# Thermocline Formation in the Persian Gulf

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*Abstract:* **-** Persian Gulf (PG) is a semi-enclosed water basin that is connected to the Gulf of Oman through the Strait of Hormuz. There are different forcing and climatic parameters influencing the thermocline development in the PG from winter to summer. These factors include tide, river inflow, solar radiation, evaporation, northwestern wind, and water exchange with the Gulf of Oman. In fact, the thermocline, which is often observed in the oceans and open seas, can be considered as a seasonal phenomenon in the ocean. In the present study, it is studied theoretically; and compared with the results of the Princeton Ocean Model (POM) in the PG. During winter to summer, solar heating created an intense thermocline that decoupled the surface mixed layer from the interior water. The data are reviewed as the measurements collected in 1992 and recent modeling results. Overall, through a theoretical study, it is concluded that thermocline formation is a seasonal phenomenon in the PG.

*Keywords:* - Persian Gulf (PG), Thermocline, POM, Modeling, Temperature, Salinity, Depth

## 1 Introduction

The thermocline is an abrupt temperature gradient in a body of water such as a lake, marked by a layer above and below which the water is at different temperatures. In fact, thermocline development and its variation in space and time represent a turbulent flow, and thus propagation of internal waves through water environment. Turbulence and internal waves propagate along the baroclinic pressure gradient in a vertical direction through the water column due to baroclinicity and tidal wind stress [2].

Tectonic- driven subsidence occurs in the seafloor of the Hormuz Strait on its southern side (200–-300 m depths are seen in some localized seafloor depressions) and produced a 70-95 deep through the Iranian side of the eastern part of the Gulf. A southward widening channel leads from the Strait south across a series of sills (water depth of ∼110 m) and shallow basins to the shelf edge [7]. The narrow Strait of Hormuz restricts water exchange between the Persian Gulf (PG) with the northern Indian Ocean. The baroclinic exchange circulation through the Strait of Hormuz is modified by the difference between the density of Gulf Bottom Water west of the Strait of Hormuz and that of water at comparable depths outside the Gulf [5]. The atmosphere plays an essential role in driving the circulation and maintaining the water properties in the Gulf [8].

The wind-driven ventilated thermocline circulation determines the thermal structure of the upper ocean in the tropics and subtropics. Also, both components of the oceanic circulation, i.e., the deep thermohaline and the shallow ventilated thermocline circulation, involve meridional overturning, and both contribute to the pole ward transport of heat by the oceans. The freshening of the surface waters at high latitudes can inhibit the sinking of cold water and hence can interfere with the heat transports. The temperature of seawater immediately below the mixed layer changes rapidly with depth. This layer of fast temperature change extends down to 1,000 m, where it is called the main thermocline. A thermocline is a thin but distinct layer in a large body of fluid (e.g. water, such as an ocean or a lake, or air, like an atmosphere) in which temperature changes more rapidly with depth than it does in the layers above or below. In the ocean, the thermocline divides the upper mixed layer from the calm deep water below. Depending largely on season, latitude and turbulent mixing by wind, thermoclines may be a semi-permanent feature of the body of water in which they occur, or they may form temporarily in response to phenomena such as the radiate heating/cooling of surface water during the day/night. Factors that affect the depth and thickness of a thermocline include seasonal weather variations, latitude, and local environmental conditions, such as tides and currents. It was previously assumed that the maintenance of the shallow thermocline depends mainly on the deep thermohaline circulation, which involves the sinking of cold, saline surface waters in certain high- latitude regions. No method is available to estimate accurately depth of weak and broad subtropical thermocline.

Water temperatures below the surface are measured using a bathythermograph, an electronic sensor that keeps track of the various temperatures at prearranged depths from the surface to the bottom. Warm water tends to be less dense and “floats” on the top of the ocean, where it is heated by the sun. Cold water is denser and sinks to the floor of deep ocean. The density of ocean water varies significantly from place to place. Temperature and salinity are two variables that greatly affect the density of seawater. As seawater warms, it expands and makes the warmer seawater less dense than the cooler one. The salt dissolved within seawater makes it denser than freshwater such that, the higher its salinity, the dense the water. Water masses with varying densities tend to form stratified layers within the water column. The difference in water layer densities acts as barriers to water mixing. This phenomenon serves as a very, important factor in ocean and estuarine water circulation. Water stratification due to water layers of high and low salinity (called a halocline) can be seen in water column profiles of salinity on depth as an area of the line graph where the slope is relatively flat. Presence of layers of cold and warm water in a water body makes a phenomenon called as the thermocline, that will be discussed through this paper.

