Journal of Coastal Research	11	3	776–787	Fort Lauderdale, Florida	Summer 1995

Monsoon-Induced Temporal Changes in Beach Morphology and Associated Sediment Dynamics, Central East Coast of India

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ABSTRACT

CHAUHAN, O.S., 1995. Monsoon-induced temporal changes in beach morphology and associated sediment dynamics, central east coast of India. *Journal of Coastal Research,* 11(3), 776–787. Fort Lauderdale (Florida), ISSN 0749-0208.

The east coast of India experiences two annual rough weather spells associated with the NE and the SW monsoons. The wave climate, littoral current patterns, longshore sediment transport, beach profile changes, sediment budget and sedimentological parameters of the beach sediments were determined for monsoon events. The waves were moderate–high ($H_\infty > 2$ m $T_\infty > 8$ sec dir 150–240°) and moderate (> 2.0 m T_∞ > 8 sec for 30% time) during the SW and the NE monsoons respectively. However, due to occurrence of cyclones/storms during the NE monsoon (p = 1 in November), there are sporadic enhancements in the wind and wave climate (wind speed > 60 km h^{-1}; H_∞ 2–4.5 m T_∞ > 10 sec). The littoral currents were moderate to strong (30–70 cm sec^{-1}) during the SW monsoon, variable during the NE monsoon (20–50), and mild (0–40 cm) during non-monsoon period. The direction of these currents also reverses during and after the NE monsoon (from the SW in the SW monsoon to mostly from the NE in the remaining period). The beach profiles, which until April accrete, are much reduced in length, have no berm, higher beach slope, and no bars and troughs, in the SW monsoon. About 58 m^3 m^{-1} were eroded from the beach during this monsoon. Despite the prevalent moderate–high wave regime, cyclonic storms and moderate–strong littoral currents, the beach profiles of the NE monsoon have accretion over the profiles of the SW monsoon (magnitude 25–30 m^3 m^{-1}). This accretion continues and about 91 m^3 m^{-1} sediments were observed to be accreted on the beach until February. The factors which contribute to the accretion in high energy regime associated with the NE monsoon are delineated based upon the following: variations in the longshore sediment transport, wave energy flux, magnitude and direction of littoral current, sedimentological parameters of the beach and location of the area in the vicinity of high fluvial discharge.

ADDITIONAL INDEX WORDS: *Monsoon, beach, size measures, sediment budget, waves.*

INTRODUCTION

Unlike the majority of the coasts of the world, which experience an annual cycle of storm and swell conditions (KOMAR, 1976; WRIGHT and SHORT, 1984; CHAUHAN *et al.*, 1988), the east coast of India experiences two phases of stormy conditions. The major condition is associated with the SW monsoon and is the result of differential heating of the Indian Peninsula. It is active in June through early September. Another monsoon (NE) prevails during October through December. During this monsoon, cyclonic storms accompanied by high speed winds and waves are frequent.

Influences of these monsoons on the beach processes are still not fully understood. This is primarily due to the fact that most of the work done along the east coast of India (SRIVASTAVA and RAO, 1976; CHAKRABARTI, 1977; CHANDRAMOHAN *et al.*, 1988; SARMA and REDDY, 1988; CHAUHAN, 1991, 1992a,b; CHAUHAN *et al.*, 1988) either reports annual cyclic changes in the beach processes or present net shore drifts determined and based upon various energy flux models. These models mainly take wave parameters as an input, are subjected to the vagaries of individual judgments on bathymetric input and spacing of wave orthogonal, and usually lack field validation. The present work is a modest effort to separate out the influences of these monsoon events on the beach. Machilipatnam Beach is located at the central east coast of India. Unlike other regions (southern and extreme northern regions), here the climatic conditions are well influenced by these monsoons. The beach is open and directly exposed to the Bay of Bengal. The climate in the area is broadly subdivided into three seasons: *i.e.*, SW monsoon (June–September), NE monsoon (October–December) and non-monsoon (January–May). The

93081 received 17 April 1993; accepted in revision 28 March 1994.

