Observed thermohaline structure and cooling of Kochi backwaters and adjoining southeastern Arabian Sea

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Thermohaline structure of Kochi backwaters under fair and rough weather conditions has been examined along with thermal structure of two open-ocean islands in the adjoining southeastern Arabian Sea (Kavaratti and Andrott in the Lakshadweep Archipelago). Longitudinal thermohaline structure of Kochi backwaters was found to be inhomogeneous, where the relatively warm and low-saline head estuary gets easily disturbed by sudden changes in meteorology, manifested by a sharp drop in temperature and salinity. The southernmost location was the most sensitive, and the easternmost location the least sensitive to meteorological changes. Thermohaline stratification was greater at the mouth region during monsoon, where a cap of (~4 m) low-saline water (≤2 psu) floats over a thermal gradient of ~3.5°C (9 m depth). Spring–neap thermohaline behaviour exhibited weak inverse correlation ($R^2 \leq 0.58$), with a relative cooling due to the incursion of seawater during spring tide. However, a stronger correlation was observed between salinity and tide ($R^2 = 0.64$). The thermal variations were mainly attributed to day/night heating/cooling processes, tides and winds. The cooling of island waters due to wind was delayed by half a day, whereas that of the Kochi backwaters was delayed by more than 1.5 days. Temperature variability at the Kochi backwaters was also influenced by its shallow depth, surrounding land mass and vegetation on its periphery. The mouth of the estuary was additionally cooled by upwelled waters from the Arabian Sea.

Keywords: Backwaters, cooling, open-ocean islands, stratification, thermohaline distribution.

THE Kochi backwaters, situated in the southwest coast of India (Figure 1), is a unique water body on account of its capacity in providing a nursery ground for a wide variety of aquatic plants, shell and fin-fishes[1–3]. This shallow estuary (<12 m deep) is used extensively for transport of goods, water sports, fishing, and a variety of anthropogenic activities. The estuary has two mouths, one at Azhikode (250 m wide) and another at Kochi (450 m wide), which are separated by ~25 km. The Kochi inlet forms the entrance to the Kochi harbour. While these two inlets cause intrusion of saline water from the Arabian Sea, six rivers originating from the Western Ghats supply large quantities of freshwater into the estuary during the southwest and the northeast monsoon seasons. The Kochi

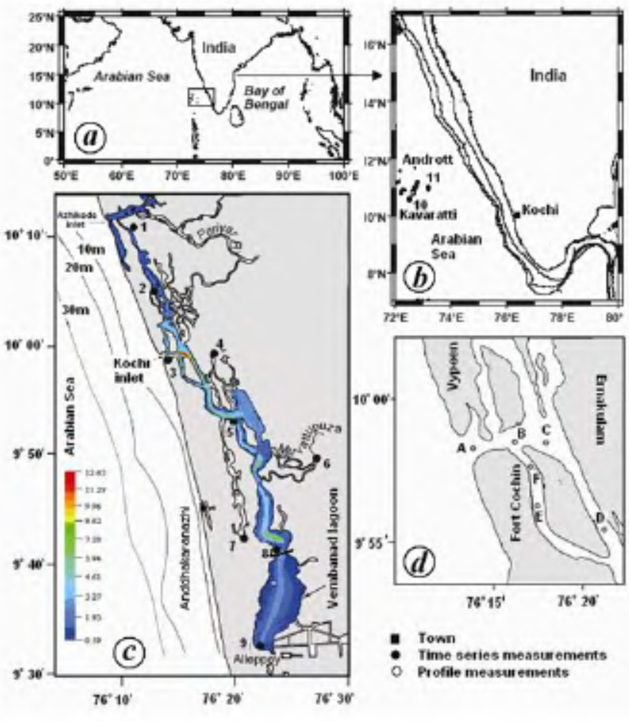

Figure 1. ***a***, Map showing broad view of the study areas in relation to the Arabian Sea; ***b***, Study region, including Kochi backwaters and the adjoining islands beyond the continental shelf in the eastern Arabian Sea. ***c***, Kochi backwaters system. Thanneermukkam barrage is indicated by a dark line near station #8. ***d***, Kochi inlet region. Locations of time-series and vertical profile measurements are indicated by filled and open circles respectively.

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backwaters has suffered natural and man-made shrinkages over the years, and its mean depth has reduced to ~66% during the past fifty years[4]. Whereas two hydraulic barriers across the estuary have been successful in preventing salt-water intrusion, the progressive ecological degradation inflicted on the entire estuary is severe[4]. Closure of the barriers arrests tidal propagation on the south estuary. Consequently, the upstream boundary regions of Kochi backwaters are stagnated and the discharges of agricultural waste (fertilizer, insecticide and pesticide residues) are trapped, thereby causing severe environmental degradation with increased growth of water hyacinth, known as African payal[5].

The Kochi backwaters generally provides a calm and pleasant environment to yachtsmen, and it finds an important position on the world tourism map because of the well-known snake-boat race conducted here annually. However, historically, navigation in the Kochi backwaters has been many a times beset with calamities and human casualties connected with wind–wave-forced boat capsizing during meteorological disturbances. Features of tidal propagation and sensitivity of water-level variability in this estuary to such disturbances have been reported elsewhere[6]. In spite of the numerous studies on physical, chemical, biological and geological aspects of the Kochi backwaters[7–14], a comprehensive study covering the entire estuary is lacking.

Thermohaline features of the Kochi backwaters have been studied in the past by several investigators only from limited areas[1–3]. Lack of synoptic measurements at closely spaced time intervals has posed restrictions in understanding the overall physical features of the estuary. Most importantly, no studies have been reported on the influence of insolation, wind and rain on its temperature–salinity structure.

The parameters employed for the study of the Kochi backwaters include time-series (10 min intervals) of temperature, salinity and water level (from ~1 m below chart datum level) at spatially separated locations, together with surface meteorological parameters during April–June 2006 and April–May 2007. Time-series of surface winds, water level and near-surface temperature measurements (from ~1 m below chart datum level) from Andrott and Kavaratti Islands of the Lakshadweep Archipelago in the adjoining southeastern Arabian Sea have also been used to examine the nature of temperature variability in the Kochi backwaters in relation to that in the open-sea island locations, together with the role of tidal cycles and wind on the near-surface thermal variability.

The Lakshadweep Archipelago consists of a conglomeration of 11 inhabited and 13 uninhabited islands. In this study, the two inhabited islands are Andrott (4.9 km^2) and Kavaratti (4.22 km^2), separated by ~120 km and located ~293 and 404 km respectively, northwest of Kochi. Since the former has virtually no lagoon in its periphery, it can be considered as an open-ocean environment. The latter has a lagoon area of 4.96 km^2 (greater than its land area) on its west.

Methods and instruments

Time-series of water temperature, salinity and water level measurements from the Kochi backwaters were made from 8, 2 and 8 spatially separated locations respectively. In addition, water temperature and water level measurements were made from Kavaratti and Andrott open-sea islands in the Lakshadweep Archipelago (Figure 1 and Table 1) to examine the characteristics of near-surface temperature variability in the Kochi backwaters vis-à-vis those in the open-sea island waters off the continental margin of the west coast of India.

EMCON-make temperature/salinity loggers and tide gauges were used for near-surface time-series data collection from the Kochi backwaters during April–June 2006. The loggers were deployed close to the chart datum level to prevent their exposure during low tide. The temperature sensor was silicon *p–n* junction semiconductor element (full-scale [FS] = 50°C), whose linearity and accuracy are better than 0.4% FS and –0.8% FS respectively. The salinity sensor was an induction-type conductivity cell (FS = 40 psu), whose linearity and accuracy are better than ±3% FS and ±5% FS respectively. The water-level sensor (FS = 200 cm) was a rotary transducer (float-in-well mechanism), whose accuracy is better than 1.6% FS and ±0.2% FS respectively, in the range 10–100 and 101–200 cm, and linearity better than 1% FS.

