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Spectra and gross features of vertical temperature and salinity profiles off the central west coast of India

M. J. VARKEY and R. NAGARAJAN

National Institute of Oceanography, Dona Paula, Goa

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सार — भारत के पश्चिमी तट गोवा के महाद्वीपीय ढलान और महाद्वीपीय चढ़ाव के सी. टी. डी. प्रणाली द्वारा अंकित तापक्रम तथा क्षारीयता के सतत् ऊर्ध्वाधर पार्श्व-चित्रों को, सूक्ष्म रचना के सकल सांख्यिकीय लक्षणों को निरुपित करने और अनिहित भौतिक प्रक्रियाओं को समझाने के लिए उपयोग किया गया है । विभिन्न स्टेशनों के तापक्रम स्पेक्ट्रमों और क्षारीयता के उतार-चढ़ावों से लगभग एक जैसे, अर्थात् 10 मीटर तरंग-दैर्ध्य की कमी की प्रवृत्ति जिसमें सामान्यत: 20 मीटर तरंग दैर्ध्य पर श्रृंग भी थे, दिखाई दिए हैं । निम्न तरंग अंकों के लिये तापमान और क्षारीयता के स्पेक्ट्रम घनत्व के आकल अपेक्षाकृत उच्च थे । उनमें 1.5 से 2 दशकों तक का अन्तर पाया गया । 0 से .11 चक्र/मिनट वाले परिसर के लिये प्रथम अंतर निस्पंदक से क्षोभ श्रेणी का उपयोग करके अभिकलित तथा निस्पंदक प्रतिक्रिया द्वारा संशोधित स्पेक्ट्रम ने –2.9 (परिसर 2.57 से –3.43 तथा मानक विचलन 0.3) तथा –2.6 (परिसर –2.05 से –3.15 तथा मानक विचलन –0.36) की प्रवणता का तापमान तथा क्षारीयता के साथ क्रमशः सहसम्बन्ध गुणांकों –0.96 तथा –0.92 को दर्शाया । 0 से 0.02 चक्र मिनट परिसर के लिए संबंद्धता आकल उच्च (> 0.8) थे और निम्न तरंग संख्या प्रक्रियाओं की स्थानिक समांगता दर्शाने वाले स्टेशनों के बीच की दूरी पर आश्रित नहीं थे । T' तथा S' के बीच सहसंबंध गुणांक तथा विभिन्न सतहों के लिये उनके मानक विचलन निस्यंदक लम्बाई बढ़ने के साथ-साथ अधिक और उनकी गहराई के साथ-साथ कम होते गए । ऊपरी जलीय स्तर (0–250 मी॰) के भीतर क्षैतिज तथा ऊर्ध्वाधर दोनों ही मिश्रण प्रक्रियाएं अत्यंत सक्रिय थी । अधिक गहरे स्तरों में (500 मी॰ से अधिक गहरे) असमान घनत्व वाली मिश्रण क्रियाएं सक्रिय होती दिखाई दीं ।

ABSTRACT. Continuous vertical profiles of temperature and salinity recorded by a CTD-system from the continental slope and the continental rise off Goa, west coast of India, were used for delineating the gross statistical features of the fine structure and to understand the underlying physical processes. Spectra of temperature and salinity fluctuations from the different stations showed similar patterns and trend of decrease to a wave length of about 10 m, generally with a crest like feature at 20 m wave length. The estimates of spectral density for temperature and salinity were comparatively very high for low wave numbers and showed a difference varying from 1.5 to 2 decades. The spectra for the range 0-0.11 cy/m computed using the perturbation series from a First Difference filter and corrected for the filter-response followed an average slope of —2.9 (range: —2.57 to —3.43 and std. dev.: —0.3) and —2.6 (range: —2.05 to —3.15 and std. dev.: —0.36) with correlation co-efficients —0.96 and —0.92 for temperature and salinity, respectively. Coherency estimates were high (> 0.8) for the range 0-0.02 cy/m and were independent of the distance between stations showing the spatial homogeneity of low wave number processes. Correlation coefficients between T' and S' and the individual standard deviations for different layers increased with increasing filter length and generally decreased with depth. Both horizontal and vertical mixing processes were very active in the upper water column (0-250 m). In the deeper layers, > 500 m, non-isopycnal mixing processes were found to be active.

1. Introduction

Continuous profiles of temperature and salinity were recorded during the 11th cruise of *RV Gaveshani* of the National Institute of Oceanography (6-11 November 1976) using a CTD-System (Guildline Instruments, Canada). The stations were occupied along a square formation (Fig. 1) across the continental slope and the continental rise off Goa, on the central west coast of India.

The CTD-system consists of a sensor *cum* sampler unit, a power winch with a multicore transmission cable and an X-Y recorder. The sensor unit comprises of sensors to measure temperature, conductivity and depth. The recorder has an option to record conductivity or salinity. Before the cruise the system

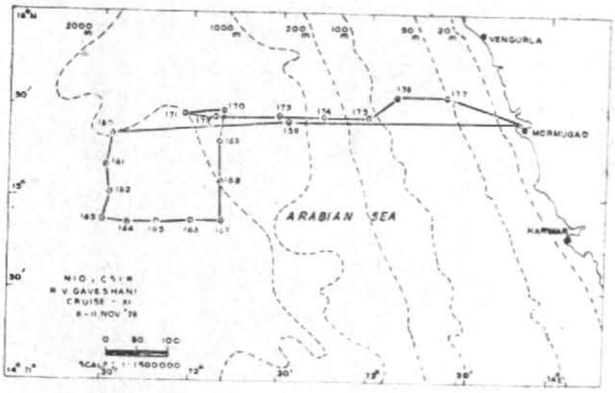


Fig. 1. Station location map

was thoroughly checked and calibrated. The characteristics of the sensors are given below :

Sensor	*Range*	*Accuracy*	*Resolution*
Temperature	—2 to 30°C	±0.01°C	±0.003°C
Salinity	28 to 40 PPT	±0.01 PPT	±0.005 PPT
Pressure	0 to 2500 m	±0.25% of full scale	±0.05% F.S (±1.25m)

Spectral studies related to temperature and salinity from the Arabian Sea are very rare. Hammon (1967) studied the medium scale (10-100 m) structures of temperature and salinity profiles from the west equatorial Indian Ocean to a depth of 1500 m. Varma, Fernandes and Rao (1979) and Varma and Rao (1978) discussed the medium scale features and the spectra for the northern Arabian Sea. Works related to other oceanic regions are numerous and a recent review by Gregg and Briscoe (1979) covers the subject abundantly. The present study covers a small area in the northeast Arabian Sea in a more detailed way.

