 × 106	1.5 × 106	Dubach, 1964
$Q(sv)$	0.2	0.2	Johns, 1999
$R(m)$	2.3 × 104	2 × 104	Bidokhti and Ezam, 2009
$S_{INT}(psu)$	38	38.5	Bidokhti and Ezam, 2009
$S_0(psu)$	37	37	Dubach, 1964
$T_{INT}(^\circ C)$	29	20	Bidokhti and Ezam, 2009
$T_0(^\circ C)$	30	20	Dubach, 1964
$T_{AIR}(^\circ C)$	33.4	17.2	Ahmad and Sultan, 1990
$F(m^2s^{-1})$	0.0028	0.0028	Johns 1999, Dubach, 1964, Ebrahimi, 2002 Sadinasab and Kampf, 2004,
$M(m^2s^{-1})$	0.216	3.122	Hasanzadeh and Khodabakhsh, 2001
$\gamma_A(m/s)$	9.7 × 10-6	9.7 × 10-6	Abualnaja 2009, Wahlin and Johnson, 2009

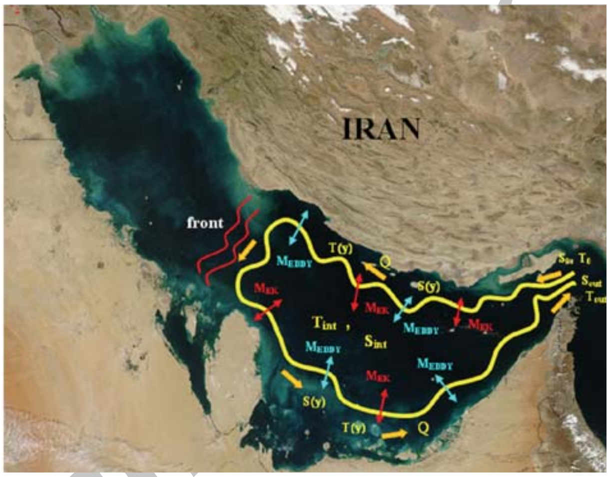

Fig. 3: The overall circulations in the Persian Gulf and existing salinity front, with the coastal boundary current.

Table 2: Parameters calculated for winter and summer.

Parameter	Summer	Winter
$M(m^2s^{-1})$	0.216	3.122
$L_S(km)$	914	64
$L_E(km)$	925	64
$L_T(km)$	455	60

calculated according to equations Eq.s (1) to (5), and, at the end, δS for the whole region could be set and the salinity can be estimated at different points along the boundary current.

In winter, the input salinity was set to S_0=37 *psu* (Fig. 4). It is 38.47 psu for S_{EQ} and -1.47 *psu* for δS_0. As $L_B / L_S >> 1$, the basin is completely adjusted then and it is concluded that $S_{EQ} = S_{out}$. Therefore, based on the values obtained in winter, the basin is completely adjusted and output salinity equals equilibrium salinity. So to speak, $\partial S_{out} / \partial S_0 = 0$, which means that inflow salinity has no effect on outflow salinity in this condition. Our calculations reveal that in winter the outflow is by 1.47 *psu*, on the values assigned, more saline than the inflow, running into the basin.

In summer, the input salinity was set to S_0=37 *psu*

(Figure Fig. 5). It is 37.51 *psu* for S_{EQ} and -0.51 *psu* for ∂S_0 . In this season, as we move along coastal boundary current, salinity increases so that salinity of the outflow current is ultimately measured as 37.41 *psu*. Our calculations reveal that in summer the outflow is by 0.41 *psu*, on the values assigned, more saline than the inflow, running into the basin.

4.2-3.2. Changes of Temperature in the Coastal Boundary Current

Changes of temperature along boundary current in summer and in winter were estimated according to equations Eq.s (6) to (12). In winter, the inflow temperature was set to $T_0 = 20^\circ C$ (Figure Fig. 5). It is 19.84˚*C* for T_{EQ} and +0.16˚*C* for δT_0. After the boundary current is completely adjusted then $T_{EQ}=T_{out}$. Therefore, based on the values obtained for winter time, the boundary current is completely adjusted and outflow temperature equals to the equilibrium temperature. So to speak, $\partial T_{out} / \partial T_0 = 0$, which means that inflow temperature has no effect on outflow temperature in this condition. It seems that changes in temperature of inflow and outflow waters in winter are slight; although, waters leaving the basin are colder than waters flowing in by about 0.2˚*C* according to our calculations.

In summer, the inflow temperature was set to $T_0 = 30^\circ C$. It is 31.24˚*C* for T_{EQ} and -1.24˚*C* for δT_0 . In this season, as we move along boundary layer, temperature increases so that temperature of the outflow current is ultimately reached 31.19˚*C* in summer (Fig. 5). In summer time, the processes affecting the changes in temperature along boundary layer are such that there will be some increase in temperature of the inflow compared to that of outflow current and, the latter being warmer than the former by 1.2˚*C*.