In the second phase of measurements (March–May 2007) in the Kochi backwaters, water-level and near-surface water temperature measurements have been made from four locations extending from the mouth region to the Thanneermukkam barrage (station no. 8). Shallow-water strain gauge depth sensor (FS = 20 m), whose accuracy is 0.1% FS and YSI's thermistor (model: 44202), whose accuracy and linearity are ±0.15°C and ±0.065°C respectively, were employed. Near-surface water temperature measurements from Andrott and Kavaratti Islands were carried out using Honeywell sensor (FS = 50°C), whose linearity and accuracy are better than 2% FS and ±1.5% FS respectively.

NIO-make autonomous weather stations (AWS) have been used for surface meteorological measurements (wind velocity, barometric pressure, relative humidity, and air temperature). Here, Young's propeller and vane (model: 05103) measured speed and direction with an accuracy of ±0.2 m/s and ±3° respectively. Honeywell's silicon piezo-resistive pressure sensor (model: HPB) measured barometric pressure with an accuracy of ±0.4 mb. Capacitive polymer hygromer sensor (FS = 100%) from Rotronic Instrument Corporation (model: MP-100) measured relative humidity with an accuracy of 3%. YSI's thermistor (model: 44202) measured air temperature with an

Table 1. Geographic coordinates of time-series measurement locations in the Kochi backwaters (station numbers as indicated in the location map; × indicates no measurements). Surface meteorological measurements were made from Kavaratti in the Lakshadweep Archipelago (lat. 10.57°N, long. 72.64°E) and Andhakaranazhi (lat. 9.75°N, long. 76.28°E) on the periphery of the Kochi backwaters

Station no.	Station	Parameters: Temperature	Salinity	Water level	Latitude (°N)	Longitude (°E)	Measurement duration
1	Maliankara	√	√	√	10.17	76.18	27 April – 4 June 2006 30 March – 8 May 2007
2	Nedumgad	√	×	√	10.07	76.23	20 April – 4 June 2006
3	Kochi Port Trust	√	×	√	09.97	76.24	29 March – 9 May 2007
5	Vaduthala	√	×	√	09.86	76.34	11 April – 3 June 2006
6	Vettikattumuku	√	×	√	09.81	76.45	11 April – 27 May 2006
7	Vayalar	√	×	√	09.71	76.34	23 April – 3 June 2006
8	Thanneermukkam	√	√	√	09.68	76.39	23 April – 3 June 2006 28 March – 10 May 2007
9	Talavadi	√	×	√	09.53	76.35	27 April – 3 June 2006
10	Kavaratti	√	×	√	10.57	72.63	20 March – 9 June 2006
11	Andrott	√	×	√	10.82	73.67	27 February – 8 April 2007

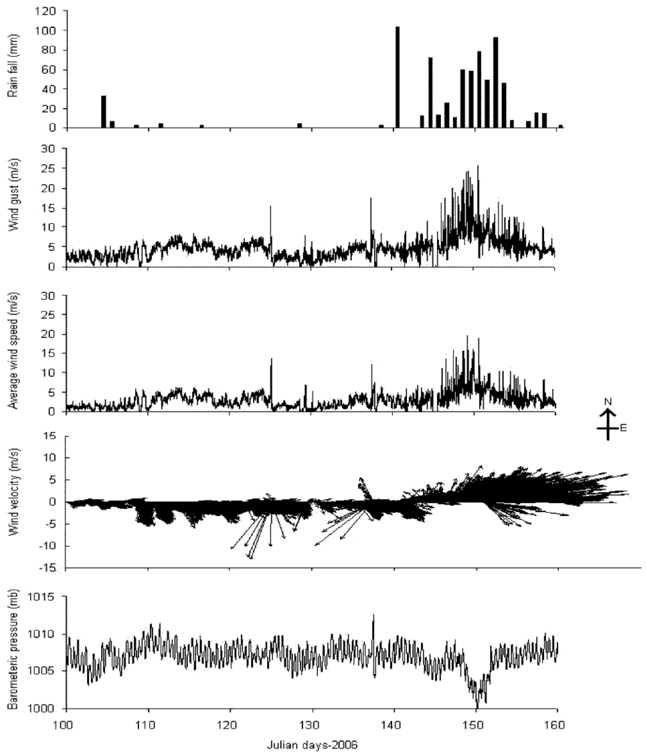

Figure 2. Sixty-day measurements (April–June 2006) depicting an episodic surface meteorological event involving heavy rainfall, intense wind and barometric pressure drop.

accuracy and linearity of ±0.15 and ±0.065°C respectively. Rainfall data have been obtained from India Meteorological Department.

Measurement scheme

Time-series of temperature and salinity measurements from the Kochi backwaters have been made at 10 min intervals from eight and two locations respectively, during April–June 2006. Since the spillway near station no. 8 remained open during the present study, the entire estuary was considered as a single water body with two openings to the eastern Arabian Sea. In another survey, repeated measurements of the vertical profiles of water temperature and salinity have been obtained from six locations (A, B, C, D, E, and F, Figure 1 *d*) in the navigation channel (mouth) of the Kochi shipyard in June 2006, following the retreat of the meteorological event depicted in Figure 2. The profiling instruments were those used for the time-series measurements during April–June 2006.

Near-surface (~1 m below chart datum level) water temperature measurements from Kavaratti and Andrott islands were carried out at 5 min intervals from the vessel-landing jetties in these islands. Surface meteorological measurements were recorded using the NIO–AWS deployed on top of the Port Control Tower at Kavaratti. Meteorological data were recorded at 10 min intervals, and each measurement was an average over 10 min (wind was vector-averaged). Gust (i.e. the largest value among the 10 s sampled wind speed in 10 min) was also recorded.

Results

Spatial distribution of temperature–salinity structure of the Kochi backwaters was clearly revealed from synoptic measurements under different weather conditions, including an episodic surface meteorological event involving heavy rainfall in association with a depression and strong winds (Figure 2). The southwest monsoon rainfall for 2006 over the west coast of India was the second largest during the past five decades. Influence of meteorological forcing on water-level variability in the Kochi backwaters and the characteristics of tides in this estuary have been addressed by Joseph *et al.*[6,15]. In this article, these tidal characteristics and wind measurements are used to explain the thermohaline variability in the estuary.

Open-sea island locations

The water temperature and tide at Andrott and Kavaratti islands during spring and neap phases are shown in Figures 3 and 4 respectively. A common feature found is superimposition of the diurnal thermal variability on low-frequency variability. In order to obtain a clear picture, the average $(\overline{T_i})$ for temperature values T_{ij} corresponding to a given ith min (5 min time slot in the present case) over all the N days has been estimated as

$$\overline{T_i} = \frac{1}{N}\sum_{j=1}^{N} T_{ij},$$

where $N = 7$, so that each value of $\overline{T_i}$ represents weekly ensemble average temperature corresponding to the ith time-slot. The sampling interval being 5 min, 288 samples exists in a day, so that i varies from 1 to 288. Examination of the ensemble average of the sea-surface water temperature (Figure 5) indicates a diurnal cyclicity. Spectrum of the temperature (Figure 6) indicates dominance of thermal energy at 1 cycle per day (cpd). The spectrum indicates that the diurnal cyclicity is superimposed on fortnightly (~0.07 cpd), weekly (~0.14 cpd) and semi-diurnal (~2 cpd) periods. Spectral estimates of wind field at Kavaratti Island (Figure 7) indicate a monthly (~0.035 cpd), fortnightly (~0.07 cpd), weekly (~0.14 cpd), and diurnal (~1 cpd) periodicity. Except for the monthly periodicity, this is broadly in conformity with the spectral estimates of water-temperature time-series from Kavaratti and Andrott islands (Figure 6), indicating coupling between sea-surface water temperature and wind fields.

