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Meso-scale convergence rainfall and surface fluxes during the Indian summer monsoon

S. SIVARAMAKRISHNAN

Indian Institute of Tropical Meteorology, Pune - 411 008, India

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सार – बैलमी तकनीक का उपयोग करते हुए तीन स्टेशनों से प्राप्त किए गए राविंडसौंदे और पिबल आँकड़ों से मेसोस्केल अभिसरण और उर्ध्वाधर वेग का आकलन किया गया। इन स्टेशनों में मानसून द्रोणी के पूर्वी छोर के निकट स्थित आर्द्र संवहन वाले क्षेत्र खड़गपुर (22.3°उ., 87.2°पू.) के आस–पास मेसोस्केल त्रिकोण के चक्र बने जहाँ पर भारतीय ग्रीष्मकालीन मानसून 1990 के दौरान मानसून द्रोणी परिसीमा स्तर परीक्षण (मौंट ब्लैक्स) किए गए। इससे यह पता चलता है कि मेसो त्रिकोण पर होने वाली कुल वर्षा, मानसून के प्रारंभ होने और सक्रिय अवस्था के दौरान बंगाल की खाड़ी के शीर्ष में बनने वाले बृहत–मान दाब प्रणाली, तत्पश्चात् पश्चिमी/उत्तर पश्चिमी दिशा की ओर बढ़ने वाली इस प्रणाली की सन्निकटता और सघनता पर निर्भर करती है। जब व्यापक प्रवाह से मध्य क्षोभमंडल तक बढ़ते हुए चक्रीय परिसंचरण का पता चला तो उस समय त्रिकोण पर होने वाली वर्षा मेसोस्केल अपसरण से प्रभावित होती प्रतीत नहीं होती है। तथापि खड़गपुर (के.जी.पी.) के निकट एक वायु सेना स्टेशन क्लाईकोंडा (के.के.ए.) में हुई वर्षा का सहसंबंध मेसोस्केल अपसरण/अभिसरण के साथ पाया गया है। मेसोस्केल अभिसरण के दौरान के.जी.पी. में 8मी. ए.जी.एल. पर ध्वनिक पवनमापी का उपयोग करते हुए आकलित किए गए सतह ऊष्मा फलक्स अधिक मात्रा में पाए गए हैं। पवन की गति के साथ इसमें बढ़ोतरी हुई है जबकि संवेग फलक्स से इसमें अधिक मात्रा में विविधता पाई गई है।

ABSTRACT. Meso-scale convergence and vertical velocity were computed using Bellamy technique from rawindsonde and pibal data obtained from three stations. These stations formed the vertices of a meso-scale triangle around Kharagpur (22.3° N, 87.2° E) - a region of moist convection located near the eastern end of the monsoon trough, where the monsoon trough boundary layer experiment (MONTBLEX), was conducted during the Indian summer monsoon 1990. We find that the total rainfall over the meso-triangle depends on the proximity and intensity of the large-scale pressure system forming in the head Bay and moving W/NW towards the land during the onset and active phase of the monsoon. When the large-scale flow showed cyclic circulation extending to mid-troposphere, the rainfall over the triangle does not seem to be affected by the meso-scale divergence. However the rainfall at Kalaikonda (KKA) -an airforce station near Kharagpur (KGP) correlates with meso-scale divergence/convergence. Surface heat flux estimated using sonic anemometer at 8m AGL at KGP was large during meso-scale convergence. It increased with wind speed while the momentum flux showed large variation.

Key words – Monsoon, Meso-scale, Boundary layer, Rainfall, Flux, Convergence.

1. Introduction

The onset of monsoon over peninsular India is heralded by increased cloudiness over south Arabian Sea and south Bay of Bengal and increased low level cross equatorial flow from south Indian Ocean (Ananthakrishnan *et al*., 1968, Rao, 1976, Kutzbach, 1987). It is also associated with the frequent formation of a tropical vortex in the Bay of Bengal or Arabian Sea. Another typical feature is the large-scale east-west oriented cloud band over south Arabian Sea (Keshavamurty and Sankar Rao, 1992).

Dense multi-layer convective clouds characterize the active monsoon conditions over the central part of the country, the eastern Arabian Sea and the Bay of Bengal. It is also marked by a strong low-level (W/SW) flow over the Arabian Sea, often with a low level jet of 25-30 m s^{-1}. Large-scale convective activity occurs during the monsoon season along the axis of the monsoon trough and to its south.

Earliest study on divergence and vertical velocity of monsoon circulation focused attention on synoptic scales. Bellamy (1949) developed the technique of computing divergence within a triangle and computed the vertical velocity by integrating the divergence values with respect to height. The technique is applied in this paper to compute the divergence and vertical velocities in the boundary layer. A network of meso-scale triangle was constructed around KGP and the divergence and vertical velocities were computed over the triangle for the case of onset and active phase of the summer monsoon. Rainfall over the triangle, at KKA and the surface fluxes at 8m AGL at KGP have been studied in relation to meso-scale convergence and the movement of large-scale pressure system originating in the head Bay and

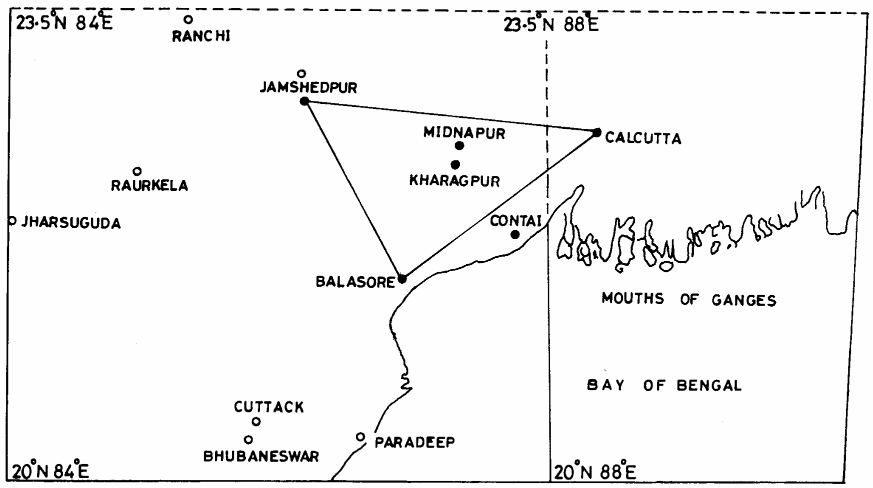


Fig. 1. Map showing stations forming the Bellamy triangle and micrometeorological tower site at Kharagpur

moving N/NW during the onset (June) and active (August) phase of Indian summer monsoon.

2. Meteorological conditions during the onset and active phase of MONTBLEX

Normally 6-10 cyclonic disturbance occur during the summer monsoon (Rao, 1976). In the year 1990, there was one depression in June and September, none in July, and two in August (Gupta, 1990, Srivastav, 1995). Active monsoon condition prevailed on a number of days in July. The movement of trough-ridge-trough pattern marked the beginning of August in the upper westerly north of the country that disturbed the monsoon circulation. The monsoon trough was not discernible for a number of days. The cloud belt shifted to the south and a weak monsoon prevailed mostly over the country. However the monsoon revived with the formation of a depression during August 13 to 15 in west, central and northwest Bay of Bengal. During the later half of August till early September, two monsoon depressions and a well marked low formed over the North Bay. They gave rise to synoptic situations corresponding to active monsoon over the Kharagpur region (Paul *et al.*, 1995). So the period June 13-17 of the onset phase and 18-20 and 27-31 August of the active phase were selected to study meso-scale divergence, vertical velocities and the associated boundary layer fluxes.

A well-marked low-pressure area lay over the northwest Bay (21° N, 89° E) with associated cyclic circulation extending up to mid troposphere levels at 0830 hr IST on June 13. The low pressure system concentrated into a deep depression, intensified, moved northwestwards and crossed the West Bengal coast on June 14 afternoon. It weakened into a depression over Gangetic West Bengal and adjoining Orissa on 15 and into a low-pressure system over the central part of east Madhya Pradesh on 16th. It became less marked over this area on 17 June. We note that during onset phase of the monsoon, the large-scale system as a low/depression was close to the boundary layer measurement site at Kharagpur on 13 and 14 June. The movement of the center of the system was very close and to the south of the experimental site. On 15 June, the depression center was located more than 2° SW of the site. The center of low on June 16 was far SW of Kharagpur and it moved far NW on 17th. Dense cloud cover existed over the entire North Bay and adjoining areas during this onset phase. The monsoon trough was apparently established during this period. Surface observations at Kharagpur showed good cloud cover (5-8 octas) over the site during 13-17 June respectively.