2. Methods

For the present study the records were digitized at 1.56 m interval. Temperature and salinity spectra were computed initially using the data at 1.56 m intervals. Then it became evident that there is no significant energy beyond about 0.11 cy/m. Hence, later the computations for the gross vertical features were done using data at 3.12 m interval. Spikings due to electronic disturbances were very less and if present were removed by visual examination of the profiles while digitizing. For the spectral computations the data (1.56 m interval) were high pass filtered using a First Difference (Bendat and Piersol 1971) filter and then the estimates were corrected for the filter response. Cross spectra (Bendat and Piersol 1971, Jenkins and Watts 1968) for selected pairs of profiles were also worked out using the same data interval (1.56 m). High pass filtering by First Difference (preemphasis filter) is found to be efficient (Gregg 1977, Varkey and Nagarajan 1978) for a study of the gross features (without any special interest on any wave number bands) of the spectra. Binomial (Roden 1968) filters and Cosine (Fedorov 1978) filters are widely used to separate the mean $(\overline{T})$ and perturbation (T') series. Whenever off-trend values were observed the computations were checked from the digitisation onwards. Gross features of the fine structure processes like mean temperature and salinity gradients, ratio of temperature and salinity gradients, ratio of the temperature and salinity perturbations, standard deviations and correlations of the perturbations, etc were computed from the data (3.12 m interval) filtered using Cosine (Fedorov 1978) filters of different characteristic lengths. The filter-lengths were selected as 9.4 m, 18.7 m and 59.3 m. The first filter almost completely eliminates the effect of internal waves. Data from the second filter contains more of the internal wave fluctuations whereas the third filter possibly contains the complete internal wave effect. One sample station (No. 167) was arbitrarily selected for a detailed analysis of the vertically averaged statistics.

The whole depth range of the profile was divided into different layers of varying thicknesses based on the observed salinity-temperature characteristics. The first layer (0-40 m) is the upper homogeneous layer, the second layer (30-70 m) is the main thermocline (also the core of the Arabian Sea high salinity water mass), the third layer (70-150 m) is a low salinity water core (the sub-surface low salinity), the fourth (200-400 m) and the fifth (400-600 m) layers are subsurface 'diffused' high salinity (Varkey *et al.* 1979 and Ramesh Babu *et al.* 1980) water layers and the sixth (600-900 m) layer is uniform intermediate water column.

3. Results and discussion

3.1. *General features*

A visual examination of the profiles did not show any well formed step structures. But step-like structures were present in the depth range 700-1000 m with eroded boundaries of vertical extensions of 10 m or less. Well defined step structures in the deeper layers (700 m) were observed from the same area in the month of May (Gopalakrishna, personal communication). Mixing processes associated with interleaving of different water masses could be very active in this area. Figs. 2 and 3 show the vertical distributions of temperature and salinity along a latitudinal section. The features are characteristics of the area. The surface homogeneous layer is thin (25 m) in the deeper waters (Stns. 160 and 171) but the layer deepens (40 m) towards the coast (Stns. 175 and 176). The surface layer is constituted by low saline water. The thermocline (30-70 m) is steep in the deeper waters and is gentle towards shallow waters. The core of the Arabian Sea high salinity water is also observed in the depth range, 20-70 m. Below the thermocline the temperature decreases monotonically. But the salinity distribution shows low salinity cell between 50 and 150 m. In the deeper layers, generally in this offshore area, high salinity layers of the Persian Gulf water and Red Sea water are observed (Varkey, Kesava Das and Ramaraju 1979, and Ramesh Babu *et al.* 1980). But these waters are not clearly observed in the section due to its proximity to the shelf areas. Fig. 4 shows the vertical distribution (Stn. No. 167) of mean and perturbation temperature series' obtained

