Seasonal variation of coastal jets in the Persian Gulf using field studies

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Received: 2017-03-07 *Accepted: 2017-05-29*

Abstract

Coastal jets and fronts are formed by the pressure gradients. The dynamics of such motions is non-linear and non-quasi-geostrophic. The Froude and Rossby numbers are on the order of unity, implying that the effects of stratification and rotation are equally important within the coastal jet. In this paper, the equations of motion for the coastal jets, initial and boundary conditions, and approximations are introduced. Then, the coastal jets in the Persian Gulf are discussed based on mathematical models and measurements. The transfer of water masses to the coastal regions of Iran and Saudi Arabia due to geostrophic equilibrium and northwest winds appear two strong jets adjacent to these regions. The surface flow in the northern half of the Persian Gulf is towards the southeast with a return flow towards the northwest at the bottom except on the Saudi side, where the strong coastal jet continues through the whole water column. The coastal jet flow near the coast of Iran is limited to the surface, but the coastal jet near the coast of Saudi Arabia exists in the whole water column from surface to bottom. The average velocity of such coastal jets is 8-10 cm/s with a southeast direction.

Keywords: Coastal Jet; Pressure gradient; Density difference; wind driven current; Persian Gulf.

1. Introduction

In oceanography, the coastal area is defined as waters extended toward the land by more than one kilometer from the highest sea level and toward sea to a depth of 30 m. The coastal area includes bottom waters, rivers entrances, estuaries, water branches, small bays and the highest tide level (Beer, 1983). The coastal regions and their motions is of great importance. The coastal motions play a key role in coastal erosion and deformation, transport of pollution and environmental issues, establishment of submarine structures and fishing and fisheries studies. One of most important coastal motions is strong streams along the beach known as coastal jet. The density gradients in the main part of the fluid bulk limit motions in the front region and shape a coastal jet.

The front is the area where the properties of seawater change with time much faster than the other parts. Such an area is usually created by the collision of two fluid masses with different properties. In fact,

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the front is the area where the gradients of fluid properties are intensified (Roisin, 1994). The most significant atmospheric jets are polar front jets. The polar jets occur at latitudes of 45°, a few kilometers above the sea level or adjacent to 300mb isobar lines on the boundary between polar and subtropical air masses. In oceans, the front region is often formed between the seabed and surface in the vicinity of continental shelf break due to differences in water properties above this area and deeper parts. Such a front is invariantly associated with water streams along the coast or coastal jets (Figure 1) [Roisin, 1994].

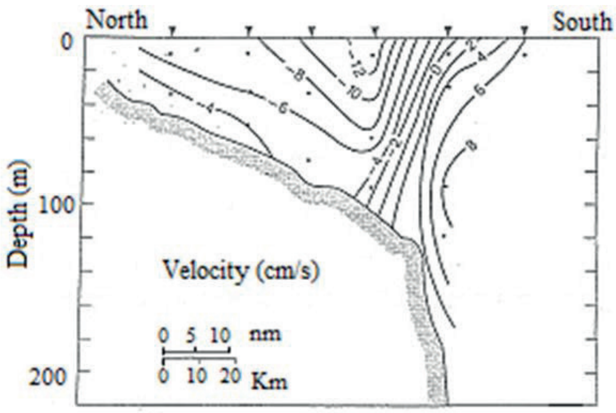

Figure 1. The monthly mean flow velocity during April 1979 along the continental shelf break, 41° N, 67° W (positive values indicate in-plane flow) (Roisin,1994)

The vertical scale of jets observed in oceans is 100 to 300 m with a mean velocity of 20 cm/s or less. For wind stress of 0.1 N/m^2, reduced gravity acceleration of g'=0.03 ms^{-2} and upper layer depth of H_1=100 m (H_2>> H_1), the rate of coastal upwelling flow is about 5 m/day. In such conditions, the velocity of flow along the coast increases up to 0.1m/s over a day. Cherny in 1955 called this flow "coastal jet" (Gill, 1982).

In this paper, the equations of motion for the coastal jets, initial and boundary conditions, and approximations are introduced. Then, the coastal jets in the Persian Gulf are discussed based on mathematical models and measurements.

2. Materials and methods

The study is based on field measurements and model results. According to different models for circulation and eddies in Persian Gulf as well as measurements of Mt-Mitchell cruise (1991), Ghods cruise (1996) and Ferdows cruise (1997) a coastal jet in the coastal regions of Iran and Saudi Arabia was detected (Lardner, 1993; Reynolds, 1993; Torabi Azad, 2000; Thoppil and Hogan, 2010).

