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# The layered structure in exchange flows between two basins

## (Middle and Southern basins of the Caspian Sea)

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**ABSTRACT:** Ocean waters often show layered structures especially where exchange flow between two basins occurs. These structures are often attributed to processes such as double–diffusive convection, internal waves, turbulent modulated mixing. In this paper by examining the vertical structures of temperature, salinity and density, of the middle parts of Caspian Sea it is shown that such layered structure may be due to the normal modes of the internal waves as double diffusive convection (the density ratio is often negative) does not often occur in these waters. Contours of isotherm, isohaline and isopycnal show the existence of rather regular wavy structures, which may indicate that internal waves, which are produced of exchange, flow between two basins; as a result of horizontal density gradients (usually from middle basin to southern basin) may generate these layers. The flow velocity associated with this gravity driven flow is about 0.1 to 0.15 m/s which gives a Froude number of about one. The wave lengths of these wavy structures are about 200 km and hence, the frequencies of them are of order of inertial frequency at these latitudes. The normal modes of these waves appear to have a near steady structure and can fold the inflow front from the Northern part of the Caspian Sea to the Southern deep basin. The thickness of formed layers is found be about 10-20 m which is in agreement with the values predicted by the model of Wong et al. (2001) and is less likely to be produced by double diffusive convection as the density ratio is often not appropriate for this process.

**Keywords:** *Internal waves, layered structure, thermocline circulation, Caspian Sea*

## INTRODUCTION

Temperature and salinity field observations in the oceans often indicate layered structure in these waters especially in the thermocline and halocline that have implications for the vertical diffusions (Fedrov, 1978). Different phenomena such as double diffusive convection, turbulent mixing, and normal modes of internal waves can be responsible for the formation of layered structure as have been implied by theoretical and laboratory studies (Ruddick,1992; Bidokhti and Griffiths, 2001). Internal waves in the oceans are ubiquitous especially in the thermocline near areas in which the exchange flow occurs over the bottom sills (Sill Exchange Flows: SEF), for example, outflow from the Mediterranean Sea into Open Ocean.

These waves are also important in exchange flows between two basins (Hogg et al., 2001). For SEF with Fr ≈ 1 a substantial part of the energy of this flow can go to the generation of internal waves, which may have some effect on the thermocline circulation. Laboratory studies of Wong et al. (2001) have shown that the outflow of plumes in enclosed basin with stratification can produce internal waves, as their phase velocity is downward and their group velocity is upward. In this case, phase velocity of waves is equal to vertical advection of velocity driven from mechanism of filling box plume. The normal modes of these waves, which have a nearly steady structure forming horizontal, shear layers (Hogg et al., 2001; Bain and Turner, 1969; Boehrer, 2000). This structure may also be formed in deep ocean basins by the same mechanism as some temperature, salinity (T and S) observations of the oceans especially near enclosed basins may show.

Boherer (2000) also have considered the layered structure of vertical profiles of temperature, salinity and density in the Constance Lake and attributed the layer to the internal waves activities.

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In the Caspian Sea also there exist two deep enclosed basins in which exchange flow between them may lead to internal waves and hence to layered structures which is the subject of this paper. The aim of this study is to consider the vertical structure in middle waters between two basins (middle and southern basins of the Caspian Sea), based on field observations, although not substantial. Such issues have been less addressed in the literature especially in large lakes as the Caspian Sea, which makes it unique for such considerations. This study is important for problems such as materials transport in exchange flows between the two basins of the Caspian Sea (thermocline circulation), internal waves and layered structure, vertical diffusions of contaminations in sea, sound propagation in these waters and large-scale fine grid circulation models.

## MATERIALS AND METHODS

### *Caspian Sea*

Caspian Sea is the largest lake of the world; it is situated between two continents Asia and Europe and also is placed on latitude 36˚, 33΄ - 47˚, 7΄ northward and longitude 45˚, 43΄ -52˚, 20΄ eastward. The water level in this lake is about -25 m from mean sea level, with an average precipitation of about 700 mm per year. This lake is surrounded with countries Iran, Russia, Azerbaijan, Turkmenistan and Gazagistan and hence is important and may be prone to pollution. The Caspian Sea is not naturally connected to open ocean and hence is not ventilated to the open seas, it is erroneously named as a sea however it is a huge lake. The length of this lake is about 1200 km in direction north-south, with an average width of about 310 km in direction east- west and an area of about 386400 $km^2$ (Rodionov, 1994; Shiklomanov, 1995). In terms of shape and depth this lake consists of three parts: northern shallow area, middle and southern deep basins (fig. 1-a).

