

Spatial and temporal variability of the heat budget parameters and currents in the coastal waters of Visakhapatnam, east coast of India

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Analysis of the thermal structure in coastal waters off Visakhapatnam revealed sub-surface inversions during October. In postmonsoon, a good association existed between wind stress (τ) and total heat loss ($Q_e + Q_s$) and between SST and heat content (H) on diurnal scale. Horizontal eddy diffusion coefficient (K_x) estimated from the horizontal advection equation was $3 \times 10^4 \text{ cm}^2 \cdot \text{s}^{-1}$ during October. During February 1993, surface currents had magnitudes of $105\text{-}126 \text{ cm} \cdot \text{s}^{-1}$ and the flow was towards north-east.

Studies on variability of heat fluxes off central east coast of India¹ and heat flux divergence in the coastal waters of Visakhapatnam^{2,3} have been carried out on a limited scale. In the present investigation, an attempt has been made to study spatial and temporal variability of the heat budget parameters, thermal structure and currents in the coastal waters of Visakhapatnam.

Materials and Methods

Four stations (Fig. 1) were selected off Visakhapatnam coast for these studies. Time series data on surface meteorological parameters, temperature and current profiles were collected for various periods (Table 1) during 1989-90 and 1993. The depth at sts 1 and 4 was 30 m and at sts 2 and 3 was 50 m. The inertial period ($T = 2\pi/f$) at the centre of the study area is about 40 h.

Surface meteorological data were collected at hourly interval and temperature and current profiles were taken at 2 hourly intervals. Total duration of observations was 22 h for periods I to IV and 10 h for the periods V to IX.

Mechanical bathythermograph (MBT) was used for temperature profiles and a direct reading current meter (Model DNC 3 accuracy: speed $\pm 5 \text{ cm} \cdot \text{s}^{-1}$; direction $\pm 10^\circ$) for current profiles at 10 m interval. Dry bulb and wet bulb temperatures were measured by a Psychrometer and the wind speed by a portable air-meter.

The heat budget components: Q_a (available insolation at the sea surface after reflection), Q_b (effective back radiation), Q_e (latent heat flux), Q_s (sensible heat flux), H (heat content) and Q_t (rate of change in heat content) were estimated^{1,2}, from

the above data set. Wind stress (τ) was computed by bulk aerodynamic method, $\tau = \rho C_d U^2$, where ρ = density of air and C_d is the drag coefficient evaluated from Kondo's method⁴ and U is the wind speed.

Results and Discussion

Spatial and temporal variability of heat budget parameters—Figure 2 shows the heat budget parameters for October 1989 (I and II) and January/February 1990 (III and IV). There is a good relation between SST and heat content (H) (Fig. 2A,B) and with wind stress (τ) and total heat loss ($Q_e + Q_s$, THL) in both the periods (Fig. 2C,D). Correlation coefficients obtained between H and SST and between THL and τ were 0.98 and 0.52