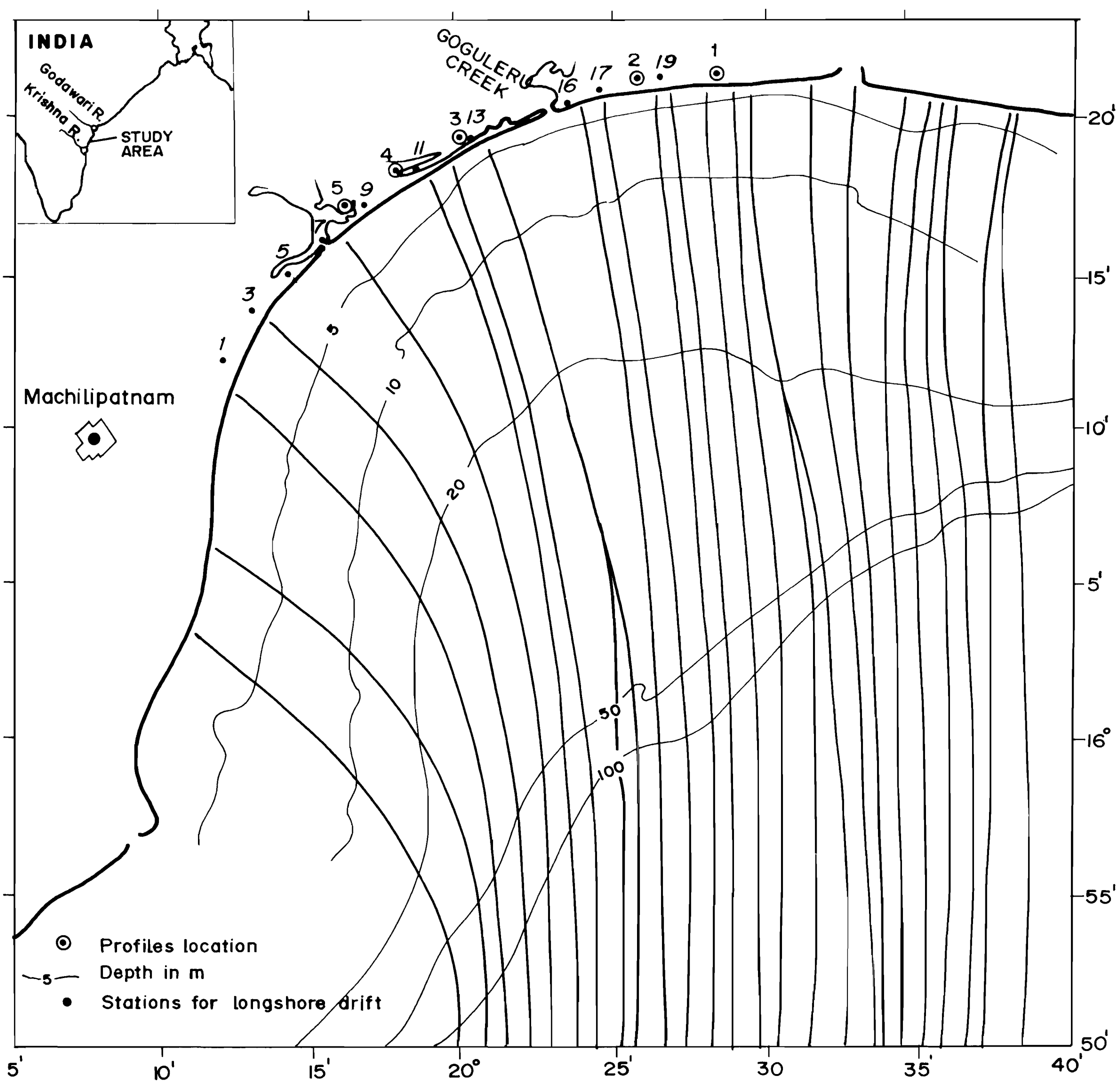

Figure 1. Location map of the study area. The beach profile and stations identification used for calculation of drift along the coast is also given. Wave rays for T_∞ = 12 sec and wave approaches 180° are presented.

present study encompasses determination of the following: (1) wave parameters, (2) qualitative and field measurements of littoral currents, (3) beach profile monitoring, (4) determination of longshore drift, (5) long and short term sediment budget, and (6) sedimentology of the beach sediments. During these monsoons, based upon available sedimentological tools (binary plots), the processes which affect the environment of deposition are identified.

METHODOLOGY

The study area covers an approximate 30 km stretch of the central east coast of India at Machilipatnam (Figure 1). Between February of 1981 and November of 1982, five transects, spaced at about one km (Figure 1) and extending from berm to 2 m water depth (below low tide level), were monitored. A permanent reference point (tied to about +2 m datum above mean sea level) was established for each profile. During low tide, levels

Table 1. *Deep water wave height H_∞ (percent) for different months along the Central east coast of India. Refer to methodology for details of data source.*

Months	Wave Height (m) 1	1.5	2.0	2.5	3.0	3.5	4.0	>4.0
Jan.	56.27	30.93	6.8	6.8				
Feb.	74.07	22.22	3.70					
Mar.	58.74	20.58	11.76	8.82				
Apr.	58.62	27.58	3.44	3.44			3.44	
May	40.33	16.66	23.80	14.28			4.76	
June	20.68	3.44	24.13	13.79	27.58	6.89	3.44	
July	5.50	16.66	19.44	27.77	11.11	11.11	2.77	5.5
Aug.	12.50	22.50	15.00	25.00	10.00	5.00	7.50	2.5
Sep.	26.08	26.08	21.73	8.69	13.79	4.34		
Oct.	47.26	18.42	13.50	10.52	7.89	2.63		
Nov.	33.33	16.66	20.00	13.13	9.90	3.30	3.3	
Dec.	52.94	23.52	17.64	5.88				

along these transects were obtained deploying a theodolite and a measuring staff (accuracy ±1%). The points taken for the measurements were the places of visual changes in the gradient of the beach (CHAUHAN, 1992b). Seven such observations were made on each transect, in November, February and September of 1981, 1982, and April of 1981. The beach profiles of November were measured to separate out the influence of the NE monsoon, and the profiles of September represent conditions of the SW monsoon. In February and April, profiles were measured to determine transitional conditions between the NE and the SW monsoons. Based upon comparison of successive beach profiles, temporal variations in the sediments budget were obtained between February 1981–November 1982.

Between latitude 15–17°N and longitude 81–83°E, the swell wave parameters, documented in the daily weather reports of the India Meteorological Department (period 1978–1990), were retrieved. These data based upon ship borne visual estimation by a trained observer include swell wave height and period and wave direction. The data when compared with the wave parameters obtained through a wave rider buoy deployed in the study area show a high correlation (CHANDRAMOHAN *et al.*, 1988). Since direct use of these visually observed wave parameters has been justified for most of the coastal applications (JARDINE, 1979; CHANDRAMOHAN *et al.*, 1988), the retrieved wave heights and periods are considered as significant wave heights and zero crossing wave periods respectively.

CHANDRAMOHAN *et al.* (1988) have reported that the equations of SHORE PROTECTION MANUAL (1977) give close approximation for determination of longshore drift along the east coast of India. The longshore sediment transport rates, along 19 stations (Figure 1), have been estimated from the following empirical relation (SHORE PROTECTION MANUAL, 1977):

$$Q = 1{,}288\text{Pls} \qquad (1)$$

Q = volume transport rates (m^3/yr) and Pls is longshore wave energy (watts/m). Also, by linear wave theory (SHORE PROTECTION MANUAL, 1977) the longshore energy flux is given as:

$$\text{Pls} = [\rho g^2 T_\infty (H_\infty K\gamma)^2 \text{Sin } 2\alpha\beta]/64\pi \qquad (2)$$

where H_∞ = significant wave height, T_∞ = wave period, $K\gamma$ = refraction coefficient, $\alpha\beta$ = breaker angle, ρ = density of sea water (1,025 kg/m). Further shoaling coefficient is given by

$$H_\zeta = (C_\infty/2nC)^{0.05} \qquad (3)$$

where H = shoaling coefficient and C = $(gd)^{0.5}$. Using equations 2 and 3 in equation 1

$$Q = 1{,}288[\rho g^2 T_\infty (H_\infty H\zeta K\gamma)^2 \text{Sin } 2\alpha\beta]/64\pi.$$