The Area of northern part is about 80000 $km^2$ and its average depth is about 5-6 m and its maximum depth is about 15-20 m. Area of middle part is 138000 $km^2$ and its average depth is about 190 m and its maximum depth is 780 m. The Southern part, which ends by coasts of Iran, has an area of 168400 $km^2$ and has the deepest part of Caspian Sea of about 1025 m (Baidin and Kosarev, 1986). A narrow shallow sill in Abshouran area, 150 m deep and about 100 km width, connects the two middle and southern basins. Between these two basins buoyancy driven deep flow occurs due to the north-south density gradient, which consists of a part of themohaline circulation.

### *Analysis of some field observations*

The field measurements (taken during ten days continuous records in spring 1995) used in this study is obtained by the cruise of Atomic energy

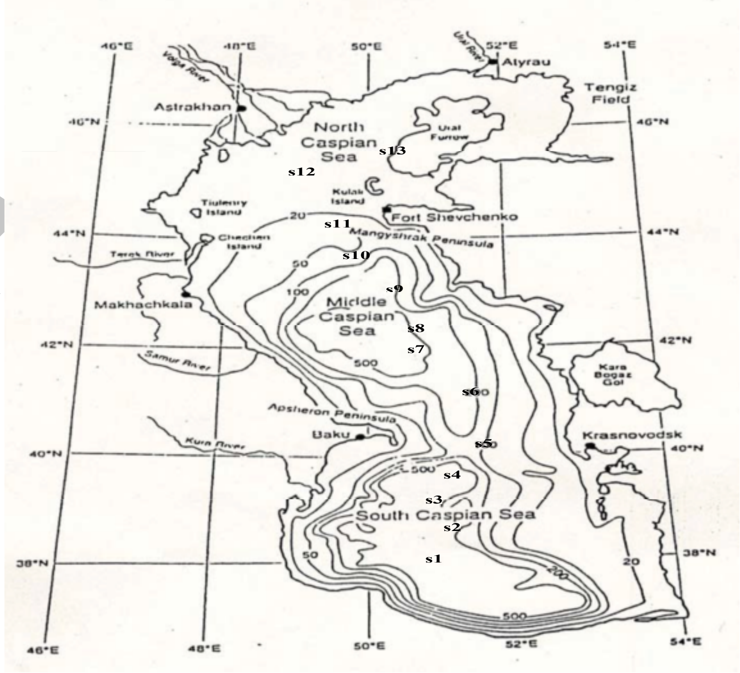

Fig. 1-a: Map of the Caspian Sea and the stations of measurement.

Organization of Unesco 1995 (UNESCO, -IHP-IOC-IAEA, 1995). The positions of CTD stations are marked on the Hydrographic map of the Caspian Sea (Fig. 1-a). In (Fig. 1-b) bottom topography of the Caspian Sea along its north-south axis is indicated by distance from northern shore of the Caspian Sea in direction north–south. These stations are aliened nearly in the direction of the axis of the Caspian Sea and scan the middle waters of the Caspian Sea. The sampling depths in these measurements are typically 0.5-3 m to the depth of about 100 m and 5-7 m for deeper parts (Fedrov, 1975).

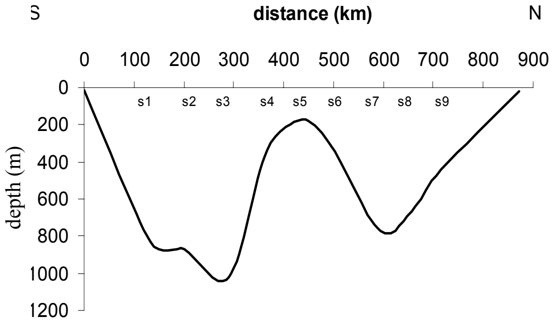

Fig. 1-b: Bottom topography of the Caspian Sea is indicated by distance from southern shore in southern –northern direction.

Fig. 2 shows the vertical salinity profiles for stations 1-9. According to this figure, the average salinity increases from southern basin to northern basin. Layered structure is evident in these profiles especially for station 5 in depth of about 20-60m, which is nearly placed on the Abshouran portion.

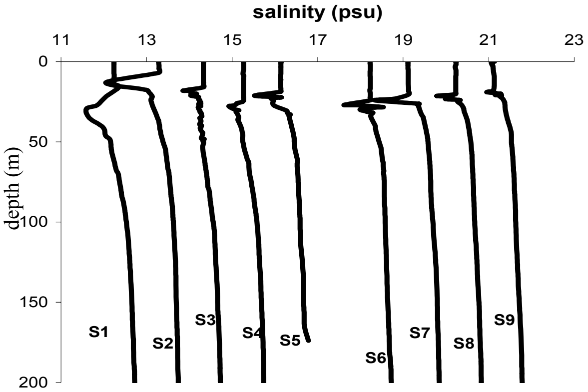

Fig. 2: Vertical salinity profiles for stations 1-9 .For clarification, one unit has been added to data of station 2, two units to data of station 3 and… and eight units to data of station 9.