The period 18-20, 28, 30-31 and 18-20 and 31 August was marked with monsoon depressions and low-pressure systems. The axis of the monsoon trough lay to the south of Kharagpur. A low to the SE of Kharagpur on 19 August developed into a deep depression and crossed the coast down south of Kharagpur on 21.

On 18 August, cloudy region extended from north Arabian Sea to northwest Bay. It was more marked on 19

August, from Gujarat and adjoining NE Arabian Sea to west central Bay and Andaman Sea. On 20 August organized clouds over northwest Bay was extending in the south to the central Bay. At the experimental site at Kharagpur, amount of cloud cover varied from 2-6 octas during 18-20 and 31 August.

Another low pressure system developed over the northwest Bay and the neighbourhood on 27 August, lay as a well marked low over northwest and adjoining parts of west central Bay, south of Kharagpur on 28 and about 300 km southwest of Kharagpur on 29th. It crossed the coast, lay over coastal Orissa and continued its west-northwestward movement. On 31st morning, the well-marked low-pressure area was far SW of Kharagpur. It weakened later.

3. Experimental details

3.1. *Meso-scale network*

During MONTBLEX, the India Meteorological Department (IMD) took upper air observations. In addition to these routine observations, special pilot balloon observations were taken at certain designated stations around the regions of the monsoon trough. To study the meso-scale features in and around Kharagpur, we selected Jamshedpur (22.8° N, 86.2° E), Calcutta (22.4° N, 88.3° E) and Balasore (21.6° N, 87.1° E) to form the vertices of the triangle so that Kharagpur is approximately at the center of the triangle, Fig. 1. At Calcutta we have routine RS/RW data at 0530 and 1730 IST. In addition, special observations were taken at Calcutta using low-level sonde at 1130 hr IST on specified dates. Corresponding to these observations we have pilot balloon observations at Jamshedpur and Balasore. Aerial distance of these three stations from Kharagpur is Balasore : 80 km S, Jamshedpur: 130 km NW and Calcutta: 110 km NE. The area of the triangle formed by these stations is 15862 km^2 .

3.2. *Micrometeorological observation*

A 30 m tower was erected and fitted with micrometeorological instruments, at the Indian Institute of Technology (I.I.T) campus at KGP, by the Indian Institute of Science, Bangalore. KGP is located near the eastern end of the axis of the monsoon trough where the large-scale convection is fully moist. The topography of the site was a gently rolling agriculture field. There was no cultivation on the East, South and West of the tower. At North about 100 m away a small area was cultivated. Generally, winds at the site are southerly during monsoon. A good fetch (aspect ratio > 30) was available for measurements when winds were SE-S-SW.

Field was covered with jungle type grass (30-60 cm high) during the experiment. Scattered trees and buildings could be sighted at far west and North of tower.

Instrumentation on the tower consisted of cup anemometer, wind vane, Gill propeller anemometer, hot wire anemometer, sonic anemometer (orthogonal array: Applied Tech. Inc., USA) at 8 m AGL, thermistor and Pt wire sensors, Lyman α humidity sensor and humicap sensor, fitted at various levels (1,2,4,8,15 and 30 m), nearly logarithmically spaced. Complete details of the instrumentation and data acquisition procedure are contained in the report Prabhu *et al*. (1990) and Rudrakumar *et al*. (1991a, 1991b, 1997). Sonic anemometer data at 8 m AGL, sampled at 8.42 Hz for 10-15 min, has been utilized in the present study to compute the flux of sensible heat and momentum by eddy correlation technique. Lyman α sensor did not function well and hence the water vapour flux could not be computed.

4. Theory

4.1. *Horizontal velocity divergence*

Bellamy technique assumes a linear wind variation across the meso-scale triangle. Using the RW and PB wind velocity data available from surface (6 m) up to 1000-1500 m above ground level, partial divergences were computed using this technique at each 300 m incremental height of observations (Vachalak, 1987) at each station. The divergence at station A forming one of the vertices of the triangle ABC is written as :

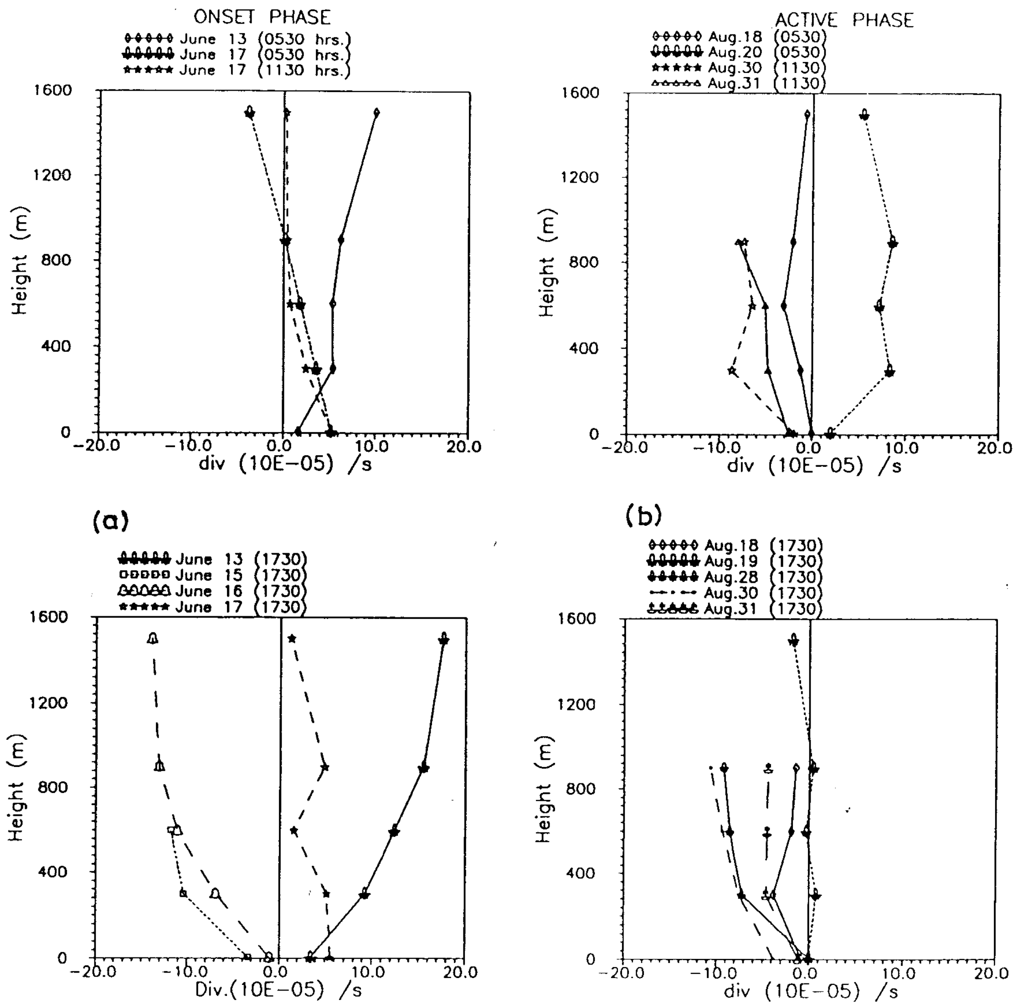
$$\Delta_A = n_A/h_A \tag{1}$$

Where n_A is the normal component of wind at the vertex A, and h_A is the length of the altitude through the vertex A to its opposite side. The total divergence is then written as :

$$\text{Div} = \Delta_A + \Delta_B + \Delta_C \tag{2}$$

$$= \frac{n_A}{h_A} + \frac{n_B}{h_B} + \frac{n_C}{h_C} \tag{3}$$

A computer program was developed to estimate the partial divergence at height increment of 300 m. The total divergence was determined using equation (3) and was attributed to the center (which is close to KGP) of the triangle.