4.3-3.3. Changes of Buoyancy Budget in the Coastal Boundary Current

Buoyancy budget along boundary layer was measured for the inflow and outflow currents in summer and winter time according to equations Eq.s (13) to (14) and parameters specified for the Persian Gulf.

Here, changes in buoyancy for both winter and summer time in the region of the Persian Gulf were independently investigated. In winter, salinity, temperature and density associated with the inflow current was estimated to be 37 psu, 20˚*C* and 1025.6 Kg/m^3, respectively (anywhere in the boundary current the amount of density is calculated based on salinity and temperature using equation Eq.(13)). In winter , salinity is completely adjusted and, achieving an equilibrium value estimated to be 1026.8 Kg/m^3 after traversing only 198 *km* through the boundary layer. According to the estimated values, therefore, density of the outflow current compared to the inflow current in winter time is increased by about 1.2 Kg/m^3 (Fig. 7). In summer, salinity, temperature and density associated with the inflow boundary current was estimated to be 37 *psu*, 30˚*C* and 1023.6 Kg/m^3 , respectively. According to parameters and values estimated, changes in density is that it is initially decreased along the boundary current down to a minimum value of 1023.59 Kg/m^3 at some point 171 *km* along the boundary current. This minimum value, then, increases until the outflow current that is being denser than the inflow current, leaving the basin with a density of 1023.69 Kg/m^3 at the end. Another thing to be considered is that waters flowing into the Persian Gulf have lower density than waters flowing out; in other words, it can be argued that waters with less density flows into the Gulf while waters leaving the Gulf have higher density as expected.

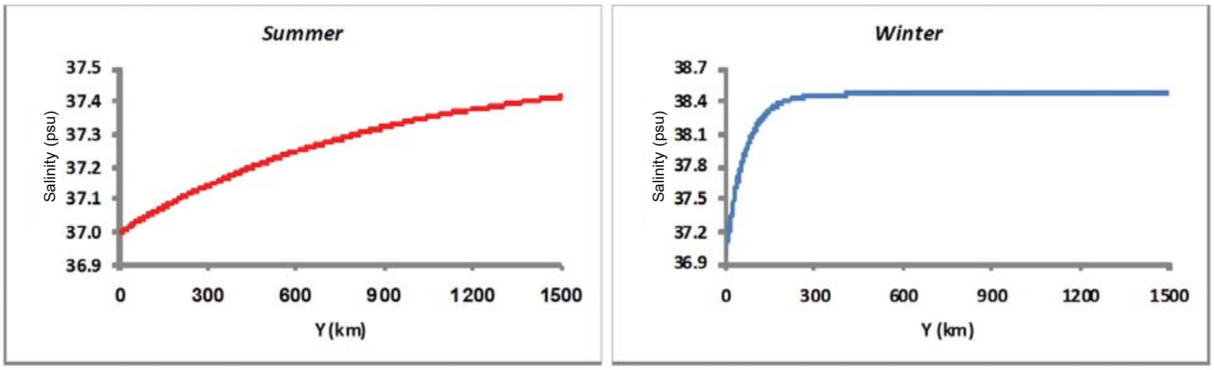

Fig. 4: The salinity changes in coastal boundary current for summer and winter.

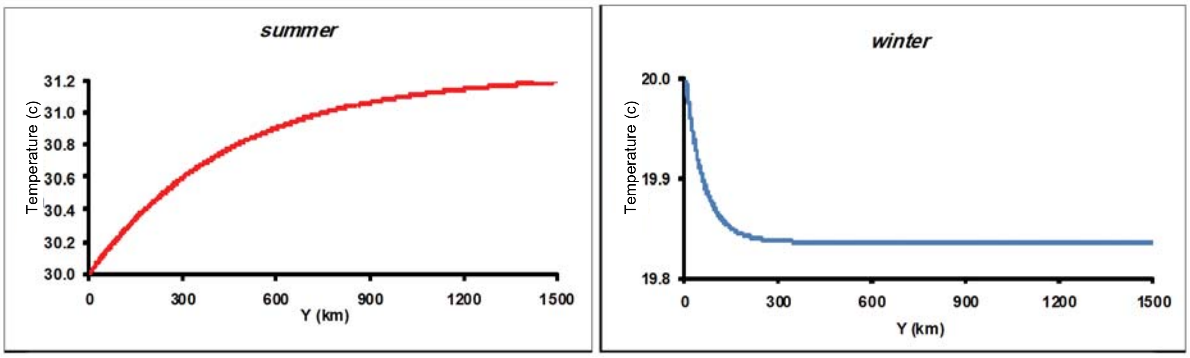

Fig. 5: The temperature changes in coastal boundary current for summer and winter.