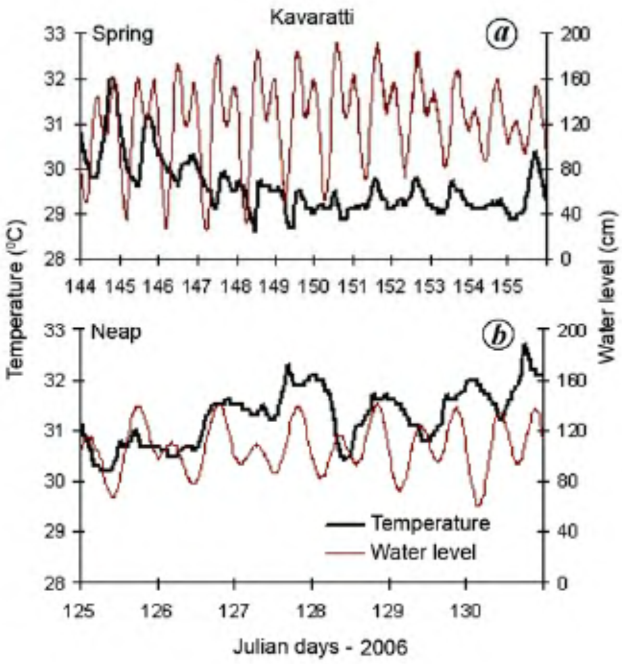

Figure 4. Near-surface temperature and tidal cycles at Kavaratti Island lagoon during (*a*) spring tide phase and (*b*) neap tide phase. Cooling is observed during spring tide phase.

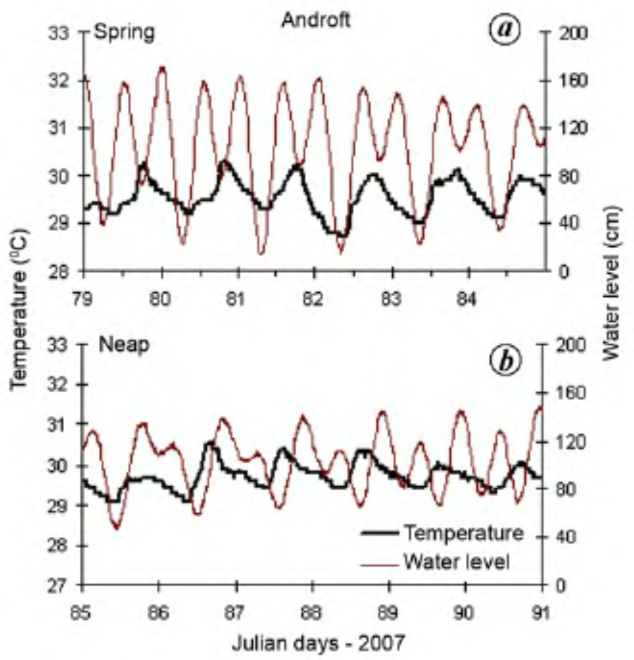

Figure 3. Near-surface temperature and tidal cycles at Andrott Island during (*a*) spring tide phase and (*b*) neap tide phase.

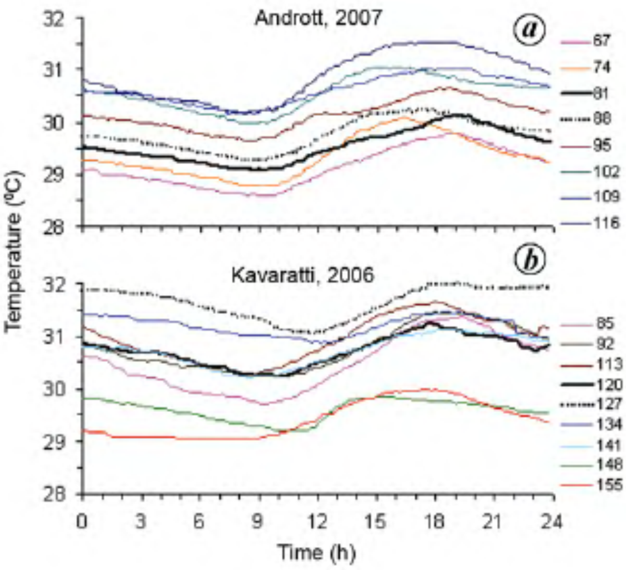

Figure 5. Cyclicity of the observed near-surface water temperature measurements from (*a*) Andrott Island (days 63–115, 2007) and (*b*) Kavaratti Island (days 82–157, 2006). Each graph represents weekly ensemble average, centred on the Julian day indicated on the right hand side of the graphs. Dark thick line and dotted line represent the thermal variability during spring and neap tides respectively.

Wind and sea-surface water temperature measurements from Kavaratti lagoon (Figure 8) indicate an inverse relationship, which is more evident on the one-day moving average (thick line). Figure 9 shows the inverse correlation between the daily-mean winds and temperature ($R^2 = 0.71$).

The Kochi backwaters

Temperature measurements from the mouth to the upper reaches of the Kochi backwaters have been obtained from seven stations for a duration of about two months. It indicates that water temperature undergoes large variability. An episodic meteorological event (Figure 2) caused a sharp drop in water temperature (Figure 10). While the influence of episodic meteorological events is in varying levels in the estuary, station no. 6 seems to be distinctly different in terms of temperature variability (Figure 11).

Salinity data at the Kochi backwaters are available only from two locations. Like temperature, salinity also undergoes large variability and a sharp drop in associa-

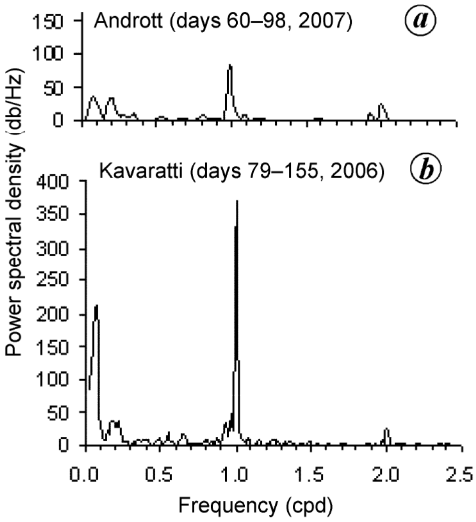

Figure 6. Spectrum of near-surface (~1 m below chart datum level) water-temperature time-series from Andrott and Kavaratti islands (Lakshadweep Archipelago) in the eastern Arabian Sea, indicating clear dominance of diurnal cyclicity (~1 cpd) followed by fortnightly (~0. 07 cpd), weekly (~0.14 cpd) and semi-diurnal (~2 cpd) cyclicity.

