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Existence of low level jet during pre-monsoon period over eastern India and its role in the initiation of nocturnal thunderstorms

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RESUMEN

Durante el periodo premonzónico la frecuencia de ocurrencia de un chorro de baja altura (LLJ) y de tormentas eléctricas nocturnas (NCTS) sobre la Planicie Ganguética de Bengala Occidental, una región de la parte oriental de La India, han sido estudiadas a partir de observacions de globos-piloto y simulaciones numéricas. El estudio observacional indica que la formación del LLJ y de NCTS es significativa sobre las estaciones interiores. Los diagramas compuestos de la estructura vertical del LLJ muestran que la velocidad máxima del viento se observa dentro de las capas entre 300 m y 600 m sobre el suelo. Observaciones del Radar Sónico revelan que el cizallamiento horizontal del viento tiene valor positivo debajo del eje del LLJ, mientras que posee valores negativos y mayores arriba del mismo. Esta conclusión difiere ligeramente de aquellas obtenidas a partir de datos de globo-piloto debido a una baja resolución de estos últimos.

El estudio con el modelo apoya también la formación del LLJ en la tarde debido al contraste tierra/mar. Las velocidades verticales deducidas con el modelo son positivas sobre los lugares de incidencia de tormentas eléctricas. El cizallamiento eólico horizontal debajo del núcleo del LLJ indica fuerte vorticidad relativa y, por consiguiente, convergencia a bajos niveles. Esta producción de convergencia por el LLJ ayuda a la formación de tormentas eléctricas nocturnas.

ABSTRACT

During the pre-monsoon period, the frequency of occurrence of low level jet (LLJ) and of nocturnal thunderstorms (NCTS) over the Gangetic Plain of West Bengal, a region in the eastern part of India have been studied from both pilot balloon observations and numerical simulations. Observational study indicates that the formation of LLJ and NCTS is significant over inland stations. Composite diagrams for the vertical structure of LLJ show that the core wind speed is observed within the layers between 300 m and 600 m above ground. Sodar observations reveal that vertical shear of horizontal wind has positive lower value below the axis of LLJ whereas it has negative and higher values above the axis. This conclusion differs slightly from those obtained from pilot balloon data because of poor resolution in the later data.

Model study also supports the formation of LLJ in the evening because of land/sea contrast. Model-derived vertical velocities are positive over the places of occurrence of nocturnal thunderstorms. The horizontal shear of wind speed beneath the core of LLJ indicates strong relative vorticity and hence convergence at lower levels. This production of convergence by LLJ helps the formation of nocturnal thunderstorms.

1. Introduction

During the pre-monsoon period (March - May), thunderstorm is a major weather phenomenon over Gangetic Plain of West Bengal (GPWB), a region in the eastern part of India (Fig. 1). The pre-monsoon thunderstorms over GPWB fall under the category of severe local storms. The earlier studies on pre-monsoon thunderstorms over the region have dealt with the synoptic conditions favourable for their formation and study of some thermodynamic and dynamic parameters in the pre-storm situations (Koteswaram and Srinivasan, 1958; Weston, 1972; Patra and De, 1997). Though the occurrence of these thunderstorms are most frequent around 1100 UTC over GPWB, nocturnal thunderstorms (NCTS) also occur here. However, there is no systematic study of nocturnal thunderstorm over the region except some discussion on nocturnal thunderstorms in the early forties (IMD, 1941).