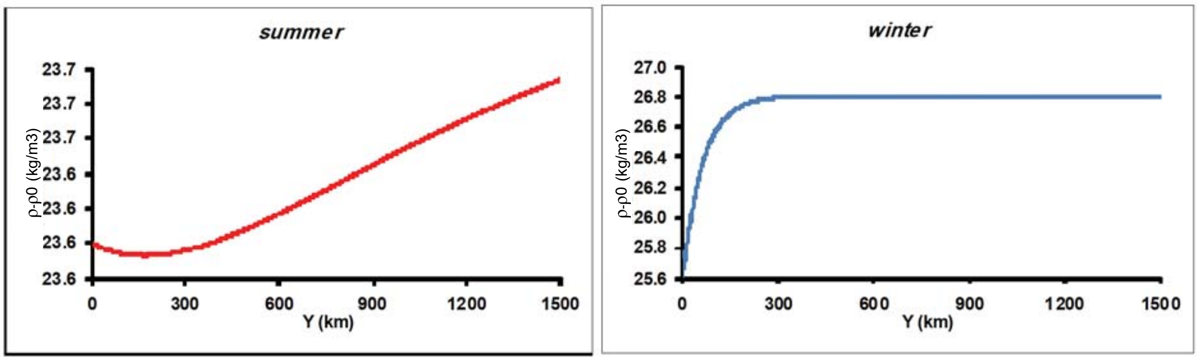

Fig. 6: The Buoyancy budget in coastal boundary current for summer and winter.

4.4-3.4. Effect of Parameter E

E values for the Persian Gulf in winter and summer time are -0.0279 and +0.60, respectively. So, *E* value being negative in winter that makes the density achieve a maximum level with which the outflow leaves the Persian Gulf. In summer, however, for *E* being positive, meaingmeaning that the boundary current density decreases down to a local minimum initially and, then, makes an increase. In both seasons, $|E|<1$ is below zero which indicates that the difference between primary salinity and equilibrium salinity produced greater effect than temperature; that is, salinity had been more effective than temperature.

4.5-3.5. Effect of Parameter η

Parameter η is the ratio of length scales L_T and L_S. Therefore, this parameter shows only the relative strength of exchange between atmosphere and interior area of the basin. If there is no exchange with the interior, $\eta = F/R\gamma_A,\ M=0$ .On the other hand, if exchange with the interior of the basin is dominant, then:. Thus, if atmospheric effect is missing, $\eta \rightarrow 1,\ M >\ R\gamma_A,\ M >> F$ temperature and salinity with similar length scales both will have the same adjusting effects.

According to the parameters specified for the Persian Gulf, $F/R\gamma_A << 1$ and $(0<\eta<1)$ which indicates that when only atmospheric effect is considered, temperature of the boundary current will be adjusted faster than salinity. η values obtained in winter and summer time are 0.94 and 0.5, respectively. Considering that η comes from the ratio between temperature and salinity length scales, it shows the relative strength of the two parameters- i.e., salinity and temperature. $0<\eta<1$ is true in both winter and summer for the Persian Gulf, indicating that temperature of the boundary layer would be adjusted faster than salinity.

CONCLUSION

Results obtained by the model (Wahlin and Johnson, 2009) revealed that the length scales of coastal boundary current entering the Persian Gulf for temperature and salinity are about 455 km and 914 km, respectively, in summer time when density of the inflow current is initially decreased down to a local minimum and, then, increased, making the outflow leave the basin with higher density compared to the inflow.

The estimated length scales of coastal boundary current for temperature and salinity are about 60 km and 64 km, respectively, in winter time when, with the length scales being of almost the same value, the density increases initially with a steep slope up to a constant value, and then the outflow leaves the basin with the same density value. As a result of changes in salinity and temperature, as expected, the inflow waters running into the Persian Gulf have lower density in summer than winter, and on the whole a lower density than outflow waters in both summer and winter time.

These found length scales for winter and summer are in accordance of the facts that in winter the Persian Gulf has a highly mixed up environment as strong cold northwesterly winds totally removes the thermocline leading to quick adjustment of the current, while in summer due to the establishment of a strong thermocline in the whole area, it has a very stable condition, leading to a much slower adjustment of the boundary current.

Nomenclature

B	Anomaly of dimensionless normalized density
L	Length scale, *m*
M	Mass exchange, m^2s^{-1}
Q	transport of boundary current, m^2s^{-1}
R	Width of current, *m*
S	Salinity, *psu*
T	Temperature, ˚*C*
y	longitude of boundary current, *m*
α	Coefficient of thermal expansion, $^{\circ}C^{-1}$
β	Coefficient of salinity, psu^{-1}
γ_A	Coefficient of thermal exchange, *m/s*

air	AIR	air
EDDY	eddy	
EK	Ekman	
EQ	equilibrium	
int	INT	interior
out	OUT	output
0	input	

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