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A case study on the genesis of a monsoon depression in the northern Bay of Bengal during Monsoon-77 experiment

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सार —19 अगस्त 1977 को बंगाल की खाड़ी में बने एक अवदाब के लिए एक उष्णकटिबन्धीय चक्रवात की उत्पति पर डब्ल्यू० एम० ग्रे द्वारा प्रस्तावित परिकल्पना के मूल्यांकन के लिए 11 से 19 अगस्त 1977 के दौरान सर्वप्रथम उत्तरी बंगाल की खाड़ी के ऊपर सोवियत रूस के चार-जलयान द्वारा बने स्थायी बहुभुज से प्राप्त उच्च महासागरीय ताप आंकड़ों के समुच्चय तथा थोड़े से समय के लिए उच्च वायु रेडियो-सौंडे पवन की श्रेणियों के संग्रह, एक अद्वितीय अवसर प्रदान करते हैं। (क) निम्नस्तरीय भ्रमिलता, (ख) कोरियोलिस प्राचल, (ग) निम्नत्तर से उच्चत्तर क्षोभ मण्डलीय क्षैतिज पवन के ऊर्ध्वाधर अपरूपण के प्रतिलोम (व्युत्क्रमानुपात), (घ) 26° से० से अधिक ऊपरी 60 मीटर तल के महासागरीय ऊष्मीय ऊर्जा, (ङ) भूपृष्ठ से लेकर 500 मिलीबार ऊंचाई तक आर्द्र स्थायित्व और (च) ग्रे के चक्रवातजनक प्राचल से ज्ञात मध्य क्षोभमण्डलीय आपेक्षिक आर्द्रता के, छह प्राचलों के गुणनफल को जब उचित रूप से संशोधित किया जाता है तो वह उस मानसून अवदाब की उत्पति के लिए भी सुदृढ़ संकेत प्रदर्शित करता है जो प्रेक्षित अवधि के अन्त के लगभग, बहुभुज के समीप उत्पन्न हुआ था।

ABSTRACT. The collection of a short time series of upper air radiosonde, wind and upper ocean temperature data sets from the USSR four ship stationary polygon over the northern Bay of Bengal for the first time during 11-19 August 1977 affords a unique opportunity to evaluate the hypothesis proposed by W. M. Gray on the genesis of a tropical cyclone for a monsoon depression which formed over the Head Bay on 19 August 1977. The product of six parameters (a) low level vorticity, (b) coriolis parameter, (c) inverse of the vertical shear of the horizontal wind from lower to upper troposphere, (d) ocean thermal energy of the top 60 m layer above 26 deg. C, (e) moist stability from surface to 500 mb, (f) middle tropospheric relative humidity known as Gray's cyclogenesis parameter when modified suitably has also shown strong indications for the genesis of a monsoon depression which formed towards the end of the observational period in the neighbourhood of the polygon.

1. Introduction

During the summer monsoon season depressions form over the Head Bay of Bengal and move towards the west or northwest. The statistics of these disturbances over the Bay of Bengal are documented in the literature by Ananthakrishnan (1964). However, studies on the three dimensional structure and life histories of these disturbances are mostly based to either land originated systems or systems located over the land mainly due to non-availability of upper air observations over the Bay of Bengal. The question still remains regarding the physical mechanism of the formation of these monsoon disturbances over the Bay of Bengal. An attempt is made in this study to investigate the genesis of a monsoon depression with the aid of the observations collected from the USSR four-ship stationary polygon over the northern Bay of Bengal during the last phase of Monsoon-77 experiment.

Assuming that the conditions for the genesis of a monsoon depression are nearly similar to that of a tropical cyclone, the hypothesis proposed by Gray (1975) is modified and utilised to make a case study on the genesis of a depression formed over the Head Bay of Bengal towards the end of Phase III of Monsoon-77 experiment. Similar studies were carried out earlier by McBride and Gray (1979).

2. Methodology

Gray (1975) defines the Cyclone Genesis Parameter (CGP) as the product of six components listed below :

$$\text{C.G.P.} = (\text{Dynamic potential}) \times (\text{Thermal potential})$$

$$\text{Dynamic potential} = \zeta_r \times f \times 1/S_z$$

$$\text{Thermal potential} = E \times \frac{\partial \theta_e}{\partial p} \times \text{RH}$$

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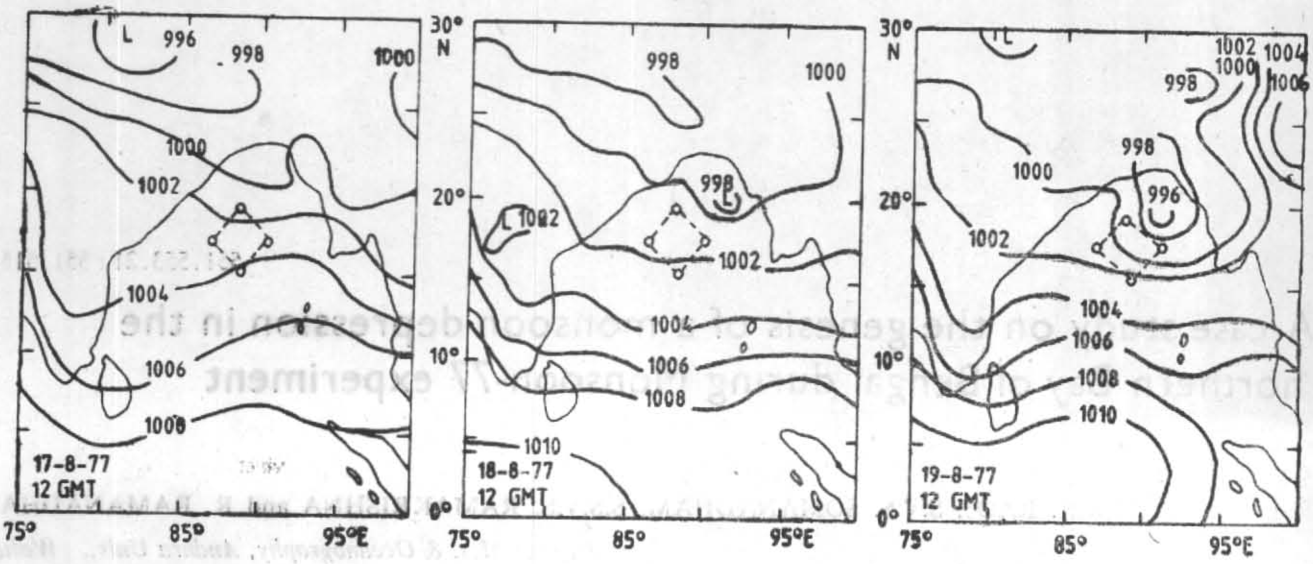