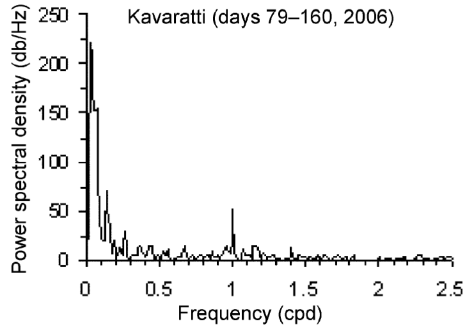

Figure 7. Spectrum of wind-speed time-series from Kavaratti Island (Lakshadweep Archipelago) in the eastern Arabian Sea, indicating clear dominance of monthly cyclicity (~0. 035 cpd), followed by fortnightly (0.07 cpd), weekly (~0.14 cpd), diurnal cyclicity (1 cpd) and half-weekly (~0.26) cyclicity.

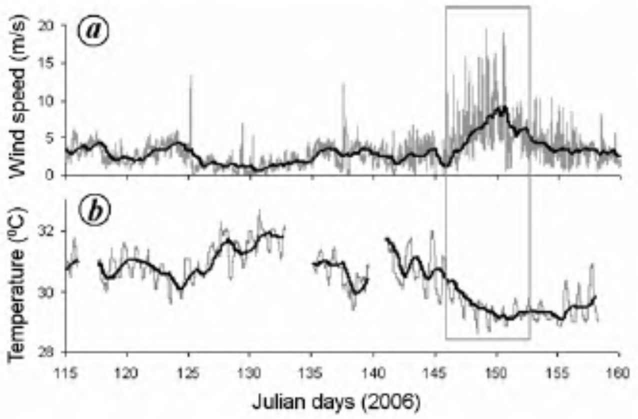

Figure 8. Wind-speed measurements from Kavaratti Island (***a***) and the corresponding near-surface water-temperature measurements from Kavaratti lagoon, indicating an inverse relationship between the two parameters (***b***). The thick lines superimposed over the time-series measurements represent one-day moving averages.

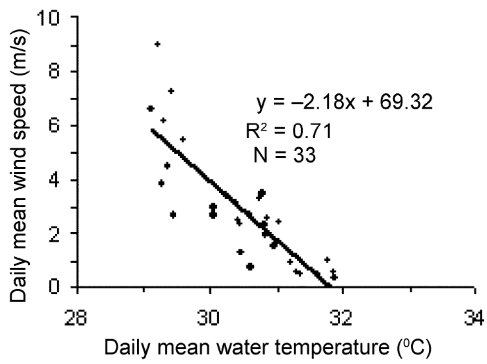

Figure 9. Inverse correlation between daily-mean wind-speed measurements from Kavaratti Island and the corresponding daily-mean near-surface (~1 m below chart datum level) water-temperature measurements from Kavaratti lagoon. *N* represents the number of data points.

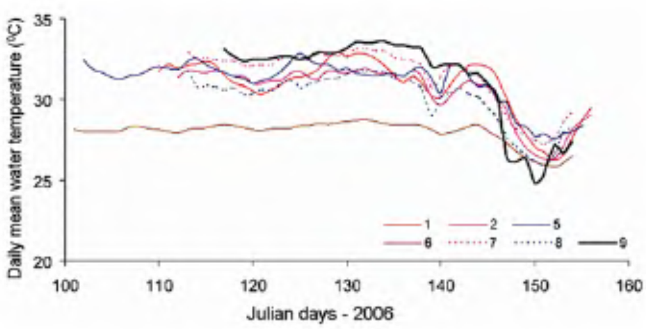

Figure 10. Daily-mean temporal variability of subsurface temperature at seven stations from the mouth to the upper reaches of the Kochi backwaters. The sharp drop in water temperature around Julian day 150 coincides with heavy rainfall induced by a meteorological event. Numbers shown in the legend are the station numbers indicated in Figure 1.

tion with the episodic meteorological event mentioned earlier (Figure 12). Examination of the thermohaline variability of the Kochi backwaters from its mouth region to the upstream boundary region indicates that in addition to the temporal variability, there is considerable spatial variability (Figure 13). Salinity greater than 35 psu occasionally observed at station no. 1 is not surprising, because this station is located close to the Azhikode inlet, where a strong influence of the Arabian Sea waters (salinity >35 psu during February–April) is expected[16].

The observed spring and neap tides at the Kochi backwaters indicate two crusts (one higher high tidal level [HHT] and one lower high tidal level [LHT]) plus two troughs (one lower low tidal level [LLT] and one higher low tidal level [HLT]) in 24 h. While this cyclicity is distinctly seen during spring tide (Figure 14 *a*), it decays considerably during neap tide (Figure 14 *b*), as noticed in earlier studies[6,17]. The temperature and salinity exhibit cyclicity, but salinity is broadly in phase with the tides (Figure 14 *a* and *b*). This is in conformation with earlier studies, but the variation of salinity between HHT and LHT is relatively weak compared to the water-level variability. The inter-relationship between temperature and salinity during spring and neap tides is shown in Figure 14 *c* and *d* respectively. In order to obtain a clear picture about the representative nature of temperature cyclicity in this estuary, we removed the temperature data collected during the episodic meteorological event and pooled data corresponding to the fair-weather days. From this dataset, the average thermal cyclicity over every week has been determined, where each datapoint is an average ($\overline{T_i}$) of 144 samples (10 min sampling interval). Thus, each value of $\overline{T_i}$ represents weekly average temperature corresponding to the *i*th time (ensemble average). The weekly ensemble average temperature (Figure 15) indicates a diurnal cyclicity at all stations. While the minimum temperature occurs in the morning (at about 8 h), the maximum temperature occurs in the afternoon (at about 15–18 h). An exception to this was noticed at Maliankara, where a phase reversal was seen on days 121 and 135. The thermal spectrum (Figure 16) generally identifies thermal energy at 1 cpd, except at Vettikattumuku, where variability is absent. Most of the stations have thermal energy at 0.07 cpd (fortnightly variability), while some stations have 2 cpd (semi-diurnal variability). Thermal energy at 0.07 cpd is observed at Maliankara. Figure 17 shows the 7-day ensemble-averaged salinity at Maliankara. Figure 18 shows the spectrum of salinity at Maliankara, indicating diurnal (~1 cpd), fortnightly (~0.07 cpd) and semi-diurnal (~2 cpd) cyclicity. Figure 19 shows salinity anomaly corresponding to astronomical tides at Maliankara, indicating fortnightly cyclicity of salinity in this station.

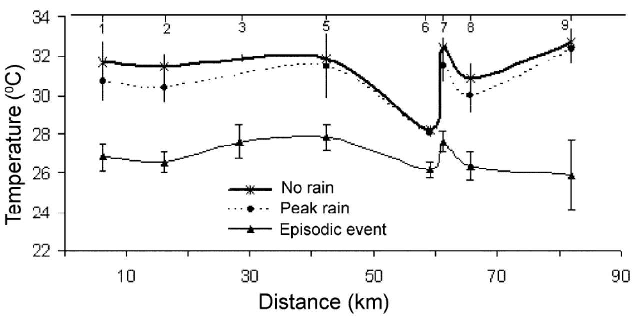

Figure 11. Distribution of mean subsurface (~1 m below chart datum level) water temperature during the respective measuring period, indicating the sensitiveness of locations to different meteorological conditions (no-rain [days 110–130, 2006], peak rain [days 138–141, 2006], and episodic strong wind and incessant rains [days 148–152, 2006]). Station numbers are indicated on the top line that runs parallel to the distance axis. The vertical bar represents the standard deviation of temperature measurements taken during the respective measuring period mentioned above.

