Hydrographic Processes in a Tropical Coastal Lagoon on Western Bay of Bengal

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Short Report

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Abstract

In this article, hydrographic processes of a tropical coastal lagoon is studied that control inherent biological mechanisms of the lagoon environment. Realizing the interest of environmentalists over physio-chemical studies of a wetland tropical wetland system on the western boundary of the Bay of Bengal, a high-resolution intensive vertical hydrographic field campaign was carried during monsoon to uncover peculiarity in vertical hydrographic processes that was long-awaited to address many environmental issues. Vertical hydrographic profiles on spatio-temporal scale were made at nine stations in a zonal direction of the Chilika lagoon system. Results of vertical variability of salinity showed the presence of higher saline water over less saline water in the central-western region. The higher and lower water temperature in the western and eastern parts of the lagoon, respectively, indicated temperature dipole between the two regions. The encapsulation of water mass having higher temperature by the water of lower temperature at the central region resulted evolution of thermal inversion. The highest dissolved oxygen concentration was observed in the sub-surface layers of the western part of the lagoon. However, a layer of near-hypoxia occurred below 1.5 m depth in the central region. This study proposes comprehensive inter-seasonal studies to address the vertical variability of biogeochemical parameters and the fate of organic flux.

Research Highlights

- Evolution of temperature dipole between the western and eastern region
- Higher saline water towards east vertically separates water masses
- A sub-surface near hypoxia bed from central to eastern region of lagoon
- Salinisation in Chilika depends tidal influx from southern boundary with mere influence through outer channel during monsoon

1. Introduction

The Bay of Bengal (BoB) is a semi-closed basin with an open southern boundary and surrounded by the south-Asian countries on the other three sides.The northward flowing warm East India Coastal Current(EICC) from February to May transports saline waters from the southern to northern BoB (Shetye et al., 1996; Dandapat et al., 2018; Mandal et al., 2018; 2019) (Figure.1). The EICC flows southward from October to December and carries a vast amountof freshwater discharges from the Ganga, Brahmaputra, and Mahanadi rivers from the northern to the southern BoB (Jana et al., 2015; Dandapat et al., 2020). Chilika, the largest brackish water lagoon of Asia, communicates to the Bay of Bengal on the east coast of India. It is one of the critical Ramsar wetlands of the Asian continent that supports a wide range of biodiversity and natural resources. Unlike other coastal lagoons, Chilika providesa broad spectrum of ecosystem services and influences coastal communities' socio-economy conditions that depend on fishery and tourism (Kumar et al., 2020). However, in recent decades, the increased anthropogenic stress due to intensive aquaculture, agricultural runoff, sewage discharge, etc., adversely affects Chilika's water quality regimes and its fishery resources (Panigrahi et al., 2007; Nag et al., 2020).Additionally, several natural processes such as siltation, eutrophication, perturbation in salinity pattern,and quantum of river/marine flux also control Chilika's ecology in a great concern (Panigrahi et al., 2007; Sahu et al., 2014). Over the past few years, Chilika lake is experiencing dynamic variations in salinity due to the simultaneous mixing of freshwater and marine water, categorizing four different ecological sectors (Figure. 1) (Srichandan et al., 2015a,b; Barik et al., 2017; Sahoo et al., 2017). The dynamics of the tidal inlet influence the salinity regime of the lagoon (Gopikrishna et al., 2014). In order to restore the reduced salinity and ecological characteristics of the lake due to sea inlet choking, an artificial mouth was dredged by Chilika Development Authority in September 2000 (Ghosh et al., 2006). Since then, many studies have reported improvement in Chilika's aquatic life (Parida et al., 2013; Mohanty et al.,2015; Pattanaik et al., 2020). However, increasing anthropogenic activities in the catchment region and influx of pollutants through river discharge threaten and declines dissolved oxygen (DO) concentration in the lagoon. Many studies have addressed DO variability in Chilika (Nayak and Behera, 2004; Nayak et al., 2004; Panigrahi et al., 2007; Barik et al., 2017) and among them recent study reported a wide range (0.3 to 14mg.l^{-1}) of DO variability in Chilika (Muduli and Pattnaik, 2020). However, a thorough study of available literature confirms no such work on vertical thermohaline and DO variability. However, Chilika has an average depth of 2 m; investigating the variability of the above parameters along the subsurface can help understand the water mass properties, organic matter decomposition,seawater intrusion, etc. The complexities in physical processes associated with the varying salinity and DO distributions, seasonal river discharges in the Chilika need to be understood. Thus, the objective of this studyis to understand the variability of temperature,salinity, and DO along the subsurface towards the end of the southwest monsoon in Chilika using the observations collected from field campaigns.