Fig. 1(a). Sea level pressure maps of 17, 18 and 19 August 1977

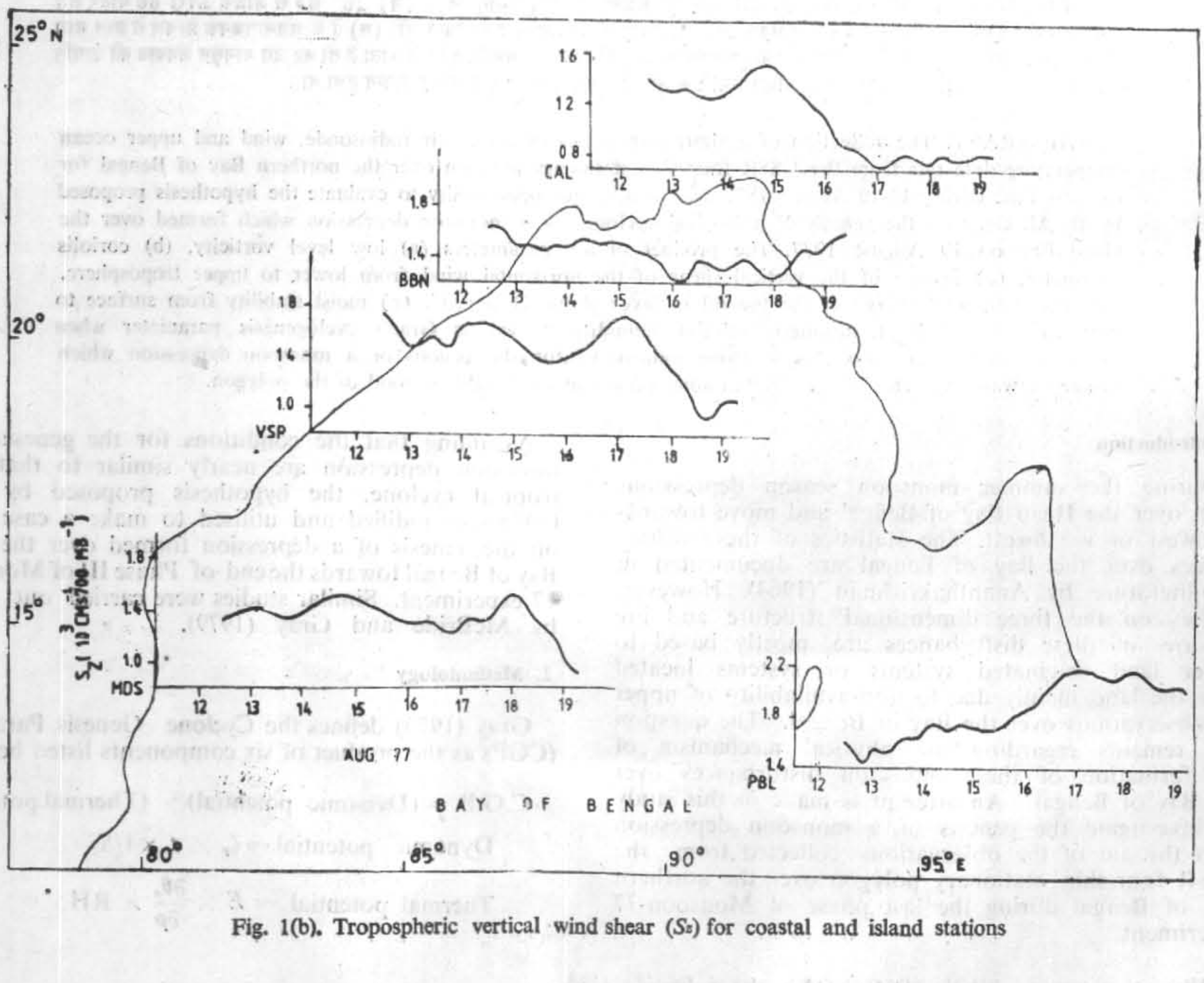


Fig. 1(b). Tropospheric vertical wind shear (S_z) for coastal and island stations