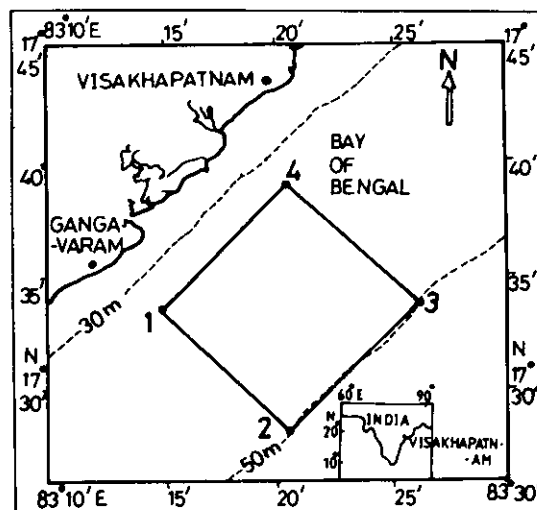


Fig. 1—Location map

Table 1—Mean meteorological parameters during different periods

Sampling periods	*Temperature (°C)				U (m.s ⁻¹)	es - ea (mb)	Ts - Ta (°C)
	Ta*	Tw	Td	Ts			
I 17-21 Oct. 89	29.7	23.8	21.4	29.6	3.0	15.9	-0.1
II 25-29 Oct. 89	29.3	26.1	25.1	29.7	2.9	9.9	0.4
III 09-13 Jan. 90	25.2	21.7	20.1	25.7	2.6	9.5	0.5
IV 31-04 Feb. 90	26.4	23.8	22.7	27.1	4.2	8.3	0.7
V 18-21 Apr. 90	30.0	27.8	27.1	29.0	7.0	4.5	-1.0
VI 28-31 Jul. 90	29.2	26.9	26.1	27.5	4.5	2.8	-1.7
VII 23-26 Sep. 90	29.5	27.1	26.3	29.7	4.3	7.5	0.2
VIII 22-25 Feb. 93	25.6	23.8	18.8	26.4	3.1	12.7	0.8
IX 28-29 Oct. 93 04-05 Nov. 93.	29.2	26.2	25.2	29.4	5.4	8.4	0.2

* Ta = Dry bulb temperature; Tw = wet bulb temperature; Ts = sea surface temperature; U = wind speed; es - ea = vapour pressure gradient; Ts - Ta = sea-air temperature difference.

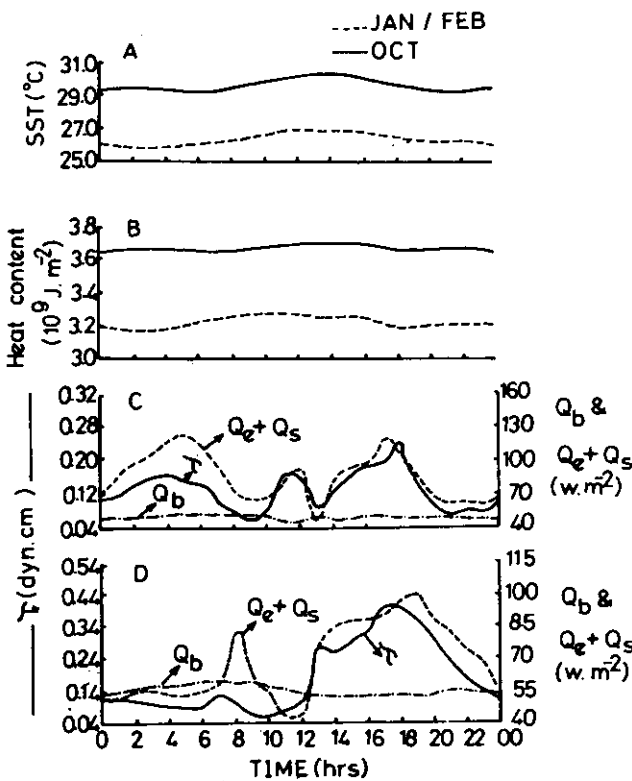


Fig. 2—Diurnal variability of—(A) SST; (B) heat content; (C, D) wind stress (τ), total heat loss ($Q_e + Q_s$) and effective back radiation (Q_b) during October 1989 (I and II) (C) and January/February 1990 (III and IV) (D)

respectively. The corresponding regression equations are given below:

$$H (10^9 \text{ J.m}^{-2}) = 0.13 T_s - 0.206 \quad \dots (1)$$

where T_s is sea surface temperature.

$$\text{THL} = 126.7 \tau + 57.36 \quad \dots (2)$$

(τ is in dyn.cm^{-2} and THL in W.m^{-2})

In view of good correlations obtained, the above equations are useful to estimate H and THL on diurnal scale from the satellite derived winds and SST. However, the validity of above equations have to be tested for other coastal areas. Effective back radiation fluctuated between 45-55 W.m^{-2} in January/February 1990 and 50-65 W.m^{-2} in October 1989 (Fig. 2C and D).

Table 1 shows mean surface meteorological parameters, vapour pressure gradient (VPG) and sea-air temperature difference (SATD). Dry bulb temperature (T_a) was maximum (30°C) in April 1990 (V) and a secondary maximum was observed in October 1989 (I and II). Since, there was no observation during May/June, SST during the period II (29.7°C) appears to be maximum and is close to the value reported earlier². Average SST for the periods III and IV was 26.4°C which is close to the computed value (26-26.5°C) by a model⁵. Dew point temperature (T_d) was high (27.1°C) in period V and low (20.1°C) in III which are comparable with those (28 and 22°C) reported earlier⁶. Average values of all parameters during October, 1989 (I and II) are in good agreement with mean monthly values reported earlier².