2. Material And Methods

A field campaign was conducted during 25th – 26th October 2017 across the Chilika lake (track with red dots in Fig. 1 with a particular focus on understanding the diurnal variability and vertical distribution of hydrographic parameters (temperature, salinity, and DO).Field observations have been collected at a total number of 9 stations using a global positioning system (GPS), each at a distance of 4 km along thetransect. The sampling frequency at station 2 (S2) is 5 minutes precisely to monitor the diurnal variability of hydrographic parameters. The profiles of salinity, temperature, density, and DO were measured using a castaway Conductivity-Temperature-Depth (CTD) profiler equipped with a DO sensor (Instrument:RBR Concerto) (Sutherland and O'Neill, 2016). During the forenoon (09:00–12:00 hours), the sampling was done to get undisturbed profiles of temperature, salinity, and DO due to fewer wind gusts over the water surface.

3. Results And Discussion

3.1 Spatial Variability of Hydrographic processes

The vertical distribution of temperature along thetransect (east-west direction) of Chilika depicts relatively colder water towards the eastern region than the western (Fig. 2). The variabilities in temperature indicated strong signatures of thermal inversions in thecentral and westare as of Chilika. The thermal inversion phenomena occurred below 1.5 m depth in the central Chilika with a larger (~ 10 km) horizontal extent, while the higher-order temperature inversions occurred below 1 m depth along the western boundary at a smaller horizontal extent (Fig. 2). Relatively warmer water along the western Chilika could be due to the weak interaction of freshwater in this region andthe evolution of the temperaturedue to the low heat capacity of saline water (Murray, 2004). As a result, a temperature dipole has emerged between the western and eastern Chilika during post-monsoon. It might potentially impact microbial activity and the mineralization process to decomposethe organic matter into nutrients (Ganguly et al., 2013; Muduli et al., 2013; Barik et al., 2017). A similar trend of higher saline water associated with warmer temperatures has beenobservedin the Ria Formosa lagoon located in a meso tidal regime of Portugal (Newton and Mudge, 2003). Besides, a peculiarity in such temperature evolution could alter the phytoplankton species composition and growth rate (Ganguly et al., 2013). Since temperature is a limiting factor for carbon and nitrogen metabolism, variability in these processes is expected between Chilika western and eastern boundaries (Paerl and Justic, 2011). Retention of higher temperature water below the depth of 1.5 m indicates the encapsulation of saline waters by freshwaters.

In concomitant to the present pattern of salinity variation, the vertical structure of density anomaly showed positive values along the western Chilika than the eastern (Fig. 2). Besides the above facts, instability in the water column below 1.5 m might be due to the static nature of water with a higher density over the lower density water parcel.Western Chilika is relatively shallow and has a weak interaction with freshwater, thereby exhibiting higher salinity than the eastern region. The water mass belowthe 1.5 m acted as a barrier layer separating the water column into two layers. Less saline waters propagated westward in the top layers, and relatively higher saline waters propagated eastward. This pattern indicated vertical circulation of water masses through the sinking of high saline waters at the western boundary and translation of freshwaters towards the western boundary from the eastern. The well-mixed salinity structure alongthe eastern boundary of Chilika is attributed to the influx of freshwaters from the Mahanadi river through the dredged channel connecting from Magarmukh to the northern reach. The vertical salinity structure showed stratified conditions in the central region of the transect (Fig. 2).

A relatively higher saline tongue was observed to extend into the lagoon from the west within 1 -1.5 m depth.The intrusion of higher saline waters from the western to eastern boundary indicates the influence of the Palur Canal (a narrow channel connecting Rushikulya Estuary with Chilika) that dilutes the marine influx received from the outer channel of the lagoon with freshwater discharge. Based on the vertical profile of salinity, the water mass of Chilika can be categorized into three categories with freshwater at the eastern boundary while the other two water masses spread over the central-western region with higher salinity waters at the bottom and lower salinity waters at the top associated with higher and lower temperatures, respectively. In general, the western partof Chilika near the Palur inlet remains higher saline in the summer period. However, during the monsoon, the unidirectional freshwater flow from the north to the west could have resulted in lower salinity values in surface and near-surface layers. The currents are stronger during monsoon and mostly unidirectional towards the outer channel caused by heavy inflow from the northeast rivers (Gupta et al., 2008; Muduli et al., 2013). The pathway for water discharge is from the northern and western parts of Chilika to the BoB, through the Magarmukh area, the outer channel, and the inlet mouth resultingin a significant reduction in salinity compared to other sectors of the lagoon (Mohanty and Panda, 2009).