Figs. 3. show the vertical temperature profile for stations 1-9 that indicate the average temperature decreases from southern basin to northern basin. Isopycnal layers have different salinity and temperature, so that they are compensator from view of density. Heat molecular diffusion coefficient is 100 times as salinity molecular diffusion coefficient in water, hence narrow layers can lose their heat during motion, but keep their salinity, so the formed layered structure is kept for more time in salinity profiles, while less layered structure exists in temperature profiles. Therefore the layered structure more distinctively appears in vertical salinity profile.

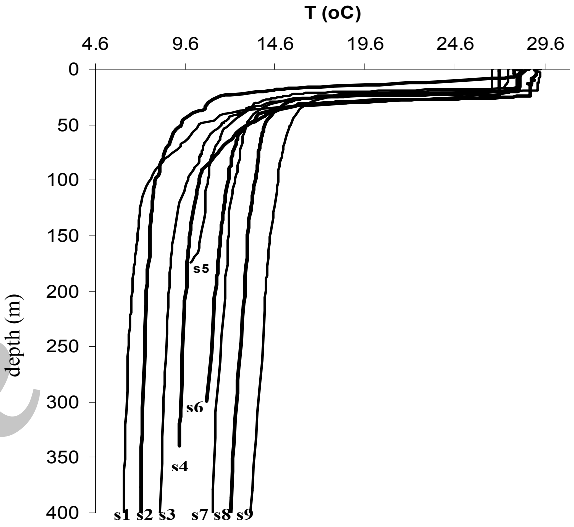

Fig. 3: Vertical temperature profiles for stations 1-9.For clarification one unit has been added to data of station 2, two units to data of station 3 and… and eight units to data of station 9.

Fig. 4 shows vertical density (or sigma-T= (ρ-1000) profiles for stations 1-9. The layered structure especially layers with constant density is also observed in them.

The mixed layer near the top has an average depth of about 15 m, which seems to decrease towards the southern basin, indicating that surface mixing processes is becoming less. In fact the wind frictional velocity that the mixed layer depth depends on is probably larger towards north as the westerly winds are stronger. The mean frictional wind velocity (u*) is about 0.005 m/s with the Coriolis parameter f ≈10-4 s-1 this gives a mixed layer depth of about h≈10m (using h~ αu*/f, with α≈0.2, Monin, and Ozmidov, 1985).

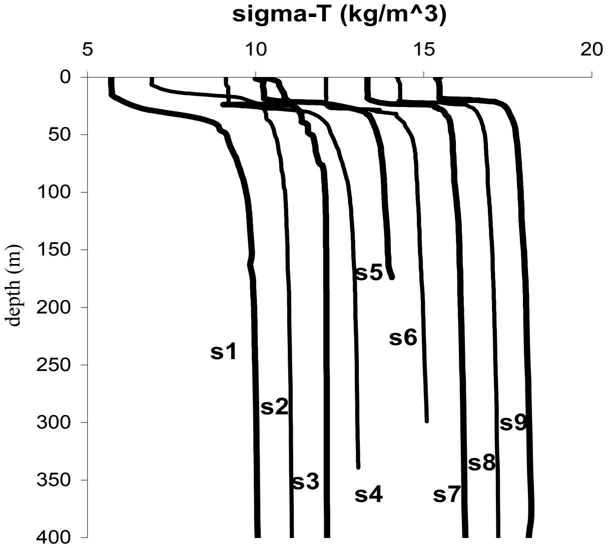

Fig. 4: Vertical potential density profiles for stations 1-9.For clarification, one unit has been added to data of station 2, two units to data of station 3 and... and eight units to data of station 9.

For revealing the vertical structure along the axis of the lake we present the horizontal changes of temperature, salinity and potential density from southern stations to northern stations as shown in Figs. 5, 6, 7 for different depths.

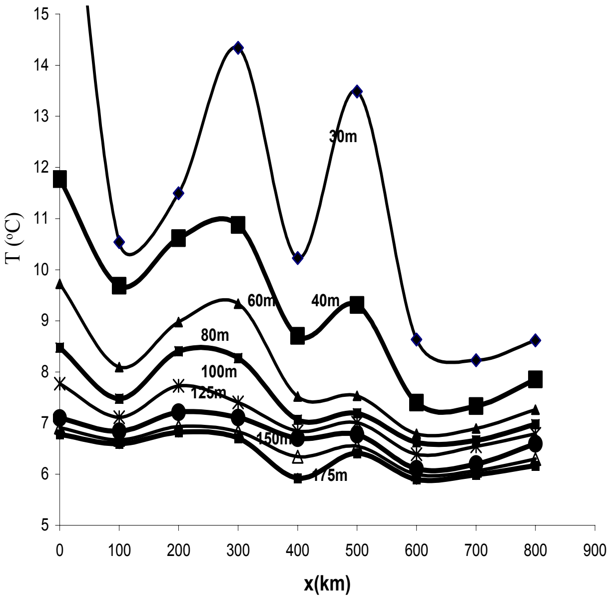

Fig. 5: Horizontal changes of temperature with distance from southern shore of the Caspian Sea in the south–north direction for nine depths.