To obtain K_γ, H_∞ and $\alpha\beta$, the wave parameters retrieved from the daily weather reports (Tables 1–3) were used as an input, and numerical wave refraction studies were carried out on a Norsk Data 570 computer (HARRISON and WILSON, 1964; SHORE PROTECTION MANUAL, 1977). Wave orthogonals were drawn at 50 m intervals, and bathymetry as given in the Naval Hydrographic Chart Number 355 was used. Values of K_γ, H_∞ and $\alpha\beta$ were obtained at 2 m water depth following details given in SHORE PROTECTION MANUAL (1977). Longshore drifts were obtained for non-monsoon (December–February), transition period (March–May), the SW monsoon (June–September) and the NE monsoon (October–November). Frequency of the occurrence of H_∞ T_∞ and direction of wave approach in a month (Tables 1–3) were used as input to calculate monthly variations in longshore sediment transport using following relation (CHANDRAMOHAN *et al.*, 1988; CHANDRAMOHAN and NAYAK, 1991)

$$\text{Qm} = 1/12\left[\sum_{H=0}^{H=\infty}\sum_{T=0}^{T=\infty}\sum_{\alpha\beta=30}^{\alpha\beta=260} \text{Qf}(H, T, \alpha\beta)\right].$$

Qm = monthly longshore drift, f = frequency occurrence of (H_∞, T_∞, $\alpha\beta$) in a month.

A qualitative picture of littoral currents was

Table 2. *Same as Table 1 but for deep water wave period (T_∞).*

	Wave Period (sec)								
Months	5	6	7	8	9	10	11	12	>12
Jan.	20.68	17.24	13.39			3.40	3.40	31.03	10.34
Feb.	55.55	18.50	3.70		3.70	3.70		7.40	7.40
Mar.	47.05	14.70	11.78	2.94	2.94	8.80	2.94	2.94	
Apr.	37.93	17.24	10.34		3.44	13.79		3.44	13.89
May	21.95	14.63	4.76	19.04	11.90		4.76	21.42	
June	20.68	3.44	6.89	20.68	10.34	3.44	13.79	10.34	10.34
July	13.88	11.11	16.66	30.55	2.77	11.11	8.33		5.55
Aug.	10.80	13.51	16.21	18.91	2.70	16.21	5.40	5.40	10.80
Sep.	34.78	13.04	4.34	17.39	8.69	8.69	4.34	4.34	4.34
Oct.	21.08	10.52	13.15	10.52		15.78	5.26	7.89	10.52
Nov.	26.66	20.00	20.00	13.33				6.60	13.13
Dec.	47.05	17.64	23.52	5.88		5.88			

also obtained from the wave refraction studies. The most prevalent wave directions during the SW, the NE and non-monsoon period, and the orientation of the coast (NE–SW) were considered; wave refraction patterns for wave approaches 90–210° and wave periods 6–12 sec were used. Further, due to similarity in the patterns of wave period T_∞ 5–6, 7–8, 9–10 and 10–12 sec, the results were presented for 6, 8, 10, 12 sec. For validation of the refraction simulation studies, the patterns of littoral currents were also measured at 2 m water depth in February of 1981, 1982 and April, September and November of 1981. The standard float and dye movement methods were used (SHORE PROTECTION MANUAL, 1977; CHAUHAN, 1986).

Along and across the beach porfiles, during the NE and the SW monsoons, 150 sediment samples were collected from the upper 2 cm of beach surfaces (CHAUHAN, 1992a). The sediments were washed, oven dried (at 70 °C), and representative 100 g samples were sieved at 0.25 phi intervals using A.S.T.M. 20 cm diameter sieves and a Ro Tap sieve shaker (FOLK, 1966). The moment size measures (FRIEDMAN, 1979) were determined on the ND 570 computer. Binary plots used to separate beach, river, inland and nearshore dunes (between standard deviations *vs.* skewness; standard deviation *vs.* mean cubed deviation; cubed standard deviation *vs.* mean cubed deviation; > 63 μm fraction *vs.* standard deviation for the size measures; FRIEDMAN, 1961, 1967, 1979) were obtained to delineate the imprints of the environment of deposition. To further understand the processes of the deposition of the sediments, a plot between first percentile (M) and median of

Table 3. *Deep water wave approaches for different months along the central east coast of India (refer methodology for date source).*

	Direction of Wave Approach (degree; values are in percent)											
Month	0	30	60	90	120	150	180	210	240	270	300	330
Jan.		13.79	37.93	31.03	3.44	10.34	3.44					3.44
Feb.	3.70	14.80	24.13	13.79	10.34	10.34	10.34		6.89			
Mar.		8.82	11.76	11.76	2.94	8.82	11.76	14.7	11.76	8.82	5.88	2.94
Apr.	3.44	6.89		3.44	13.79	3.44	13.79	24.13	10.34	6.89	6.89	3.44
May	2.38	4.76	2.38		4.76	9.52	21.42	28.57	16.66	7.14	2.38	
June	3.44					3.44	17.24	17.24	31.03	20.68		6.89
July	2.77			2.77	2.77		16.66	13.88	33.33	22.22	5.54	2.77
Aug.						2.5	17.50	22.50	30.00	20.00	5.00	2.50
Sep.			4.34	4.34		4.34	17.39	34.78	21.73	8.69		4.34
Oct.		5.26	10.52	5.26	10.52	10.52	21.05	13.15	13.15	7.89		2.63
Nov.	10.00	20.00	30.00	16.66	6.60	20.00						
Dec.	5.88	11.76	41.17	29.41			5.88			5.88		