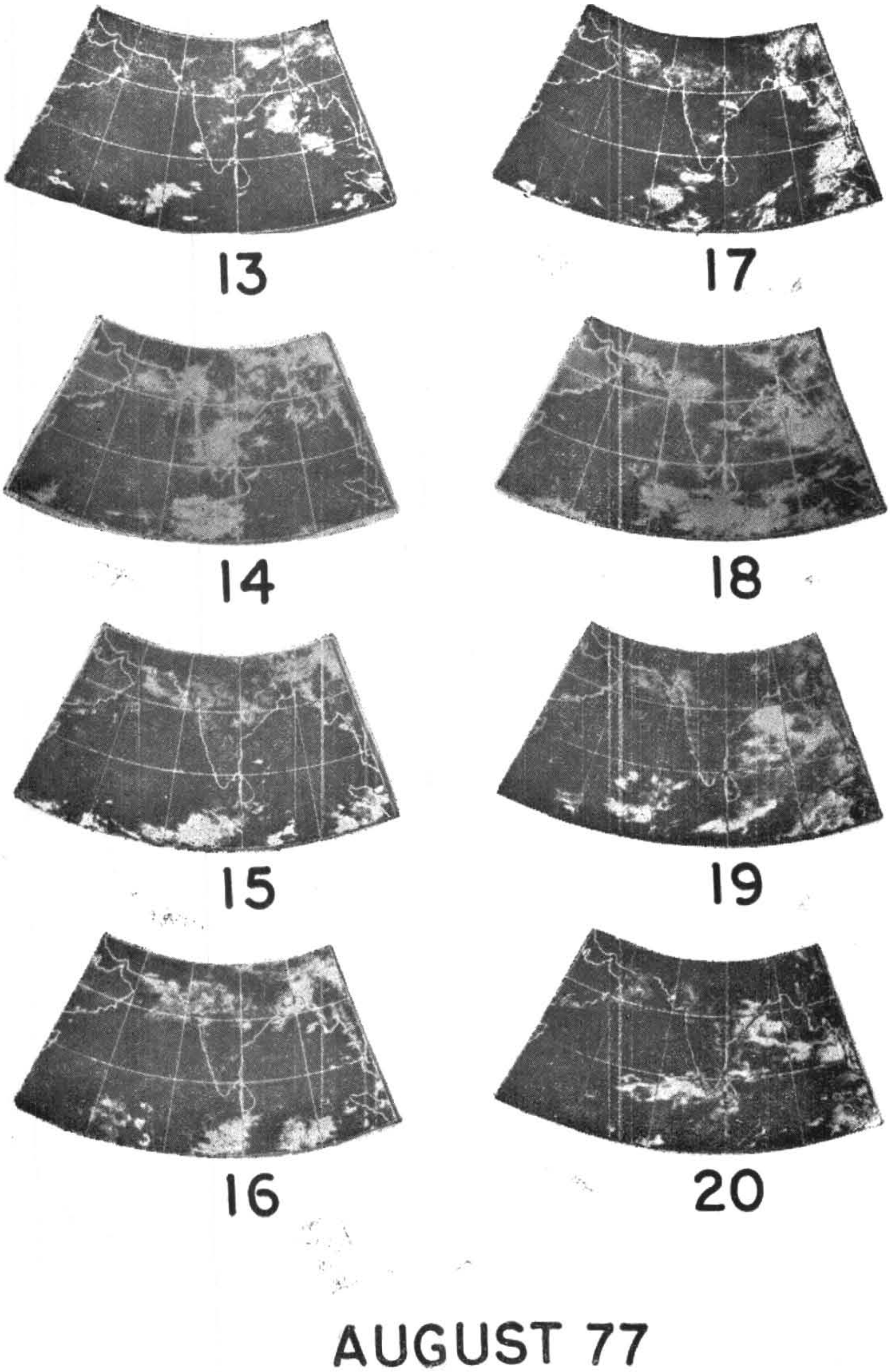


Fig. 1 (c). Satellite pictures in the visible channel from 13 to 20 August 1977

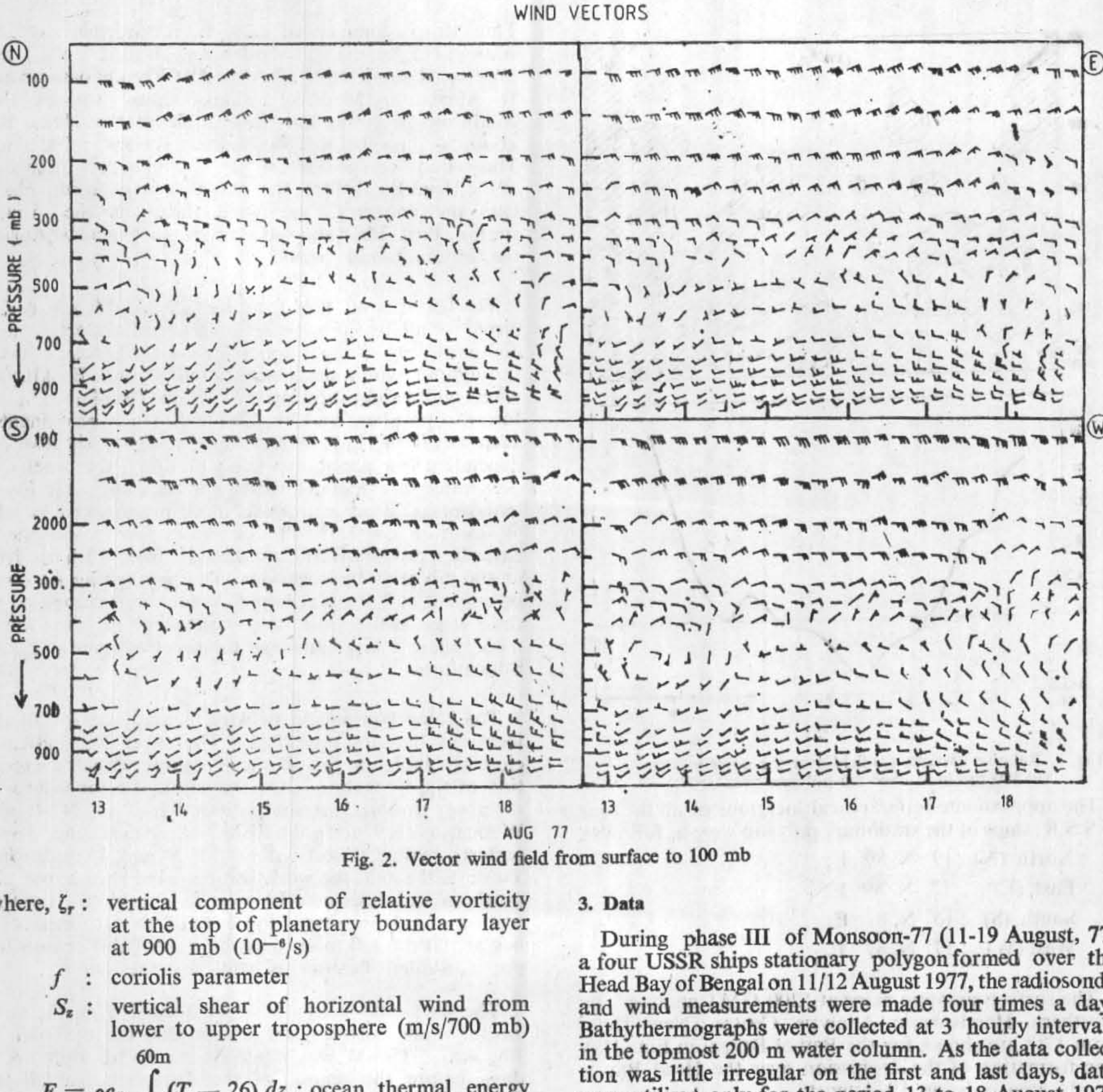


Fig. 2. Vector wind field from surface to 100 mb

where, ζ_r : vertical component of relative vorticity at the top of planetary boundary layer at 900 mb (10^{-6}/s)

f : coriolis parameter

S_z : vertical shear of horizontal wind from lower to upper troposphere (m/s/700 mb)

$$E = \rho c_p \int_0^{60\text{m}} (T - 26)\, dz$$: ocean thermal energy above 26° C to 60 m depth (Joules)

$\frac{\partial \theta_e}{\partial p}$: moist stability from surface to 500 mb (k/500 mb)

RH : $\bar{r}_h$-40/30 : mid-tropospheric (500-700 mb) ralative humidity parameter

$\bar{r}_h$: mean relative humidity of 500 mb and 700 mb

The limits for some of the parameters were slightly modified as the meteorological conditions over the northern Bay of Bengal during summer monsoon season are not similar to those in the tropics elsewhere. The modifications made in the limits for some terms of Gray's scheme are shown in Table 1 with appropriate reasoning.

3. Data

During phase III of Monsoon-77 (11-19 August, 77) a four USSR ships stationary polygon formed over the Head Bay of Bengal on 11/12 August 1977, the radiosonde and wind measurements were made four times a day. Bathythermographs were collected at 3 hourly intervals in the topmost 200 m water column. As the data collection was little irregular on the first and last days, data were utilised only for the period 13 to 18 August 1977 in the present study.