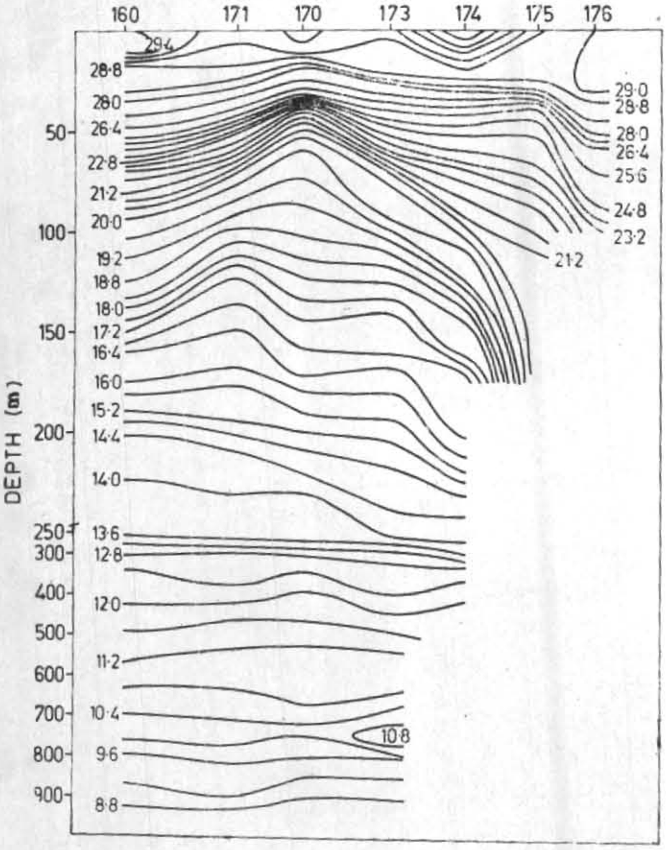


Fig. 2. Vertical temperature structure along the latitudinal section

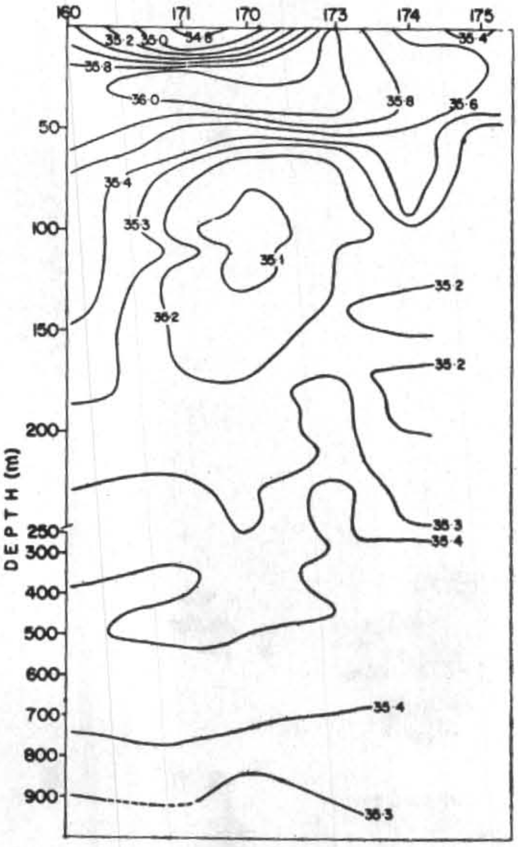


Fig. 3. Vertical salinity structure along the latitudinal section

using the different Cosine filters by the relation $T=\bar{T}+T'$. The mean profiles are smoothed more and more as the filter length increases whereas the perturbation profiles show increased fluctuations. The averaged sigma-*t* profile is also shown in the same figure. The perturbations are very small for the smallest filter length (9.4 m) in the deep layers and is insignificant in comparison with the accuracy of the temperature sensor (.01 deg. C).

Table 1 gives the mean wave length of the prevailing eddies for the filtered range and the full significant corrected spectral range (0-0.11 cy/m). The wave lengths are calculated using the expression (Fedorov 1978) :

$$K=\left[\frac{\int f^2 S(f)\, df}{\int S(f)\, df}\right]^{\frac{1}{2}}$$

where f is the wave number and $S(f)$ is spectral density.

The mean wave length for processes with wave lengths less than 9.4 m is found to be the same, 7.2 m, (Table 1) from both temperature and salinity profiles. This value may be seriously doubted as the noise level for the wave number range, $>$ 0.11 cy/m, was high. The difference between the two estimates is more for the values computed using the second filter (18.7 m). For the longest filter (59.3 m) the difference again narrows down. This suggests that in the intermediate scales the mixing processes are different for heat and salt. The mean wave lengths for the significant spectral range (0-0.11 cy/m) computed using the different Cosine filters agreed very well except for the estimate from salinity profile using the longest (59.3 m) filter. This is because this filter (59.3 m) passes wave lengths from 60 m downwards with unit response (100%) whereas the other filters have cut-offs at much lower wave lengths and hence the high wave number contributions become very insignificant. Again, the mean wave length of 142 m shows the dominance of low wave number processes in the area.

Standard deviations (Table 1) of perturbations (T' and S') for the complete profile increased as the filter length increased. This is due to the addition of more and more of the low wave numbers into the perturbations increasing the relative magnitude of the fluctuations (*see* Fig. 4 also) due to the different filter response properties. Layer-wise values of standard deviations (Table 2) also showed the same pattern of increase with increasing filter length. The standard deviations decreased regularly as the depths increased, except in the