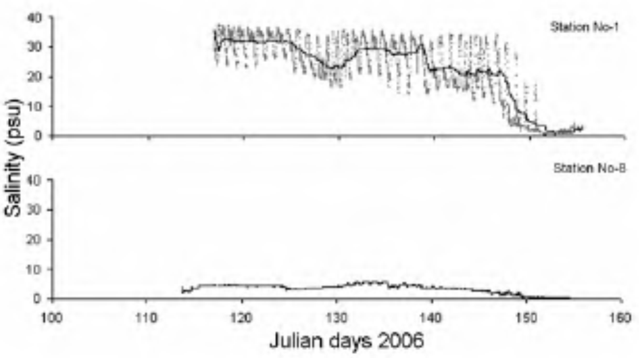

Figure 12. Temporal variability in salinity at two sites in the Kochi backwaters covering a short period of incessant and strong rains around Julian day 150. The thick line superimposed over the time-series salinity measurements from station no. 1 represents 144-point (one-day) moving average.

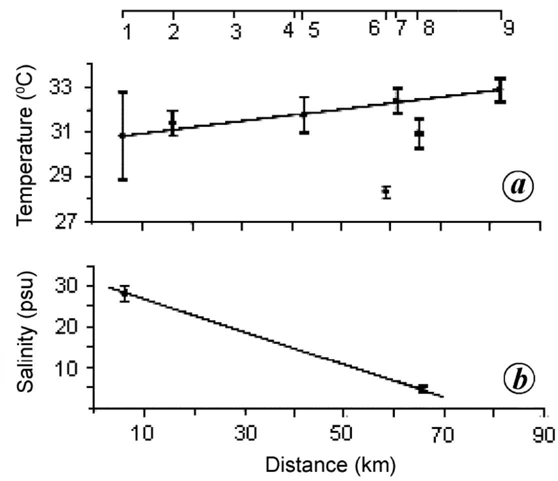

Figure 13. Spatial variability of mean subsurface (~1 m below chart datum level) (***a***) water temperature and (***b***) salinity measurements from the northern mouth region to the southern head region of the Kochi backwaters during the measuring period (Julian days 118–140). Station numbers are indicated on the top line that runs parallel to the distance axis. The vertical bar represents the standard deviation of measurements taken during the above period.

Figure 14 *c* and *d* shows an inverse relationship between salinity and temperature during spring as well as neap tides. However, given the diurnal temperature cyclicity in the open-ocean conditions (Figure 5) as well as estuary (Figure 15), whether a strong inverse relationship exists between these two parameters throughout the month needs to be examined. This can be done by correlating salinity and temperature on a week-to-week basis. The first result is a poor correlation between the absolute values of temperature and salinity. Nonetheless, visual observations indicate an alternating component (short-period fluctuations superimposed on diurnal component) riding on low frequency. The alternating components (anomaly) of these two parameters have been separated out by applying a band-pass Butterworth filter (3–72 h window). Figure 20 depicts the correlation between temperature and salinity anomalies ($R^2 \leq 0.58$), suggesting a poor correlation between water temperature and salinity. Figure 21 shows the correlation between salinity anomaly and tidal swing, which indicates a stronger direct relationship ($R^2 = 0.64$).

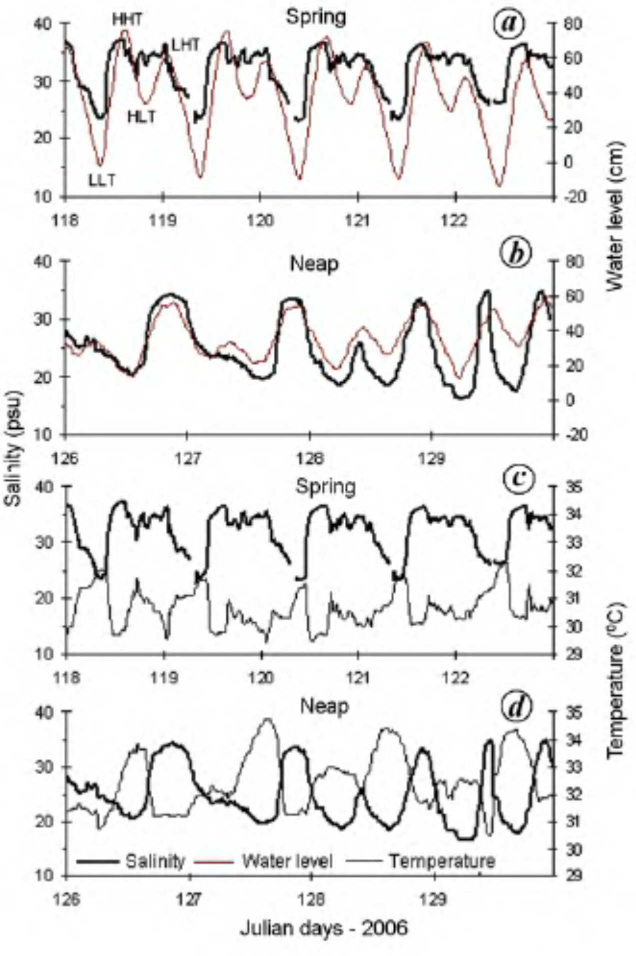

Figure 14. ***a***, ***b***, Cyclicity of near-surface salinity, temperature and tidal cycles at Maliankara (Kochi backwaters) in the absence of rainfall. Salinity cycles during (***a***) spring tide phase and (***b***) neap tide phase. ***c***, ***d***, Observed salinity–temperature inter-relationship during the above. (***c***) Spring tide phase and (***d***) neap tide phase.

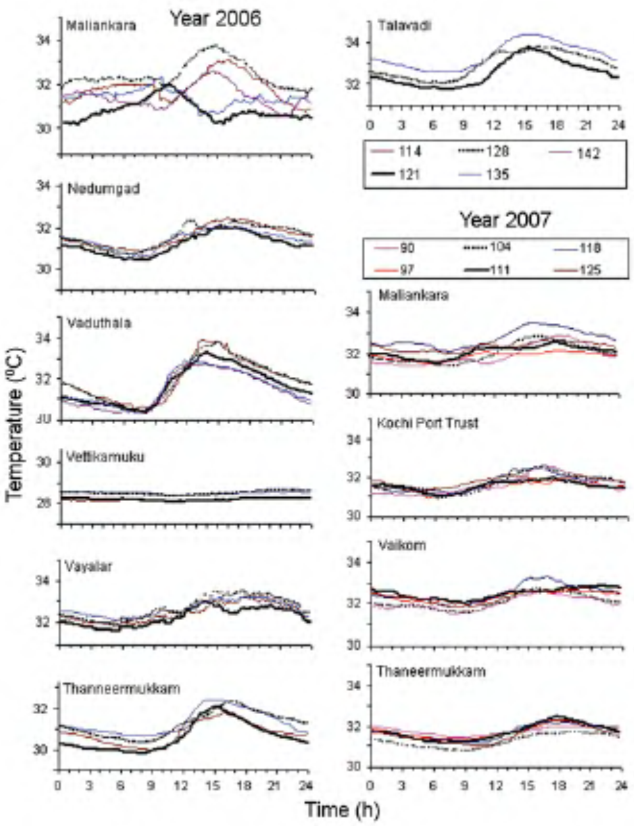

Figure 15. Diurnal day/night cyclicity of near-surface thermal measurements from the Kochi backwaters during summer 2006 and 2007. Each graph represents weekly ensemble average, centred on the Julian day indicated within the text box. Dark thick line and dotted line represent the thermal variability during spring and neap tides respectively.