4. Discussion

4.1. *Weather during* 13-18 *August* 1977

A weak low moved towards the Orissa coast on 14th. The axis of the seasonal monsoon trough shifted to the foot of the Himalayas causing break conditions in the monsoon. Another north-south trough formed on 15th along the east coast of India and persisted till the end of the phase. An incipient low appeared on 18th intensified into a depression over the northern Bay of Bengal centred at 0300 GMT on 19th within half degree of 19°N and 91° E. It further intensified into a deep depression and crossed the Orissa coast. Surface pressure registered a fall from 14th and the wind field strengthened attaining a maximum on the last day. A detailed documentation of marine meteorological parameters for this period was presented by Rao *et al.* (1985).

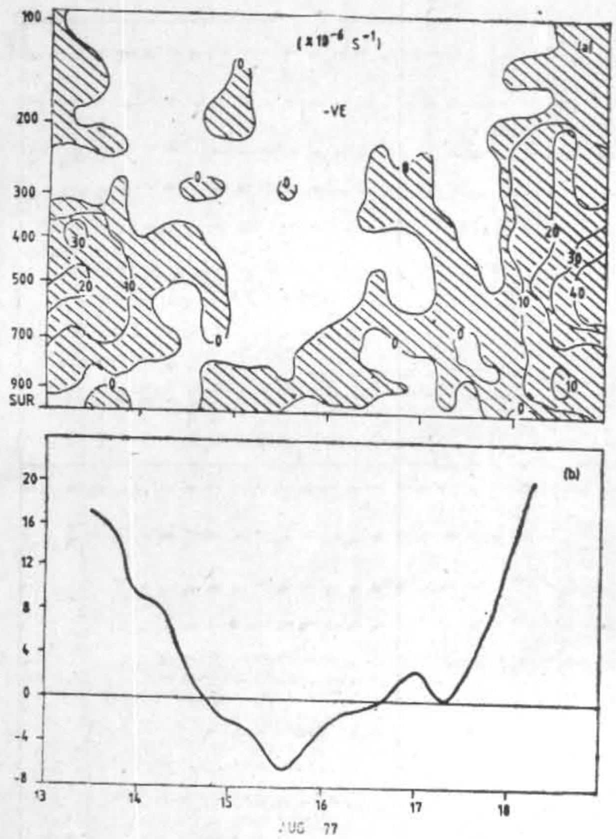


Fig. 3. Relative vorticity (a) field over the polygon area ζr^{500} (b) 500 mb level over the polygon area (ζr^{500})

The approximate geographical locations of all the four U.S.S.R. ships of the stationary polygon were as follows :

North (N) : 19° N, 89° E;
East (E) : 17° N, 89° E;
South (S) : 15° N, 87° E;
West (W) : 17° N, 87° E.

