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Wave pattern observed in cellular clouds over the Arabian Sea

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सार — पश्चिमी अरब सागर में 8 अगस्त 1985 को निकट कोशिकीय मेघों की सीमा के अंतर्गत एक असामान्य तरंग प्रतिमान का प्रेक्षण किया गया। तरंग प्रतिमान में अलग-अलग पट्टियों की लम्बाई 266 कि.मी. से 345 कि.मी. तक थी और वे निम्न क्षोभमंडलीय प्रवाह से लम्ब की दिशा में पंक्ति बद्ध थी। तरंग प्रतिमान की तरंग लम्बाई 103.3 कि. मी. थी और 28.3 मी. प्रति से. की गति से पूर्व की ओर चल रही थी। यह प्रतिमान, निम्न स्तर जैट की सीमा के अंतर्गत पार्श्विक और ऊर्ध्वाधर पवन अपरूपण के क्षेत्र में, उथले गौण संचरण के कारण उत्पन्न होता है।

ABSTRACT. An unusual wave pattern was observed on 8 August 1985 in the western Arabian Sea within the field of closed cellular clouds. The individual bands in the wave pattern were 266 km to 345 km in length and were aligned normal to the lower tropospheric flow. The wave pattern had a wave length of 103.3 km and propagated eastward at a speed of 28.3 ms^{-1}. The pattern appears to have formed due to shallow secondary circulation in the field of lateral and vertical wind shears within the low level jet.

1. Introduction

Closed cellular clouds usually occur over the central and north Arabian Sea west of Long. 70° E during the southwest monsoon season, at times extending upto the west coast of India during weak monsoou activity (Onkari Prasad *et al.* 1983). The closed cells represent a pronounced and persistent inversion (Agee *et al.* 1973). Such an inversion exists over the western Arabian Sea during the southwest monsoon, with the level of inversion lifting up eastward. An unusual wave pattern was observed in satellite pictures in the field of the cellular clouds over the western Arabian Sea on 8 August 1985. The wave pattern is described in this paper, and factors responsible for its formation are discussed. Cloud pictures received from the Indian geostationary satellite INSAT-1B, with a ground resolution of 2.75 km in the visible channel (0.55-0.75 μm) and 11 km in the infrared channel (10.5-12.5 μm), have been used in this study.

2. Unusual wave pattern in cellular clouds

The INSAT-1B visible channel pictures of 8 August 1985 showed closed cellular clouds over whole of the Arabian Sea north of Lat. 14° N. The cloud cells were arranged in cloud lines or streaks, which were oriented along southwest to northeast direction close to Oman coast and were aligned west to east further southeastward around Lat. 15°N. The cloud organisation indicated southwesterly to westerly difluent flow over the north and central Arabian Sea in the lower levels. West of Long. 60° E, the individual cloud cells had horizontal dimensions less than the ground resolution of the satellite, *i.e.*, 2.75 km in the visible channel, so that they merged into a uniform gray shade. The closed cells increased in width and in vertical thickness in the downwind direction indicating progressive increase in the height of boundary layer eastward.

At the southern boundary of this cellular cloud field, a wave pattern started forming at about 0300 GMT between Lats. 14° N to 17° N and Longs. 56°E to 62°E, northeast of Socotra Island. The pattern developed subsequently, and by 0600 GMT it showed cloud bands consisting of closed cells and separated by equally spaced cloud-free areas (Fig. 1). The cloud bands were more distinct east of Long. 60° E as compared to those between Longs. 56° E and 60° E northeast of Socotra. West of Long. 60° E the individual cloud bands were oriented northwest to southeast, while further eastward they were more longitudinally oriented. The cloud bands thus appeared to be practically normal to the low level flow. Cloud cells within these bands were similar to those occurring further north and showed a progressive increase in their size downwind.

This wave pattern showed its peak development at 0900 GMT (Fig. 2), when 4 well developed bands existed between 'A' and 'B'. The length of cloud bands ranged from 266 km to 345 km. Diffused wave pattern existed on both sides of the well developed bands. The complete wave pattern consisting of 9 waves extended from 14°N, 57.5°E to 16.8°N, 66.5°E. The wavelength increased from west to east and the mean wave length was 103.3 km. The temperature of tops of cellular clouds within the wave pattern ranged from 14°C to 18°C, as derived from INSAT-1B thermal infrared channel (ground resolution 11 km). The cloud top temperatures decreased downwind from west to east. However, considering that the horizontal dimension of individual cloud cells was less than 10 km, the satellite derived cloud top temperatures could be somewhat higher than the actual because of coarse infrared resolution of the satellite sensor viewing the cloud cells, depending upon the temperature of the underlying sea surface and the percentage areal coverage of cloud cells. From these considerations the cloud-top heights could have ranged from 2.0 to 3.0 km, increasing from west to east.