Figs. 2(a&b). Profile of meso-scale horizontal velocity divergence over Kharagpur during the (a) onset and (b) active phase of monsoon

4.2. *Vertical velocity*

The vertical velocity ω at any level is calculated using the relation

$$[\omega]_{i-1}^{i} = -\int_{P_{i-1}}^{p_i} \left(\nabla . V_j\right)_{i-1}^{i} \mathrm{d}p \tag{4}$$

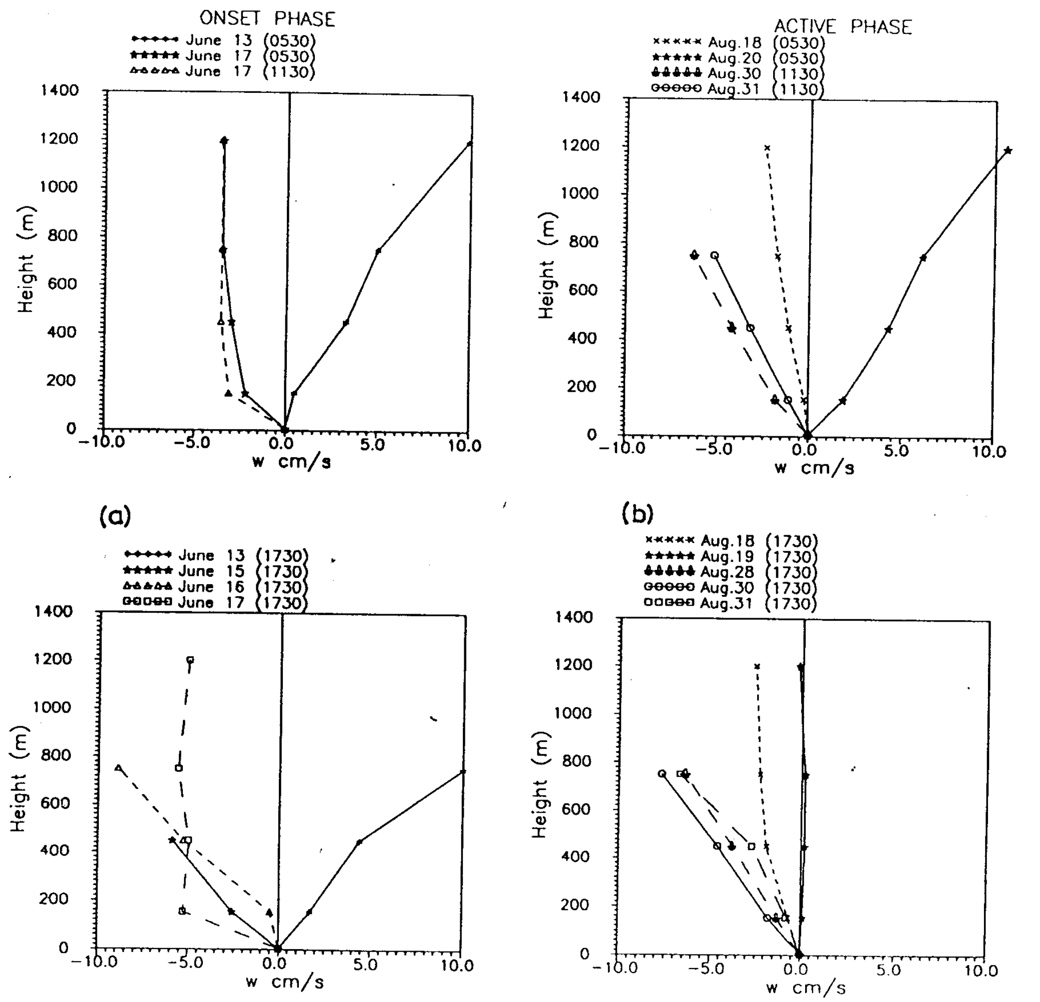
where the subscript j varies from pressure level p_i to a level p_{i-1}, V is the horizontal velocity. Equation (4) can also be expressed in discrete form as :

$$\omega_i = \omega_{i-1} - \frac{\left[(\nabla . V)_i + (\nabla . V)_{i-1}\right]}{2}\left[\Delta p\right]_{p_{i-1}}^{p_i} \tag{5}$$

Near the surface, we assume a bottom level (6m) boundary condition of ω = 0. Equation (5) has been used to compute the vertical velocity at the i^{th} level and is ascribed to the average height Z_j between the two levels (i) and (i-1).

$$Z_i = \frac{Z_i + Z_{i-1}}{2} \tag{6}$$

When we compute divergence and vertical velocity in the region enclosed or bounded by the Bellamy triangle, it is necessary to consider whether the divergence and associated vertical motions are perpendicular to the earth's surface over the region. We treat that for all practical purposes that the terrain of this region is relatively flat and therefore the computed divergence and vertical motion reflect the true values perpendicular to the surface of the earth over this region.



Figs. 3(a&b). Same as Fig. 2 but for meso-scale vertical velocity

4.3. *Surface fluxes*

Fluxes of sensible heat and momentum were estimated from the turbulent fluctuations of wind and temperature by eddy correlation technique. The fluxes of sensible heat H_s and momentum τ were determined from the relations

$$H_s = \rho \, C_p \, \overline{w' \theta'} \quad (7)$$

$$\tau = -\rho \, \overline{u' w'} \quad (8)$$

Where ρ is the density of air, C_p the specific heat under constant pressure, and u', w' and θ' are the fluctuations in longitudinal and vertical wind components, and virtual temperature respectively.

TABLE 1

Period and number of divergence cases at meso and micro-scales

	Meso-scale		Micro-scale	
Description	Onset phase June 1990	Active phase August 1990	Onset phase June 1990	Active phase August 1990
No. of days	4	6	4	4
Total cases	7	9	11	14
Divergence	5	2	6	6
Convergence	2	7	5	8

Applying standard error test and the student-*t* test, significance of estimated covariance in terms of probability level was determined. A tolerance limit of 10% in standard error was adopted. An eddy correlation program was

TABLE 2

Sensitivity of vertical velocity to change in wind direction

Height above surface (m)	18 August 1990 (Con) 0530 hrs IST					20 August 1990 (Div) 0530 hrs IST					31 August 1990 (Con) 1130 hrs IST				
	ω	ω_{r+}	Err r+ (%)	ω_{r-}	Err r– (%)	ω	ω_{r+}	Err r+ (%)	ω_{r-}	Err r– (%)	ω	ω_{r+}	Err r+ (%)	ω_{r-}	Err r– (%)
150	–24	–37	–54	–11	56	186	173	7	196	–5	75	–113	–51	–107	–43
450	–109	–133	–22	–83	24	427	386	10	462	–8	320	–329	–3	–305	5
750	–174	–203	–17	–142	18	608	540	11	669	–10	509	–533	–5	–493	3
1200	–245	–286	–17	–200	22	1060	913	14	1200	–13	793	–952	–20	–881	–11
1800	–334	–393	–18	–269	19	1290	1070	17	1490	–16					

ω = Vertical velocity (hPa/day); ω_{r+} and ω_{r-} are the Vertical Velocities after rotating the RW wind direction by +10° and –10° respectively. Err = Error

developed to estimate the fluxes using equation (7) and (8). The program incorporates a subroutine to perform coordinate rotation on wind measurements so as to align the wind components, measured by the orthogonal array sensors of the sonic anemometer, parallel to the coordinate axes of wind.

5. Results

5.1. *Convergence/divergence and vertical velocity*

Table 1 shows the number of divergence/ convergence cases identified using this technique during the onset and active phases of monsoon. Fig. 2 shows a plot of divergence/convergence profile during the onset and active phase. It is seen that the level at 1500 m depicts convergence on 17^{th} at 0530 hr IST though the flow is divergent from surface to about 1000 m. On 15 and 16 June 1990, the flow depicts convergence. The flow at 1730 hr IST on 19 August is a transition between divergences at lower levels to convergence at 1500 m level. It was divergent on 20 August and convergent on other days, *viz*. 18, 28, 30 and 31 August. There was a well-marked divergence, which increased with height at 0530 and 1730 hr IST on 13 June during the onset phase and at 0530 hr IST on 20 August during the active phase. There was no data at 1730 hr IST on 20 August, so the divergence/convergence could not be computed. We find that the large-scale low/depression lay over the NW Bay to the south of the meso-scale triangle at this time.