The surface synoptic maps at 1200 GMT analysed by Northern Hemispheric Analysis Centre, New Delhi from 17th are shown for the Bay of Bengal in Fig. 1(a). The formation of the depression over the Head Bay is clearly seen only on 19 August.

The time sequence of satellite derived cloud cover in the visible band from 13 to 20 August is shown in Fig. 1(c). The Head Bay was almost free from cloudiness from 15th till 17th and only on 18th widespread cloud clusters appeared over the northern Bay of Bengal. A bright cloud patch associated with a depression moved northwestward with further intensification.

Raman *et al.* (1978) studied the variability of the vertical zonal wind shear at the coastal and ship stations (Monsoon-77) over the Bay of Bengal. They reported that fall in wind shear acts as an important precondition for the formation of a disturbance over the Bay of Bengal. Fig. 1(b) shows the six hourly variation of vertical wind shear (S_z) at four coastal stations and one island station in the near vicinity of the stationary polygon.

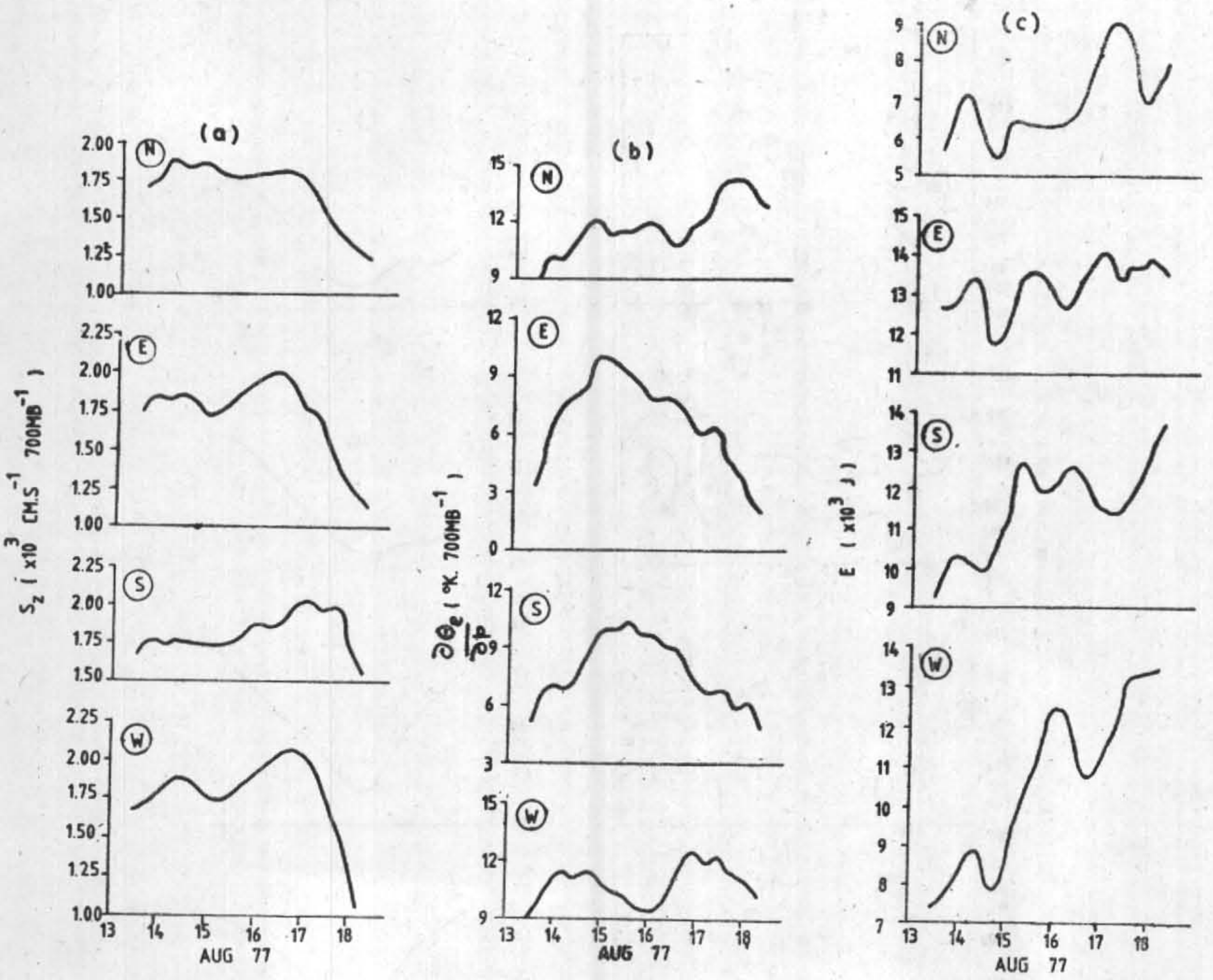
All the coastal stations exhibited drop in the vertical wind shear towards the end of the observational period. This drop commenced early at the northern coastal stations (15 August at Calcutta and Bhubaneswar) and progressed southward (17 August at Visakhapatnam and 18 August at Madras). This feature implies that conditions first became favourable at the Head Bay about 4 days before the actual genesis took place. This may be considered as an important indicator at the Head Bay before the actual genesis took place. On the contrary, the wind shear at the island station, Port Blair showed a progressive increase during the observational period.