Further, towards the end of the eastern region, salinity was homogenous throughout the water column. This region's lowest salinity (1 psu) could be due to the high freshwater discharge from rivulets, freshwater-sewage release from the nearby township, or marine influence.Besides, the freshwatersewage discharge from the nearby townships through Dayaand Makara River (Nag et al., 2020) might have played a key role in reducing salinity levels which is evident from the westward transmission of low saline (high density) water from the eastern boundary (Fig. 2).

The vertical profile of DO showeda higher concentration in the western boundary than the eastern boundary (Fig. 2). The DO concentration increased with depth in the western region, and this pattern was observed until 5 km from the western boundary. However, the central partwas observed with DO concentration within 6-8mg.l^{-1} between 1.5 m to 2 m and less than 3mg.l^{-1} below 2 m depth extending from western to eastern region. The thickness of water with low DO is relatively higher in the east and central regions than in the west. The higher DO concentration below 1 m depth inthe western region could be attributed to the incursion of oxygen-rich freshwater anda higher rate of photosynthesis by aquatic weeds (Mishra and Jena, 2013).The higher oxygenated water along the westcould be due to the nutrients fluxes from the Balugaon urban area, leading to a higher algal photo-synthesis process (Nazneen et al., 2019).The near-hypoxia zone in the central region of Chilika below 1.5 m depth of the water column is possibly due to the microbial degradation of autochthonous and allochthonous organic matters. It's important to mention that Chilika receives a considerable quantum of natural and anthropogenic organic matter through river-rivulet discharge and terrigenous runoff from the catchment region (Sahay et al. 2019). In addition, organic residues released from intensive shrimp culture within the lagoon might havebeena significantsource of organic matter. In general, DO concentration in an aquatic system is primarily reliant upon the rate of photosynthesis by phytoplankton and macrophytes, organic matter decomposition by microbes, and chemical properties of water (Aston, 1980;Granier et al., 1999). Therefore,the formation of near-hypoxia condition/reduction in DO concentration could be due to the gradual sinking of organic matter to the bottom and subsequent bacterial decomposition. Besides, a relatively lower DO concentration below 2 m might indicate an active nitrification process,which consumes a significant amount of oxygen or poor mixing of surface and sub-surface water (Muduli et al.,2012). Lower levels of DO near hypoxia in the sub-surface waters could be very detrimental and lethal for benthic biota (CPCB New Delhi, 1986; Hale et al., 2016). Chilika is a recognized suitable habitat for economical shellfishes such as mud crabs, prawns and shrimps (Mohapatra et al. 2015). Recent estimate shows mean fisheries landing during 2017 & 2018 is 1388 tonne, which is 18% higher compared to mean fisheries landing during 2016 (1172 tonne) (Fig. 3, upper). This fisheries constitutes of fish (69.72%) followed by Prawn (28.36%) and crab (1.92%) (Fig. 3, lower) representing 11613 tonnes of both shell fish& finfish, 4724 tonnes of prawn and 320 tonnes of crab. Distribution of monthly fish landing shows an increasing trend during pre-monsoon & monsoon and a decreasing trend during north-east monsoon compared to mean fisheries landing for two years (Chilika Lake Health Report Card, 2017-18). Decline fish landing trend during later phase of monsoon clearly indicates less abundance of marine fisheries within lagoon which could be either due to evolution of stratified saline and fresh water masses or genesis of a near hypoxia environment below the 2 m depth. On the other hand, the possibility of vertical propagation/limits of low DO water to surface cannot be ruled out for such decline trend. As fishery resources in a lagoon environment is sensitive to quality of its water, therefore vertical hydrographic distribution can be serve as a proxies for understanding distribution of fisheries resources/fish dipole for different seasons. As fishery resources of Chilika is sensitive to ambient water quality, comprehensive large-scale sensor-based or autonomous buoy based observation for understanding the vertical distribution of physico-chemical parameters is very crucial.