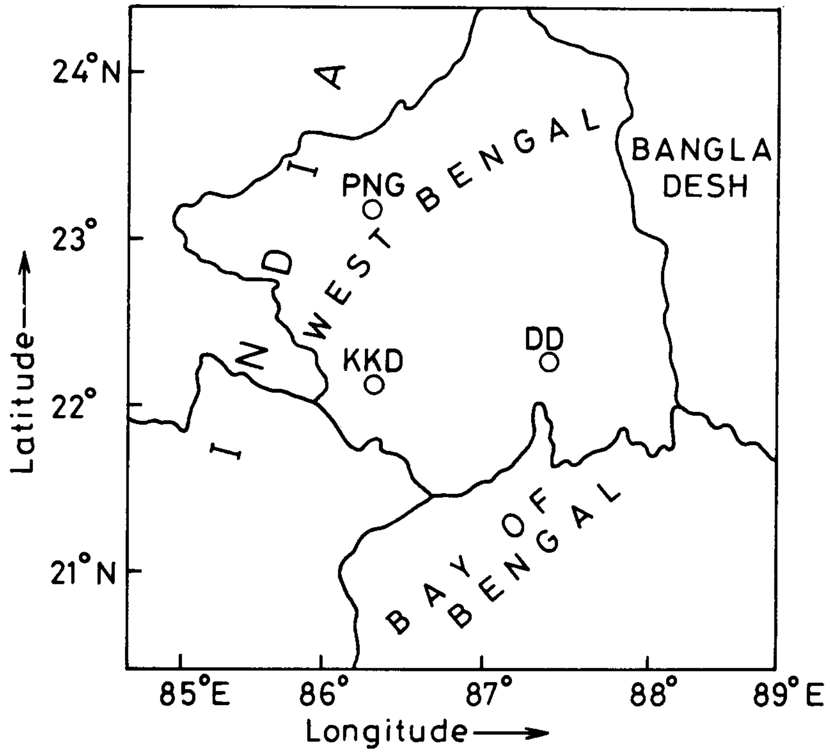

Fig. 1. Enlarged view of the region under study.

It is well established over Great Plains of United States (Pitchford and London, 1962; Bonner, 1966; Wallace, 1975) that the development of non-frontal nocturnal thunderstorms are closely associated with low level jet (LLJ). It has been found (Paegle and Rasch, 1973) that terrain slope is the greatest contributing factor to the concentration of the nocturnal wind maxima into an LLJ stream. From the numerical simulation of LLJ, McNider *et al.* (1982) have shown that LLJs owe their existence to pressure gradients reinforced by land/sea contrast and topography. Using wind profiler network data and high resolution mesoscale model, Zhong *et al.* (1996) have shown that the meridional variation of Coriolis parameter is an enhancing factor for strengthening of LLJ. A horizontal variation of soil moisture content is also important in producing convergence.

However, no such attempt has been made over the region concerned though in a recent study, Lohar (1996) has claimed the formation of LLJ over Kalaikunda (KKD) (22.29°N, 87.20°E) (Fig. 1) as a result of land/sea contrast. Model study reveals that maximum wind speed is produced in the evening when the initial synoptic wind used for the initialization is parallel to the east coast of India, which often occurs in this region. However, that study does not deal with any relationship between the formation of LLJ and the occurrence of nocturnal thunderstorms.

The present study has been made in two parts. The existence of LLJ both from sodar and pilot balloon observations, vertical structure and magnitudes of vertical shear of horizontal wind below and above LLJ have been described in observational part. Also the frequency of formation of LLJ and that of the occurrence of NCTS have been observed to indentify whether LLJ has any role on the formation of NCTS. Sodar observations are presented over Kharagpur only, a location 5 km away from KKD. In the second part, the existence of LLJ has been supported through a numerical mesoscale model.

2. Observational study

2.1. Existence of low level jet from sodar observations

No sodar observation is normally available over any station in GPWB during pre-monsoon period. However, in 1990, an extensive experiment viz., MONsoon Trough Boundary Layer EXperiment (MONTBLEX) had been perfomed over India to study the role of boundary layer during the tropical monsoon. As part of that experiment, some sodar observations were taken