The vector wind field from surface to 100 mb is depicted for all the ships in Fig. 2. Low level westerlies and comparatively stronger upper level easterlies are noticed throughout, with a shear line around 500 mb. Backing of winds with height showing the cyclonic circulation in the lower troposphere on 13th, 17th and 18th is prominently seen at all the locations corresponding to the two independent low pressure systems of which the latter one was wider in extent. However, the backing in the lower tropospheric wind regime was more pronounced at the W location on 18th. In general, upper tropospheric easterlies progressively weakened from 13th to 18th at 100 mb at all the locations. This weakening is more prominent at 200 mb at E and W locations compared to the other two while the westerlies in the lower troposphere strengthened on the last two days at E and S locations.

The zonal component of wind is analysed for all the locations but not presented. The shear line indicates close resemblance for all the locations with the exception of the S location. On the whole the zonal flow in the upper troposphere was quite similar at the N, E and W locations. During the disturbed periods the upper easterly regime descended at the N and E locations. Towards the end, the weak vertical wind shears over the northern sector seem to be most favourable for the formation of a depression. Presence of very strong easterlies at 100 mb (20 m/s) could be a probable reason for the non-intensification of the first system.

The six hourly march of vertical shear S_z in the horizontal winds between 900 mb and 200 mb is shown in Fig. 4(a). The S_z was relatively steady till 16th, *i.e.*, 2 days before the genesis of the disturbance at all the four locations. It registered a dramatic drop from 16th onwards at all the locations. But the drop rates differed within the polygon. The magnitude of S_z was nearly halved at the E and W locations. In general, the northern sector of the polygon offered very favourable conditions, *i.e.*, in terms of large reduction in S_z for the formation of the disturbance.

Raman *et al.* (1978) have estimated ζ_r for this polygon area by partitioning the polygon into triangles. They found a conspicuous rise in ζ_r over the eastern and southern triangles towards the end of the phase. The vertical component of the relative vorticity (ζ_r) pattern corresponding to the centre of the polygon computed from the wind field at the four corners of the polygon with finite difference scheme is shown in Fig. 3(a). Two prominent areas with large positive vorticity can be noticed in the lower troposphere on 13th and 18th. Both these correspond to two independent systems, the latter being stronger in magnitude and thicker in vertical extent.



Figs. 4 (a-c). (a) Tropospheric vertical wind shear (S_z), (b) Moist stability gradiant ($\partial\theta_e/\partial p$) and (c) Ocean thermal energy (E)

TABLE 1

Parameter	Gray's choice	Author's choice	Remarks
ζ	At 900 mb	At 500 mb	Larger temporal variability in ζ_r is noticed at 500 mb instead of 900 mb in the present study.
E	With respect to 26° C	With respect to 28° C	In the Bay of Bengal the genesis of meteorological disturbances usually takes place when the SST $\sim$ 28°C (Hastenrath & Lamp 1979 and India Met. Dep. 1979)
$\frac{\partial\theta_e}{\partial p}$	Upper boundary as 500 mb	Upper boundary as 300 mb	Larger temporal variability in the relative humidity is noticed at 300 mb instead of 500 mb in the present study
RH	Upper boundary as 500 mb	Upper boundary as 300 mb	Same as above

Although weak positive vorticity is noticed in the lower troposphere from 15th the actual magnitude of vorticity shot-up suddenly only from 0000 GMT of 18th. This explosive increase is very conspicuous in the following 24 hrs indicating that the actual formation of the depression occurred in a day or two. The maximum positive vorticity was centred at 500 mb in the case of this monsoon depression while the corresponding maximum was reported at 950 mb for the tropical cyclones by Frank (1976). During the undisturbed period the negative voriticity was very weak.

The six hourly march of relative vorticity at 500 mb level ($\zeta_r{}^{500}$) is shown in Fig. 3(b). A very well defined pattern in $\zeta_r{}^{500}$ can be noticed from this figure. The $\zeta_r{}^{500}$ was positive with large magnitude during disturbed weather regimes and was negative during undisturbed weather regimes. The progressively decreased during the first two days as the first sytstem moved away from the polygon towards the Orissa coast. After the short fair weather regime it again strengthened during the last two days under the influence of the later growing system.