## 2 Princeton Ocean Model (POM)

The available Princeton Ocean Model (POM) has been already applied elsewhere by the authors of this study, making some modifications to it. In the present study, the POM was fit for the PG. The material and methods applied in this work are in accordance with Mellor and Blumberg (1985). POM is a 3D model that is run in the ocean in Sigma coordinate. The model, which was developed by Mellor and Blumberg (1985) at Princeton University, is run in FORTRAN. The main components of the model are continuity, x-momentum, y-momentum, heat conservation, and salinity conservation equations.

$$\frac{\partial DU}{\partial x} + \frac{\partial DV}{\partial y} + \frac{\partial \omega}{\partial \sigma} + \frac{\partial \eta}{\partial t} = 0 \qquad (1)$$

$$\frac{\partial UD}{\partial t} + \frac{\partial U^2 D}{\partial x} + \frac{\partial UVD}{\partial y} + \frac{\partial U\omega}{\partial \sigma} - fVD + gD\frac{\partial \eta}{\partial x} + \frac{gD^2}{\rho_o}\int_\sigma^o \left[\frac{\partial \rho'}{\partial x} - \frac{\sigma'}{D}\frac{\partial D}{\partial x}\frac{\partial \rho'}{\partial \sigma'}\right] d\sigma' = \frac{\partial}{\partial \sigma}\left[\frac{K_M}{D}\frac{\partial U}{\partial \sigma}\right] + F_x \qquad (2)$$

$$\frac{\partial VD}{\partial t} + \frac{\partial UVD}{\partial x} + \frac{\partial V^2 D}{\partial y} + \frac{\partial V\omega}{\partial \sigma} + fUD + gD\frac{\partial \eta}{\partial y} + \frac{gD2}{\rho_o}\int_\sigma^o \left[\frac{\partial \rho'}{\partial y} - \frac{\sigma'}{D}\frac{\partial D}{\partial y}\frac{\partial \rho'}{\partial \sigma'}\right] d\sigma' \qquad (3)$$

$$\frac{\partial TD}{\partial t} + \frac{\partial TUD}{\partial x} + \frac{\partial TVD}{\partial y} + \frac{\partial T\omega}{\partial \sigma} = \frac{\partial}{\partial \sigma}\left[\frac{K_H}{D}\frac{\partial T}{\partial \sigma}\right] + F_T - \frac{\partial R}{\partial z} \qquad (4)$$

$$\frac{\partial SD}{\partial t} + \frac{\partial SUD}{\partial x} + \frac{\partial SVD}{\partial y} + \frac{\partial S\omega}{\partial \sigma} = \frac{\partial}{\partial \sigma}\left[\frac{K_H}{D}\frac{\partial S}{\partial \sigma}\right] + F_S \qquad (5)$$

Where Sigma coordinates identified for the model are as the follows.

$$\left(x, y, \sigma = \frac{z - \eta}{h + \eta}, t\right) \qquad (6)$$

## 3 Thermocline Formation through Water Column

During the summer stratification period, the water column can be divided into three main bodies of decreasing temperature from surface to bottom: the epilimnion, metalimnion, and hypolimnion. The epilimnion is the most turbulent and heated layer. The bottom hypolimnion layer is the densest and coldest layer, making it the most stable and isolated. The metalimnion (also known as thermocline) is the layer of thermal discontinuity between these two layers, characterized by a steep thermal gradient, where the largest decrease in temperature with depth occurs.

Mean vertical temperature variations through the PG are shown in the following curves in winter and summer. The temperature gradients in summer show thermocline formation despite of in winter.