Figure 3 represents mean temperature profiles for all periods I to IX. Sub-surface inversions noticed during the period I seems to be a regular feature in the coastal waters of Visakhapatnam⁶. The layer becomes isothermal by the end of Oc-

tober (II). The temperature of the water column (0-30 m) almost dropped by 4°C from I to IV. There was not much change in temperature profile between October 1989 and October/November 1993.

Table 2 shows the mean heat budget parameters and heat content. Net insolation (Qa) varied between 231-326 $W.m^{-2}$ while effective back radiation ranged between 32-64 $W.m^{-2}$. Net heat exchange (Qn) was maximum in periods V and VI and minimum in IV and IX. In general, heat content (H) was maximum in I, II and IX while the minimum was noticed in periods III and VIII.

Spatial and temporal variability of the heat budget parameters are shown in Tables 3 and 4. Net heat advection (Qv) is obtained as a residual term ($Qv = Qn - Qt$) which indicates divergence of heat from the study area during the periods I-VII. Mean values of Qn and Qv for all periods were 166 and 173 $W.m^{-2}$ (Table 4) respectively while the corresponding values based on monthly data reported earlier² were 114 and 115 $W.m^{-2}$.

Currents—Table 5 shows mean current speed and direction. Abnormally strong currents (>100 $cm.s^{-1}$) were observed in the entire layer during October 1989 (I and II) with a secondary maximum in February 1990 (IV) and the flow was directed towards northeast (56°). Cutler and Swal-

low⁷ also reported similar strong north-easterly currents in February in this area based on ship drift data. Weak currents were recorded in other periods. The currents during all seasons were higher than those reported in the atlas⁷ based on ship drift data, though the directions were same. In general, speed and direction of currents were comparable with those reported earlier^{8,9} except for October and February.

Current measurements in 1993 indicated a strong northeasterly flow in February (VIII) and weak southwesterly flow in October (IX). Strong

Table 2—Mean heat budget parameters under different periods (periods are as in Table 1)

Sampling periods	$W.m^{-2}$					H ($10^9 J.m^{-2}$)
	Qa	Qb	Qe	Qs	Qn	
I	274	56	96	-0.4	122	3.69
II	261	41	69	1.6	149	3.62
III	231	60	58	1.9	111	3.16
IV	245	49	85	4.7	106	3.29
V	326	32	88	-6.0	212	3.27
VI	314	32	21	-7.8	269	3.28
VII	282	33	74	1.0	174	3.58
VIII	257	64	73	4.3	116	3.00
IX	256	37	111	1.7	106	3.60

Qa =available insolation at sea surface; Qb =effective back radiation; Qe =latent heat flux; Qs =sensible heat flux; Qn =net heat exchange; H =heat content in 0-30m layer.

Table 3—Rate of change in heat storage (Qt $W.m^{-2}$) at 4 stations during 1989-90

Sampling periods	St. 1	St. 2	St. 3	St. 4	Mean
II-I	-137	-191	-107	32	-101
III-II	-077	-066	-069	-72	-071
IV-III	068	082	099	26	069
V-IV	-006	012	020	-16	003
VI-V	015	-017	-027	16	-003
VII-VI	055	063	063	65	061

Table 4—Advection (Qv , $W.m^{-2}$) during 1989-90

Period	Qn	Qt	Qv
I & II	135	-101	236
II & III	130	-071	201
III & IV	109	069	040
IV & V	159	003	156
V & VI	240	-003	243
VI & VII	222	061	161
Mean	166	-007	173