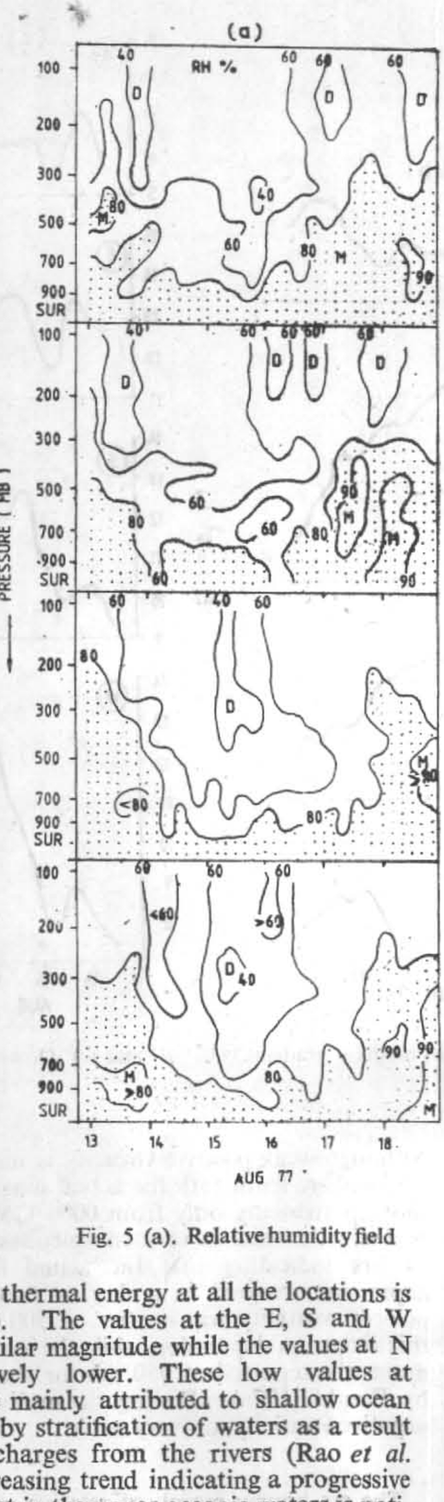


Fig. 5 (a). Relative humidity field

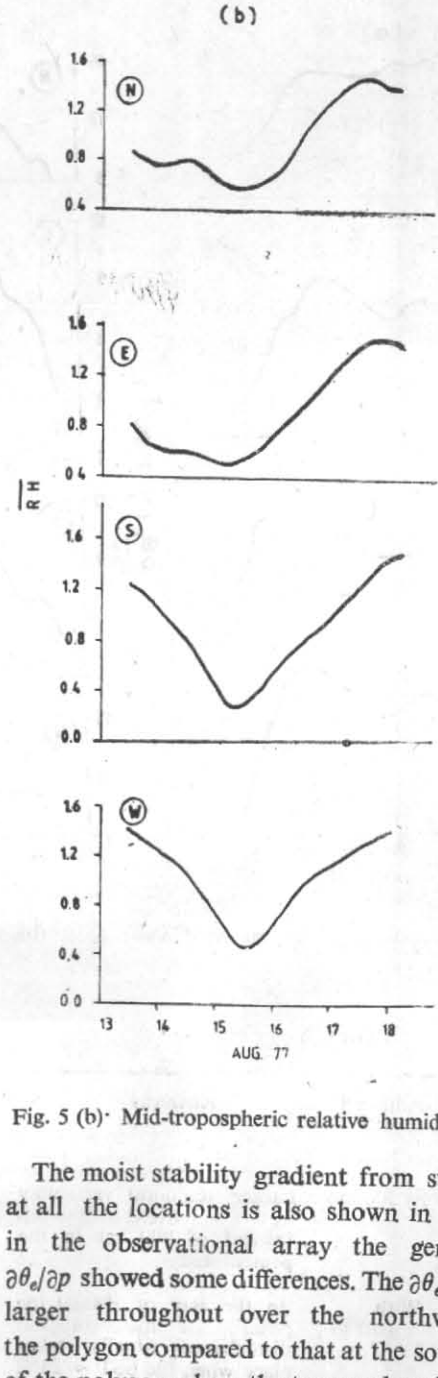


Fig. 5 (b)· Mid-tropospheric relative humidity parameter (RH)

The upper ocean thermal energy at all the locations is shown in Fig. 4(c). The values at the E, S and W locations are of similar magnitude while the values at N location are relatively lower. These low values at the N location are mainly attributed to shallow ocean mixed layer caused by stratification of waters as a result of fresh water discharges from the rivers (Rao *et al.* 1981). A steady increasing trend indicating a progressive accumulation of heat in the upper oceanic waters is noticed at all the locations with variable magnitudes. The accumulation rate was highest at the W location and least at the E location. The rates were of similar nature at the N and S locations. Such rapid accumulation of heat in the upper layers over short durations imply the relative importance of local advective processes over the surface heat exchange processes. This type of growing heat storage in the upper layer of the ocean offers good prospects for the formation of disturbance.

The moist stability gradient from surface to 300 mb at all the locations is also shown in Fig. 4 (b). Within the observational array the general pattern of $\partial\theta_e/\partial p$ showed some differences. The $\partial\theta_e/\partial p$ was relatively larger throughout over the northwestern sector of the polygon compared to that at the southeastern sector of the polygon where the temporal variations were large. The growing large moist instability regime observed over the northwestern sector suggests the favourable conditions for the genesis of the disturbance there.

The relative humidity field is shown in Fig. 5(a) for all the locations. The first one kilometre in the vertical from the oceanic surface was quite moist with relative