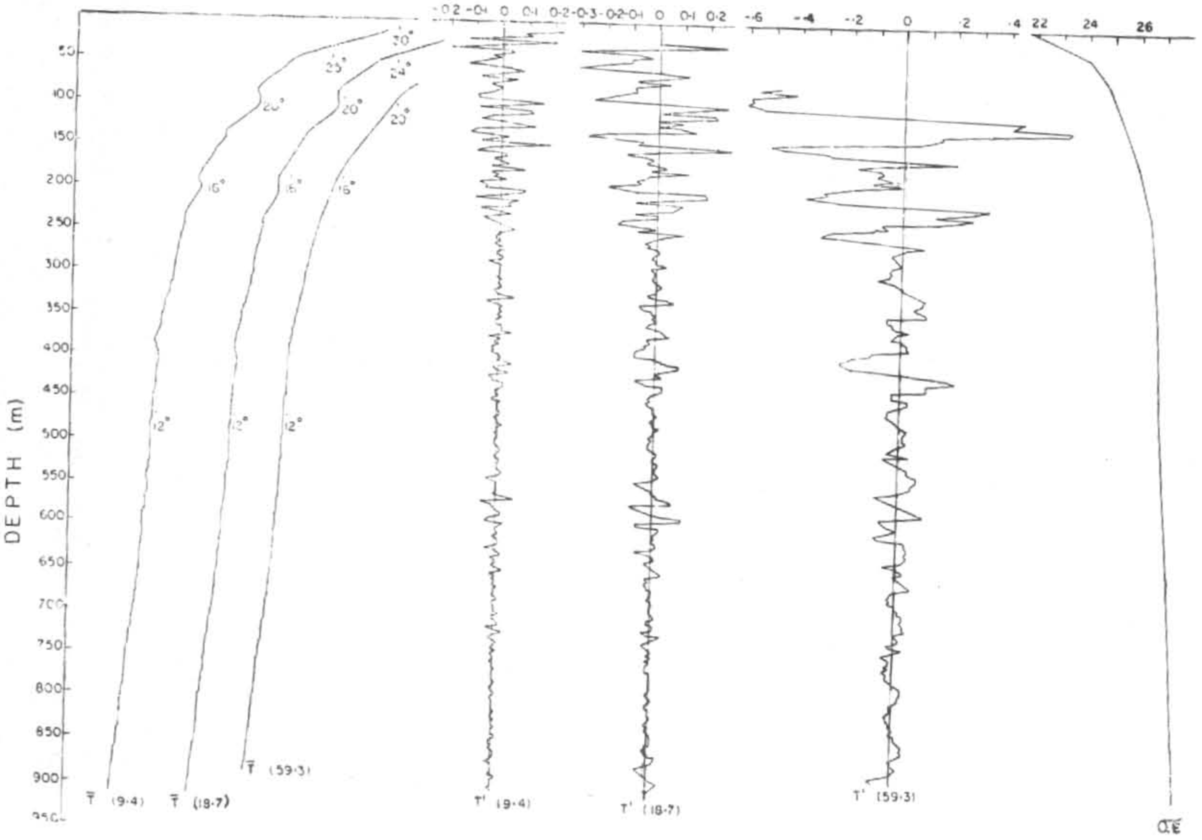
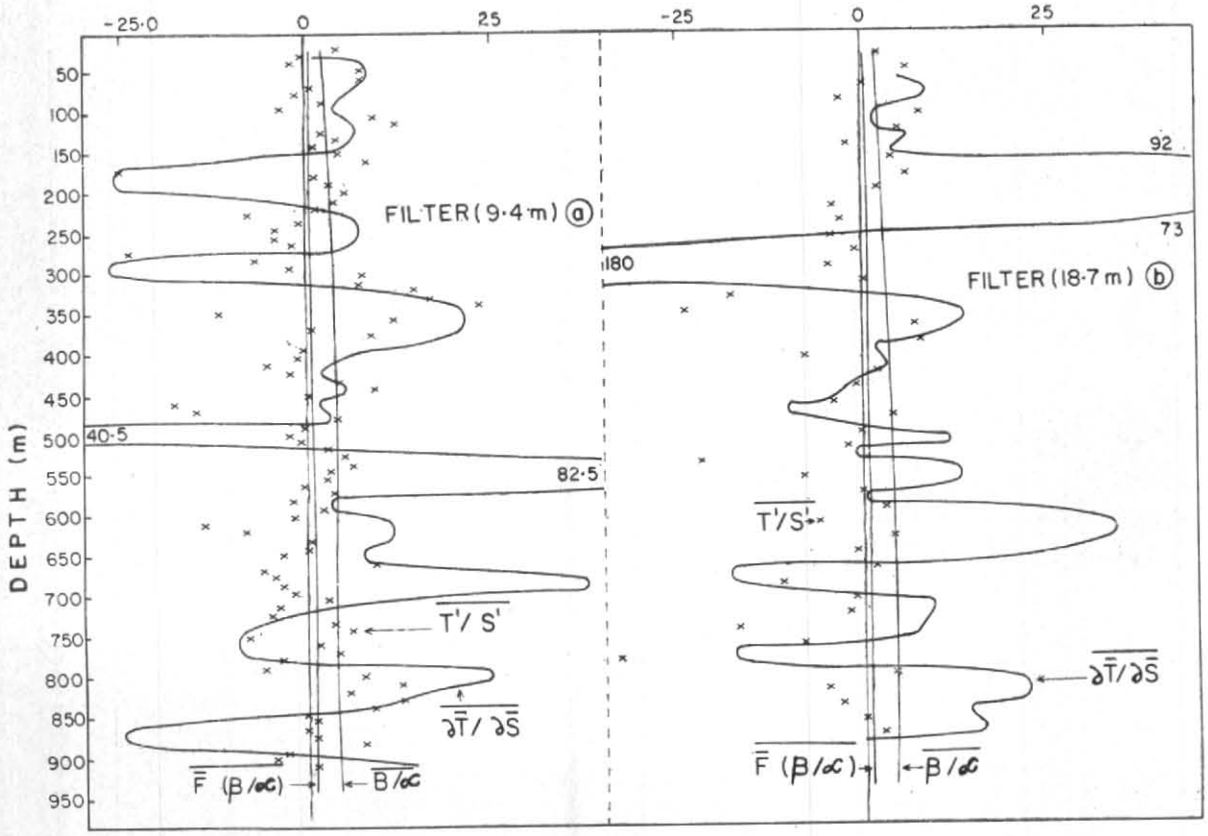


Fig. 4. Mean and perturbation data using Cosine filters with different characteristic lengths

TABLE 1

Mean statistics computed from the complete profiles (0-900 m)

Filter wave length (m) & wave number range (cy/m)	Std. deviation of temp. perturbations (T') (0-900)	Std. deviation of sal. perturbations (S') (0-900)	Mean vertical wave length for the filtered spectrum (m)			Mean vertical wave length for the full spectrum (0-0.11 cy/m)		
			Temp.	Sal.	Mean	Temp.	Sal.	Mean
9.36 (>0.11)	0.043	0.014	7.3	7.1	7.2	149	154	152
18.72 (0.053-0.11)	0.071	0.029	16.4	21.5	19.0	147	146	146
59.28 (0.017-0.053)	0.162	0.043	46.2	43.8	45.0	139	118	128



Figs. 5 (a&b) . A comparative evaluation of β/α, T'/S' and $\overline{\partial T'/\partial S'}$ at station 167

second layer (30-70 m) wherein they showed an increase. This layer is characterised by high temperature gradients and stability. The standard deviations were maximum in the surface layers. Mean vertical temperature gradients $(\overline{\partial T/\partial z})$ were high throughout the water column in comparison to the mean salinity gradients $(\overline{\partial S/\partial z})$. Salinity gradients were high in the upper two layers only. Correlation coefficients between T' and S' for different layers (except in the second layer) increased with increasing filter length. Correlation coefficients between T' and S' from the first filter are irregular in pattern. The second layer showed features different from the general pattern.