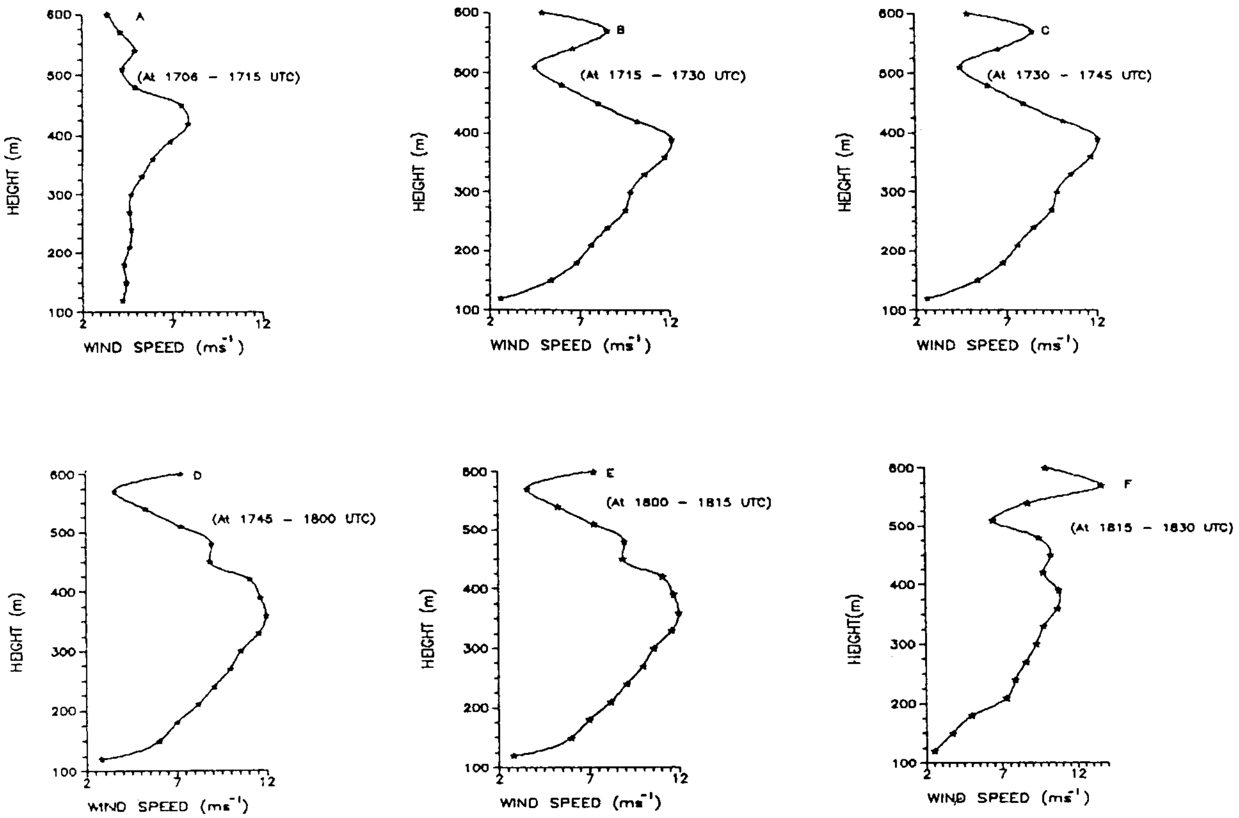

Fig. 2. Time evolution of LLJ from sodar observations over Kharagpur on 19 May 1990.

over Kharagpur in the second half of May 1990, though monsoon over GPWB starts in the early June. Out of these observations only on 19th May 1990, a clear LLJ is observed (Fig. 2). Incidentally, sodar was in operation from 1136 UTC (1706 IST) to 1300 UTC (1830 IST) for each run lasting 15 minutes except for 9 minutes from 1136 UTC to 1145 UTC. The time evolution of LLJ is shown in Figure 2. It is seen that a south-southwesterly jet with core wind speed of 12.1 ms^{-1} at 390 m in the time interval of 1200 UTC to 1215 UTC exists (Fig. 2c). The vertical extension of the LLJ was from 120 m to 510 m above the ground. It is also seen (Fig. 2d) that the LLJ was active in the next 15 minutes where the core wind speed of 12.0 ms^{-1} was observed at 360 m. Then the wind speed started declining.

2.2. Frequency of NCTS and of LLJ over GPWB

A study to look for the existence of LLJ over GPWB during the pre-monsoon season has been done for a period of three years (1987 - 1989). This study is based on the pilot balloon observations at 1200 UTC over DumDum (DD) (22.39°N, 87.27°E), KKD and Panagarh (PNG) (23.28°N, 87.26°E). These three stations are the only pilot balloon observation stations over GPWB. A core wind speed of $\geq$ 12 ms^{-1} within 600 m above ground level has been considered here as LLJ, if the wind direction remains almost the same within a reasonable depth below and above the core axis. The frequency of occurrence of NCTS during the pre-monsoon months over DD, KKD and PNG are also studied for the same period. The informations about the occurrence of NCTS have been collected from the radar observations (Non-doppler) at DD, Calcutta and also from the weather informations of the Regional Meteorological Centre, Calcutta. Here NCTSs are defined as:

(*A*) Those which occurred after 1330 UTC (1900 IST) and/or

(*B*) those which started before 1330 UTC, but continued after 1330 UTC.