Vertical velocity profiles computed over this region are shown in Fig. 3 for the case of onset and active phase of the monsoon. We observe subsidence on 13 June and 20 August (0530 IST), concurring with horizontal velocity divergence in Fig. 2. On other days the vertical velocity showing updraft agrees with convergence.

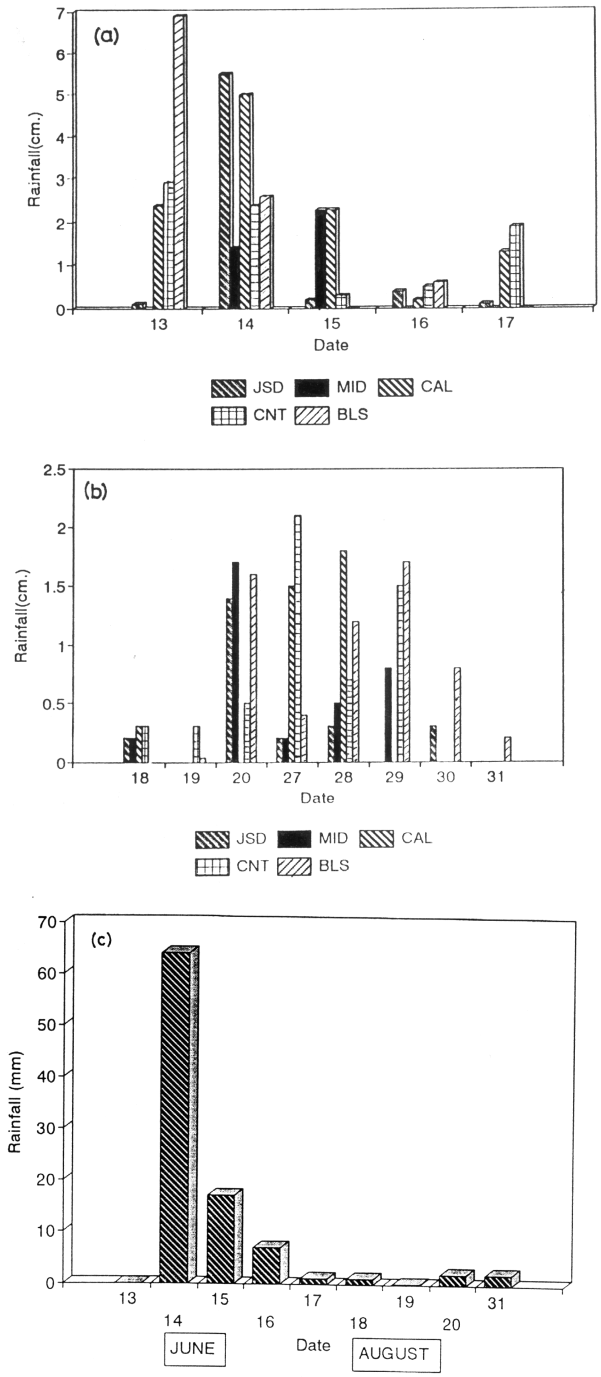
5.2. *Sensitivity experiment*

A sensitivity study was carried out on the wind data to estimate the errors arising in vertical velocity calculations due to the errors in Rawinsonde measurements. The observed wind direction at Calcutta was changed by adding +10° at all levels of observations and the vertical velocity was estimated for three cases: 18, 20 and 31 August. The results are shown in Table 2. It is seen that the error is within 20% in most of the cases for which the vertical velocity is greater than 100 hPa/day (≈1 cm s^{-1}). At the lowest level, in some cases in which the vertical velocity < 100 hPa /day, the error is considerably higher (± 50%).

5.3. *Rainfall distribution*

The rainfall distribution in and around the meso-scale network as recorded by the five surface meteorological stations of IMD considered for the period of our study is shown in Fig. 4. Of these five stations, three of them lay on the vertices of the Bellamy triangle. The remaining two stations are (*i*) Midnapur (22.9° N, 87.3° E) located on one of the sides (joining Jamshedpur-Calcutta) of the triangle, which is north of Kharagpur, and (*ii*) Contai (21.8° N, 87.8° E), a coastal station close to the other side (Balasore-Calcutta) of the triangle, which is SE of Kharagpur. In addition to these stations, Kalaikonda (KKA), an airforce station close to KGP has recorded rainfall during MONTBLEX. Fig. 4(c) shows the rainfall at KKA during the onset and active phase of monsoon.

During the onset phase when there was a low-pressure system NW of Kharagpur and also over NW Bay, divergence occurred. On 13 June, the total rainfall was 12.3 cm, the coastal stations contributing maximum. There was no rain at Kalaikonda, which agrees with



Figs. 4(a-c). Distribution of daily rainfall during the onset and active phase of monsoon over the stations around the meso-scale grid (a),(b) and at Kalaikunda (c)

divergence. On 14 when the low concentrated into a deep depression and crossed the West Bengal coast in the evening, the total rainfall increased by 4.9 cm to 16.9 cm. The rainfall was well distributed over the network in Fig. 4. Jamshedpur received 5.5 cm rainfall as Calcutta (5 cm). The PB stations reported no launch due to rain; hence convergence and vertical velocity could not be determined. KKA recorded 6.5 cm rain. However from rainfall distribution we infer that 14 June could be a day of convergence and hence an increase in rainfall compared to 13 June. During 15-17 June, the system moved inland and weakened. Meso-scale feature shows convergence at 1730 hr IST on 15, 16 and weak divergence on 17 June at 0530, 1130 and 1730 hr IST [Fig. 3 (a)]. The vertical velocity was negative on 17 and nearly constant implying convergence. The rainfall on 15,16 and 17 is shown in Fig. 4 (a) for different stations in and around the triangle.

In the case of active monsoon when a low lay over North Bay 250 km southeast of Kharagpur, and moved westwards developing into a depression, we find weak convergence (Fig. 2) on 18th. It was a very weak divergence on 19th. On 20th the low developed into a depression in the NW Bay with associated cyclic circulation extending up to mid-troposphere level. This shows large-scale convergence resulting in an increase in rainfall (5.2 cm) though the meso-scale circulation at 0530 hr IST was divergent. Thundershowers were reported at KKA on 20th.

On 27th August, the trough axis passed through the triangle and lay south of it during 28-31. Meso-scale circulation was convergent on 28-31 August. There was a good rainfall during 27-29 August due to the formation, intensification and westward movement of the low-pressure system close to the triangle. On 30-31 August the low-pressure system was moving westwards away from KGP and hence a decrease in rain though the meso-scale circulation showed convergence. We see that there was an increase in rainfall during large-scale convergence due to movement and intensification of low-pressure system from the Bay towards land, during the onset and active phases of the monsoon. When the pressure system lay over the head Bay as a well marked low/depression 200-350 km SE of Kharagpur, meso-scale flow was divergent whereas when it was located S/SW/WSW/W of Kharagpur, it was convergent. This shows that the rainfall follows large-scale circulation, the quantum of rain depends on the intensity and closeness of the system to KGP.

5.4. *Variation of wind and temperature*

Diurnal variation of mean wind component u and mean virtual temperature θ averaged over a sampling duration of about 10 min for the onset phase and 15 min for the active phase of the monsoon is shown in Figs. 5&6. It can be seen that the temperature shows a diurnal variation of about 2 to 2.5° C with its maximum mostly around 1430 hr. IST. Wind speeds were < 5 m s^{-1}.