3.2 Diurnal variability of Hydrographic Processes

3.2.1 Evolution of thermohaline

The diurnal variation of the thermohaline structure near Magarmukh is has been depicted in Fig. 4. The analysis shows that during the monsoon period, there is a presence of thermocline during day time (08:00 hrs to 19:00 hrs), the occurrence of mixed layer/thermal inversion layer during night time. The thickness of the thermocline, starts at 1.5 m, and continues to increase until 17:00 hrs. The mixed layer/thermal inversion phenomena occur upto 2 m until morning 6:00 hrs during the night. The hourly variation of thermocline data indicates air-sea interaction in the lagoon. During the daytime, the less saline waters up to 1.5 m depth heat up, which further heating up the subsurface waters. Later during the night time, comparatively colder waters are observed at the surface. In contrast, the subsurface waters remain warmer, which appears to be the primary reason behind the formation of the thermal inversion during nighttime. The depth of thermal inversion persists up to 2 m, as a layer less saline surface waters exist over the higher saline subsurface waters. The process of temperature inversion has a significant effect on the biological processes (Sahu et al., 2017) and biomass distribution, which is limited to the upper 2m in Chilika (Madhupratap et al., 1981). Figure 2 depicts the temperature and salinity gradient of the water column in the vertical along the transect. The analysis shows that while the temperature gradient is higher during daytime, it is significantly less during the night time until morning at 10:00 hrs. The surface to bottom temperature gradient varies between – 0.11 to 1.40°C with an average value of 0.30°C. It was observed that the increasing trend of salinity is associated with the decreasing trend of temperature with depth during the daytime, while such a relationship does not hold tight during night time. Besides the high variability trend of salinity along the subsurface, there was increasing temperature and sometimes thermal inversion during night.

3.2.2 Diurnal variability of Temperature and Salinity

It can be understood from Fig. 5 that while the decrease in temperature is slight, the increase in temperature is more rapid in the upper layers (until 1 m) during 25th – 26th October 2017. Conversely, the rate of rising salinity is relatively slower compared to its fall. This is possibly due to the dominance of the river waters over the intrusion of sea waters. According to Fig. 5 (lower left), the predominant maximum temperature ranges are 28.75-29°C, 29.5-29.75°C, and 29.75-30°C. Similarly, the salinity variation is depicted as a rightly skewed distribution representing the dominance of seawater for a more extended period than freshwater discharge Fig. 5 (lower right).

Figure 6 represents the data on water current, which gives the variability of fresh and saline water at the Magarmukh region. This shows that water flow is westward most of the time, indicating the intrusion of seawatersinto the lagoon through the mouth. On the other hand, strong evidence of fresh waters along the western Chilika suggests influx from different distributaries of the Mahanadi river system on the west side of the lagoon (nearly 10%). Besides, persistence of calm environment (current speed < 0.1 m/sec) for 1/4th of observation period indicates freshwater and saline water are in equilibrium without any interaction during the tidal cycle. The thermohaline structure remains intact and generates a stratification compared to the rest during the calm period.

4. Conclusion

Vertical distribution of salinity, temperature, and dissolved oxygen has been investigated in the Chilika lagoon. This is the first endeavor to study the vertical distribution of the above parameters in this lagoon. The salient outcomes of this study can be summarized as 1) the hypoxic condition below 1.5 m depth in the central region of the lagoon, 2) apparent thermal inversion with water of lower temperature overlying the water of higher temperature in the central region, and 3) stratified high saline water over less saline in the central-western region. Further long-term systematic studies evaluating the vertical distribution of physic-chemical-biological parameters are recommended to understand their inherent properties better and mitigate the pollution. Additionally, the information on vertical hydrographic distribution can be used for studying fish habitat and their spatial distribution.

Declarations

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Authors contributions

RKS: Conceptualization, field campaign, data analysis and preparation of first draft of manuscript; SS and RNS: Project administration, fund acquisition, supervision and manuscript revision; SP: field survey and data acquisition; SM and SKB: edited the manuscript and preparation graphical illustration.

Conflicts of interest

Authors have no conflict of interest to declare.

Availability of data and material

All the observed datasets in the present study is included in the manuscript.

Code availability

Not applicable.