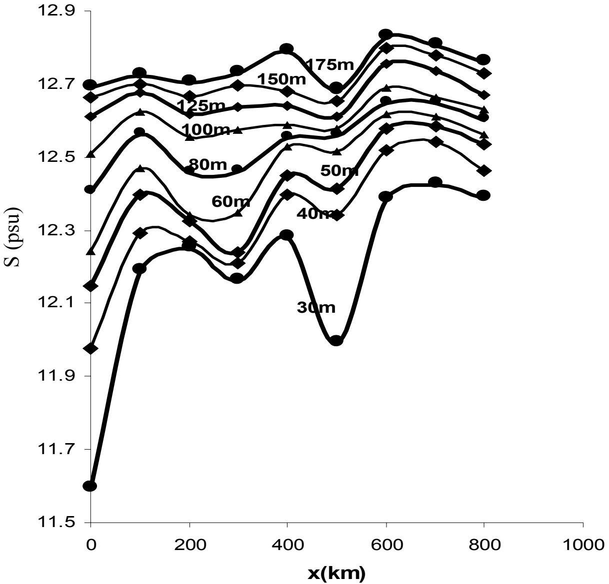

Fig. 6: Horizontal changes of salinity with distance from southern shore of the Caspian Sea in direction for nine depths. south–north

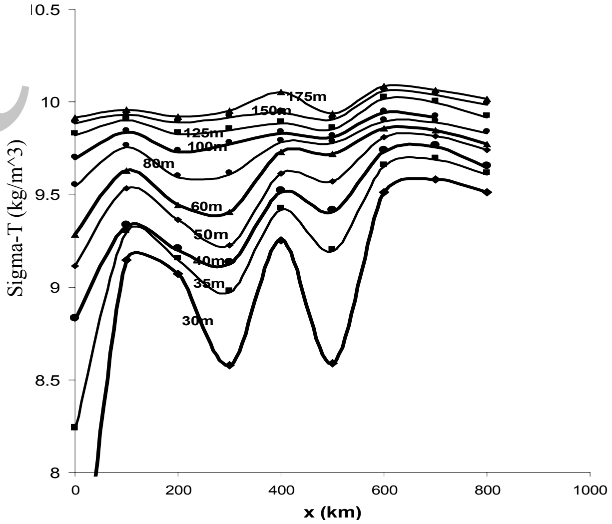

Fig. 7: Horizontal changes of potential density with distance from southern shore of the Caspian Sea in south–north direction for nine depths.

These Figures indicate that the salinity and potential density increase towards north, but temperature decreases. Hence there is a meridianal density gradient that can lead to buoyancy driven flows from the north to south over the sill between the two basins. This flow near the bottom is of order of 0.1 to 0.2 m/s regarding this density difference between two basins, which is about 0.03 kg/m3 in depth 150m. Using the buoyancy frequency of the water in this area ($N \approx 0.1 s^{-1}$) the Froude Number is found be about 1. Hence in this exchange flow, the generation of internal waves is highly probable. The northwards density increase is also associated with the wavy changers of these parameters, indicative of internal waves. These internal waves appear to have horizontal wave number, k of order of $10^{-4}$ $m^{-1}$. Considering the mean density driven flow this gives a frequency of about $\omega = uk \sim 10^{-5}$ $s^{-1}$ which is slightly smaller than the inertial frequency at this latitude (about 40 N), indicating that the Coriolis effects are important on this motion (internal gravity-inertial waves). Hence they may have a three dimensional structure. The horizontal changes (northern-southern) for different depths are shown in Figs. 8-a, b, c.