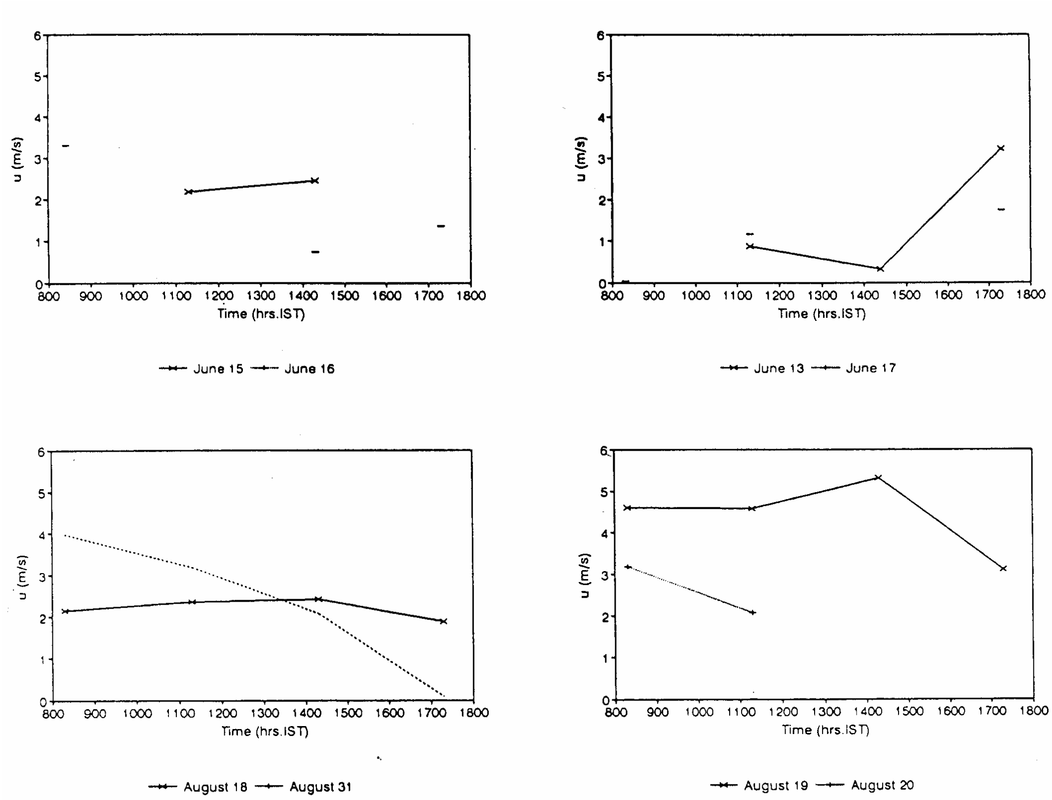


Fig. 5. Diurnal variation of windspeed at 8m AGL at Kharagpur during monsoon 1990

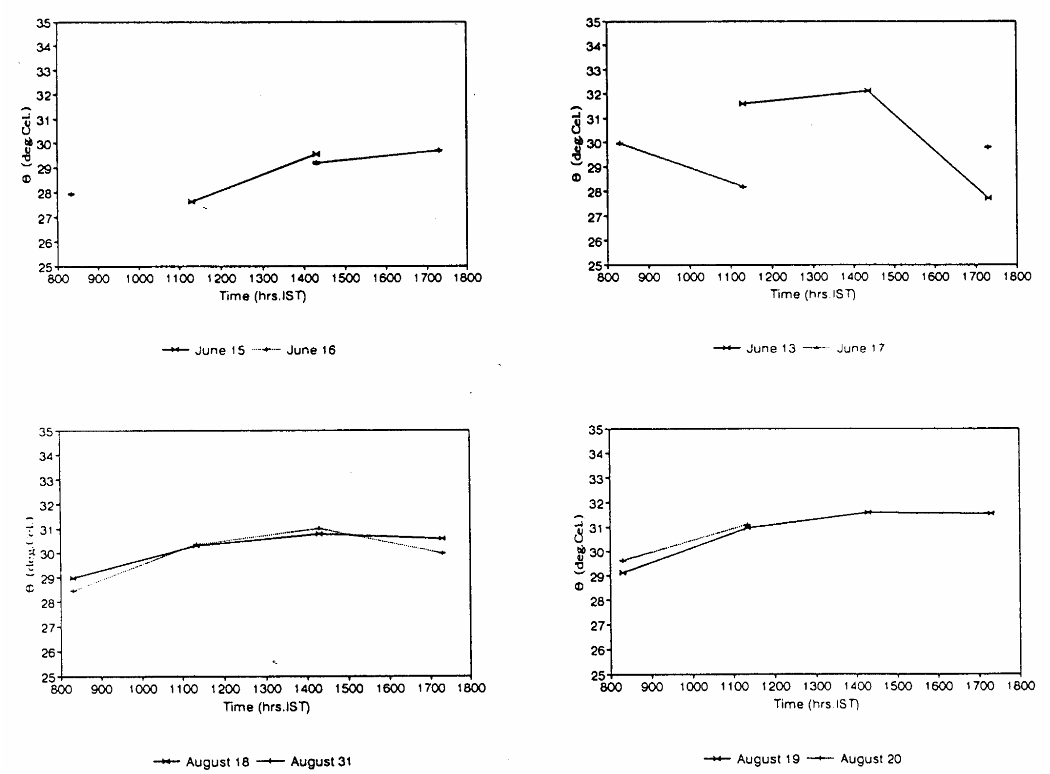


Fig. 6. Same as Fig. 5 for virtual temperature

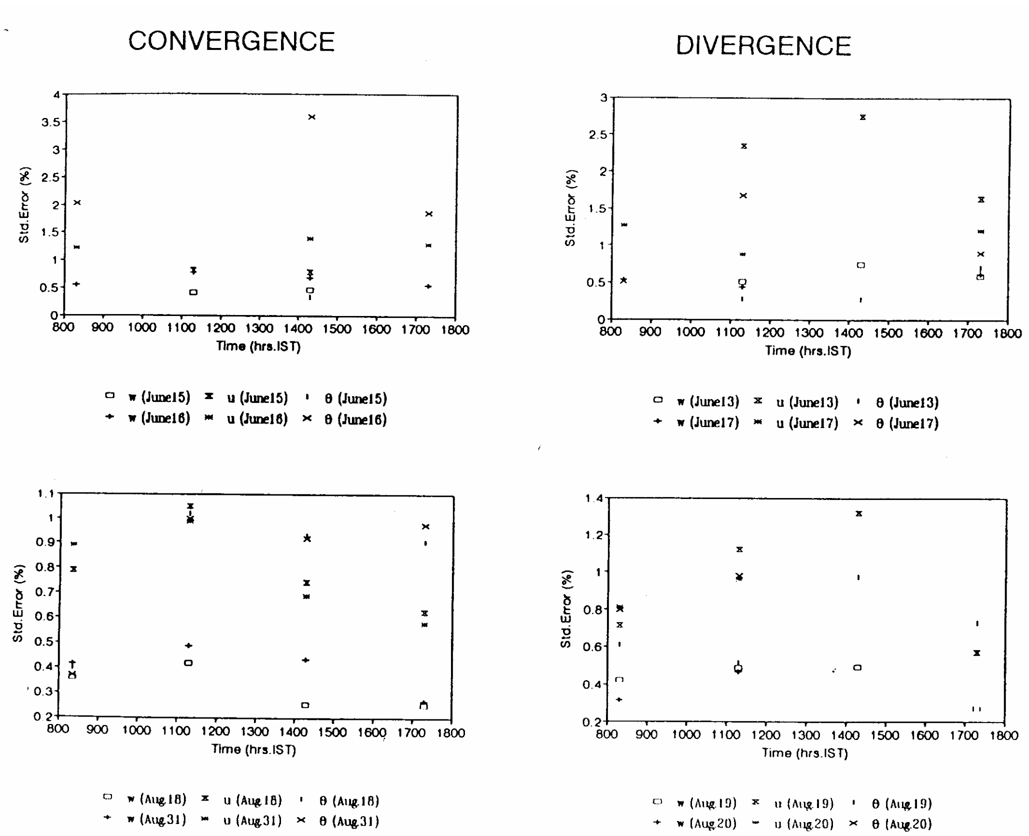


Fig. 7. Percentage standard error for wind and virtual temperature

The standard errors for u, w and θ are plotted as percentage in Fig. 7 wherein the standard error ($\sigma/\sqrt{N}$) is within 2% in August and 4% in June 1990; σ is the standard deviation and N, the number of samples.

5.5. *Variation of flux of sensible heat and momentum*

Diurnal variation of sensible heat flux is shown in Fig. 8 for the onset and active phases of the monsoon. It is seen that the diurnal variation of heat flux is well depicted. The maximum occurs at 1130 or 1430 hr IST during the onset and at 1130 hr IST during the active phase. Fig. 9 shows the relative magnitude of sensible heat flux during convergence and divergence. We note that the heat flux is larger on a convergent day than on a divergent day in most of the cases. Fig. 10 shows the variation of heat flux with wind speed during convergence (a) and divergence (b). An increasing trend in heat flux with increasing wind speed is evident in the case of convergence though there is some scatter.