The observations of the frequency of LLJ and of NCTS are shown in Table 1. It is seen that NCTS are not uncommon in GPWB. The NCTS days are maximum (46% of the total thunderstorm days) over KKD and it is 42% over DD. The lowest frequency of NCTS days (29% of the total thunderstorms days) is observed over PNG. The number of LLJ days at 1200 UTC is also more over DD and KKD whereas it is the least over PNG. Among the three stations, PNG, an inland station west of GPWB records least number of LLJ days as well as NCTS days. It signifies the possible inportance of land-sea contrast towards the formation of LLJ and NCTS.

From Table 1, it is also seen that out of total 19 NCTS days in three pre-monsoon years over DD, 8 days fall under *A* - type and 11 fall under *B* - type. In KKD during the same three years, there are 10 days for *A* - type and it is 11 for *B* - type. 3 NCTS days are of *A* -type and 7 are of *B* - type over PNG in the three years. Table 1 also gives an information about the fact that out of these total NCTS days in three pre-monsoon years over a station, how many are associated with the presence of LLJ at 1200 UTC. It is seen that only 10 (52%) NCTS days out of 19 over DD are associated with LLJ. This number for KKD and for PNG are 9 (40%) out of 22 and 3 (30%) out of 10 respectively. Again it appears that LLJs are more closely associated with *A* - type of NCTS. This is expected as LLJ are found to develop during late afternoon. In case of *B* - type, other influences are expected to have greater role.

Table 1. Frequency of NCTS days and of LLJs at 1200 UTC over DD, KKD and PNG in three pre-monsoon years.

TS⇒ Total number of thunderstorm days.

NCTS⇒ Total number of nocturnal thunderstorm days.

LLJ ⇒ Total number of low level jets from pilot balloon observations at 1200 UTC.

Year (March - May)	DD			KKD			PNG		
	TS	NCTS	LLJ	TS	NCTS	LLJ	TS	NCTS	LLJ
1987	17	9	8	22	12	11	11	3	2
1988	14	4	3	12	5	3	12	4	2
1989	14	6	7	14	5	3	11	3	3
Total	45	19	18	48	22	17	34	10	7
% of NCTS among TS		=42%			=46%			=29%	
Total no. of A type NCTS		8			10			3	
Total no. of B type NCTS		11			12			7	
Total no. of A type NCTS associated with LLJ		7			6			1	
Total no. of B type NCTS associated with LLJ		3			3			2	

2.3. Vertical structure of LLJ

During the pre-monsoon period of three years (1987 - 89), vertical structure of LLJ is studied using pilot ballon observations at 1200 UTC over DD, KKD and PNG. The composite diagram of LLJ is plotted on the basis of 18 LLJs over DD, of 17 LLJs over KKD and of 7 LLJs over PNG (Fig. 3). The horizontal wind speeds (ms^{-1}) of LLJ are plotted against the height (m) above ground. It should be mentioned that there is no pilot ballon observations at any level in between 300 m and 600 m. So some uncertainty exists in the location of jet axis from pilot balloon observations. In spite of that, one can conclude that the core wind speed of LLJ is maximum over KKD and minimum over PNG. The core wind speed of LLJ is at 300 m over DD whereas it is at 600 m over KKD and PNG. Besides, the height of the core wind speed at KKD is usually higher than that at DD. It may be due to the presence of high depth of sea breeze circulation over KKD and of the higher topographic height (Lohar, 1993).