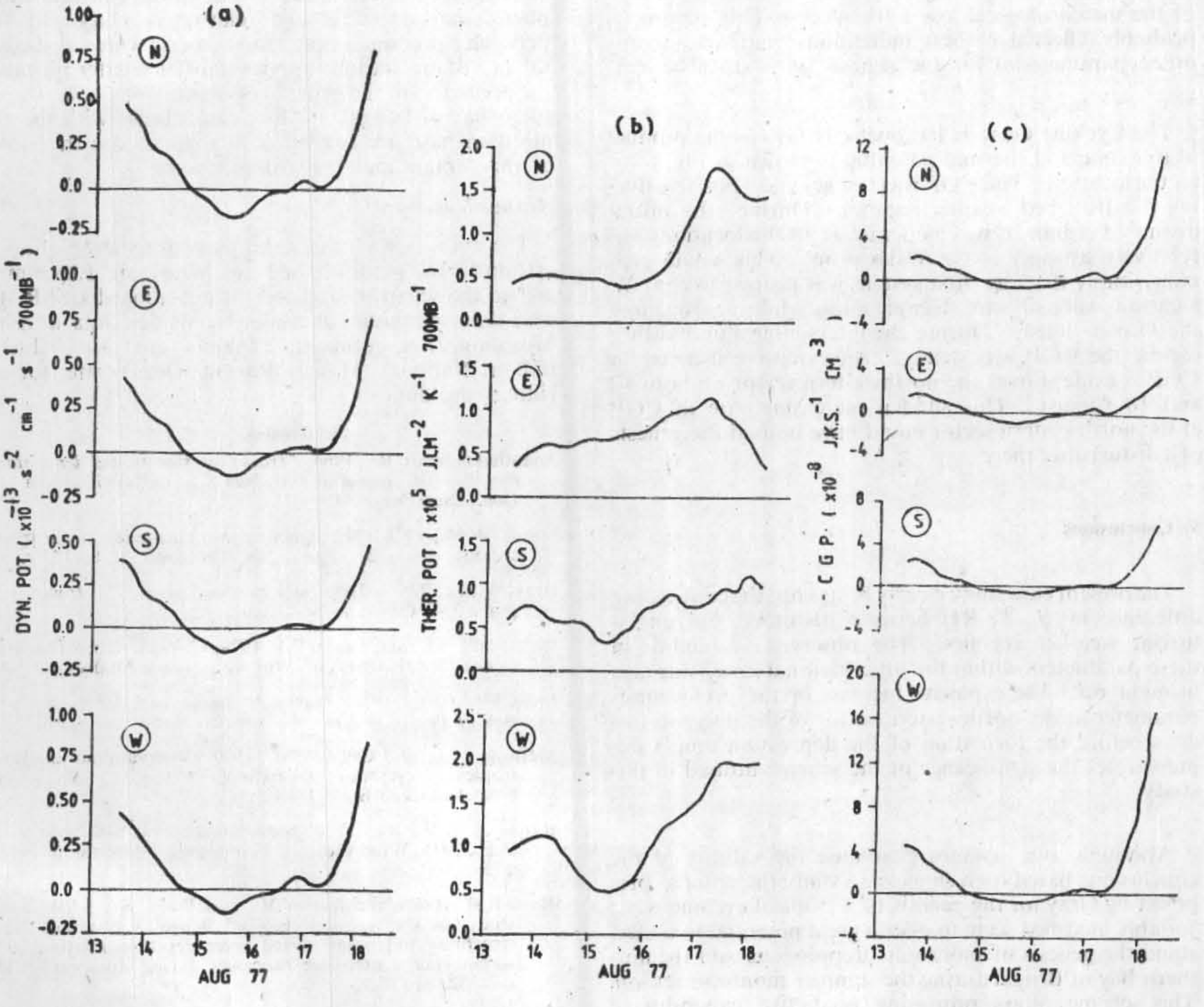


Fig. 6 (a). Dynamic potential Fig. 6 (b). Thermal potential Fig. 6(c). Cyclone genesis parameter

humidity above 80%. From 16th, *i.e.*, during pre-disturbed days, 80% relative humidity contour was ascending at all the locations indicating a possibility for a strong cumulus convection caused by the convergence of the moist air. In between the two disturbances as the weather was relatively fair, dryness prevailed just above one kilometre. Fig. 5(b) shows the mid-tropospheric relative humidity parameter for all the locations. The contrast between disturbed and undisturbed regimes in RH is quite clear from this figure. The values of RH during the disturbed regimes were two to three times of the corresponding values during the intervening fair weather regime. The concave shape of the curves very clearly indicates that moisture penetrated into the mid-troposphere only during the disturbed weather regime.

The dynamic potential as the product of the inverse of the wind shear, relative vorticity at 500 mb level and coriolis parameter is shown in Fig. 6. The predominent reflection of ζ_r^{500} [Fig. 3 (b)] in dynamic potential is evident at all the four locations. The sign of the dynamic potential closely followed that of ζ_r^{500}. It gradually decayed during the first two days as the initial system moved away from the polygon area. The rapid strengthening of the dynamic potential from 17 August onwards is a clear indication for the development of disturbed weather. The milder strengthening in the dynamic potential at the S location, perhaps, suggests that the disturbance might had been formed over the northern sector of the observational array.

The thermal potential as the product of ocean thermal energy, moist instability and mid-tropospheric humidity is shown in Fig. 6. In general, the thermal potential registered a marked increase throughout the polygon during observational period. But the rates of increase during the last few days was relatively larger at the northwestern sector of the polygon where the conditions appeared to be most favourable for the genesis of the disturbance. The rise in the thermal potential at the northwestern sector appeared from 15th, *i.e.*, 3-4 days before the genesis of the meteorological low took place. This parameter probably reflected earliest indications compared to any other parameter(s) for the genesis of a disturbance.

The Cyclone Genesis Parameter (CGP) as the product of dynamic and thermal potential is shown in Fig. 6 for all the locations. The CGP was, in general, positive during the disturbed weather regimes. During the initial disturbed regime, it was moderate at all the locations but relatively stronger at the W location. This would probably imply that the first system was nearest to the W location when it was strengthening while approaching the Orissa coast. During the intervening fair weather regime the CGP was steady. An explosive increase in CGP is evident over the northwestern sector on both 17 and 18 August. This sudden increasing rate in CGP at the northwestern sector might have infused the genesis of a disturbance there.

5. Conclusions

The present case study clearly brings out the contrasting difference in S_z, E, RH between disturbed and undisturbed weather regimes. The observed variability in these parameters within the observational array was also brought out. The explosive increase in the cyclogenesis parameter at the northwestern sector of the polygon two days before the formation of the depression amply demonstrates the significance of the scheme utilised in this study.

Although one cannot generalise the validity of the conclusions based on a single case study the criteria proposed by Gray for the genesis of a tropical cyclone when suitably modified seem to offer a great potential to understand the genesis of monsoon depressions over the northern Bay of Bengal during the summer monsoon season. This scheme offers promising predictive capability if most of the parameters suggested by Gray can be regularly monitored over the Bay of Bengal despite operational constraints. At least a careful monitoring of mid-tropospheric moisture level and relative vorticity and shear between lower and upper tropospheric winds at the coastal and island stations appear to offer greater promise in the predicton of the genesis of depressions over the northern Bay of Bengal. More case studies with the existing data base are suggested to substantiate the validity of this simple and promising scheme.

Acknowledgements

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