Figs. 11(a&b) depicts the variation of momentum flux τ during the onset and active phases of monsoon. It is seen that the diurnal variation is not very well depicted in the case of momentum transfer to the ground. The large variability in momentum flux during the onset could possibly be due to the shorter averaging time.

Fig. 12 depicts the variation of momentum flux with wind speed for the case of meso-scale convergence (a) and divergence (b). It can be seen that for wind speeds greater than 1.5 ms $^{-1}$, there is a tendency for momentum flux to increase with increasing wind speed in both the cases. Fig. 13 shows the relative magnitude of momentum flux for these cases. A large variability is seen in the case of divergence.

5.6. *Correlation coefficient*

The correlation coefficient for heat flux ($\gamma_{w\theta}$) and momentum flux (γ_{wu}) is shown in Figs. 14 (a&b). We find a poor or negative correlation between w and θ during night hours and sometimes in the evening (around 1730 hr). This occurs when stability, as ascertained from the Monin-Obukhov length L, changes from unstable (L - ve) to stable (L +ve).

$$L = -u_*^3\ \theta / (g\kappa\ w'\theta') \quad (9)$$

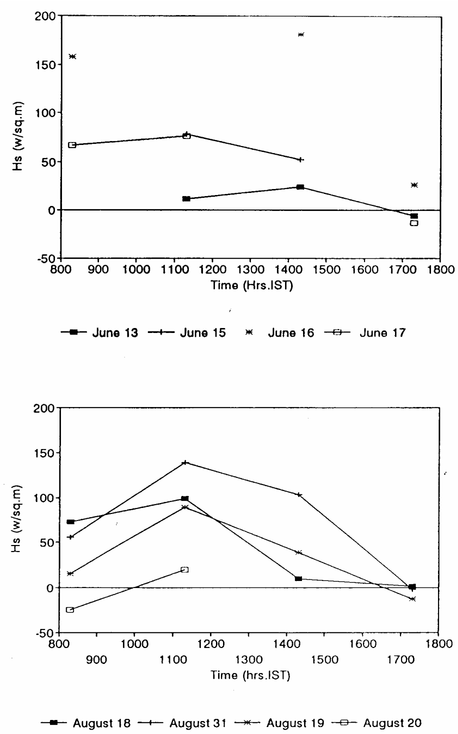
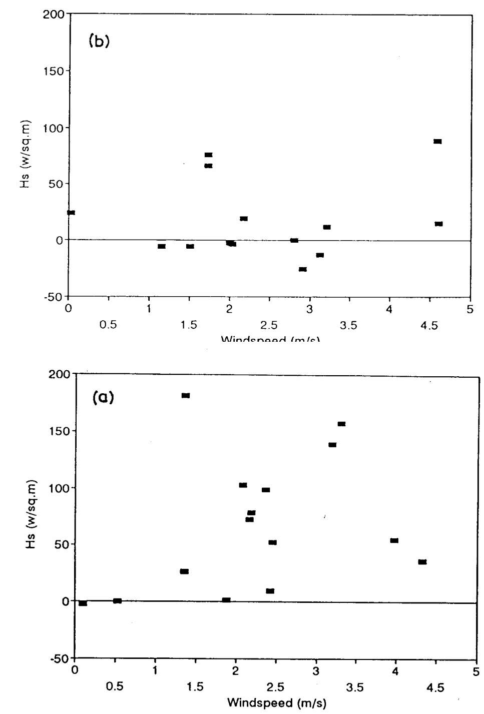


Fig. 8. Diurnal variation of heat flux at 8m AGL during the onset (top) and active (bottom) phase of monsoon



Figs. 10(a&b). Variation of heat flux with windspeed during (a) Convergence and (b) Divergence

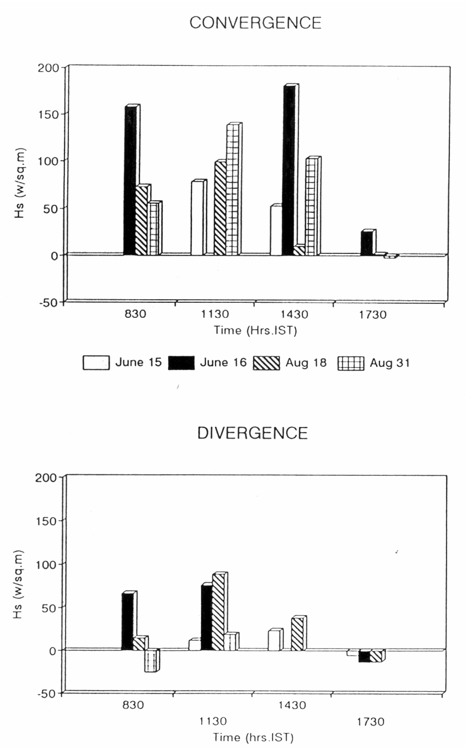


Fig. 9. Relative magnitude of heat flux during meso-scale convergence and divergence