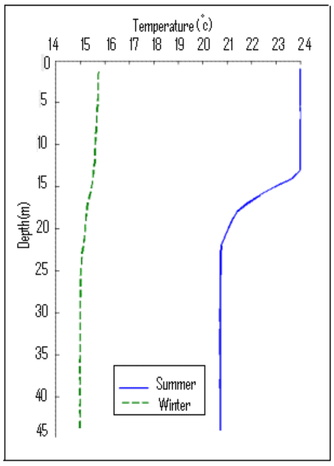



Fig.1 Mean vertical temperature variations through the PG water column in winter and summer

In fact, it could be resulted that thermocline develops in the PG since winter until summer. However, in summer the thermocline is well established and extends well into the PG. The main reasons for the formation of the thermocline in summer are strong solar heating and, more importantly, the diminishing northwesterly winds which are very strong in winter. During summer the layer below the thermocline is similar in character to the deep water in winter. Above the thermocline the temperature in summer is also much higher.

## 4 Results

The main context of this paper following an applied project is done numerically and compared with the related theoretical results of the zone. The data used in through the (POM) model have been measured during a marine cruise by Mt. Mitchell (1992). The measurement stations in the PG are shown in Fig. 2.

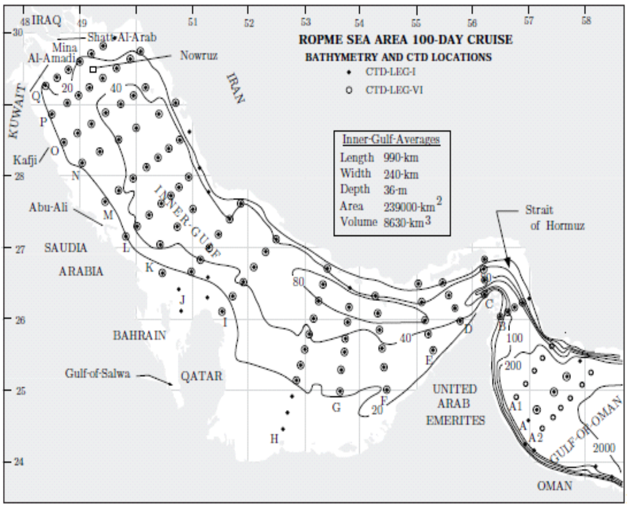



Fig. 2 An aero picture of the PG showing measurement stations in 3 measuring sections

Fig. 3 shows mean variations of temperature through the water column in the PG in summer and winter according to the collected data of temperature in Mitchell cruise 1992.