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Figures

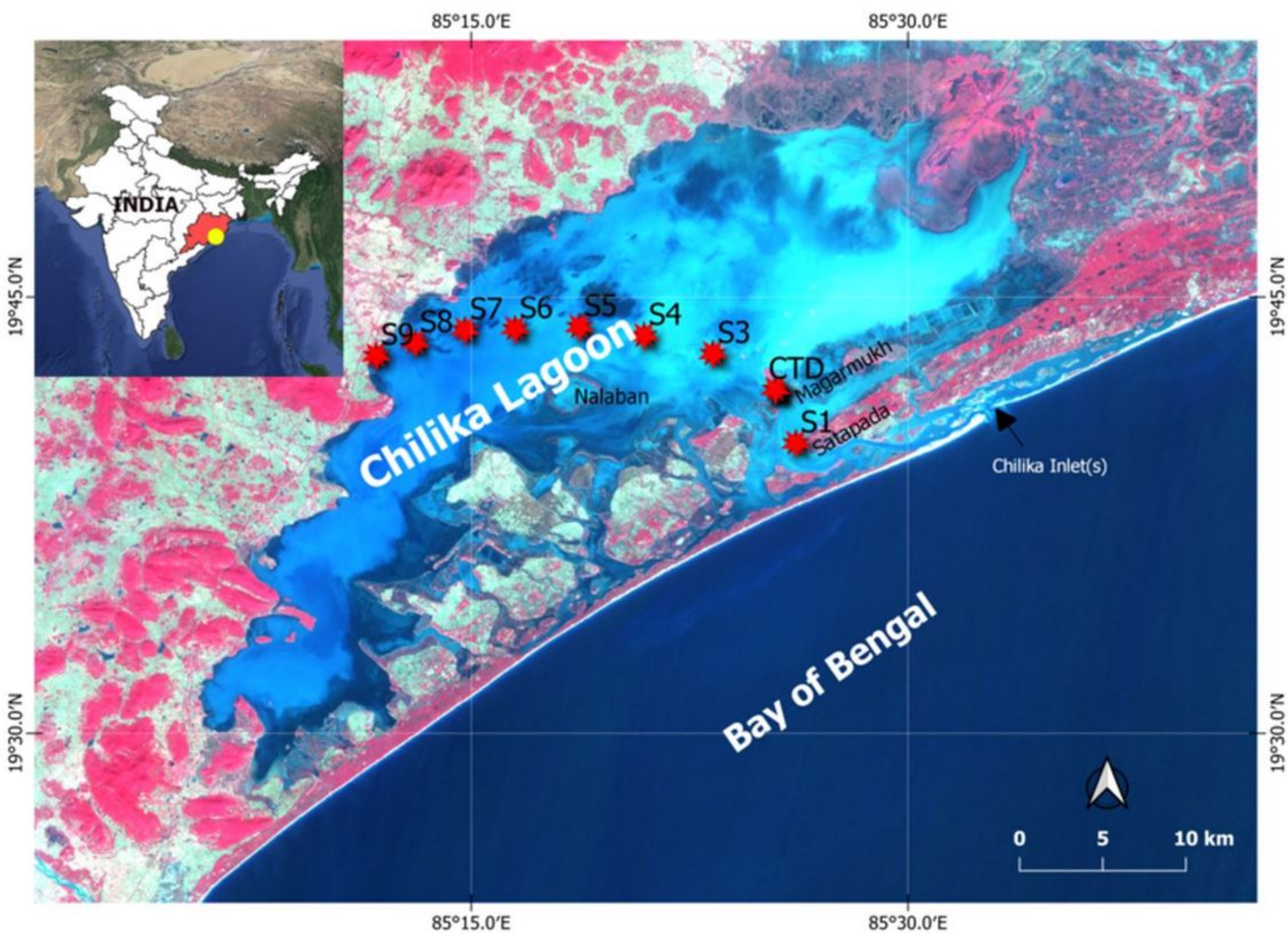

Figure 1

Sampling locations along the transects of Chilika lagoon. Circle filled with red color is profiling stations for hydrographic parameters using CTD-DO Sensors while diurnal observation for temperature and salinity is observed at S2