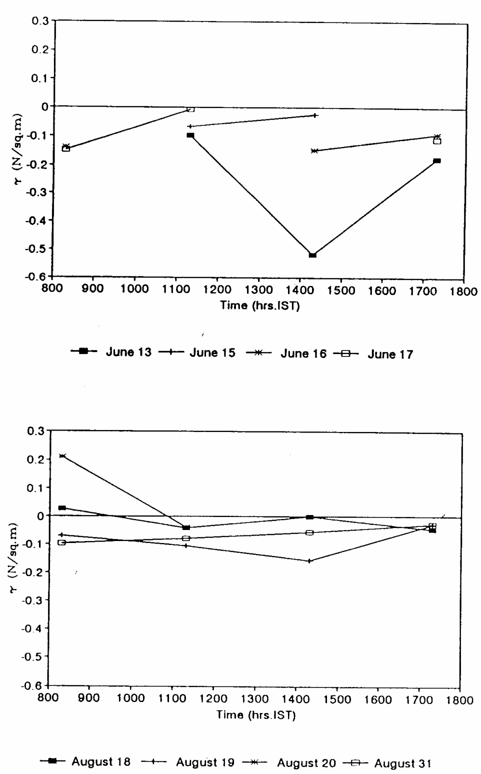


Fig. 11. Same as Fig. 8 for momentum flux

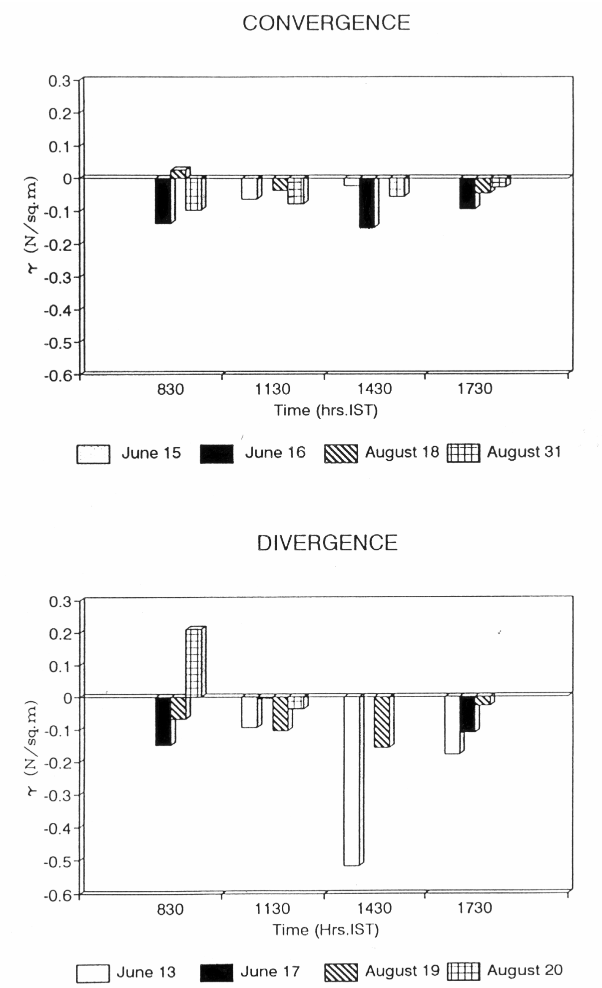
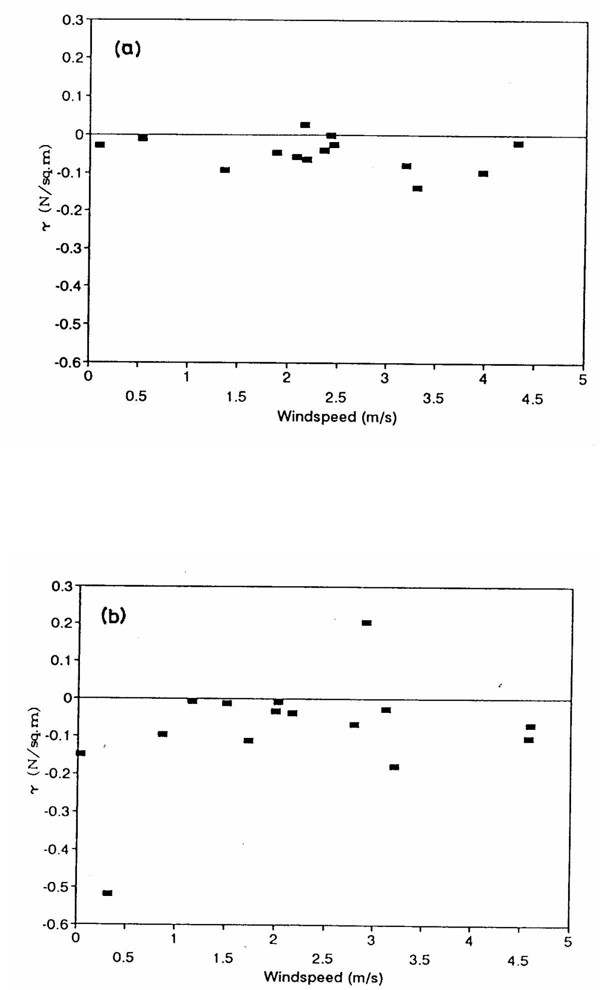


Fig. 12. Same as Fig. 9 for momentum flux



Figs. 13(a&b). Same as Fig. 10 for momentum flux

where κ is von Karman constant, g, the acceleration due to gravity, θ, the mean virtual temperature at level z and u_*, the friction velocity.

Significant correlation between w and θ is evident in unstable/convective conditions despite some scatter. $\gamma_{w\theta}$ increases with increasing instability whereas γ_{wu} decreases. Similar feature was observed during the monsoon period of 1989 over the same site (Sivaramakrishnan *et al*., 1992). In the case of divergence $Y_{\omega\theta}$ shows a poor correlation whereas for $\gamma_{\omega u}$, the correlation is better.

6. Discussion

When the Bay of Bengal monsoon depression moves W-NW, heavy rainfall (> 7.5 cm in the preceding 24 hr) extends to about 500 km ahead and 500 km in the rear of the depression center and this area has a width of 400 km lying entirely to the south of the track (Pisharoty and Asnani, 1957). Movement of monsoon depression across a large track has a profound influence on rainfall over a wide area (Rao, 1976). When a low-pressure system developed into a deep depression and moved close to KGP (100 km SE) on 14 June, the total rainfall over the network was considerably large (Table 3). A depression on 20 August, 350 km SE of KGP has resulted in good rainfall though the meso-scale circulation was divergent.

Satellite (INSAT) pictures revealed heavy cloudiness over this area during the period. This shows that the rainfall over a region depends mainly on large-scale features rather than the meso-scale circulation.

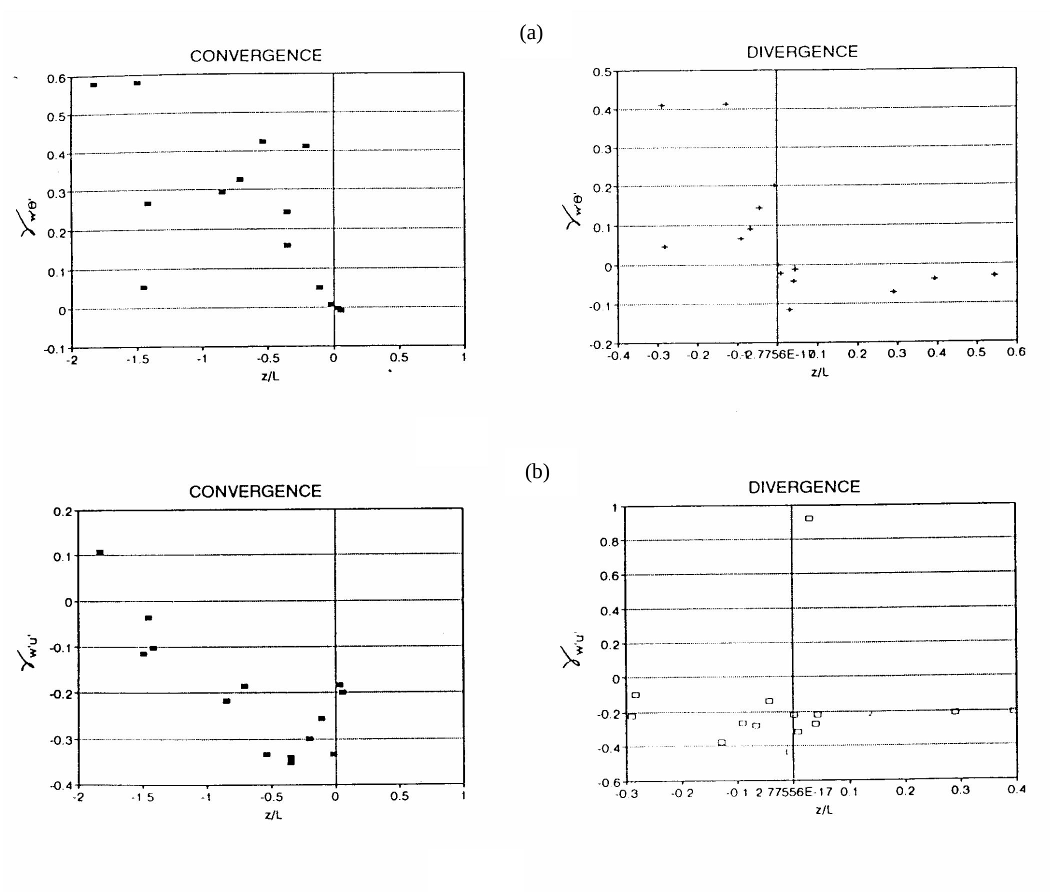
Analysis of vertical velocity at KGP using SODAR observations at the site showed a weak descending motion of air (< 1 ms $^{-1}$) at 200 m AGL during 19-31 August

TABLE 3

Large and meso-scale features and rainfall

Date	Phase of Monsoon	Synoptic features *w.r.t.* KGP			Meso-scale features over the triangle	Total daily rainfall (cm)
		Pressure System	System center km (approx)	Trough axis		
13 Jun 1990	Onset	* L	200 SE	Through	Divergent	12.3
14 Jun 1990	”	DD	100 SE	”	Rain	16.9
15 Jun 1990	”	D	300 SW	South	Convergent	5.1
16 Jun 1990	”	L	500 SW	”	”	1.7
17 Jun 1990	“	L	800 NW	Through	Divergent (Weak)	3.3
18 Aug 1990	Active	L	700 NW	Through	Convergent (Weak)	1.0
19 Aug 1990	”	L	350 SE	South	Divergent (Weak)	0.3
20 Aug 1990	”	D	350 SE	”	Divergent	5.2
27 Aug 1990	”	L	150 E	Through	--	4.4
28 Aug 1990	”	*L	400 S	South	Convergent	4.5
29 Aug 1990	”	L	300 SW	”	Rain	4.0
30 Aug 1990	”	L	450 WSW	”	Convergent	1.1
31 Aug 1990	”	L	900 W	”	”	0.2

L - Low pressure Area, D - Depression, DD - Deep Depression, *L - Well marked Low