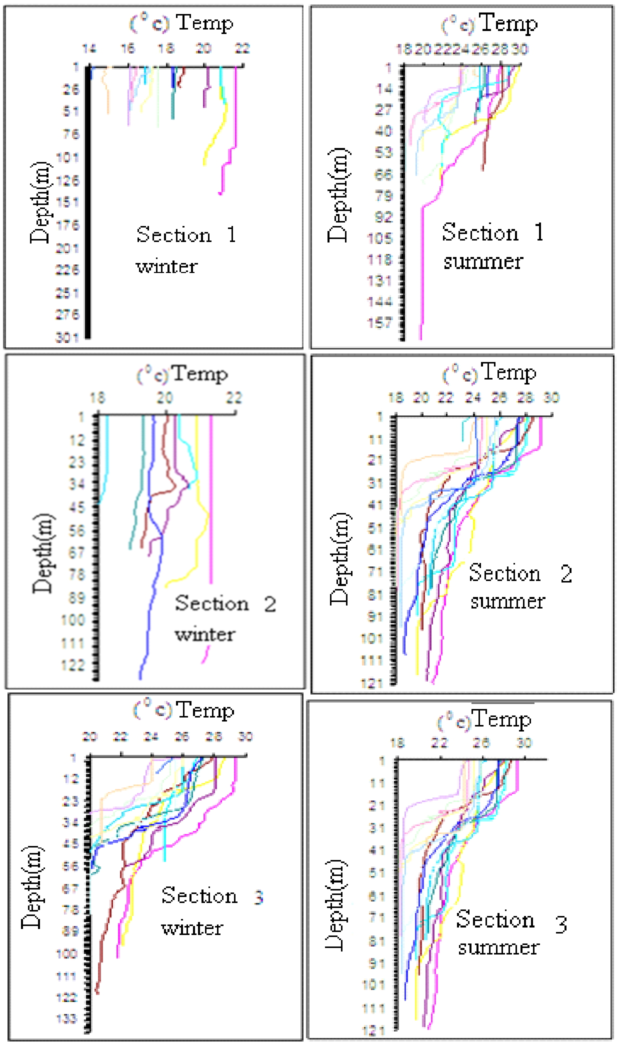
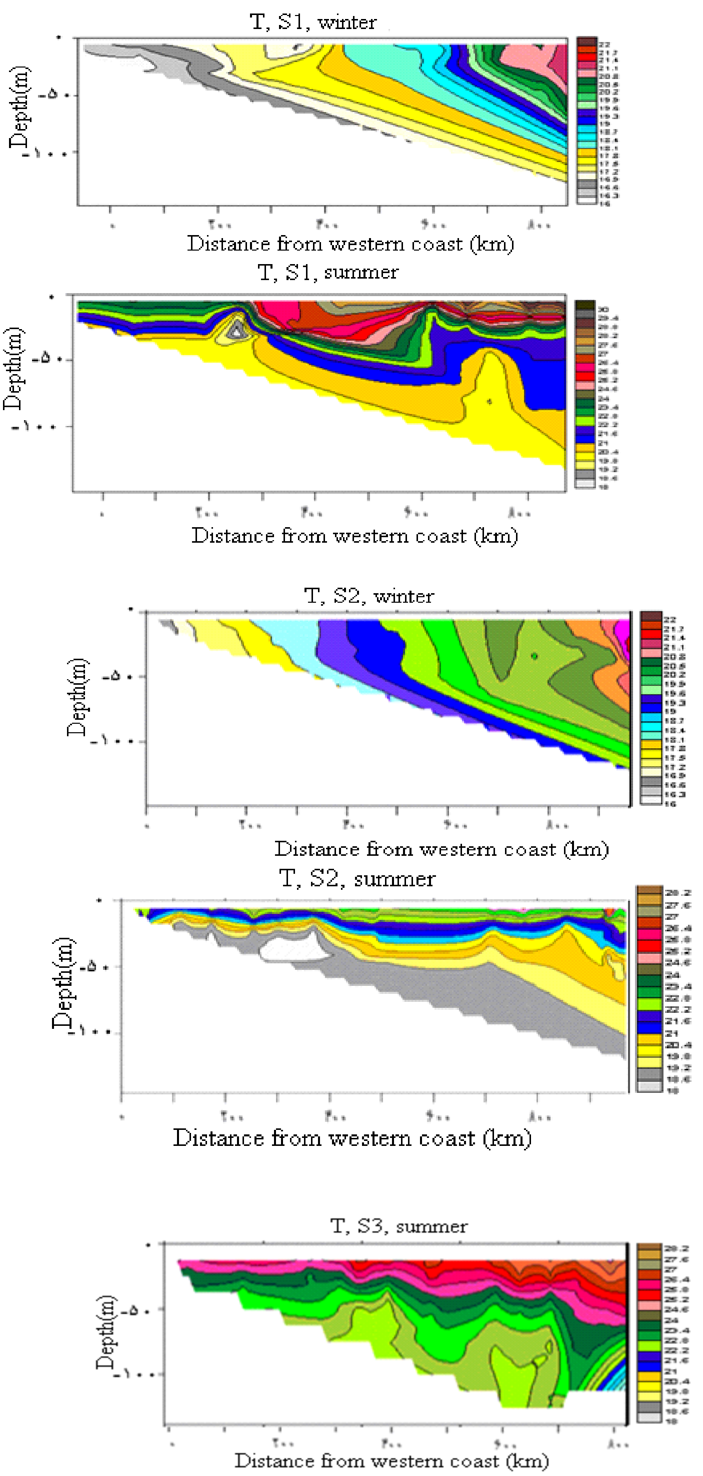
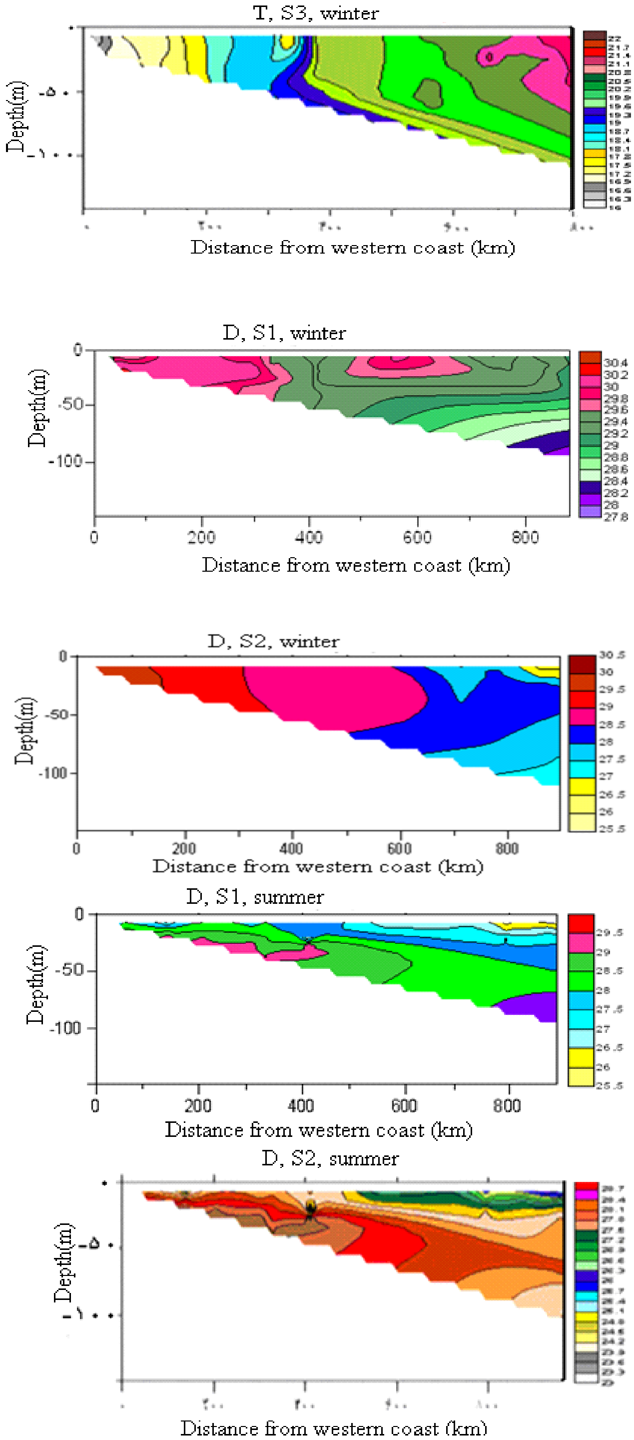