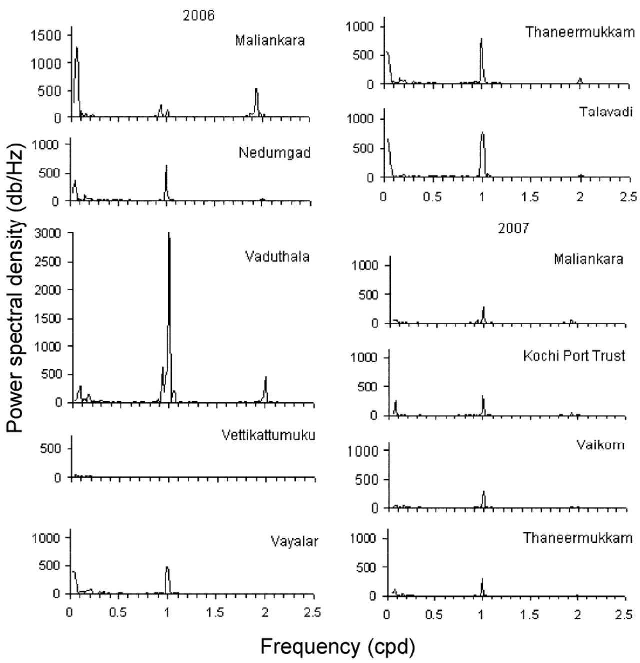

Figure 16. Spectrum of near-surface (close to chart datum level) water-temperature time-series from the Kochi backwaters, indicating the relative dominance of diurnal (~1 cpd), fortnightly (~0. 07 cpd), and semi-diurnal (~2 cpd) cyclicity at different locations.

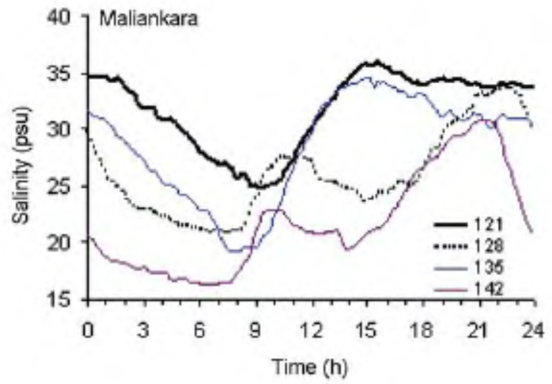

Figure 17. Cyclicity of the observed near-surface water-salinity measurements from Maliankara during summer 2006. Each graph represents weekly ensemble average, centred on the Julian days indicated on the right hand side of the graphs. Dark thick line and dotted line represent the thermal variability during spring and neap tides respectively.

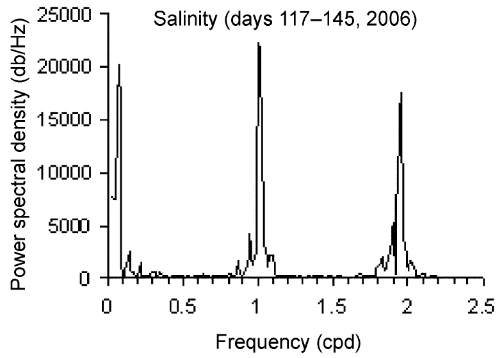

Figure 18. Spectrum of near-surface (close to chart datum level) water-salinity time-series from Maliankara (near Azhikode inlet of the Kochi backwaters), indicating the relative dominance of diurnal (~1 cpd), fortnightly (~0. 07 cpd) and semi-diurnal (~2 cpd) cyclicity.

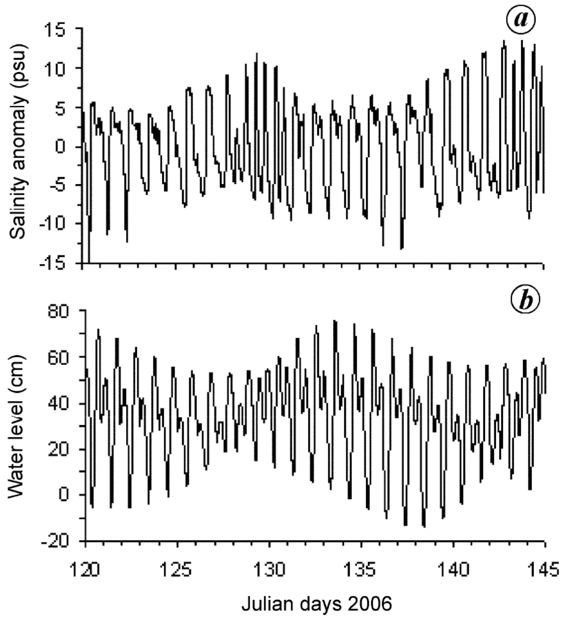

Figure 19. Anomaly of water-salinity (***a***) and the corresponding astronomical tides (***b***) from Maliankara (near Azhikode inlet of the Kochi backwaters), indicating fortnightly spring–neap cyclicity of salinity variability.

Figure 22 shows the influence of wind on the sea surface temperature in the estuary, where an intense wind causes cooling after a delay of several days. However, cooling observed on Julian day 114 ± 2 is not associated with enhanced winds. Figure 23 shows the spectrum of wind from Andhakaranazhi, indicating clear dominance of diurnal (1 cpd), over fortnightly (~0.07 cpd) and semi-diurnal (~2 cpd) cyclicity.

Vertical profiles of temperature show that the bottom waters at the mouth of the estuary are cooler (gradient ~3.5°C, Figure 24). The vertical salinity structure from these locations reveals a 4 m layer of very low salinity water (≤2 psu) floating over a moderately saline (~20–32 psu) bottom water (4–10 m).

Discussion

Kavaratti and Andrott islands are located in the open ocean, where air–sea interaction and oceanic circulation

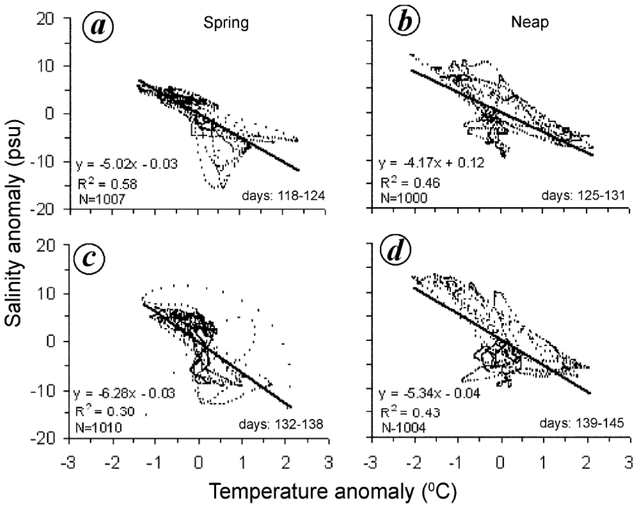

Figure 20. Inverse correlation between salinity and temperature anomalies.

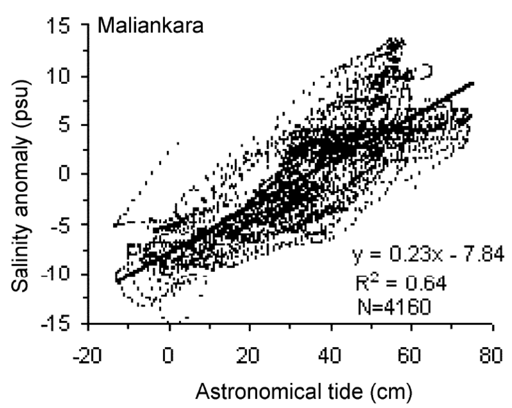

Figure 21. Direct correlation between salinity anomaly and astronomical tide. *N* represents the number of datapoints.

might influence the thermal characteristics. In contrast to the Andrott Island, the Kavaratti Island is surrounded by a large lagoon so that bathymetry may have some influence on the thermal characteristics. However, the Kochi backwaters body is additionally influenced by river discharge, topography and land/sea breeze, and all these factors would affect the physical processes here at varying levels as discussed below. We first examine the two open-ocean locations and then the Kochi backwaters to identify the physical differences between these two widely different water bodies.