The wind-driven response of the Persian Gulf appears to be the typical adjustment of the pressure

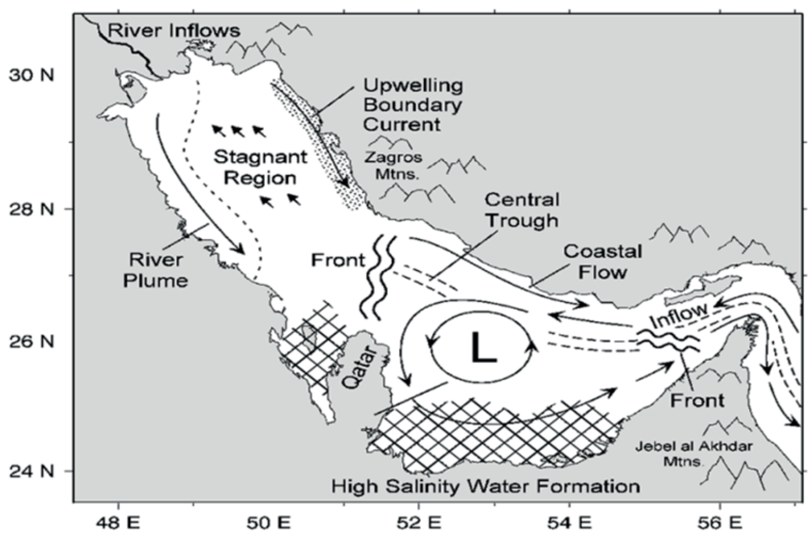

Figure 2. Schematic of circulation, river plume and coastal boundary current region for the Persian Gulf (Reynolds, 1993)

field such as to produce a down-wind flow, i.e. there is downwelling on the western coast and upwelling on the coast of Iran, and evidence for a southeastward flowing coastal current along both the northern and southern coasts (Reynolds, 1993). The flow along the Kuwait and Saudi coast is augmented by the freshwater input from the north which forms a riverine plume. As shown in Figure 2, the river in flows are approximately split between the flow out of the Shalat Arabi (Tigris and Euphrates) and rivers flowing out of the highland of Iran (The Hendijan, Hilleh, and Mond) [Reynolds, 1993].

2.1. The equations of motion for the coastal jets

Momentum equations, density and continuity equations, Boussinesq approximations and β-plane are used to study oceanic coastal jets (Lardner, 1993; Pedlosky, 2002). So:

$$(\rho u)_t + (\rho uu)_x + (\rho uv)_y + (\rho uw)_z = f\rho v - p_x + (\mu u_z)_z$$

$$(\rho v)_t + (\rho vu)_x + (\rho vv)_y + (\rho vw)_z = -f\rho u - p_y + (\mu v_z)_z$$

$$p_z + \rho g = 0$$

$$w = -\frac{\partial}{\partial x}\int_{-h}^{z} u\,dz - \frac{\partial}{\partial x}\int_{-h}^{z} v\,dz$$

$$\frac{\partial \rho}{\partial t} + \kappa\rho - wN^2/g = -Q$$

where ρ(x, y, z) is the density of seawater, p is pressure, f=2Ω sinφ is the Coriolis parameter, μ is perturbation viscosity coefficient, and u, v and w are components of the velocity vector along the x- and y and z-axes, respectively. The seabed is located at z = h (y, x). If the upper level at the time t is z = η (x, y, t), then H= h + η is the total depth of water. N is the buoyancy frequency and Q is a function of the applied force on motion. Positive Q represents a decrease in density indicating the mixing of the fluid lighter than thermocline in deeper ocean with higher density which provides a source of buoyancy force. The continuity equation is written in an integral form and used to calculate the vertical velocity (w). Typically, the vertical momentum equation is approximately replaced by the equation of hydrostatic pressure. The appropriate boundary conditions for these equations are presented as follows:

u= 0 x= 0, L

z= 0, -h w= 0

The vertical component of the mass transfer vector on coastal boundaries is assumed to be zero. The dimensionless Rossby number for coastal jets is approximately equal to 1.

2.2. Coastal Jets in the Persian Gulf

The seasonal water flow in the Persian Gulf is largely dependent on the density differences and winds. The water stream in the southern part of the Persian Gulf, adjacent to the Strait of Hormuz, is predominantly due to the density difference. Low salinity water from the Oman Sea always enters the Persian Gulf through the Strait of Hormuz and flows in the opposite direction of prevailing winds towards the northwest. The waters moving northward are cooled and concentrated due to evaporation. Finally, such waters flow toward deeper regions and flow out as a lower current with high salinity through the Strait of Hormuz.

During the summer, the water stream is wider and reaches much farther northward near the top of the Persian Gulf. This is why stratification and buoyancy forces in Oman Sea increase during summer. In contrast, the intensity of northwestern winds from the Persian Gulf is reduced. In such conditions, the water stream penetrates the coast of Iran and even reaches the areas adjacent to the top of the Persian Gulf. But in the winter, the flow is substantially reduced and its advance reaches the half of that in the summer. This is the cause of strong winds blowing from the northwest which cause separation of the flow near Iran and spread it toward the southeast of the Persian Gulf and Arabic countries (Torabi Azad, 2000; Torabi Azad, 2001).