Fig. 5 shows a comparative picture of $\overline{T'/S'}$ from the two Cosine filters (9.4 m and 18.7 m) in relation to β/α, $\partial\bar{T}/\partial\bar{S}$ and $\bar{F}(\beta/\alpha)$, wherein F is a mean ratio (Fedorov 1978) of the transport of mass of salt to transport of mass due to heat from observed temperature and salinity values (T and S), and β and α are $-\partial\rho/\partial T$ and $\partial\rho/\partial S$ respectively. An average value (0.28) of $\bar{F}$, for the complete profile was used to draw the line $\bar{F}(\beta/\alpha)$, β and α were calculated (Chen-Tung, Chen and Millero 1976) from T, S and P — the observed pressure. $\partial\bar{T}/\partial\bar{S}$ was calculated using the filtered mean values ($\bar{T}$ & $\bar{S}$). The upper 250 m water column shows very distinctive characteristics. The T'/S' values in both Figs. 5(a) and 5(b) cluster around the β/α and $\partial\bar{T}/\partial\bar{S}$ lines indiscriminately showing the presence of strong activity, both horizontal and vertical. T'/S' values entered in Fig. 5(b) are more influenced by the long wave components than those values in Fig. 5(a). The T'/S' and $\partial\bar{T}/\partial\bar{S}$ values vary within narrow limits. The vertical correlation structure, $\bar{\gamma}$ (Fig. 6) also shows high positive values (~ 0.4) for the depth range 0–250 m. The stability parameter (Fedorov 1978) $\bar{R}$ $(\beta.\triangle T/\alpha.\triangle S)$ also show consistent high values in the layer 0–250 m (Fig. 6). These findings strongly suggest that this layer is active in isopycnal advection. From Fig. 3 it is clear that the high salinity waters are limited to this depth. The presence of different water masses necessitate strong vertical mixing also. Below 250 m the T'/S' values show negative trends. Within the layer, 250–350 m, internal wave mixing appears to be vary active. This layer particularly shows (Fig. 6) high negative correlations ($\bar{\gamma}$) between T' and S' showing the dominant effect of vertical mixing. In depths greater than 350 m vertical processes seem to be more eloquent. Fig. 7 also shows the same features, but very vaguely. The presence of double diffusive processes are not clear from Fig. 5 at depths greater than 700 m even though step structures were very clear in some profiles collected from the same area in the month of May.

3.2. *Auto spectra*

Figs. 8 and 9 show the response corrected spectra computed from the temperature and salinity data (1.56 m interval) and filtered using a First Difference Filter. The gross patterns are similar. Two consistent breaking points are noticed at 0.05 cy/m and at

TABLE 2

Mean statistics computed for the different layers separately

Parameter	Filter length (m)	First layer 0–40 m	Second layer 30–70 m	Third layer 70–150 m	Fourth layer 200–400 m	Fifth layer 400–600 m	Sixth layer 600–900 m
C.C. between *T′* and *S′*	9.4	—0.1068	—0.2176	0.0567	—0.0504	—0.1024	—0.3004
	18.7	0.4370	—0.0897	0.5528	0.3887	0.2240	—0.0755
	59.3	—	—	0.8912	0.3042	0.5894	0.3396
Std. dev. of *T′* (*S*1)	9.4	0.1289	0.0748	0.0844	0.0344	0.0194	0.0102
	18.7	0.1515	0.1245	0.1546	0.0606	0.0339	0.0158
	59.3	—	—	0.3963	0.1256	0.0586	0.0246
Std. dev. of *S′* (*S*2)	9.4	0.0431	0.0181	0.0239	0.0082	0.0051	0.0025
	18.7	0.1142	0.0294	0.0458	0.0141	0.0089	0.0037
	59.3	—	—	0.1079	0.0318	0.0138	0.0054
Ratio of std. dev. (*S*1/*S*2)	9.4	2.98	4.12	3.53	4.19	3.80	4.08
	18.7	1.33	4.23	3.58	4.28	3.81	4.25
	59.3	—	—	3.67	3.95	4.24	4.53
Ver. temp. gradient (*TG*)	9.4	—0.2020	—0.1232	—0.0480	—0.0146	—0.0047	—0.0073
Ver. sal. gradient (*SG*)	9.4	0.0122	—0.0151	0.0009	0.0001	0.0002	—0.0005
Mean value of *TG* div. by *SG*	9.4	3.25	9.20	4.60	5.68	3.58	4.89