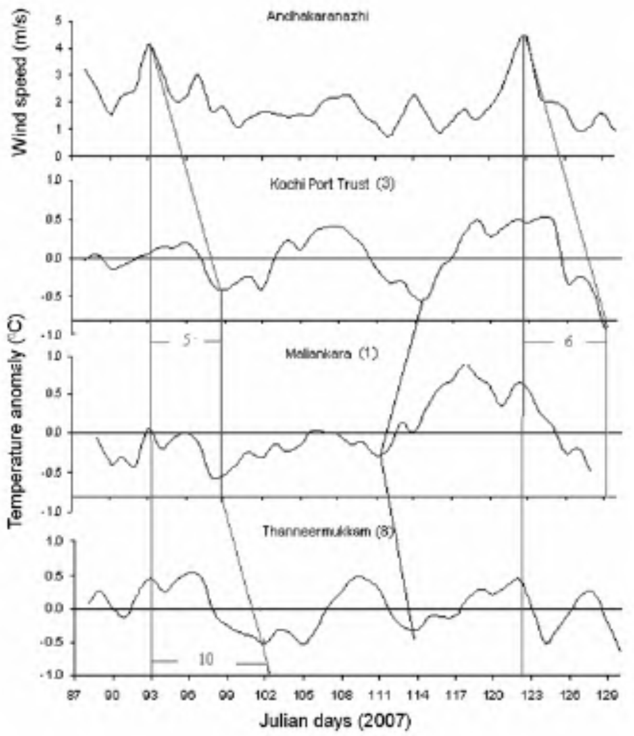

Figure 22. Comparison of wind speed measurements from Andhakaranazhi beach (Kochi backwaters region) with thermal anomaly of the Kochi backwaters body during April–May 2007. Cooling observed during days 98–102 and 128–129 is wind-induced. Cooling observed during days 111–115 is due to spring tide.

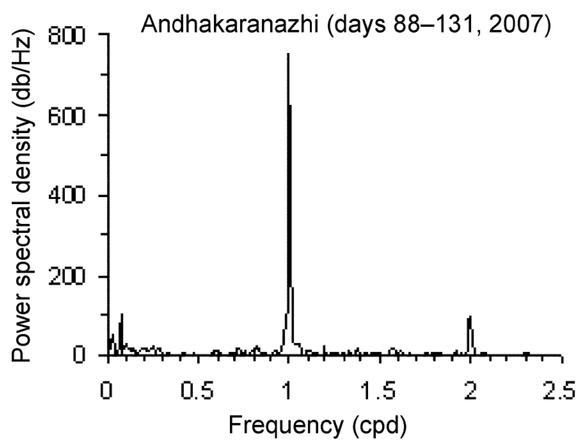

Figure 23. Spectrum of wind-speed time-series from Andhakaranazhi beach (western periphery of the Kochi backwaters) on the southwest coast of India, indicating clear dominance of diurnal cyclicity (1 cpd) followed by fortnightly(~0.07 cpd) and semi-diurnal (~2 cpd) cyclicity.

Thermal structure around Kavaratti and Andrott islands

The observed tides at Andrott (Figure 3) and Kavaratti (Figure 4) indicate semi-diurnal characteristics, with the largest height of ~1.50 m. However, the sea surface temperature (SST) exhibits a clear diurnal cyclicity (i.e. one crust and one trough in 24 h). Figure 5 shows a temperature minima and maxima occurring at about 10 and 18 h respectively. It is seen that while the thermal structure at Andrott Island (Figure 5 *a*) is uniform, the same at Kavaratti Island is slightly scattered. The only noteworthy difference between these two islands is the presence of a relatively wide lagoon at Kavaratti (4.96 km^2). The spectrum of SST at these islands (Figure 6) indicates a major signal at a period of 1 cpd, implying diurnal variability and minor signals at 0.07 cpd (fortnightly), 0.14 cpd (weekly) and 2 cpd (semi-diurnally). At Andrott (Figure 6 *a*), both fortnightly and weekly signals have identical spectral energy levels, which is quite striking. Spectrum of wind field at Kavaratti (Figure 7) also indicates a monthly (0.035 cpd), fortnightly (0.07 cpd), weekly (0.14 cpd) and diurnal (1 cpd) periodicity. The significantly weak winds at 1 cpd observed at Kavaratti relative to a strong water temperature at 1 cpd suggests that diurnal winds do not contribute to the thermal variability. However, a comparison of the two spectral estimates (Figures 6 and 7) at fortnightly and weekly periodicity

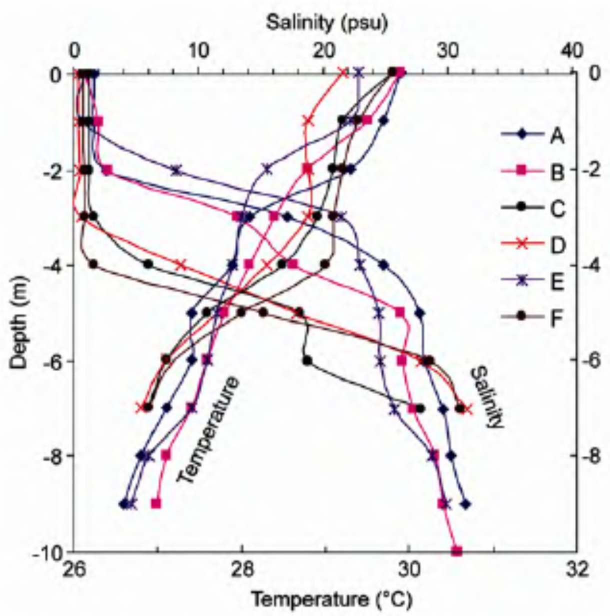

Figure 24. Thermohaline vertical profile from six locations in the Kochi mouth region of the Kochi backwaters.

indicates that wind fields at these periodicities contribute significantly to the observed near-surface thermal variability. Tides are known to have strong spring–neap variability. Figure 4 shows that cooling is clearly observed at Kavaratti during spring than neap tide. The above discussion indicates that at the open-ocean locations, the variation in water temperature (at 1 cpd) is controlled by insolation. To sum up, the thermal variability at islands appears to be influenced by a combination of the winds and tides at fortnightly and weekly intervals. Especially, the fortnightly variability is considerably large at Kavaratti than at Andrott.

The graphs on wind and SST from Kavaratti are like a mirror image (Figure 8), indicating wind-induced cooling. No correlation was found between 10 min averages of these two parameters, but one-day moving averages (Figure 9) show a good correlation ($R^2 = 0.71$). This suggests that the response time of sea water to wind-induced cooling in the open-sea is about half a day. In analogy, earlier studies reveal that currents in the eastern Arabian Sea lag the winds by half a day[18].

Warming and cooling of the Kochi backwaters

Thermohaline variability of the Kochi backwaters under fair weather as well as rough weather is addressed below. A comparison is also made here to link the open-ocean environment and the estuary in terms of day/night heating/cooling processes and wind-induced effects.