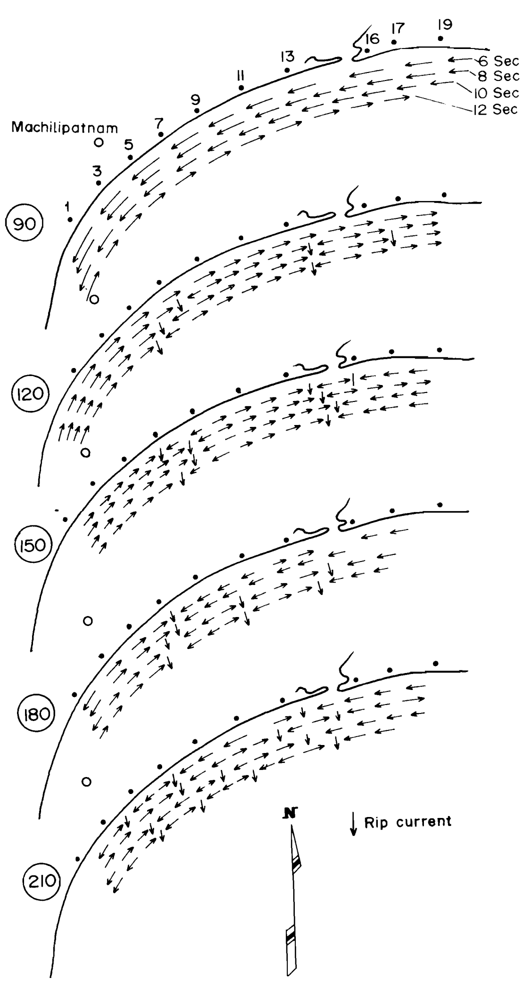

Figure 2. Patterns of the littoral currents for wave approaches 90–210° and wave periods 6–12 sec (refer methodology for details).

the size distribution (M) was also obtained (CM diagram, PASSEGA, 1957, 1964).

RESULTS

The variations in the wave parameters during the NE, SW and non-monsoon periods are presented in Tables 1–3. From these data, it is deduced that the waves during December through February are mild and have low periodicity (H_∞ < 1.5 m T_∞ < 8 sec). The most prevalent wave directions during this period are from the NE (30–90°). The wave environment begins to modify in April. The waves are mild to moderate, and there is a large variation in their heights and periods (Tables 1–3). The direction of wave approaches, though highly variable during this season, shifts from <90° to 180–300°. From June to September, the area is under the influence of the SW monsoon and a high wave environment prevails in the region (H_∞ > 2 m, T_∞ > 8 sec). During this period, the general direction of wave approach is from SW (180–270°, 210–240° for >60% time). Between October and November, the waves reduce in intensity, but there are frequent sporadic enhancements in wave height and period (H_∞ > 2 m for 40%, T_∞ > 8 sec for 30% time; Tables 1–3). The area also experiences cyclonic storms/depressions during this period, and also in May. The frequency of their occurrence is the highest in November (probability of occurrence of cyclone/depression, (p) is 1.0 and 0.72 in November and May respectively).

From the wave refraction simulation studies (Figures 1–2), it is inferred that when the wave approaches <90° the currents are from the NE; whereas, the wave approaches from 120–210° will give rise to the flows from the SW. Based upon the variations in the wave parameters in the SW, the NE and non-monsoon periods (Tables 1–3), it is deduced that the littoral currents during the SW monsoon are from the SW, variable during the NE monsoon, and from the NE in February.

These results match with the patterns of littoral currents measured through dye and float release (Figure 3), and validate the results of the refraction studies. Mild to moderate currents (0–40 cm sec^{-1}) from the NE prevail in February; whereas, the moderate/strong (20–70 cm sec^{-1}) currents from the SW were observed in September (SW monsoon). In April and November, the magnitude of the currents was mild to moderate, and they had variable directions (Figure 3).

The beach responds to the changes in hydraulic conditions (Figure 4). There are temporal and spatial variations in the beach slope and beach width under different environmental conditions. Table 4 suggests that low gradient long beach profiles (slope 2.3–3.6°) with swell berm (length about 15 m) modify to the steeper (gradient 4.5–6.5°), shorter profiles with troughs and bars and no berm, during the SW monsoon. However, the changes in the prevalent wave conditions in March do not affect the beach profiles. With the cessation of the SW monsoon, characteristics of the beach modify. Despite the prevalent moderate–high wave climate, beach profiles of November (NE monsoon) were gentler than the profiles of the SW monsoon (3.5–4.8°). The beach was wider, and had accretion over the profiles of the SW monsoon (Figure 4).

During the SW monsoon 48–53 m^3 m^{-1} sediments were eroded from the beach; whereas, during the NE monsoon (which has short term sporadic enhancement in wave parameters and cyclones/depressions), no erosion of the sediments was observed (Table 5). The beach on the contrary had an accretion of about 25–30 sediments m^3 m^{-1} over the profiles of the SW monsoon. The magnitude of deposition was also high between November–February (about 91 m^3 m^{-1}; Table 5). Also, the spatial variations in the amount of sediments eroded between the NE and the SW monsoons and *vice versa* were significant. The northern end (Profiles 1–2) had higher deposition compared to the southern portion of the study area (Profiles 3–5), during storm-swell transformation, between September and February (magnitude 113.50–98.58 m^3 m^{-1} in the north; 71–90 m^3 m^{-1} in the south; Table 5).

The longshore sediment transport during the NE and the SW monsoons and for transitional periods, together with the annual gross and net drifts, at 19 stations (Figure 1), are presented in Table 6. The drift during the SW monsoon (June–September) is high due to prevalent high wave environment (gross average drift 58.16 × 10^4 m^3; net 43.36 × 10^4 m^3, direction from the SW). The gross drift during the NE monsoon (October–November) is much reduced (gross drift 14.2 × 10^4 m^3, net drift from the NE 7.1 × 10^4 m^3). The non-monsoon periods have a drift mostly from the NE (gross drift 16.97 and 9.62 × 10^4 m^3, and net drift from the NE 16.59 and 7.4 × 10^4 m^3 for December–February and March–May, respectively). The annual net drift for the area is from the SW (14.20 × 10^4 m^3; drift from the NE and SW are 42.36 × 10^4 m^3, and 56.6 × 10^4 m^3 respectively). The gross annual drift in the area is about 99 × 10^4 m^3 (Table 6). Annual drift rates are in agreement with that of CHANDRAMOHAN *et al.* (1988) and CHANDRAMOHAN and NAYAK (1991). The monthly variations in the magnitude of the average longshore drift during the SW and the NE monsoons, and in the non-monsoon period were also compared. It is observed that the values of gross monthly drift during the SW and the NE monsoons and non-monsoon period are 14.54, 7.1 and 4.43 × 10^4 m^3 respectively.