In the northern part of the Persian Gulf, the flow is predominantly due to wind driven. The wind drift causes surface currents along the coasts of

Iran and Saudi Arabia towards the south. Along the coast of Iran, the coastal currents caused by rivers output are intensified by baroclinic force. In the central part of the northern area of the Persian Gulf, the northward current completes the se c ondary wind drift-driven circulation. So in t h is area, the secondary circulation is balanced with wind drift on the sea surface and an area with a very low net flux is created. The northward or southward circulation in this area is an energetic invariant wind which is sensitive to winds. The flux at northern end can be toward the east or the west. There is also a low-energy motion in the southern region towards the north or the south (Reynolds, 1993).

There is equilibrium between the northward baroclinic force and southward wind stress along the north for surface flow entering the Strait of Hormuz. In summer, water flows go to the latitude of 28° N through the Strait of Hormuz. The water flows of Arvand River and the Shatt al-Arab River cause clockwise westward circulation in the coastal areas of Kuwait and Saudi Arabia (Torabi Azad, 1996).

Studies indicate the formation of two distinct circulations, one clockwise circulation in the northern Persian Gulf and one counterclockwise circulation in the southern part of the Persian Gulf. Since these two water masses have different densities, a front area is starting to take shape when they collide with each other. Accordingly, the isodensity lines are inclined toward the Strait of Hormuz (along the northwest-southeast direction) and a relatively large pressure gradient arises. The slope of isodensity surfaces represents the stored potential energy. This energy is released by instability and therefore the slope of these surfaces is reduced. During this process, the vertical gradient of the velocity decreases and wave turbulences get kinetic energy. This unstable process causing the release of potential energy (by reducing the slope of isodensity surfaces) is known as baroclinic stability (Torabi Azad, 2000; Torabi Azad, 2001).

3. Results and Discussion

The extent of the transitional zone created through collision of two water masses and formation of the front area is calculated by the inner radius of Rossby deformation. This radius for the actual values measured in the Persian Gulf can be expressed as follows:

$$R = \frac{NH}{f} \cong \frac{\sqrt{g'H}}{f} = 8.5km$$

The geostrophic equilibrium adaption process begins by Coriolis force and causes a relatively high flux along the front towards the coastal areas. The velocity scale of the geostrophic flow is calculated as follows:

$$U = \sqrt{g'H} = \sqrt{0\cdot 0096 \times 40} = 0\cdot 619ms^{-1}$$

As a result, the water masses are transferred to the coastal areas of Iran and Saudi Arabia by the geostrophic equilibrium in the area where two water masses of different densities collide. Then, the prevailing northwest winds cause strong surface currents adjacent to the coasts of Iran and Saudi Arabia in the northern part of the Persian Gulf. This is called the coastal jet.

Figure 3 shows the currents caused by density difference and wind driven on the surface and bottom of the Persian Gulf during April, 1992. In the earlier summer, relatively high speed northwest winds blow. The surface current in the northern Persian Gulf toward southeast is associated with a reverse flow towards the northwest along the bed. With the exception of the coast of Saudi Arabia where there is a strong coastal jet in the whole water column, the current on the bottom of Saudi Arabia's coasts follows the coastal jet.

In the southern part of the Persian Gulf, the velocity of surface flow entering the Strait of Hormuz is about 15 cm/s. The velocity of this current reaches 10 cm/s along the coast of Iran and advances further from the Qatar Peninsula. In the vicinity of the bed in this region, an inverse current toward the Strait of Hormuz is observed. In the vicinity of the