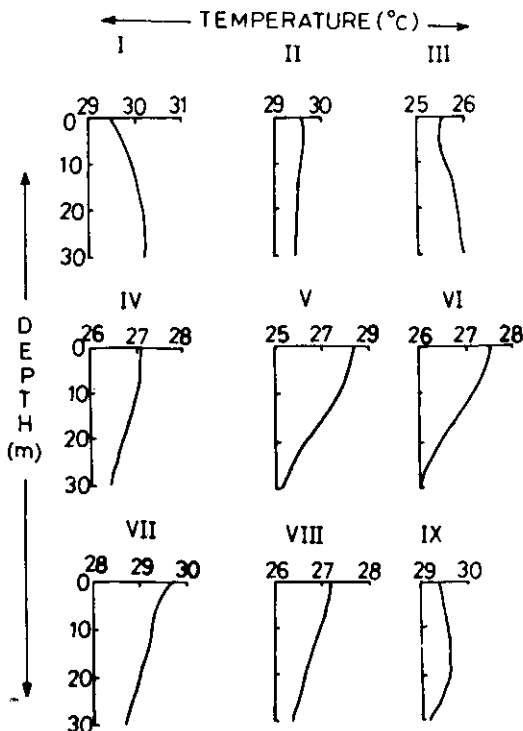


Fig. 3—Thermal structure under different periods, I to IX

Table 5—Mean current profiles during the year 1989-90 and 1993

Layer (m)	Sampling periods (as in Table 1)																	
	I		II		III		IV		V		VI		VII		VIII		IX	
	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D	S	D
0-10	119	300	131	242	29	182	73	56	21	036	18	238	26	227	93	65	19	236
10-20	106	299	125	242	17	203	50	55	09	116	23	191	36	249	76	67	15	126
20-30	095	297	128	230	11	171	39	95	13	205	28	192	34	252	60	106	16	177

S—current speed (cm.s⁻¹); D—current direction

currents generally observed off east coast of India during October/November and February could be the best evidence for the existence of boundary currents off the central east coast of India as reported earlier¹⁰⁻¹².

Horizontal eddy diffusion coefficient (Kx)—Rate of heat advection (Qv) is directly computed using

the relation, $Qv = - \left(u \frac{\partial H}{\partial x} + v \frac{\partial H}{\partial y} \right)$, where H is

heat content and u and v are the zonal and meridional components of currents in the 0-30 m layer. Advection of heat has been computed applying this relation for periods I and II where the data was available for 8 days. Values of Qv obtained were 245 and 363 W.m⁻² for periods I and II respectively. Mean value of Qv obtained as a residual from the heat budget equation ($Qv = Qn - Qt$) was 236 W.m⁻² which is comparable with the average computed value (304 W.m⁻²) for periods I and II. The difference in Qv is quite obvious in the coastal waters where the physical processes are complex with space and time¹⁴.

Making use of Qv (236 W.m⁻²) and the horizontal temperature gradient, Kx is estimated from the following equation:

$$Qv = \rho C_p Kx \frac{\partial T}{\partial x} \quad \dots (3)$$

Horizontal eddy diffusion coefficient (Kx) is found to be 3×10^4 cm².s⁻¹ during October (post-monsoon season). This value is more than double of the earlier reported value of 1.3×10^4 cm².s⁻¹ from dispersion studies¹³ off Gangavaram for November. The difference in Kx could be due to general calm conditions prevailing in November. From the data collected during October/Novem-

Table 6—Comparison between observed and computed heat fluxes during 1993 (THL in W.m⁻² and H in 10⁹ J.m⁻²)

Sampling period	THL		H	
	1A	1B	2A	2B
VIII 22-25 Feb. 93	75	77	3.23	3.00
IX 28-29 Oct. 93	119	113	3.62	3.60
04-05 Nov. 93				

1A= computed from Eq. (1)

2A= computed from Eq. (2)

1B, 2B= estimated from observed data

ber 1993 (IX), using Kx as 3×10^4 cm².s⁻¹, the computed value of Qv from Eq. (3) is 129 W.m⁻², while from the observed data $Qv(Qn - Qt)$ is about 148 W.m⁻².

Total heat loss ($Qe + Qs$), wind stress (τ) and heat content (H) was estimated from the data obtained during February 1993 (VIII) and October/November 1993 (IX) (Table 6). Computed and estimated values of THL and H (from Eqs. 1 and 2) are also shown in Table 6. The observed and computed values are very close to each other in all cases except in the heat content during February 1993. It may be stated that Eqs. (1) and (2) are useful for estimating H and THL on diurnal scale. However, their validity is yet to be tested for other coastal areas.

Surface meteorological parameters and heat budget components exhibit changes with space and time. Sub-surface inversions at the end of October seems to be a permanent feature in the coastal waters of Visakhapatnam. Mechanism for the formation of strong currents (100 cm.s⁻¹) during February and October/November, is yet to be identified. A good correlation was observed between τ and THL and SST and H , on diurnal scale. The computed value of horizontal eddy diffusion coefficient was 3×10^4 cm².s⁻¹ for the coastal waters of Visakhapatnam. This value is useful for numerical modelling studies.

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