The size measures of the sediments of the NE and the SW monsoons were also different. During the NE monsoon, the sediments had finer mean grain size ($\bar{X}$ 2.5–4.0 phi), were moderately sorted (σ 0.53–0.90), positively skewed ($\alpha 3$ +0.09–+0.52), and leptokurtic (KG 1.38–1.89; Figures 5 and 6). The sediments during the SW monsoon were coarser ($\bar{X}$ 1.8–3.05 phi), well to moderately well sorted (σ 0.38–0.73), less positively skewed ($\alpha 3$ −0.16–+0.38) and mesokurtic to leptokurtic (KG 1.13–1.79).

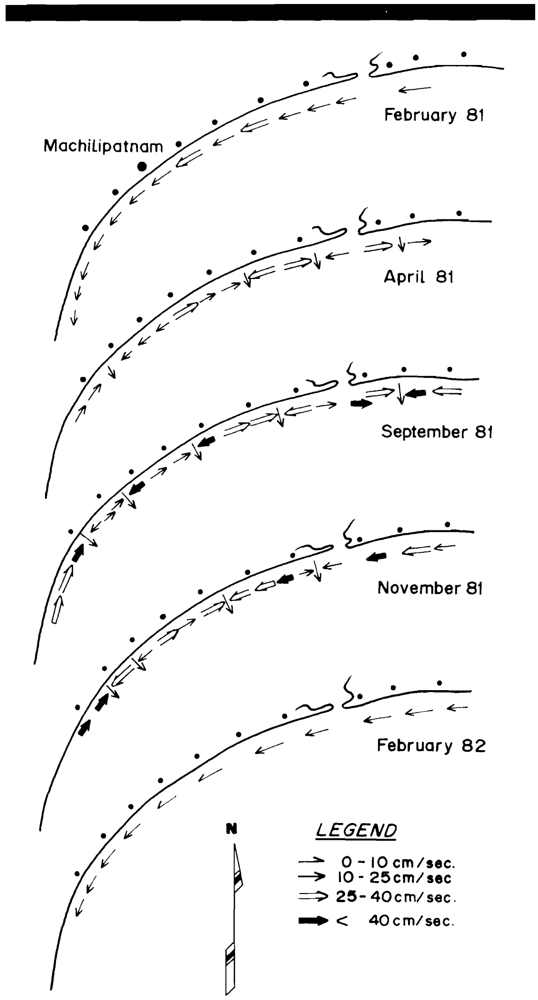

Figure 3. Observed current patterns during February of 1981, 1982, and April, September, and November of 1981.

DISCUSSION

The contrast in the rate of sediments exchanged along the study area, during different seasons, is significant. Deposition is observed on the profiles

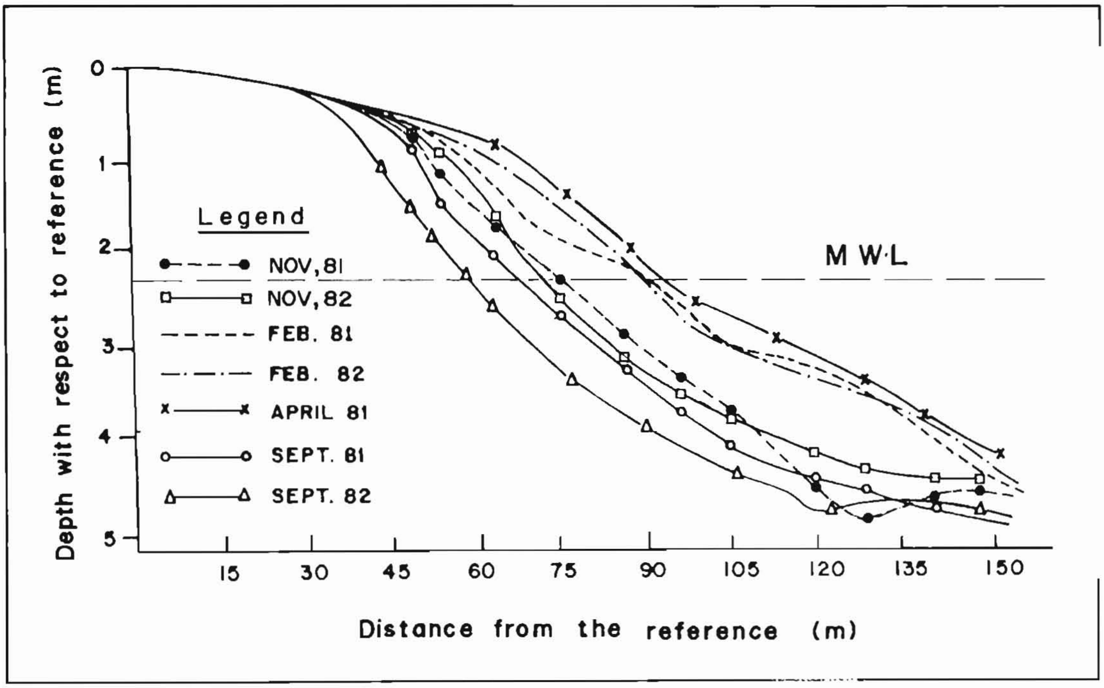

Figure 4. Variations in beach profiles at Station 1 during February 1981 and November 1982. Note accretion on November profiles (NE monsoon) compared to September profiles (SW monsoon).

of the NE monsoon, despite the prevalent high waves ($H_\infty > 2$ m for 40% time; $T_\infty > 10$ sec for 30% time), and strong littoral currents (~40 cm/sec). These observations imply that the depositional processes are dominant over the erosional component during the NE monsoon. Deposition in a high energy environment is interesting. To better understand this deposition, particularly the sediment dynamics during the NE monsoon, we evaluated the wave energy flux, longshore drifts, sediment input, the littoral current patterns and the sedimentological parameters of the beach sediments of the area.