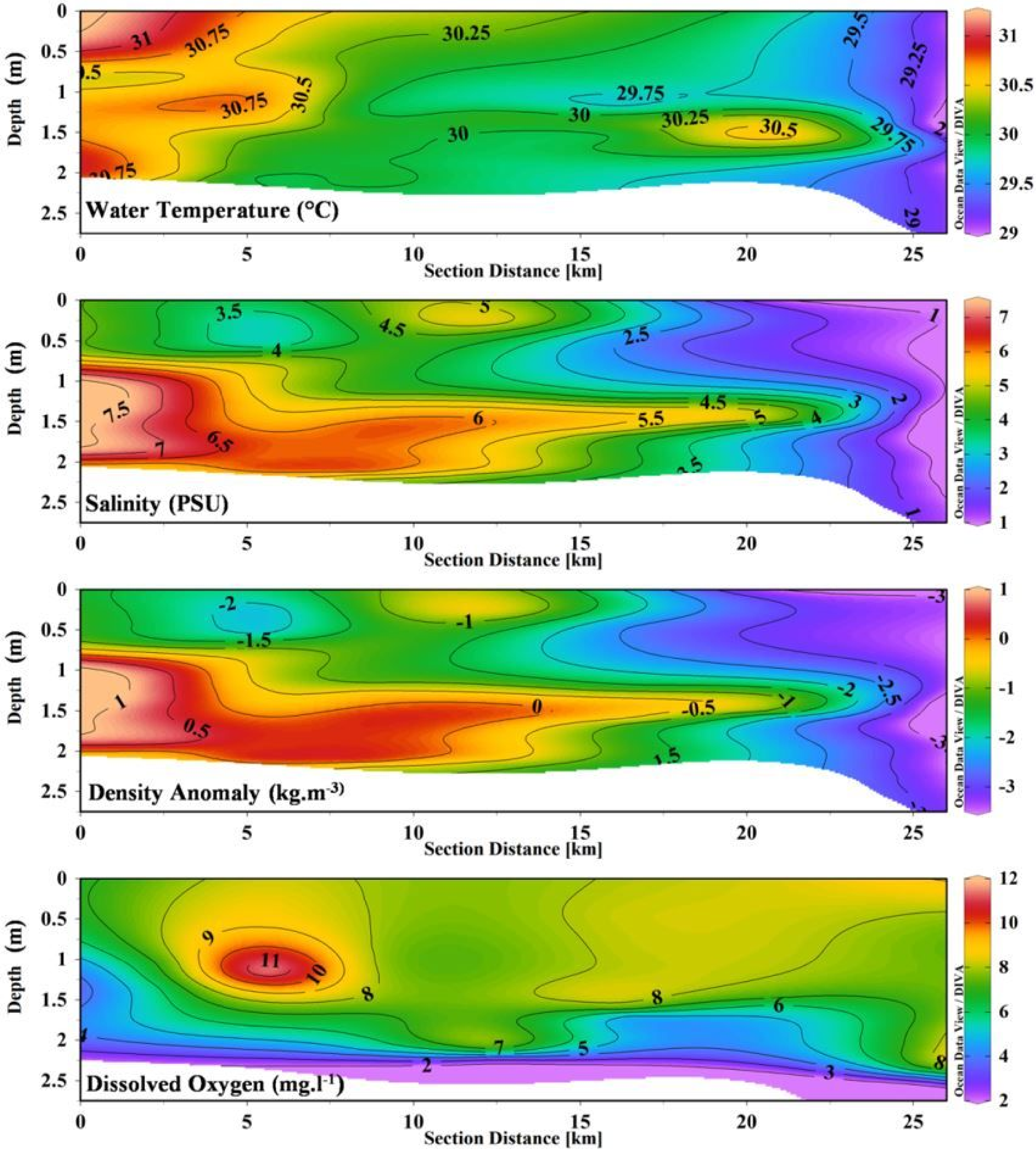

Figure 2

Vertical distribution of temperature, salinity, density anomaly, and dissolved oxygen (DO) across Chilika Lake (transect in Figure 1).

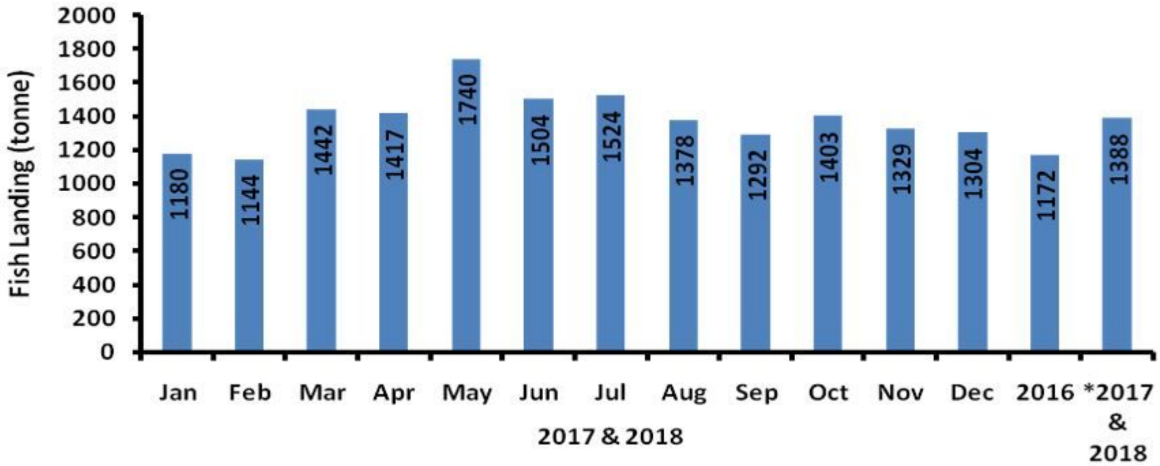

Figure 3

Fish landing information in Chilika lagoon. Monthly distribution of fish landing where * indicate mean value of fish landing during thoserespective years(upper), Category of fish landing during 2017 & 2018 (lower) (source: Chilika Lake Ecosystem Health Report, 2017-18)