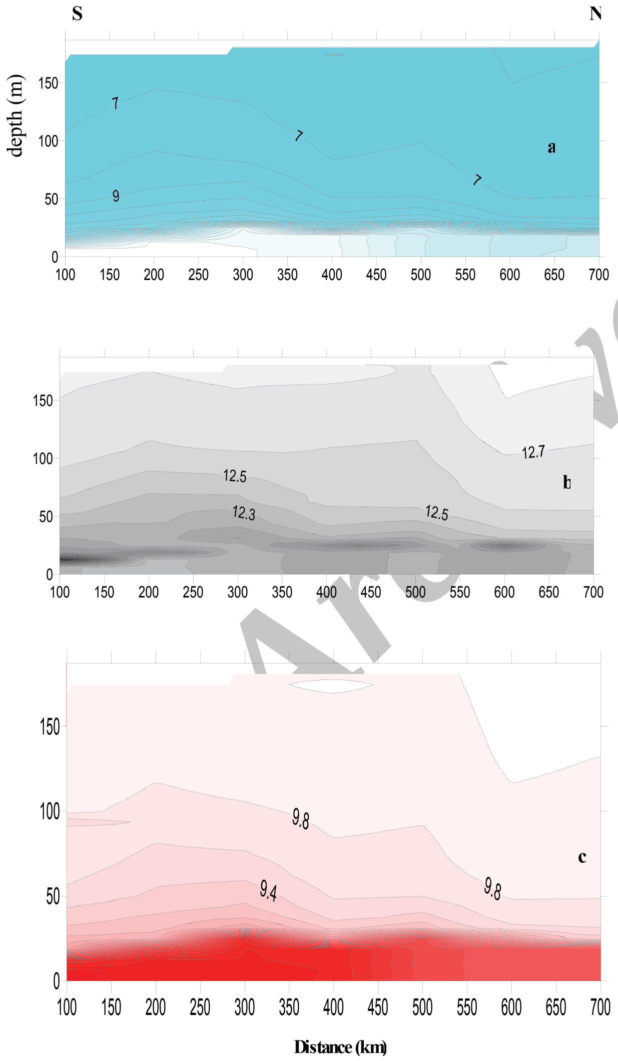

Fig. 8: Contours of a: potential density, b: salinity and c: temperature with distance from station 1 in the Caspian Sea in south–north direction. Horizontal axis shows distance from station 1 and vertical axis shows depth of water, also depth of zero shows the water surface.

The changes again indicate the wavy structures of the T/S distributions which are probably due to these low frequency internal waves that may be stationary with respect to the sill. The spatial oscillatory changes of these parameters indicate wavy structure especially in southern basin (at depth of 200 m). The horizontal changes at different depths indicate the wavy structure in portions with depth of 30 m – 70 m with maximum value of N. Internal gravity-inertial waves in fluids with continuous density stratification have baroclinic modal structure (Gill, 1982). Vertical local gradient of physical quantities for stations near sill are indicated in Figs. 9, 10 and 11 which may indicate the presence of these modal structures with distinctive layers.

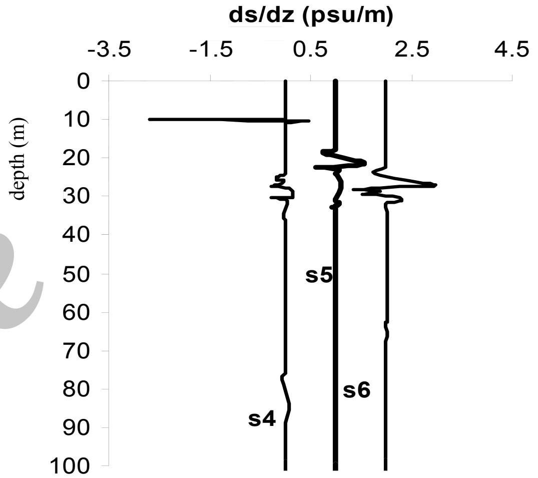

Fig. 9: Vertical local gradient of salinity for station 4 (southern basin), station 5 (on the sill), station 6 (middle basin). For clarification, one unit has been added to data of station 5, two units to data of station6.

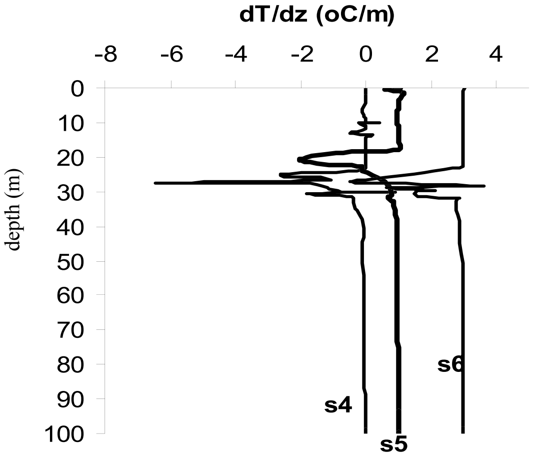

Fig. 10: Vertical local gradient of temperature for station 4 (southern basin), station 5 (on the sill), station 6 (middle basin). For clarification, one unit has been added to data of station 5, three units to data of station6.

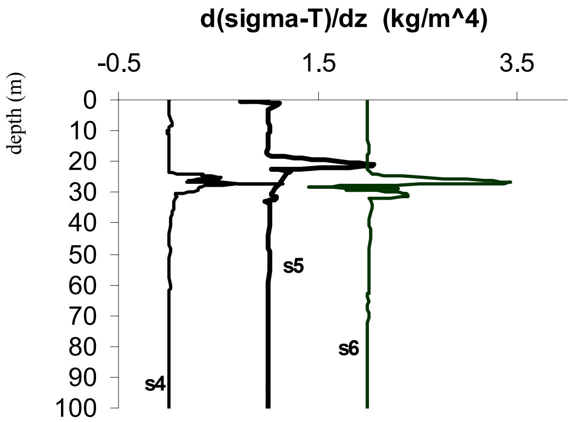

Fig. 11: Vertical local gradient of potential density for station 4 (southern basin), station 5 (on the sill), station 6 (middle basin). For clarification, one unit has been added to data of station 5, two units to data of station6.