The area undertaken for this study lies between the Rivers Godavari and Krishna (Figure 1), two major rivers of peninsular India having high annual discharge (122 10^9 m^3) loaded with suspended matter (Total Suspended Matter (TSM) 1,845 and 1,158 for Godavari and Krishna respectively; SUBRAMANIAN, 1987). A high fluvial sediment input in the vicinity of the study area (1.56 10^6 m^3 yr^{-1} at Vijayawada anicut) is reported

Table 4. *Beach profile parameters at different stations along the central east coast of India. For the location of the beach profile stations, refer to Figure 1.*

	Profile Length (m)			Beach Slope (degree)		
Profile No.	NE Monsoon/ November	SW Monsoon/ September	February	NE Monsoon/ November	SW Monsoon/ September	February
1	125–135	120–130	150–155	3.01–3.6	6–6.5	3.01–3.6
2	130–140	136	150–160	3.21–3.3	4–4.5	2.21–2.3
3	115–120	110–115	145–150	3.07–3.7	4.6–5.9	2.07–3.07
4	125–130	145–150	155–165	3.3–4.1	4.3–4.9	2.3–3.1
5	105–115	110–120	140–145	4.3–4.7	4.09–4.62	2.3–3.2

Table 5. *Budget of sediment exchanged at different beach profile stations along the central east coast, between February 1981 and November 1982.*

Period	Average Length of Beach Profile	Profile Numbers (values are in $m^3\ m^{-1}$) 1	2	3	4	5	Average
Feb. 81–Apr. 81*	150	+14.117	+11.72	+19.05	+17.21	+13.64	+15.15
Apr. 81–Sep. 81	110	−53.24	−56.78	−40.52	−42.97	−49.52	−48.60
Sep. 81–Nov. 81	115	+22.32	+23.15	+27.22	+25.45	+29.18	+25.46
Nov. 81–Feb. 82	150	+113.90	+98.58	+71.47	+83.65	+90.97	+91.74
Feb. 82–Sep. 82	110	−78.82	−70.21	−52.73	−41.45	−47.50	−58.16
Sep. 82–Nov. 82	120	+7.82	+15.42	+19.72	+18.35	+22.35	+18.73
Net change between Feb. 1981–Nov. 1982		+154.04	+137.15	+118.41	+127.45	+142.50	+135.93
Net change between Feb. 1981–Nov. 1982		−132.6	−126.99	−93.24	−84.42	−96.92	−106.76
Budget between Feb. 1981–Nov. 1982		+21.44	+10.16	+25.17	+43.03	+45.58	+29.17

(+) indicates deposition, (−) indicates erosion, (*) values not taken for the budget

Table 6. *Variations in the longshore sediment transport rates ($10^4 m^3$) during the SW and the NE monsoons, and transitional period at 19 stations, along the study area (refer to Figure 1 for the location of the stations).*

	Seasons								Average			
	Transition period				SW Monsoon		NE Monsoon					
Sn. No.	Dec.–Feb.		March–May		June–Sept.		Oct.–Nov.		Annual		Budget	
	NE	SW	NE	SW	NE	SW	NE	SW	NE	SW	Net	Gross
1.	1.06	16.26	0.21	3.13	58.13	2.06	4.30	12.36	65.60	33.81	33.79	99.41
2.	0.23	17.36	0.53	6.61	38.16	1.35	2.93	11.28	41.85	36.60	5.25	38.45
3.	0.12	18.96	2.0	6.56	42.16	0.89	4.32	18.92	48.60	37.33	11.27	85.93
4.	0.11	17.39	0.73	7.59	44.39	13.35	4.30	9.29	49.53	47.62	1.91	97.15
5.	0.14	14.39	0.60	6.68	68.29	0.96	6.30	10.57	75.33	32.60	42.73	107.93
6.	0.12	16.39	0.73	7.32	41.16	12.68	3.63	14.36	45.64	50.75	−5.11	96.39
7.	0.06	12.36	0.82	5.92	58.93	8.06	2.63	9.36	62.44	35.70	26.74	98.14
8.	0.16	14.36	0.93	7.82	41.93	12.36	2.68	11.36	45.70	45.90	0.2	91.60
9.	0.21	18.36	2.16	9.37	66.94	11.93	4.32	9.56	73.63	49.22	24.38	112.82
10.	0.16	16.59	2.36	7.36	69.72	1.19	5.60	9.36	77.84	34.50	43.34	112.34
11.	0.07	22.26	0.63	9.62	36.29	1.39	2.61	5.96	39.60	39.23	−2.63	75.83
12.	0.12	24.12	0.26	10.62	54.12	1.96	4.36	8.69	58.86	45.39	13.47	104.16
13.	0.16	28.32	2.07	11.26	76.12	1.36	5.68	11.76	84.03	52.70	31.33	136.73
14.	0.19	11.20	1.96	8.90	51.39	2.36	4.39	10.63	57.93	33.09	24.84	91.02
15.	0.11	12.20	0.76	9.90	68.12	1.39	2.36	12.08	71.35	35.57	35.75	106.92
16.	0.06	16.76	0.16	10.90	41.26	1.96	1.86	12.69	43.34	52.31	−8.97	95.65
17.	0.16	11.26	0.78	9.16	36.39	12.46	1.63	13.69	38.96	46.57	−7.61	85.33
18.	0.19	16.96	0.36	12.96	48.60	11.36	1.76	7.86	50.91	49.14	1.76	100.40
19.	0.17	13.36	2.16	10.16	41.39	12.66	1.79	10.69	45.51	46.87	−1.36	92.38
Average	0.19	16.78	1.11	8.51	57.76	6.40	3.55	10.65	56.6	42.36	−14.20	98.96
Net	−16.59		−7.4		43.36		−7.1		14.20			
Gross	16.97		9.62		58.16		14.20		98.96			
Gross monthly drift	4.43				14.54		7.10		8.24			