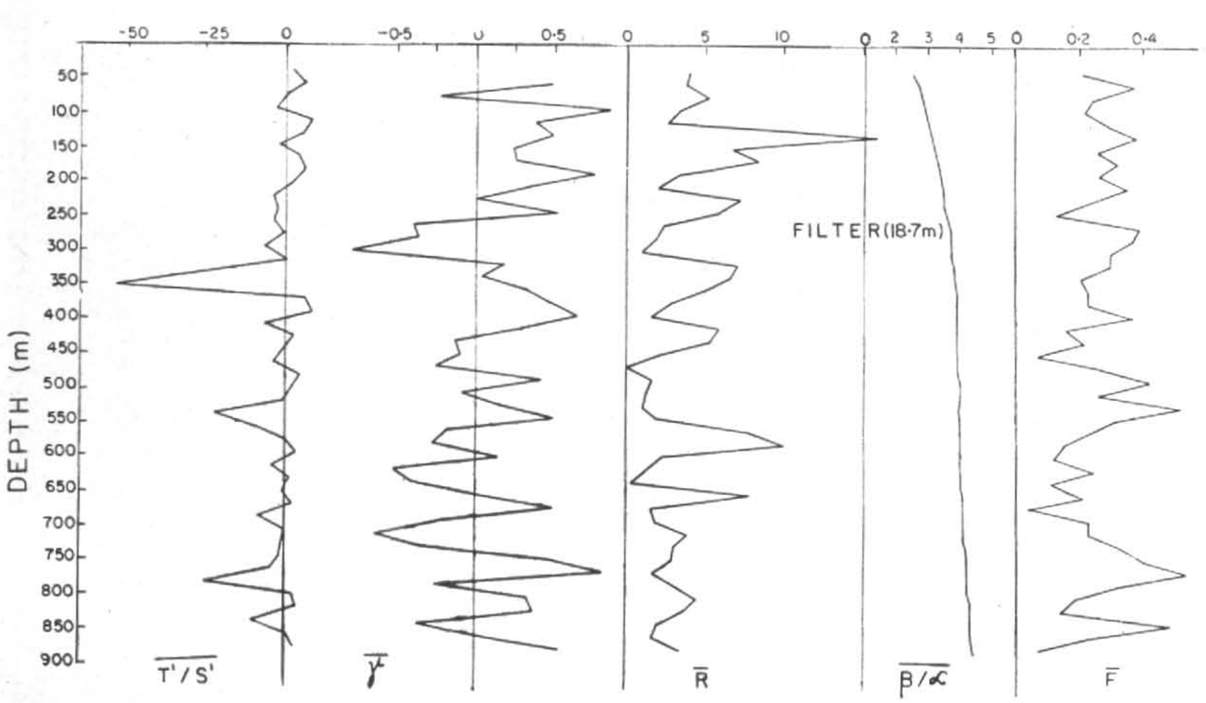


Fig. 6. Vertical structure of averaged (over 18.7 m) statistics computed from data filtered using a Cosine filter (18.7 m)

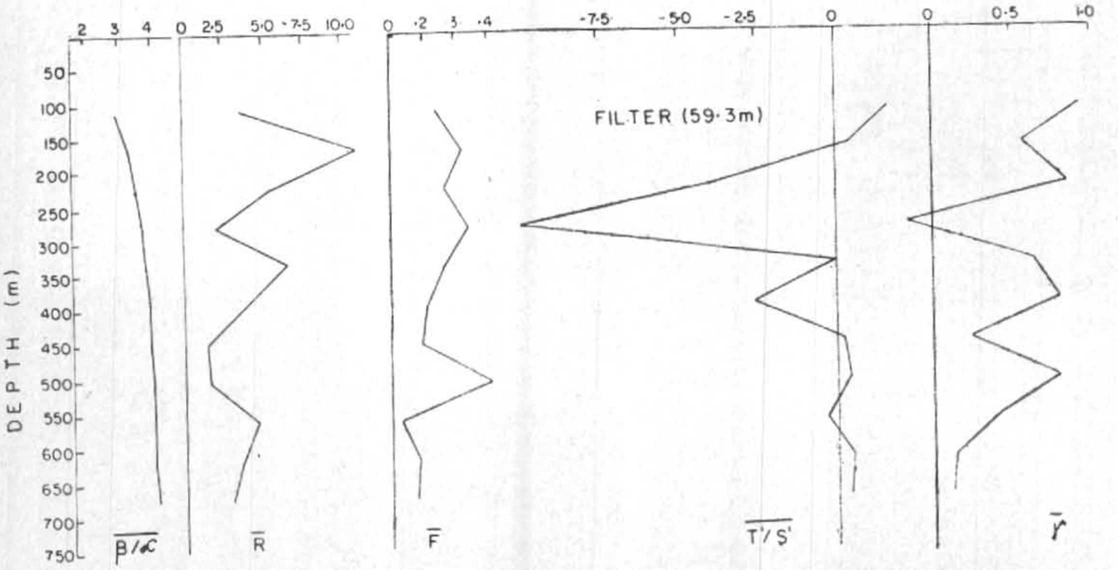


Fig. 7. Vertical structure of averaged (over 59.3 m) statistics computed from data filtered using a Cosine filter (59.3 m)

about 0.11 cy/m. The cuspy feature observed between 0.04 and 0.1 cy/m was more prominent for the temperature spectra. The breaking point at 0.05 cy/m may point out to the prevalence of internal waves. This is corroborated from Table 1 wherein the average wavelength of processes for the range, 0.05 to 0.11 cy/m is found to be 19 m. Jumps or discontinuities between 0.1 cy/m and 0.06 cy/m were observed by earlier workers also. Above 0.1 cy/m the spectra is very irregular and highly noisy and hence this part cannot be considered good for reliable conclusions. Spectra (Fig. 10) computed using Cosine filter (without any pre-emphasis effect) showed zero level (with negative values) energy above a wave number of 0.11 cy/m, wherein the sampling interval was 3.12 m. Hence, it can be safely concluded that a sampling interval of 3-4 m could have produced equally good spectral estimates.

The spectra was divided into two parts for evaluating the slope, since there existed a significant break of slope at or around 0.1 cy/m and also because the estimates for higher wave numbers were highly noisy. Gregg (1977) also followed a similar process to estimate the slopes. The temperature spectra (Fig. 8) showed a mean slope of —2.89 (C.C. = —0.96) whereas the salinity spectra gave the mean slope as —2.61 (C.C.= —0.92). The mean slopes had a range of —2.57 to —3.43 (std. dev.= —0.3) for temperature and —2.05 to —3.15 (std. dev. = —0.36) for salinity. The high standard deviations show the wide differences in the spectral slopes possibly arising out of the large differences in the station physiography resulting in processes with varying intensities. The turbulence spectra for the inertial subrange shows a power dependence of —5/3 (Phillips 1969). The increase in the slopes to close to —3, is due to the comparative increase in the spectral densities for the low wave numbers. The present estimates for the range 0.005 to 0.11 cy/m are very close to Roden's (1971) estimates of —8/3 and —9/3 for the range 0.003 to 0.03 cy/m. Varma (1979) got estimates around —3 for the range 0.002 to 0.017 cy/m. Gregg's (1977) estimates for the range 0.002—0.1 cy/m is —1.8 and is much less than the present estimates and that of Roden (1971) and Varma *et al.* (1979). The present study and Varma's (1979) work showed spectral levels well above 100 (°C^2/cpm). The increase in the energy level can be attributed to the presence of energy transfers or instabilities of an internal wave field or of large horizontal mean flows (Pochapsky 1972). The presence of internal waves and larger horizontal flows are evident from the present analysis of gross statistics (Figs. 5–7).