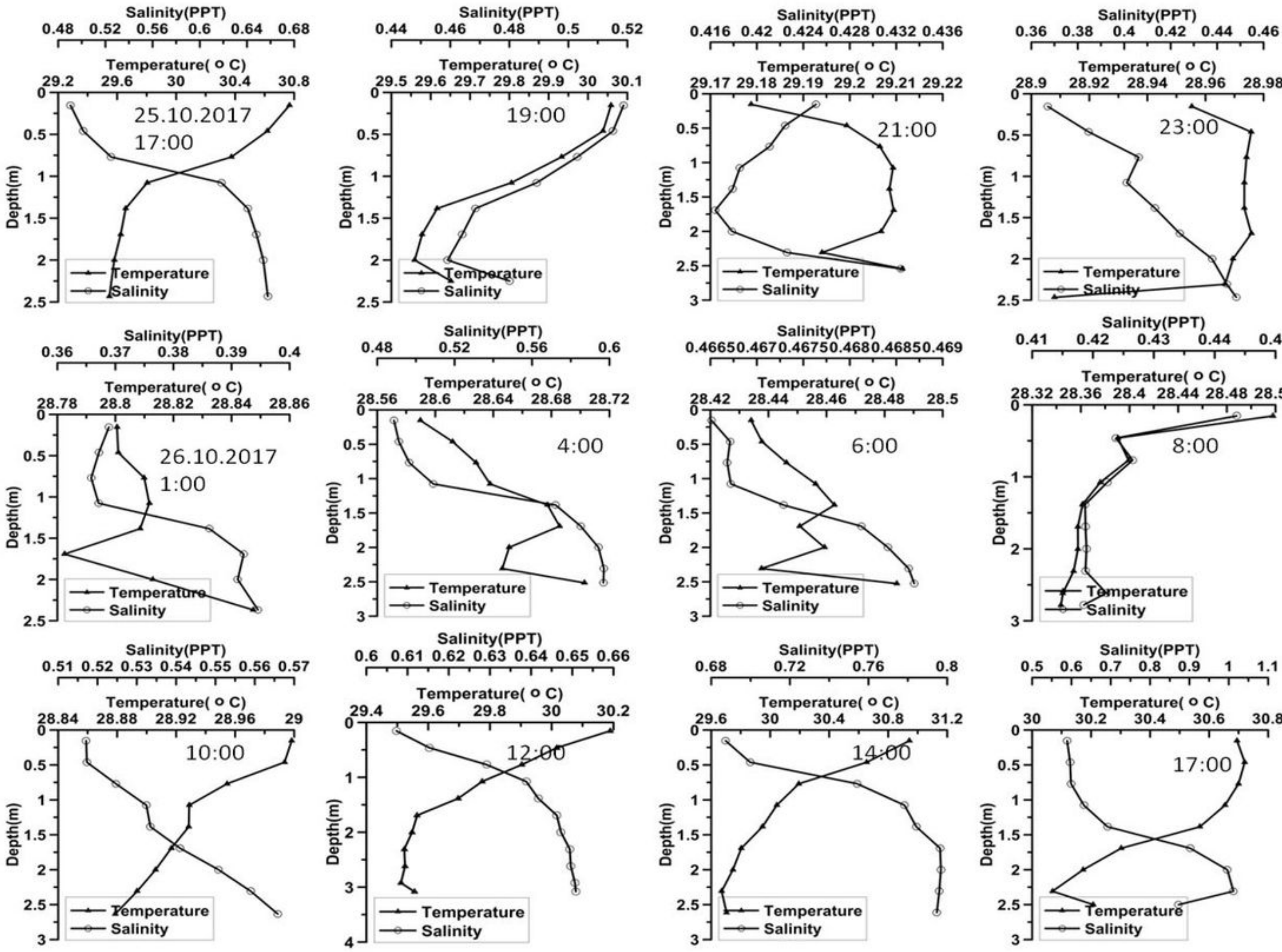

Figure 4

Vertically diurnal variation of thermohaline structure at Magarmukh in Chilika lagoon