SW = drift from SW, NE = drift from NE, (−) net drift from NE

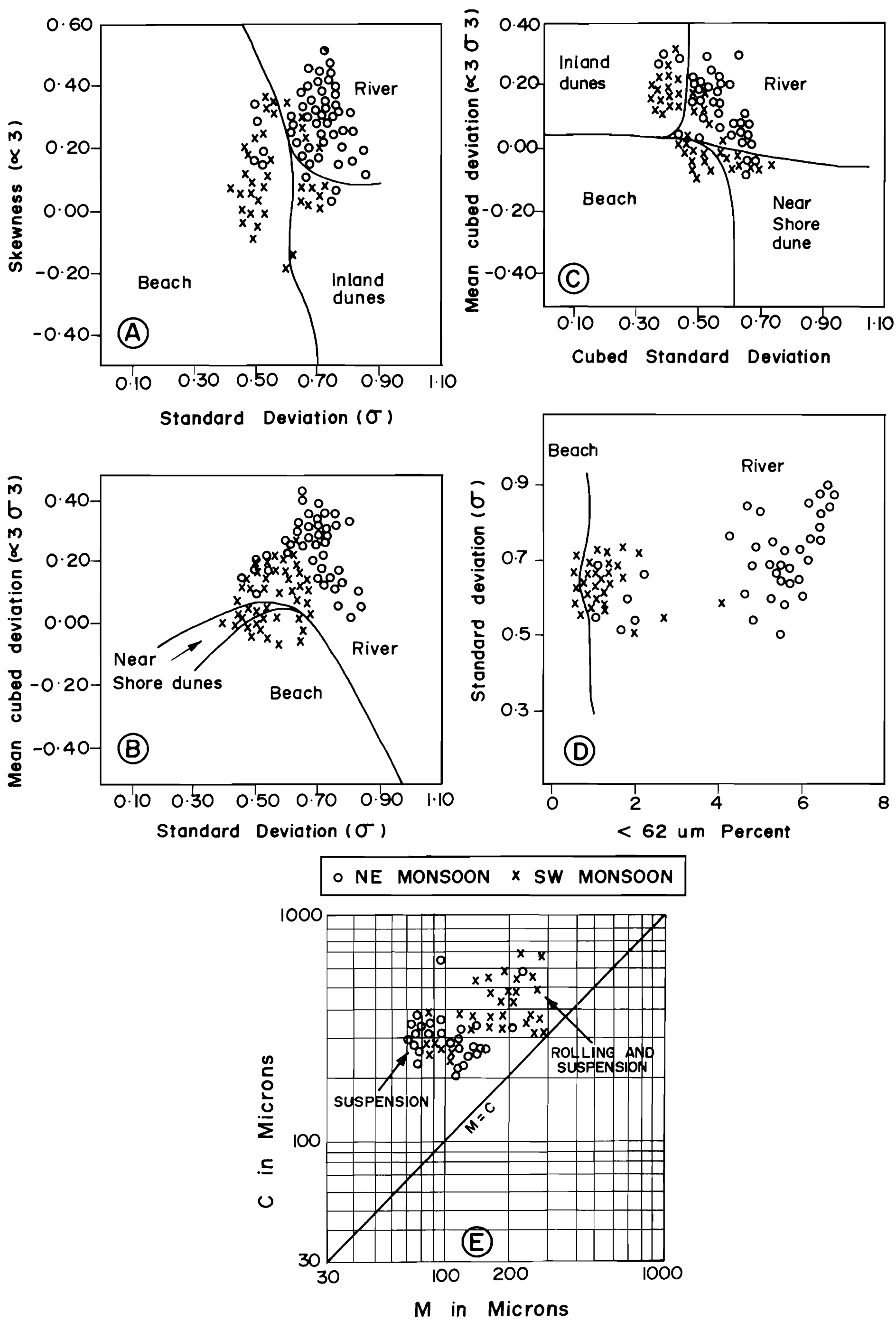

Figure 5. Binary (A–D) and CM (first percentile *vs.* median grain size) plots of the sediment of Machilipatnam Beach (E). Note that the sediments of the NE monsoon predominantly occupy the area demarcated for the "River" domain.

(KUNTE and WAGLE, 1993). In Thematic Mapper imagery of this area, the coastal waters along the entire coast are observed to be highly turbid (<20 m water depth) due to contribution of sediments by fluvial plumes (KUNTE and WAGLE, 1993). These results confirm the high input of fluvial sediments in the study area.

Amount of sediments, in turbid suspension, in the coastal waters is regulated through available wave energy flux and supply of sediments. Wave energy flux in the littoral zone (equation-2) is directly related to wave height and angle of wave approach, since other parameters like d and g are constant. To maintain a high density of suspended matter in the coastal waters, high wave energy is a prerequisite. Intermittent and frequent changes in wave height and directions, and associated reduction in wave energy flux in the littoral zone, will lead to deposition of sediments supported in the suspension during higher wave environments.

For the SW and the NE monsoons and non-monsoon periods, the average wave energy flux (Pls) is 1.35, 0.66 and 0.4 K watts/m. The high flux in the SW monsoon gives rise to high longshore drifts (58 10^4 m^3). This suggests that wave environment can support a high sediment load, including the sediments contributed by the fluvial sources. However, during the NE monsoon, intermittent changes in the wave parameters are recorded (Tables 1–3). Compared to the SW monsoon, during the NE monsoon, the wave energy flux (0.66 K watts/m) and the longshore sediment drift (gross 14.2×10^4 m^3) are also reduced. Generally, this wave power should have been utilized in suspension and transportation of beach sediments, leading to an erosion on the beach. However, in the study area, there is a high input of the fluvial sediments, and a part of the available wave energy is utilized to support these fluvial sediments in suspension. During the NE monsoon, there are frequent variations in the wave parameters (Tables 1–3) which lead to change in the magnitude and directions of the longshore drift (Table 6), and the wave energy flux. The capacity to hold sediment in the turbid plume will also decrease with any such reduction in the magnitude of available energy, and deposition of sediments from turbid waters will take place. Thus, despite the prevalent high–moderate wave environment, sediments get deposited in this area.

In CM pattern (Figure 5E), the sediments of the NE and the SW monsoons occupy "suspension" and "suspension and rolling" domains respectively. Evaluating these results in the light of wave energy flux, it may be inferred that during the SW monsoon, due to prevalent high wave environment, beach sediments are subjected to rolling and suspension, and erosion (magnitude 58.16 m^3 m^{-1}) is observed. The deposition on the beach during the NE monsoon is 25–30 m^3 m^{-1}. The fluctuations in the wave energy lead to the deposition of sediments from turbid water plumes. In CM diagram, this is reflected as "suspension" and provides the mechanism of deposition during the NE monsoon. The location of the study area and the prevalent littoral current patterns also make this area a favourable depositional site. The area is located between Rivers Krishna and Godavari (Figure 1). The longshore currents during the SW monsoon are from the SW (Figures 3–4). These currents distribute the sediments of the River Krishna to the turbid waters as seen in the Thematic Mapper image. The frequent reversal in the current directions, during the NE monsoon, does not affect this supply; change in the current direction from the SW to the NE will instead transport the sediments discharged by the River Godavari (located north of the study area, Figure 1) and the supply of the sediments will be maintained. Irrespective of current direction during the NE monsoon, the fluvial sediment input will not diminish, but any reversal or chagne in the magnitude or in the direction of longshore currents will significantly reduce their capacity to carry a high sediment load leading alongshore. This will also lead to the deposition in the area.