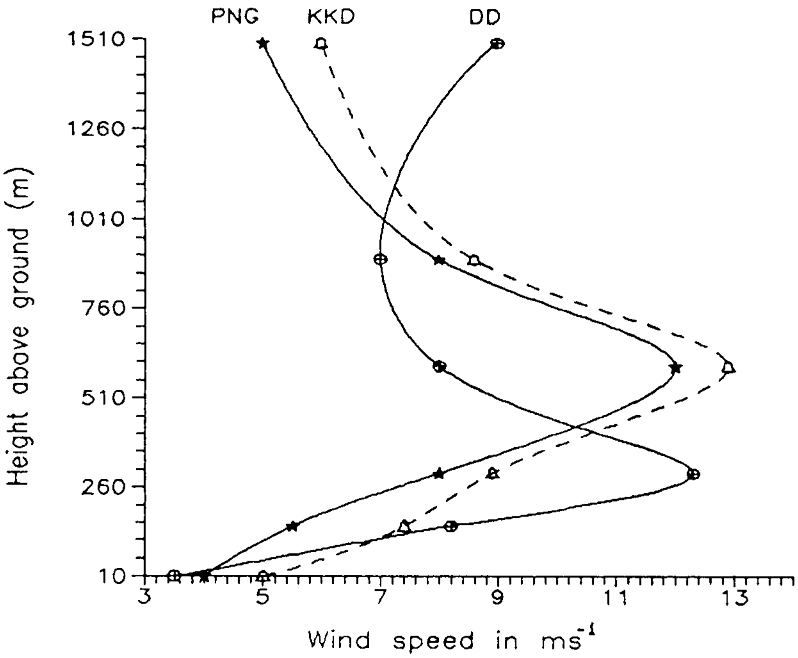

Fig. 3. Composite diagrams for vertical structure of LLJ over DD, KKD and PNG during pre-monsoon period.

2.4. *Magnitude of vertical shear of horizontal wind below and above LLJ*

(*A*) From sodar osbervations over Kharagpur

The sodar observations between the time interval of 1200 UTC and 1215 UTC on 19 May 1990 over Kharagpur are used to find out the vertical shear of horizontal wind both below and above the axis of LLJ (Table 2). The wind profile from sodar observations were available at a vertical interval of 30 m with the help of an in-built algorithm.

It is seen that magnitude of wind shear is less and positive below the jet axis whereas it is negative and higher above the jet axis. The positive value of wind shear below the axis of LLJ signifies convergence whereas the higher negative value of wind shear apparently helps to diverge the airmass better above the LLJ axis.

Table 2. Magnitude of vertical shear of horizontal wind below and above the axis of LLJ.

From Sodar observations at 1200 - 1215 UTC over Kharagpur		From Pilot Balloon observations at 1200 UTC Magnitude of wind shear ($\sim 10^{-2}s^{-1}$)			
At levels	Magnitude of wind shear ($\sim 10^{-2}s^{-1}$)	At levels	DD	KKD	PNG
(surface - 120 m)	0.54	(Surface - 150 m)	3.35	1.71	1.07
(120 m - 150 m)	9.33	(150 m - 300 m)	2.73	1.00	1.66
(150 m - 180 m)	4.66	(300 m - 600 m)	-1.43	1.63	1.33
(180 m - 210 m)	2.66	(600 m - 900 m)	-0.33	-1.43	-1.33
(210 m - 240 m)	3.00				
(240 m - 270 m)	3.33				
(270 m - 300 m)	1.00				
(300 m - 330 m)	2.66				
(330 m - 360 m)	3.66				
(360 m - 390 m)	1.33				
(390 m - 420 m)	-6.33				
(420 m - 450 m)	-7.33				
(450 m - 480 m)	-6.66				
(480 m - 510 m)	-5.00				
(510 m - 540 m)	7.00				
(540 m - 570 m)	6.33				
(570 m - 600 m)	5.00				

(*B*) From pilot balloon observations

The values of wind speed (ms^{-1}) used in the drawing of composite diagrams of LLJ are used to find out the vertical shear of horizontal wind both below and above LLJ axis. Depending on the resolution of pilot balloon observations, the wind shears are evaluated at the layers: surface to 150 m, 150 m to 300 m, 300 m to 600 m. The results are presented in Table 2. It is observed that in some layers wind shear has positive but higher values below the axis of LLJ whereas it is negative and of lower value above the axis. However, this conclusion is not exactly identical with the observations from sodar. This discrepancy arises because of the poor resolution in the pilot balloon observation.