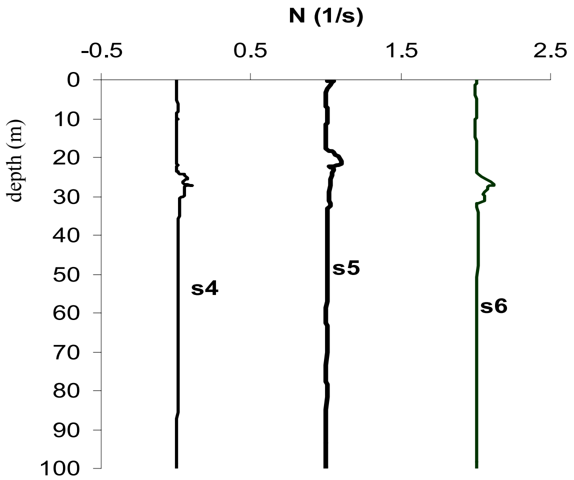

Fig.12: Vertical profile of the Brunt – Vaisala frequency for station 4 (southern basin), station 5 (on the sill), station 6 (middle basin). For clarification, one unit has been added to data of station 5, two units to data of station6.

The depth of these layers is about 10-20 m. These layers can be formed by two mechanisms: shear layers of baroclinic modal structure of internal waves as indicated above (Wong et al, 2001) or they may be generated by the double diffusive convection. For assigning effect of double diffusive convection in these waters stone the vertical profiles of the density ratio (Rρ) are presented in Fig. 13. Rρ is defined as:

$$R\rho = \frac{\alpha \Delta T}{\beta \Delta S} \approx \frac{\alpha\, \partial T/\partial z}{\beta\, \partial S/\partial z}$$

where α and β respectively show the coefficients of density change due to temperature and salinity ant the gradients are local ones. Double diffusive convection can occur if $0 < R\rho < 10$ (Turner, 1973). In these profiles values of Rρ are often about zero or negative, hence the occurrence of this convection in these waters may not occur as frequent. Therefore other factors may be responsible for the formation these layers of which the internal gravity waves are more probable.

## RESULTS AND DISCUSSION

### *A mechanism for the layered structure*

The southward bottom current with negative buoyancy in the shape of a wide plume from middle basin to southern basin over the sill at Abshouran can generate the internal waves. This bottom current affects the waters near the sill and southern basin to the depth of about 100-200 m (Figs. 5, 6 and 7).

The thickness and velocity of the outflow can be predicted (to be predicted by the dominant internal wave mode excited by the outflow to the southern basin) using the model developed by Wong et al. (2001) for a two dimensional flow in a long channel in which the outflow from a plume generated the internal waves. This is the mode having a downward phase speed equal to the upward advection speed, in this case induced by the outflow volume flux. The thickness of the outflow (identified as the lower most shear layer) in a long narrow channel (where the outflow can be considered two-dimensional) is given by

$$\lambda \approx 2\pi E (H/W)^{1/2} H \qquad (1)$$

(Wong et al., 2001), where E is an entrainment coefficient (about 0.13 in unconstrained vertically falling plumes), H is the height of fall of the plume and W is the width of the basin. The outflow velocity is given by (combining (6) and (45) of Wong et al.)

$$U \approx 1.37\, E^{1/3} F^{1/3} H^{1/6} W^{-1/2} \qquad (2)$$

where F is the plume buoyancy flux. These quantities are therefore independent of the length L of the basin. As the laboratory experiments have indicated that the normal modes of these internal waves make the shear layers (Wong et al. (2001); Bidokhti and Noroozi, 2004) and Griffiths and Bidokhti, (2008), as shown in Fig. 14. such mechanism can fold the plume outflow front and generate the layered structure in the upper water of the basin.