The binary plots, used to distinguish the environment of deposition (FRIEDMAN, 1979), also provide the evidence of fluvial input. In the present study, the sediments of the NE monsoon predominantly occupy the "River Domain", whereas the sediments of the SW monsoon, besides beach, were found to have some spread over "Inland and Near Shore" domain (Figure 5A–D). These results further corroborate the deposition of the fluvial sediments during the NE monsoon.

The mean grain size of the sediments during the NE monsoon is finer than in the SW monsoon, particularly in the mid and low tide regions (Figure 6). The sorting of the sediments of the NE monsoon is also poorer, and they are more positively skewed (Figure 6). Variations in the mean size and skewness have been utilized to understand the depositional processes. Positive skewness and reduced mean grain size reflect a de-

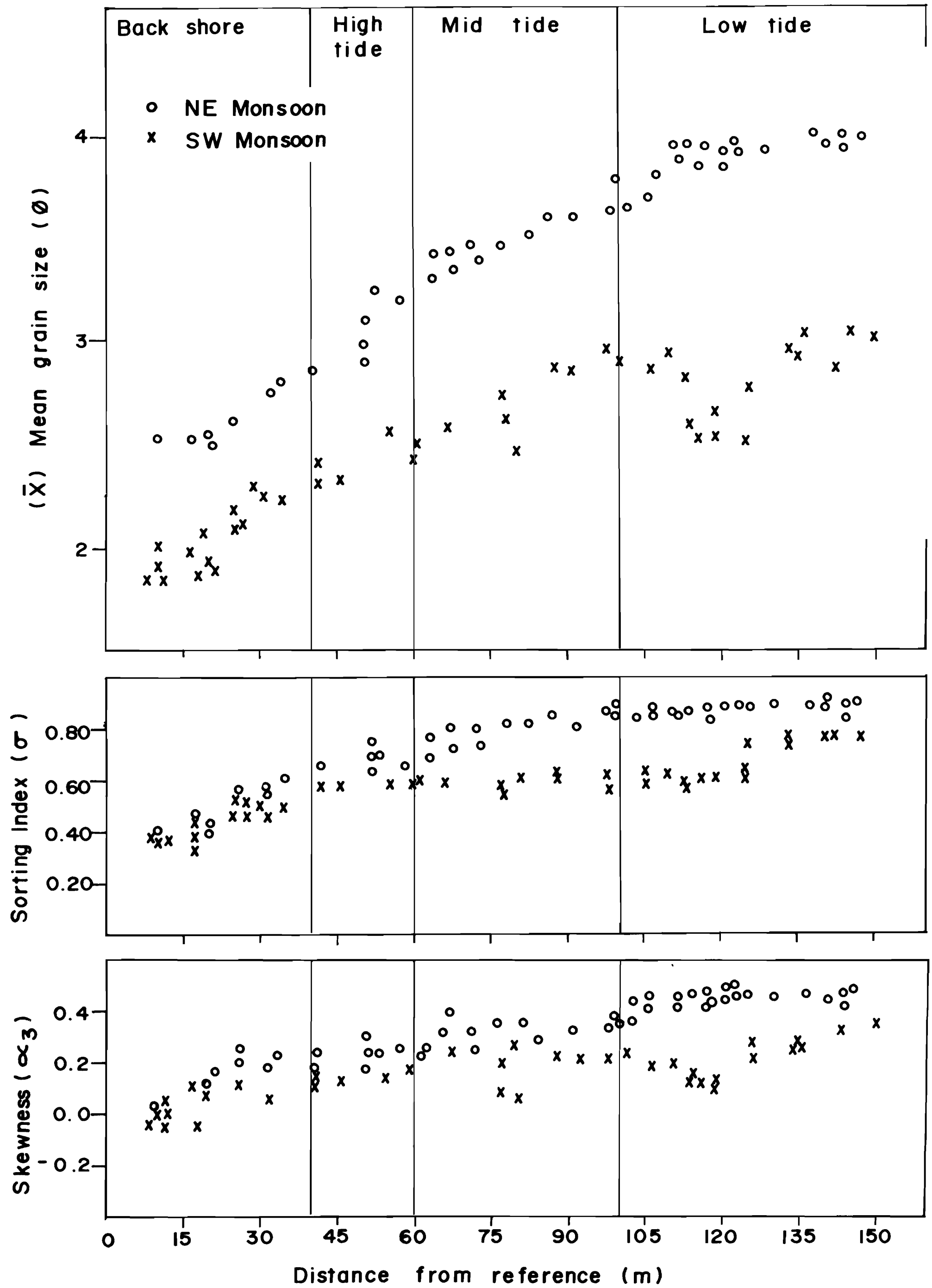

Figure 6. Variations in the mean grain size, sorting index and skewness along the beach profiles during the NE and the SW monsoons. Note reduced mean grain size and positive skewness of the sediments of the NE monsoon, particularly in the mid and low tide regions.

position on the beach (DUANE, 1964; CHAUHAN *et al.*, 1988; CHAUHAN, 1990). From the variations in the mean grain size and skewness of the sediments of the SW and the NE monsoon, it is further inferred that on the beach during the NE monsoon fine sediments accumulate and depositional environment prevails.

CONCLUSION

The results of the present work lead to the following conclusions:

(1) During the NE and the SW monsoon, the central east coast of India experiences high wave environment associated with moderate–high littoral currents. The probability of storms/depressions, during the NE monsoon, is the highest ($p = 1.0$).

(2) A high wave and current regime during the NE monsoon does not have any erosional effect on the beach, and the area has accretionary tendency. High input of the fluvial sediments and their deposition on the beach due to fluctuations in the wave energy flux, from the turbid water plumes during this monsoon, appears to be the contributing process.

ACKNOWLEDGEMENTS

The author is grateful to the Director, National Institute of Oceanography, Dona Paula, Goa for providing facilities and to Dr. R. R. Nair for encouragement and comments on the manuscript. The author also expresses his sincere gratitude to Dr. Charles W. Finkl and two anonymous referees for improving the quality of the manuscript and for their valuable suggestions.

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