3. Model Study

3.1. Model description

A 2D version of a mesoscale model, orignally developed by Pielke (1974) and later on modified by him and his colleagues is being employed here. It has already been tested over the region for the simulation of sea breeze circulations (Lohar, 1993). The governing equations (Pielke, 1974), parameterizations and various numerical techniques (Deardorff, 1978; McNider and Pielke, 1981) are discussed in Pielke (1984).

Table 3. Input parameters for initialization of the model.

Height in Metres	Potential Temperature (K)	Specific Humidity (gm/kg)	Wind Speed (ms^{-1})	Wind Direction (Degree) (Meteorological Angle)
2	300.9	19.3	2.0	180
10	301.0	19.3	2.5	180
50	301.1	19.2	4.0	181
100	301.2	19.1	6.3	182
200	301.4	19.0	8.3	183
300	301.8	18.4	10.9	185
500	302.4	17.9	11.2	188
1000	306.8	12.0	13.0	216
1500	310.7	5.8	15.4	233
2000	312.4	4.0	17.0	249
2500	313.3	4.4	16.0	261
3000	313.6	5.0	15.9	268
3500	314.0	5.6	16.4	267
4000	315.4	5.1	16.3	270
5000	319.6	2.4	14.3	268
6000	324.7	1.2	14.1	264

Table 4. Other input parameters necessary to initialize the model.

Surface Pressure	1003.4 mb
Surface Specific Humidity	0.0193 kg/kg.
Sea Surface Temperature	301.0 K
Initial Depth of PBL	500m
Soil Wetness	0.07
Soil Conductivity	0.003 $cm.^2s^{-1}$
Soil Density	1.48 g. cm^{-2}
Soil Specific Heat	0.23 Cal. g^{-1} K^{-1}
Mean Latitude	22.6° N
Albedo	0.15
Von Karman Constant	0.35
Time Step	60 sec

3.2. *Input data*

Initialization of the model is based on the homogeneous land surface, and potential temperature, specific humidity and wind profile of a station representing the initial condition. For this purpose radiosonde data has been collected from DD, Calcutta for 25th April 1987 (Table 3). This date has been purposely choosen because of the fact that on that day NCTS occurred over several stations including DD, so as to represent the initial condition which may be favourable for NCTS. The various other parameters used to initialize the model are given in Table 4.

3.3. *Model domain*

In order to find out the impact of land-sea contrast, a model domain of 46 × 16 grid points is choosen, where first 32 grid points are considered as land surface and the rest are as sea surface. Constant horizontal grid spacing of 9 km is used whereas variable grid spacing with higher resolution near the ground is used for the vertical. With the above mentioned input data, simulation has been carried out for 24 hours starting fom 0000 UTC on 25 April 1987.

3.4. *Results*

The following results are obtained from the model study:

3.4.1. *Formation of LLJ*

The model-derived horizontal wind speed (ms^{-1}) is studied at different hours. To locate the simulated LLJ distinctly, the first 153 km of the land area and the last 100 km of the sea area have been excluded in Figure 4. Again for the clarity of the vertical cross-section of LLJ, heights especially at lower levels are not scaled. The horizontal wind speed begins to decrease as time progresses from 0000 UTC. It is noticed that a sea-breeze circulation forms around 0600 UTC and moves towards inland. Then the horizontal wind speed also starts increasing. At around 1400 UTC, sea-breeze front moves more than 70 km inland (Fig. 4). At 1400 UTC, the wind