Figs. 14(a&b). Correlation coefficient for (a) heat flux and (b) momentum flux

TABLE 4

Cloud type, amount and base height at Kalaikonda during monsoon 1990

Date	Type of cloud	Amount (octas)	Height AGL meter
13 Jun 1990	Sc, Cu, Cb, AC, Ci	6 - 8	750 - 900
14 Jun 1990	St, Sc, AC, AS, Ci	7 - 8	180 - 240
15 Jun 1990	Sc, Cu, Cb, AC, Ci	6 - 7	600 - 900
16 Jun 1990	Sc, Cu, Cb, AC, Ci	5 - 7	600 - 900
17 Jun 1990	St, Sc, Cu, AC, Ci	3 - 7	360 - 900
18 Aug 1990	Sc, Cu, Cb, AC, Ci	4 - 6	750 - 900
19 Aug 1990	St, Sc, Cu, AC, Ci	6	240 - 900
20 Aug 1990	Sc, Cu, Cb, AC, Ci	6	600 - 900
31 Aug 1990	St, Sc, Cu, AC, Ci	3 - 6	300-1200

(Paul *et al*. 1995). Cloud height measurements made at KKA air force station (Table 4) showed that the height of the cloud base was varying from 200-900 m during 13-17 June and 18-20 August. On 31 August the height varied from 300-1200 m during the day. This shows large variability due to moist convection and weak descending motions in the ABL. However the formation of the depression SE of KGP and its movement from the Bay to land appears to have resulted in an increase in rainfall over the network on 20 August. Mostly the rainfall over the triangle correlates fairly well with the meso-scale features if we take in to account the large-scale movement of pressure systems from the Bay and treat weak divergence as convergence. The position and movement of the monsoon trough result in the variation of rainfall (Rao, 1976, Webster *et al*., 1998). Another interesting feature to note is that the quantum of rainfall during the onset (14 June) is more than that of the active phase, which could be due to the intensity of the large-scale depression.

Experiments conducted elsewhere by eddy correlation technique to compute the surface fluxes (Dyer and Maher, 1965, Dyer, 1975, Kaimal, 1975) showed large scatter in flux values particularly in light winds. Variability in flux estimates were attributed to contribution of large-scale eddies when shorter sampling periods (5 min) are used, but over longer periods (hourly) they average out to a negligible value. According to Kaimal and Finnigan (1994), averaging times of several hours are undesirable for computing the fluxes and variances in the presence of diurnal variation. Hence we adopt that the turbulent fluxes estimated from 10-15 min sampling to be adequate enough to give an insight into turbulent exchange of heat and momentum as the micro-scale of turbulence peaks around one minute (Burroughs, 1992). In an earlier study (Sivaramakrishnan *et al*., 1992), we used the data from MONTBLEX-89 pilot experiment at Kharagpur to estimate the fluxes. Turbulent heat flux estimated over a 10-min sampling period at the same site during 6-8 July in the monsoon season of 1989 showed diurnal trend, while momentum flux showed variability but no particular trend which agrees with the present study. Heat flux values are comparable as also the range of momentum flux. Comparing our results with the variation of fluxes observed during pre-monsoon conditions 1987 (Raman *et al*., 1990) in New Delhi and in monsoon 1987 in Bangalore, we find good agreement. The diurnal variations were more regular during monsoon conditions over Bangalore than during pre-monsoon conditions over New Delhi. The flux values of heat and momentum in the present study are within the normal range of their variations observed elsewhere.

7. Conclusion

Position and movement of large-scale pressure systems (low/depression) from the Bay of Bengal gives rise to large-scale convergence and divergence and rainfall over the land. A fair correlation exists between meso-scale convergence and total rainfall in the network (over the Bellamy triangle) - an increase in rainfall during convergence.

Heat flux increases during meso-scale convergence. It shows, despite some scatter, an increase with increase in wind speed during convergence. Momentum flux shows a similar trend with wind speed (>1 m s^{-1}) during convergence and divergence. Correlation coefficient for heat and momentum flux shows dependence on stability and is around 0.3 when the atmosphere is unstable during convergence.

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References

Ananthakrishnan, R., Srinivasan, V., Ramakrishnan, A. R. and Jambunathan, R, 1968, "Synoptic features associated with onset of southwest monsoon over Kerala", IMD, FMU. Rep. IV-18.2.

Bellamy, J. C., 1949, Objective calculations of divergence, vertical velocity and vorticity", *American Met Soc. Vol. xxx*, 2.

Burroughs, W. J., 1992, "Weather cycles: real or imaginary? Cambridge University Press", p58.

Dyer, A. J. and Maher, F. J, 1965, "Automatic eddy-flux measurement with the evapotron", *J. Appl. Meteorol.*, **4**, 622-625.

Dyer, A. J., 1975, "Measurement of turbulent fluxes by fluxatron and NIFTI techniques", *Atmospheric Technology*, **7**, 24-29.

Gupta, M. G., 1990, "Monsoon trough boundary layer experiment, operations control center report", India Meteorological Dept., New Delhi.

Kaimal, J. C., 1975, "Sensors and techniques for direct measurement of turbulent fluxes and profiles in the atmospheric surface layer", *Atmospheric Technology*, **7**, 7-14.

Kaimal, J. C. and Finnigan, A. A., 1994, "Atmospheric Boundary Layer Flows-The Structure and Measurement", Oxford University Press, p285.

Keshavamurty, R. N. and Shankar Rao, M., 1992, "The physics of monsoons", Allied publishers, New Delhi, India.

Kutzbach, G., 1987, "Concepts of monsoon physics in historical perspective: The Indian monsoon (Seventeenth to early twentieth century) in Monsoons", Eds. J. S. Fein and P. L. Stephens, John Wiley, New York.

Pisharoty, P. R. and Asnani, G. C., 1957, "Rainfall around monsoon depressions over India", *Indian J. Met. & Geophys*., **8**, 15-20.

Paul, D. K., Ganekar, S. P., Murthy, B. S. and Vernekar, K. G., 1995, "Wind profiles in the boundary layer over KGP associated with synoptic scale systems", *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, **104**, 317-326.

Prabu, A., Rao, K. N., Kusuma, G. R. Kailash, S. V., Rudrakumar, S., Ameenulla, S. and Srinivasan, H. P., 1990, "The MONTBLEX pilot experiment. Report-90, AS2, Center for Atmospheric Sciences, IISc, Bangalore, India.

Raman, S., Temple man, B., Templeman, S., Holt, T., Murthy, A. B., Singh, M. P., Agarwal, P., Nigam, S., Prabhu, A. and Ammenullah, S., 1990, "Structure of the Indian southwesterly pre-monsoon and monsoon boundary layers: Observations and Numerical simulation", *Atmos. Environ.* **24**A, 723-734.

Rao, Y. P., 1976, "Southwest monsoon", Meteorol. Monograph, Synoptic Meteorol.1, India Met.Dept, p367.

Rudrakumar, S., Srinivasan, H. P., Satyadev, H. N., Amanulla, S. and Prabu, A., 1991a, "Surface layer data from MONTBLEX 90", Report No.91, MD2, IISc. Bangalore.

Rudrakumar, S. and Prabhu, A., 1991b, "Assessment of quality of tower data from MONTBLEX-90", Ind. Inst. Sci., Report 91, MD3, Bangalore.

Rudrakumar, S., Ameenulla, S. and Prabhu, A., 1997, " The Monsoon Trough Boundary Layer", Eds. R. Narasimha, D. R. Sikka and A. Prabhu, Indian Academy of Sciences, Bangalore, p422.

Sivaramakrishnan, S., Saxena, Sangeeta and Vernekar, K. G., 1992, "Characteristics of turbulent fluxes of sensible heat and momentum in the surface boundary layer during the Indian summer monsoon", *Boundary Layer Meteorol.*, **60**, 95-108.

Srivastav, S. K., 1995, "Synoptic meteorological observations and weather conditions during MONTBLEX", *Proc. Indian Acad. Sci.(Earth and Planet. Sci.)*, **104**, 189-220.

Vachalak, R. E., 1987, "Case studies of divergence and vertical velocities calculated using different sensing systems", M. S Thesis, University of Wisconsin, Madison.

Webster, P. J., Magana, V. O., Palmer, T. N., Shukla, J., Tomas, R. A., Yanai, M. and Yasunari T., 1998, "Monsoons: Processes, predictability and the prospects for prediction", *J. Geophys. Res*., **103**, C7, 14451-14510.