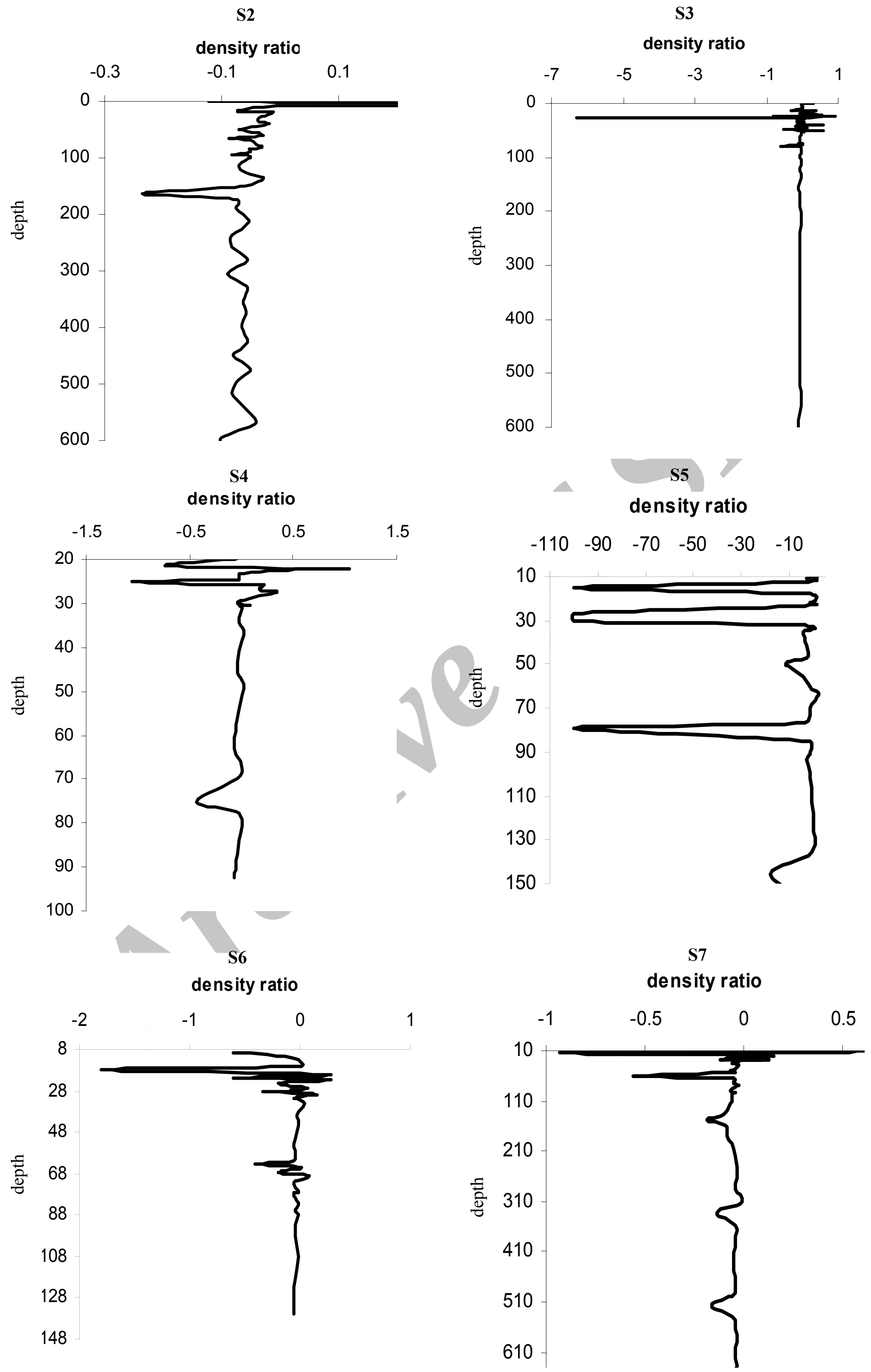

Fig. 13:Vertical profile of density ratio for stations 2, 3, 4, 5, 6, 7 (Depth is meter).

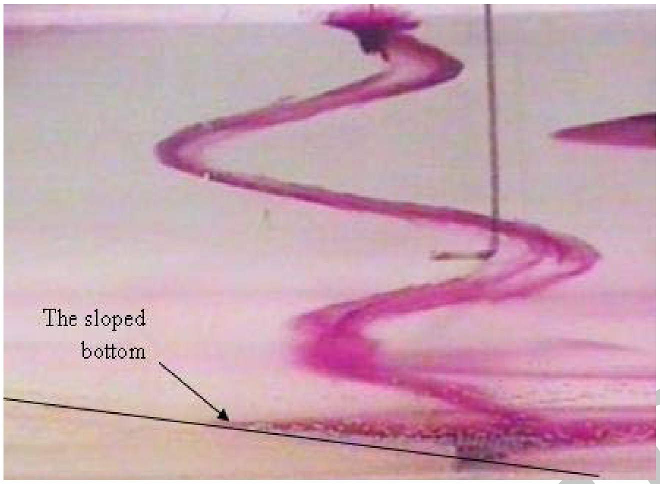

Fig.14: Shear layers by down slope flow into a stable density stratified closed basin (Bidokhti and Noroozi, 2004). The down slope flow is from left. The angle pf the bottom is 15 degrees.

It is reasonable to apply the same theoretical solution given above, while keeping in mind the two dimensional and non-rotating simplifications in the analysis. However, we should first ask whether double diffusive convection will influence the buoyancy available to drive intrusions. As indicated above the double diffusive convection is too weak to influence the outflow buoyancy and shearing motions. The outflow is predicted to behave as a single component flow (apart from any small scale structure produced by convective instabilities) and we proceed to apply the results (1and 2).