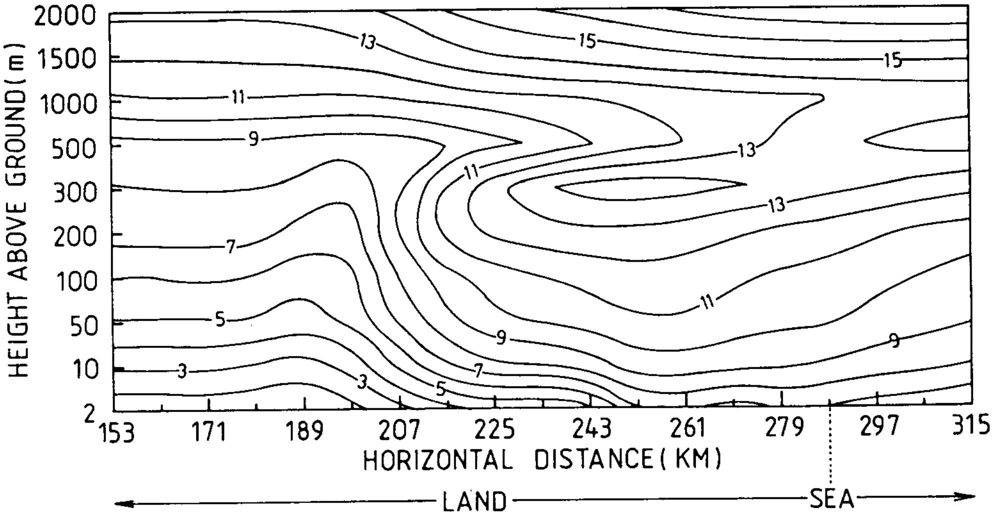

Fig. 4. Model simulation of low level jet at 1400 UTC on 25 April 1987 (Contour interval of horizontal wind speed $= 2\ \mathrm{m\ s}^{-1}$).

speed reaches maximum (14.6 ms^{-1}) at a height of 300 m and forms the core of a low level jet. After 1400 UTC, the wind speed begins to decrease. The ascending part of the sea breeze front at 1400 UTC is observed around the places of 80 km from the sea. The results verify the importance of sea breeze circulation for the formation of LLJ.

3.4.2. Ascending motion associated with LLJ

The model-derived vertical velocities (cm s^{-1}) are postive around the places of 80 km from the sea towards land at 1400 UTC (Fig. 5). It indicates the ascending part of the sea-breeze circulation and is obviously associated with convergence. It is the region of downstream section of the LLJ. It is established (Bonner *et al.*, 1968) that if the synoptic situation is favourable in these places, the downstream section is favourable for the formation of NCTS. The NCTS are reported over the stations around the places of about 90 km from the sea towards land in the model domain. The right hand side of Figure 5 indicates negative vertical vorticity and hence is associated with descending motion.

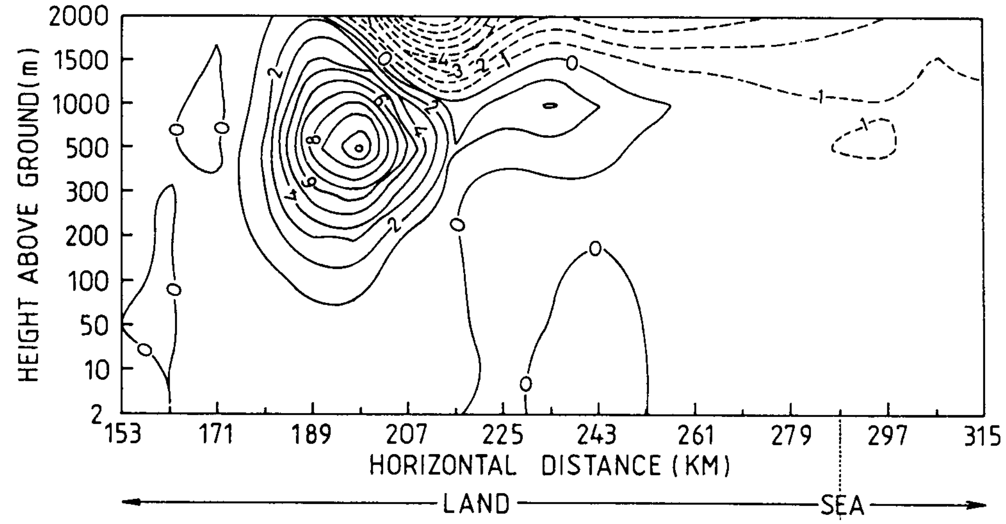

Fig. 5. distribution of model-derived vertical velocity at 1400 UTC on 25 April 1987 (Contour interval for solid line = 1 cm s^{-1} and for dashed line = -1 cm s^{-1}).