Since the southern part (head region) of the Kochi backwaters is considerably shallower than the Kochi inlet, the thermal properties of the former are likely to be influenced by the land mass and of the latter by relatively cooler sea water. This could be the reason for a temperature gradient of ~2°C observed between the mouth and the head regions of the Kochi backwaters. The existence of a discernible salinity gradient across the mouth and head of the Kochi backwaters, and its inverse relation to the temperature (Figure 13) support this argument. The relatively lower temperature observed at station no. 6 (Figures 10 and 11) could be a distinct feature of this location, as the entrance point of the Muvattupuzha River draining from the Western Ghats.

The thermohaline structure (Figures 10 and 12) shows that the estuary is cooled by sudden rain and strong winds (Figure 2), indicating its sensitivity to meteorological disturbances. However, Figure 11 suggests that station no. 6 is distinct in temperature variation, primarily due to its proximity to the Muvattupuzha River. It is evident that apart from shallowness and land mass, the thermal structure of the Kochi backwaters is influenced by precipitation and river run-off. While the estuary is warm (up to 32°C) during fair weather, the surge associated with storm and heavy rainfall considerably cools (to ~7°C) the estuary.

Thermohaline vertical structure at the Kochi inlet

Time-averaged thermohaline vertical structure of the major inlet (Kochi inlet) region of the Kochi backwaters body after the retreat of an episodic surface meteorological event is interesting. The vertical thermal structure indicates a clear trend of gradual decrease with increasing depth. The accompanying vertical salinity structure reveals a layer of very low salinity water in the upper 4 m layer and a considerably larger salinity at the bottom layer. While the larger salinity (30–32 psu) observed at the bottom layer arises from sea-water intrusion, the very low salinity layer (≤2 psu) floating on the surface results from a large river influx resulting from incessant rainfall (Figure 2). The dominant influence of rainfall in the generation of a surface layer of low-salinity water in the mouth region of the Kochi backwaters can be appreciated from the occurrence of a similar episode in the open ocean (for example, in the western equatorial Pacific) after a spell of rainfall associated with the westerly wind bursts[19,20]. Similarly, supply of large amounts of freshwater to the Bay of Bengal both as rainfall and river runoff[21,22] induces large salinity stratification in this bay[23–25]. Such vividly present salinity stratification has important ecological implications. In the Kochi backwaters, the observed large salinity stratification, which is developed and sustained by rainfall and the associated river influx, plays a major role in sustaining a unique environmental habitat by providing a nursery ground for a wide variety of brackish-water species of plants, shell and fin-fishes[26,27].

Thermal variability

Temperature variation in the Kochi backwaters during summer 2006 and 2007 (Figure 15) exhibits a diurnal nature, when meteorologically disturbed days (Figure 2) have been excluded. Figure 15, depicting weekly ensemble average temperatures for each location, is a clear indication of the diurnal thermal feature of the Kochi backwaters. The summer 2007 observations corroborate the above finding. Except Maliankara (which is located close to the Azhikode inlet), temperature spectra (Figure 16) indicate dominant energy at 1 cpd and lesser energy at 0.07 cpd, and much lesser or no energy at 2 cpd at some locations. The wind field from the western periphery of the estuary (Figure 23) shows maximum spectral energy at 1 cpd, indicating strong land/sea breeze across the estuary. This suggests that the relatively weak spectral energy at 0.07 and 2 cpd in the thermal spectra is a contribution from the tides. Influence of the sea on water temperature is explicitly seen at Maliankara, where maximum spectral energy is at 0.07 cpd (fortnightly) followed by 2 cpd (semi-diurnal) and 1 cpd. However, this feature observed at Maliankara during summer 2006 was absent during summer 2007. If tidal influence were the reason for the thermal variability of 0.07 and 2 cpd at Maliankara during summer 2006, similar energy would have prevailed at this station during summer 2007 as well. Another peculiar effect seen only at this station during summer 2006 (Figure 15) is that the usual diurnal cyclicity of thermal variability, in which the thermal minima and maxima are expected to occur at about 8 and 16 h respectively, was largely upset (two cycles exhibit phase reversal too, thereby contradicting the usual day/night heating/cooling feature). Close resemblance of the non-uniform and disturbed features of temporal structures of the 2006 summer temperature (Figure 15) and salinity (Figure 17) at Maliankara indicates that sea-water intrusion was responsible for the observed deviation of the thermal structure from the usual pattern. Absence of such a deviation at Maliankara during 2007 summer suggests that tidal excursion alone is not responsible for the observed anomalous thermal and salinity temporal structure at this station during summer 2006. Ramamirtham and Jayaraman[7] have observed cooling at the estuarine mouth during summer under the influence of upwelled waters. This suggests that intrusion of upwelled waters through the Azhikode inlet could be responsible for the observed thermal and salinity anomaly at Maliankara station during summer 2006. Sufficiently long and uninterrupted temperature/salinity data from the Kochi inlet during summer 2006 are not available for comparison.

Examination of daily-mean wind speed and daily mean temperature anomaly reveals a wind-induced, but delayed cooling in the Kochi backwaters (Figure 22). Gusty winds on days 93 and 122 result in a greater cooling. However, the cooling was delayed with increase in distance from the mouth. The cooling on days 111–114 was not supported by correspondingly swift winds. From Figure 15 it is seen that these days in 2007 correspond to spring tide, during which, the water temperature was lower than that during other days. The entry of cool sea water was due to larger tidal swing during spring tide. In contrast, the response time at the Kavaratti Island was just half a day, in which, the daily mean wind and temperature look like mirror images (Figure 8). It appears that the relatively large response time to wind cooling exhibited at the Kochi backwaters may be attributed to the influence of shallow depth, surrounding land mass, and luxuriant vegetation in its periphery.

Summary and conclusions

Tidal measurements and spectral estimates of SST and wind speed indicate that the thermal structure of Kavaratti and Andrott islands exhibits a progressively decreasing diurnal, fortnightly, weekly and semi-diurnal cyclicity. Diurnal cyclicity is caused by solar irradiance and wind. Fortnightly periodicity results from spring–neap tidal cyclicity as well as wind-induced cooling. Weekly periodicity is attributable to wind, whereas semi-diurnal cyclicity is caused by tides alone, having no contribution from wind at this periodicity. It was found that the open-ocean surface is cooled by winds with a response time of approximately half a day.

In the present study, we have examined the thermohaline structure of the Kochi backwaters under fair as well as disturbed meteorological conditions and compared the results with open-ocean island measurements. Fortnightly spring–neap variability in temperature–salinity has been observed, with the two parameters having a weak inverse correlation ($R^2 \leq 0.58$), with lower temperature and higher salinity during spring tide. A relatively stronger correlation was observed between salinity and tide ($R^2 = 0.64$).

Horizontal temperature–salinity structure of the Kochi backwaters was inhomogeneous, where the shallower head region was warmer and less saline than the deeper mouth region. This structure was disturbed by changes in the meteorology. The response of the estuary to episodic meteorological events was manifested as a sharp drop in temperature and salinity. During heavy rains, salinity at the mouth region fell considerably (~2 psu). The southernmost and the easternmost locations were the most and the least sensitive areas to temperature variability. The temperature–salinity vertical profiles at the mouth region showed large stratification, with a temperature gradient of ~3.5°C and a cap of 1–4 m thick low saline waters (≤2 psu) floating on the surface.

It was found that thermal variation in the Kochi backwaters is influenced by factors such as solar irradiance (diurnal processes), spring–neap tidal cyclicity (fortnightly processes), winds, depth, and vegetation in the surrounding land mass. At the mouth region of the estuary, the temperature was also influenced by the intrusion of upwelled waters from the Arabian Sea.

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