Fig. 3 Profiles of mean variations of temperature through the water column in measuring stations in 3 sections, winter and summer 1992

Based on Fig. 3 and comparing the curves, it is observed that thermocline does not form in winter, except in the Strait of Hormuz. However, it forms all over the PG through the water column in summer, suggesting that thermocline development from the Strait of Hormuz to the PG North from winter to summer. The main cause of the phenomenon is some factors such as wind stress and evaporation. Again, interpolating temperatures and densities in summer and winter collected through Mt. Mitchell cruise, the related contours are drawn in Fig. 4 in 3 sections from north of the PG to the Strait of Hormuz.



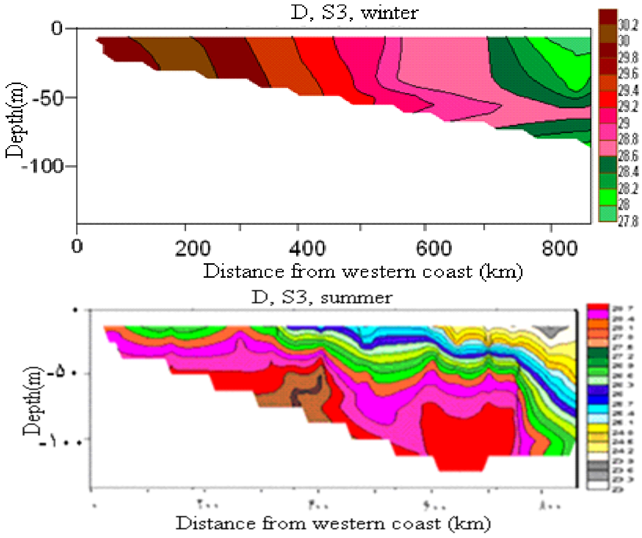



Fig. 4 Contours of temperature and density in 3 measuring sections (S1, S2 and S3) in the PG, summer and winter 1992

Relying on the contours in Fig. 4, it can be stated that there is vertical gradient of temperature and density in the subsurface of the water column in the summer but in winter, it is high only in the Strait of Hormuz as a result of water exchange in winter. To justify the recent results by the model and theoretical study in the zone, we compared the vertical mean of temperature and salinity through the water column in 3 sections (Strait of Hormuz, Middle of the PG, and Northwestern of the PG) in Fig. 5. As can be mentioned, thermocline exists all over the PG in summer according to the model run and measurements of Mt. Mitchell 1992. Correlation coefficients between temperature and salinity resulted from modeling and measurements are (0.77, 0.91), (0.75, 0.81), and (0.82, 0.90) in the Strait of Hormuz, Middle of the PG, and Northwestern of the PG. These results are in a relatively good agreement with the theoretical results, representing thermocline development from the Strait of Hormuz to the Northwestern of the PG from winter to summer.