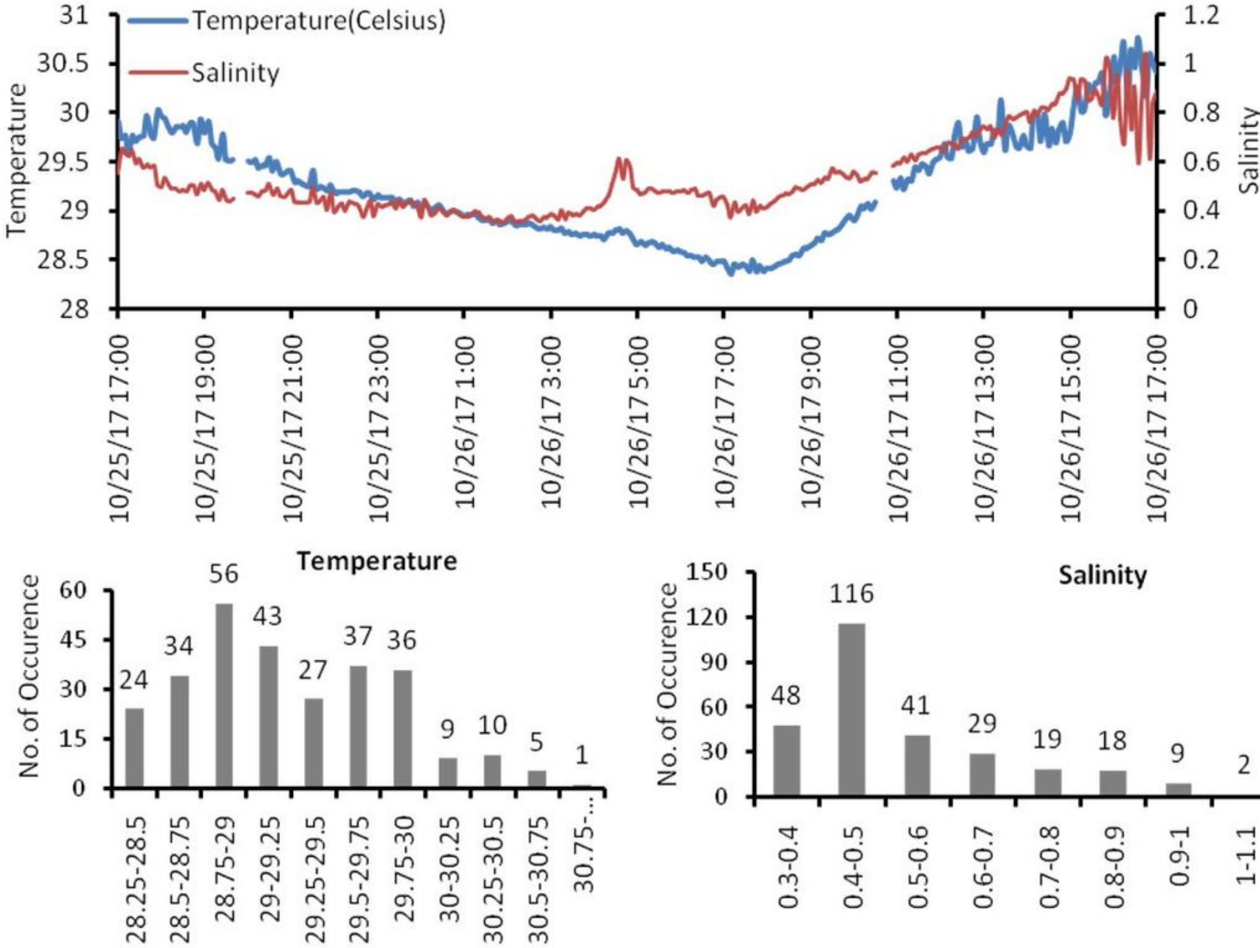

Figure 5

Diurnal salinity and temperaturevariation during 25th – 26th October 2017 (Upper), frequency distribution of water temperature (lower left), and frequency distribution of salinity at Magarmukh (lower right)

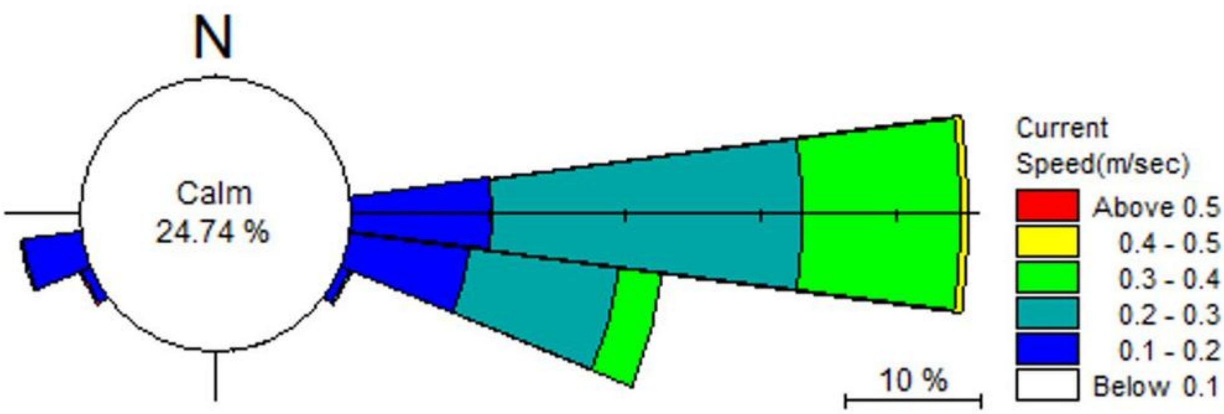

Figure 6

Distribution of current speed and direction nearMagarmukh during the monsoon