The spectra (Figs. 8 & 9) for the range 0.005 to 0.1 cy/m showed a definite change in the slope at 0.016 cy/m. But slope estimates could not be made separating the two parts (0.005 to 0.016 and 0.16 to 0.11) as spectral estimates for the range 0.005 to 0.016 were very few. The temperature fine structure spectra for the range 0.11 to 0.32 cy/m showed a mean slope of —2.52 (C.C.= —0.72) whereas the salinity spectra showed a slope of—1.7 (C.C.= —0.48); the correlations were very poor and insignificant. Spectra (Fig. 10) computed from the perturbations obtained using Cosine filters showed noise-level values for wave numbers larger than 0.1 cy/m. Even though spectra using First Difference filter showed vague signal levels for the range 0.1–0.18 cy/m, the spectra were very irregular. Hence the slope estimates for the range (0.1–0.32 cy/m) is very unreliable but is noted for completeness. The noised part of salinity spectra showed more fluctuations compared to that of temperature. This is a result of low amplitudes of S' compared to T' and the accuracy of the sensors (0.01 units).

3.3. *Comparison of different spectra*

Fig. 10 gives a comparative picture of the different spectra (non-normalised) using different filters, at one station (No. 167). All the response-corrected spectra

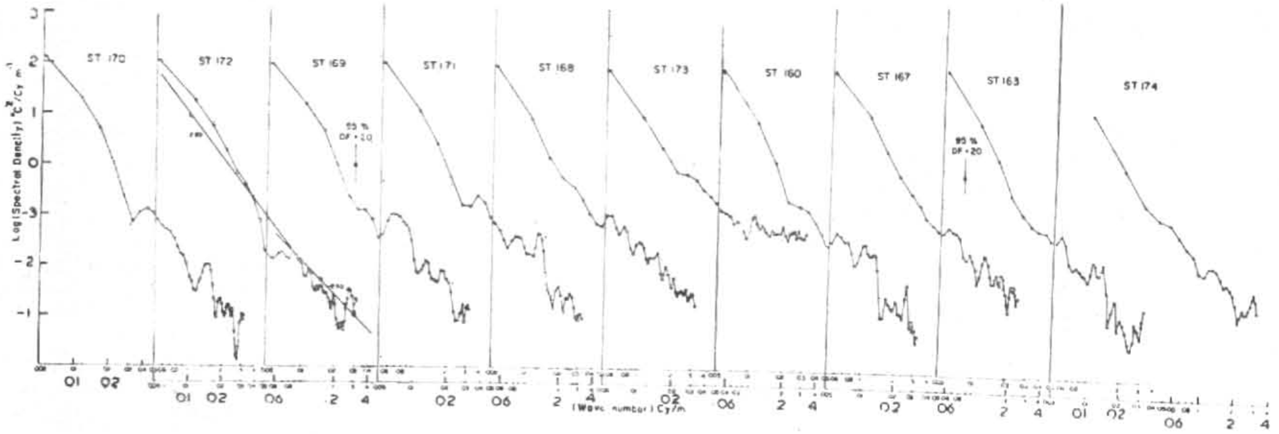


Fig. 8. Temperature spectra from different stations. The mean slope is shown against station 172

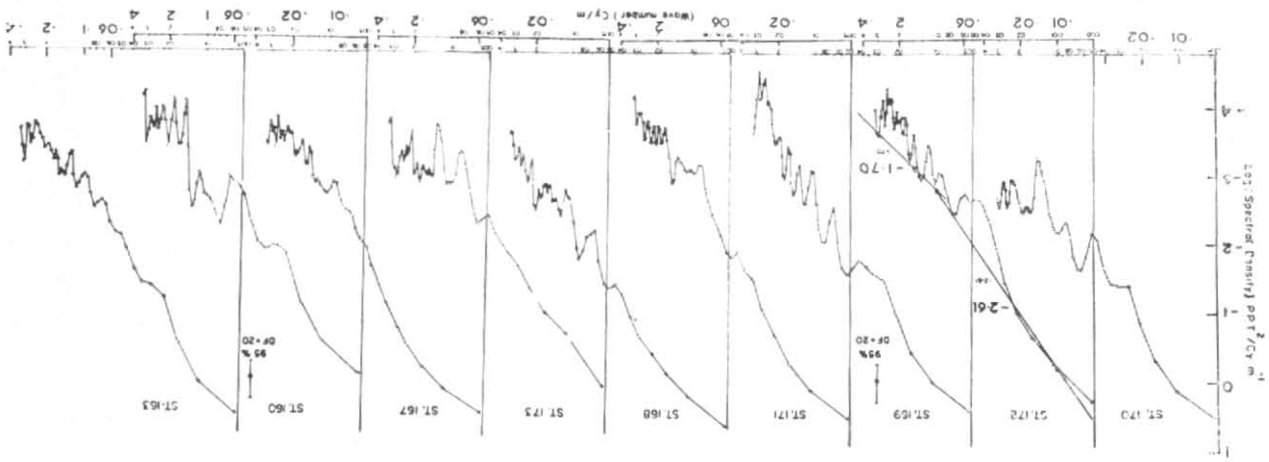


Fig. 9. Salinity spectra for different stations. The mean slope is shown against station 172

agree very well. For the Cosine-filtered spectra negative energy levels were computed from 0.086 cy/m, but the limit shifted to 0.11 cy/m for the normalised spectra. For the first difference spectra (pre-emphasised) the negative values were not observed. This is because, the noise-level of the spectra depends on the significance of the perturbations in relation to the sensor accuracies. All the filtered spectra gave uniform levels upto the filter cut-off wave length. This is due to the high energy levels at low wave numbers. Roden's (1968) spectra for binomial-filtered profiles show a steep forward face in disagreement to the present study. Hence, it is clear that for profiles collected from regions where low wave number processes are very intense Cosine filters are ineffective in disseminating the different spectral regimes.

3.4. *Cross spectra*

Coherency and phase spectra (Bendat and Piersol 1971, Jenkins and Watts 1968) were computed for selected pairs of stations. Grouping of stations were done in a way to get a range of distances between stations varying from 7 to 97 km. Selected stations are only shown in Fig. 11 as the features were similar for all the station-pairs. The cross spectra is plotted upto a wave number of only 0.16 cy/m to show the signal range (0-0.11 cy/m) and the noise-range (>0.11 cy/m) distinctively. Coherency was high (>0.80) for long wave lengths (>50 m) with low consistent phase spectra ($<45°$). For low wave lengths (<50 m) the coherency was found to be highly irregular with unstable phase spectra. As a result of the large distances between stations high coherency was observed only at low wave numbers. Earlier studies showed a horizontal radius of correlation of 0.4 only between the perturbations even with a distance of 2.5 kn. miles (Fedorov 1978) hence the absence of significant coherency for the present station-pairs (>7 km).