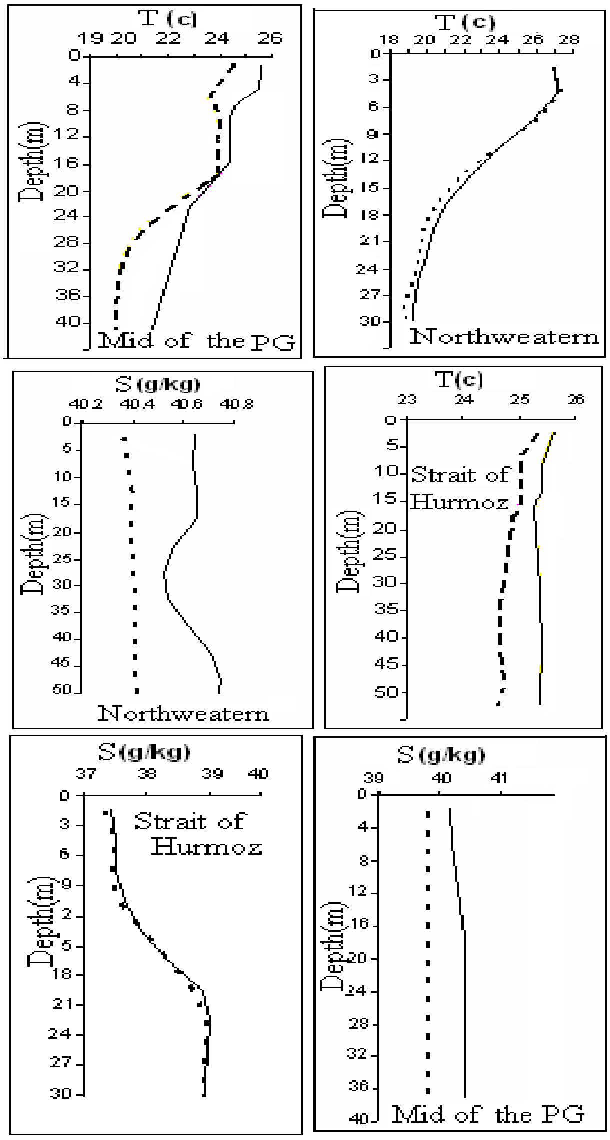



Fig. 5 Model run (- - -) (dashed line) and vertical mean (-------) (dot line) profiles of temperature and salinity in the zone through the water column in 3 sections

It is concluded that in the Persian Gulf, thermocline can form in summer, unlike the winter, in whole water body of the PG. This result is consistent with those reported in [1] and [5]. Thermocline axis in the PG has more fluctuations during summer due to the turbulence factors varying rapidly; in the deeper section.

## 5 Conclusion

Running the model in the PG according to the data in 1992 and topography data, and applying wind it is recognized that thermocline is formed in the Strait of Hormuz in all of the seasons per year as a result of water exchange between the Gulf of Oman and the PG and temperature vertical gradient here. However, thermocline develops from the Strait of

Hormuz to the northern part of the PG from winter to summer with the most rates in mid spring and the highest temperature gradient in the summer.

The model-simulated thermocline depth is generally consistent with the observations derived from measurements according to the diagrams in Fig. 5. According to the theoretical results, we conclude that in the Persian Gulf, thermocline can form in summer, despite of in winter. The seasonal thermocline in the PG is developed from winter to early summer 0.2 m/day in the mid part of the PG and 0.1 m/day in other parts. Also, the main changes of temperature between the surface layer and sub-surface layer occur in the mid part from 0.1℃ in winter to 3.5℃ in summer while the highest temperature difference through the water column in summer is 9℃.

*References:*

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