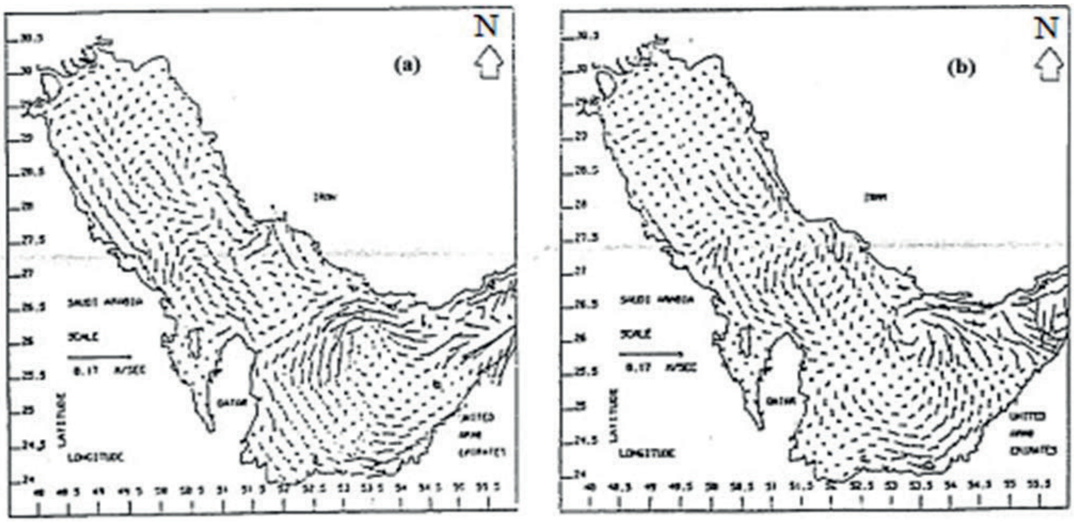

Figure 3. The current caused by the monthly mean wind drift and the density difference during April, a) Surface, b) Bottom (Lardner *et al*., 1993)

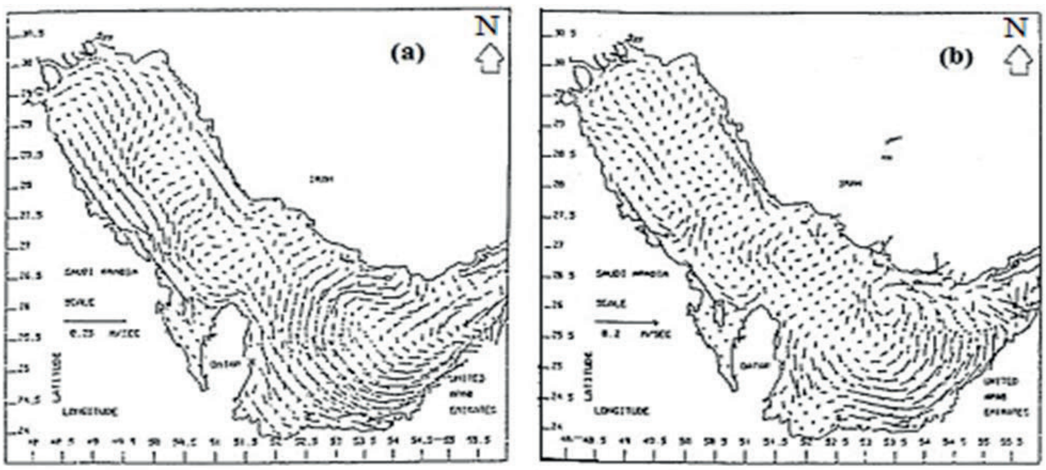

Figure 4: The current caused by the monthly mean wind drift and the density difference during August, a) Surface, b) Bottom (Lardner *et al*., 1993)

UAE, there is a strong surface current towards the east with a velocity of 12-15 cm/s. This current is caused by the wind force. This force transfers the bed stream in the same surface direction, near to the UAE coast. In the southern part of the Persian Gulf, wind driven and density difference cause a counterclockwise rotation along the seabed. This pattern exists along the seabed on the entire area of interest.

Figure 4 indicates the currents caused by density difference and wind driven on the surface and bottom of the Persian Gulf during August. Due to the reduction in the mean wind speed during summer, the effect of increased density difference becomes more important. In the northern half of the Persian Gulf, the coastal jet almost disappears near the coast of Iran. The coastal jet near the coast of Saudi Arabia has been considerably weakened compared to April. The surface flow entering the Strait of Hormuz passes through the Qatar Peninsula and further advances along the coast of Iran.

Conclusion

The Seasonal water currents in the Persian Gulf are greatly dependent on wind driven and density differences. As the water flow with higher salinity entering the Strait of Hormuz is mixed with northern rivers of the Persian Gulf with lower salinity flows, a front region is formed in the central region which is associated with baroclinic instability. The transfer of water mass by geostrophic equilibrium to the coastal areas of Iran and Saudi Arabia and the prevailing northwest winds appear a coastal jet in this region.

The coastal jet stream near the coast of Iran is limited to the surface southeastern motions. There is a reverse northwestern flow on the bottom. There is a southeastern coastal jet stream near the coast of Saudi Arabia in the whole water column from the surface to the bottom. With reduction in the speed of prevailing southwest winds in the Persian Gulf, the coastal jet stream near the coast of Iran is weakened and completely disappeared adjacent to the coast of Saudi Arabia. The Froude and Rossby numbers for the coastal jet of the Persian Gulf are approximately equal to 1. For further studies on this issue, the following items are recommended:

- In the northern region of the Persian Gulf, the variability of currents, especially due to winds and a suitable mathematical model can be presented for studying coastal jets.
- The flow rate and velocity of the wind jet and affective physical parameters in all seasons can be measured for the northern area of the Persian Gulf.
- Required arrangements should be conducted with the Persian Gulf neighbors and relevant international and regional organizations.

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