The horizontal wind shear (~ 10^{-4} s^{-1}) is also evaluated from the model derived horizontal wind speeds (Fig. 6). The horizontal shear at height of 250 m has been calculated from the difference between the horizontal speeds at surface and at 500 and so on. As the curvature of the flow near the core of the jet is generally small, horizontal wind shear can be treated approximately as relative vorticity. It shows that maximum horizontal wind shear and hence maximum relative vorticity is observed beneath the core of the LLJ (Bonner *et al.*, 1968). In the right hand side of the jet (shown as dashed line), wind shear is negative. The situation indicates a strong convergence beneath the jet.

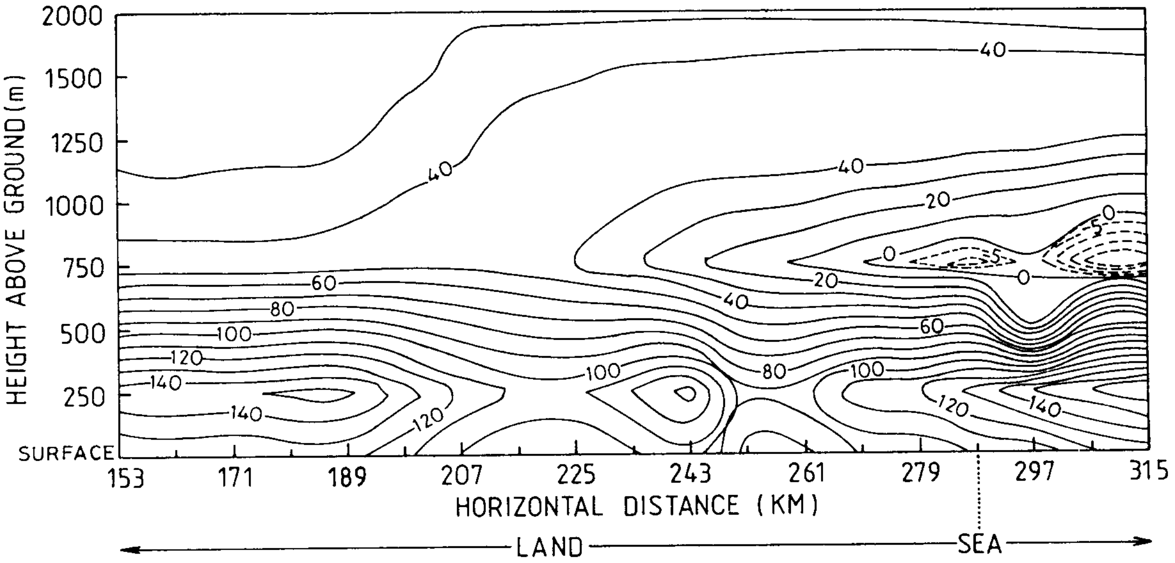

Fig. 6. Distribution of horizontal wind shear (~ 10^{-4} s^{-1}) at 1400 UTC on 25 April 1987 (Contour interval for solid line = 10×10^{-4} s^{-1} and for dashed line interval = -5×10^{-4} s^{-1}).

4. Conclusions

During the pre-monsoon period, the frequency of occurrence of low level jet and of nocturnal thunderstorms over the Gangetic Plain of West Bengal, a region in the eastern part of India have been studied from both pilot balloon observations and numerical simulations. Observational study indicates the formation of LLJ and NCTS over DD as well as over KKD quite significantly, but it is insignificant over PNG, a far inland station. It is also seen that *A* - type of NCTS are more closely related with LLJ.

Composite diagrams for the vertical structure of LLJ during the premonsoon season show that the core wind speed is observed at 300 m above ground over DD whereas it is at 600 m over KKD and PNG. From sodar observations it is seen that magnitude of vertical shear of horizontal wind has positive lower value below the axis of LLJ whereas it is negative and of higher value above the axis of the LLJ. Because of the poor resolution of pilot balloon observations, this conclusion is not exactly identical with those obtained from pilot balloon observations.

Model study also supports the formation of LLJ in the evening because of land/sea contrast. The positive vertical velocity in the downstream section of the LLJ over GPWB may be sufficient to trigger NCTS. The presence of strong horizontal shear beneath the core of the jet indicates strong circulation associated with positive relative vorticity. However, since all NCTS are not associated with LLJ, there may be some other factor for their occurrence.

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