3.5. *Findings*

(*i*) In the upper 250 m where in the high salinity water masses are observed, mixing is affected by isopycnal advection and vertical processes.

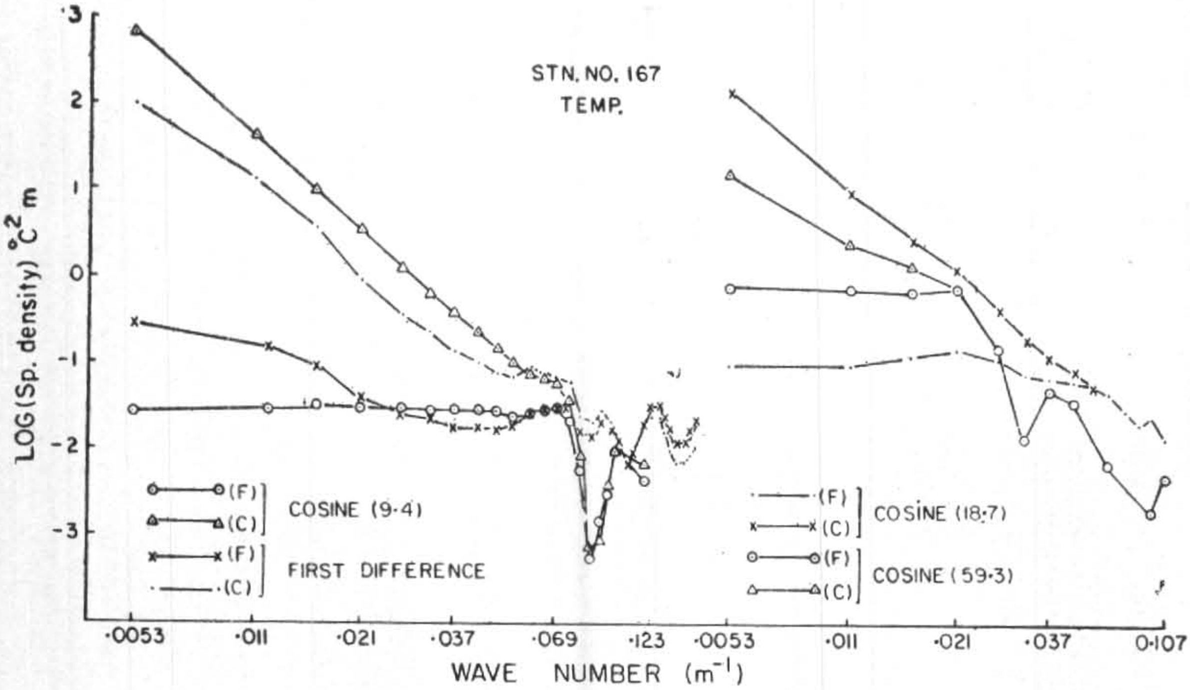


Fig. 10. Comparison of spectra using different filters. F-means filtered spectra, C-means response-corrected spectra

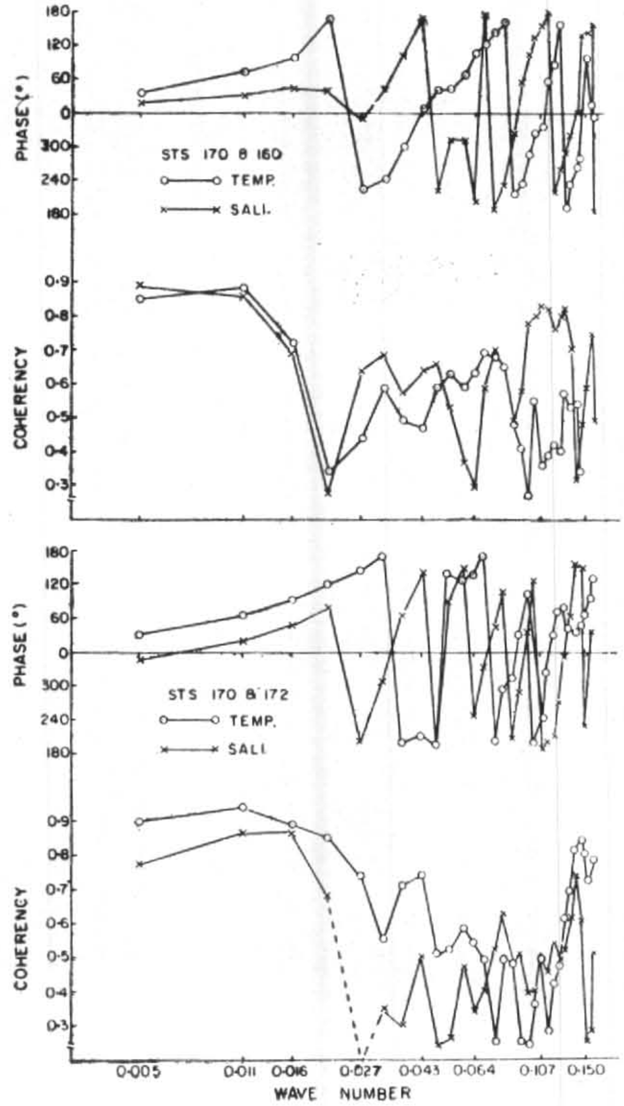


Fig. 11. Cross spectra of temperature and salinity profiles for selected station pairs

(*ii*) The high values of the spectral slopes (—2.9 & —2.6) are due to the intense activity of the low wave number processes.

(*iii*) Cosine and first difference filters are ineffective in differentiating the different regimes when the low wave number processes are intense. The use of unitary filters are suggested to give better results.

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