Thickness of the layers can be estimated by (1) using an entrainment coefficient $E \approx 0.1$ for plume over a slope (Turner, 1986) and outflow depth $H \approx 200$ m. Taking some account of the highly irregular width (due to eddies) of the current formed by the outflow, we use $W \approx 10000$ m (and this is also the internal Rossby radius for the outflow). The relevant basin length in (3) implying $L \approx 10^5$ m. Friction and Coriolis effects might also influence the effective length of low frequency motions in the basin. With these values relation (1) gives $\lambda \approx 20$ m. This value conforms to the thickness of observed layers in Fig. 9.

These layers are more observable in salinity distribution as for salinity the molecular diffusion coefficient is smaller than that of heat. Of course lenses of more salinity are broken and create a three-dimensional current structure towards the southern basin. This can be due to large-scale flow, which can break up the plume outflow from middle basin to southern basin creating a three-dimensional flow. Presently with this data we could not substantiate these.

If we use typical values for $F=qg'$ where q is the water volume flux of plume outflow from middle basin to southern basin, based on a gravity current velocity (Simpson, 1997), which is about 105 m3s-1 and $g'$ is nearly 0.02 $\mathrm{ms^{-2}}$, hence F is equal $2 \times 10^3$ $\mathrm{m^4s^{-3}}$ and the equation (2) gives a velocity of plume outflow in southern basin of about 0.2 $\mathrm{ms^{-1}}$. The layer thickness $\lambda$ is also independent of the buoyancy flux. Wong et al. (2001) also predicts that the amplitude of the modal structure is reduced due viscosity. The exponential decay height $\gamma$ is

$$\gamma = 2\pi Re(H/L)(\lambda/2\pi H)^4 H = (2\pi Nm/\nu L)(\lambda/2\pi)^4$$

Where H/L is the basin aspect ratio and $Re = N_m H^2/\nu$ is a Reynolds number based on the buoyancy frequency at the outflow. Putting typical value for $N \sim 0.2\ \mathrm{s^{-1}}$ and an vertical eddy diffusivity of about 0.1 $\mathrm{m^2/s}$ for $\nu$ we find $Re \sim 80000$ and $\gamma \sim 0.01$ m which shows that the decay of the modal structure with depth should occur over a short distance as observed in the vertical variations of water properties with depth (Figs. 2 and 5-7).

## CONCLUSION

Field measurements of physical parameters of middle waters, between the middle and southern basins of the Caspian Sea show that the water is layered specially at depth of 50 to 175 m (Fig. 7). The horizontal density gradient between the waters of the two basins ($\partial\rho/\partial y > 0$) induces a bottom gravity current towards south. As this current passes over the sill in Absharan it excite internal waves with a phase speed of order of the current speed (Froude number ~1), creating a quasi stationary wave pattern shown in the contours of T, S and sigma-T (Fig. 8). As the gravity current flows into southern basin it spreads as an intrusive flow that causes deepening of the contours of T/S in which a series of tongues appear (Fig. 8). Such modulated structures are also observed in the out flows from semi-enclosed seas as the Persian Gulf outflow (Bower et al., 2000) that leads to layered structure in the vertical profiles of T/S (e.g. Fig. 2). This structure may be the result of the normal modes of the internal waves excited by the outflow. Using a model of plume outflow in an enclosed basin (Wong et al., 2001) to predict the layers thickness we have found some agreement between observed and predicted values. The observations used in this study is however for a limited time of measurements and the continuous records of flow properties in these water is not available and we have looked at the flow in short period of time assuming that the flow has not changed substantially. Repeated measurements of these waters are required to find the charterstics of this exchange flow. Current meter moorings in the mid-water of the Caspian Sea are also required to see the vertical structure of the flow. Apart from exchange flow forcing mid-latitude atmospheric weather systems forcing in this area may also be important in setting up internal waves in the Caspian Sea that required further studies. The density ratio in these waters is often negative indicating that the double diffusive convection may be less important.

We have shown that the layered structures of the mid-water of the Caspian Sea may be due to the internal waves vertical structures which may be set up as a result of exchange flow between the two deep basins of the Caspian Sea. The deep bottom flow (with a typical speed of 0.2 m/s) from the north over the sill between the basins, as inferred from the density field may appear as an outflow plume into the southern basin. The waves inferred from the salinity and temperature field have long wavelength which may have a gravity-inertial character. Hence they may have a three-dimensional structure as the vertical structure of the water properties indicate. As the decay depth of the modal structure of these waves is small the wave activities remain near the surface waters below the mixed layer as indicated in contour plots of the water properties (Fig. 8). The layer thickness estimated by the model is about 10-20 m roughly similar to the observed layer thickness. Number of the layers observed is also about 4-6 similar to the cases in the lab models.

We refrain from further estimations as the model used has several shortcomings for use in this case and a more complete; say three-dimensional model should be used for this exchange flow. Also some detail observations of temperature, salinity and density in area are required for better understanding of these layered structures.

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