The cloud bands showed eastward movement, as evident from the positions of the individual cloud band 'C' at 0900 GMT (Fig. 2) and 1000 GMT (Fig. 3). The average velocity of propagation of the wave pattern of the cloud bands was westerly, 28.3 m/s (55 kt) between 0600 and 1100 GMT. Although the wave pattern moved eastward, it extended only upto Long. 67°E. Successive waves dissolved on reaching Long. 67°E and merged with the convective clouds which had reached their maximum size by then and were distributed randomly (Figs. 2, 3).

No upper air observations were available from this area for 8 August 1985. The only surface observation, a ship at Lat. 19°N, Long. 66°E reported a surface wind of WSW/30 kt on 8th afternoon, indicating the likelihood of strong westerly winds in the lowest layers of the troposphere in which the wave pattern existed. The existence of low level jet within southwesterly monsoon current over the central and south Arabian Sea has been reported by several authors on the basis of observations gathered during various monsoon experiments, *e.g.*, IIOE 1962, ISMEX 1973, MONEX 1977 and Monsoon 1979 (Bunker 1965; Pant 1978; Kuettner & Unninayar 1981; Mohanty *et al.* 1982) wherein wind speed upto 60 kt at 500-1500 metres above m.s.l. have been observed. The wave pattern appears to have moved with this low level jet.

3. Discussions

The cloud bands appear to have formed at the interface of the boundary layer and the overlying inversion/isothermal layer. As no direct observations from these layers are available, an indirect estimation of the thermodynamic conditions is attempted below.

The existence of the inversion in the lower tropospheric layers over the Arabian Sea north of Lat. 14° N is evident from the cellular cloud pattern over this area, extending upto the Gujarat-Maharashtra coast. The height of the base of the inversion layer is given by the top of cloud cells, *i.e.*, 2-3 km above the sea level. The base of the cellular clouds may be taken as 500-1000 metres above sea level.

From the satellite pictures the cloud pattern appears to correspond to a fast moving (28.3 m/s) wave pattern of considerable lateral extent (≈300 km). If one assumes that this pattern is of the billow cloud type, then the two-dimensional small amplitude theory (Scorer 1978) shows that the most likely wave length 'λ' which will appear in a vortex layer of thickness 'h' (Fig. 4) is

$$\lambda = 4\pi h \tag{1}$$

Thus, for a wave length of 103.3 km to become unstable, the depth of the vortex layer should be more than 8.0 km. This instability cannot set in unless the Richardson number is less than 0.25 within the vortex layer.

Assuming the value of Richardson number R_i to be 0.25 in the vortex layer and from the relationship

$$R_i = \frac{g\beta}{\eta^2} = \frac{\pi h}{\lambda} \tag{2}$$

where, g = acceleration due to gravity,

$\beta = (1/\theta).\partial\theta/\partial z$, static stability factor,

$\eta = \partial u/\partial z$, vertical wind shear,

and θ = potential temperature

we get the minimum value of the vertical wind shear required for the formation of billow clouds:

$$\frac{\partial u}{\partial z} = 2 \, . \, (g.\beta)^{\frac{1}{2}} \tag{3}$$

Thus, the vortex layer should have a small potential tempeature gradient in vertical alongwith a large vertical wind shear. As no upper air observations are available from this area, the authors have tried to derive the static stability factor β and vertical wind shear $\partial u/\partial z$ from the mean charts for the month of August based on International Indian Ocean Expedition (IIOE) 1963 data (Ramage & Raman 1972) and from observations for Seeb airport (23.6°N, 58.3°E), the nearest station from which upper air data are available for 8 August 1985. From the IIOE data it is seen that in the layer between 850 and 500 mb over the area of our interest the potential temperature gradient is 4.4°K per km, corresponding to a value of β equal to 13.9×10^{-6}m^{-1}. For Richardson number to have the proper value, the vertical wind shear should be close to 23.3 ms^{-1} per km in the vortex layer. This value of estimated wind shear is not supported by the IIOE data which show wind speeds of less than 35 kt at all levels below 100 mb and the average vertical wind shear of less than 2.5 ms^{-1} per km between 850 mb and 200 mb. Similarly from Seeb observations the corresponding values are 5.0×10^{-6}m^{-1} for β and 13.9 ms^{-1} per km for the vertical wind shear in the vortex layer. Again, this theoretically estimated wind shear is not supported by wind observations at Seeb which show a vertical wind shear of only 1.4 ms^{-1} per km between 850 mb and 200 mb. It, therefore, appears reasonable to assume that strong wind shears through a vortex layer of more than 8.0 km thickness required for the formation of billow clouds of this magnitude do not prevail over the area of our interest. Climatologically, strong vertical wind shears are expected over the region of interest only in the lower troposphere below 2.0 km, where a low level jet exists during monsoon regime. Thus, the presence of a deep layer of strong wind shear in the vertical and small stability as required by the dynamics of billow clouds, does not appear to be borne out by the available observations.

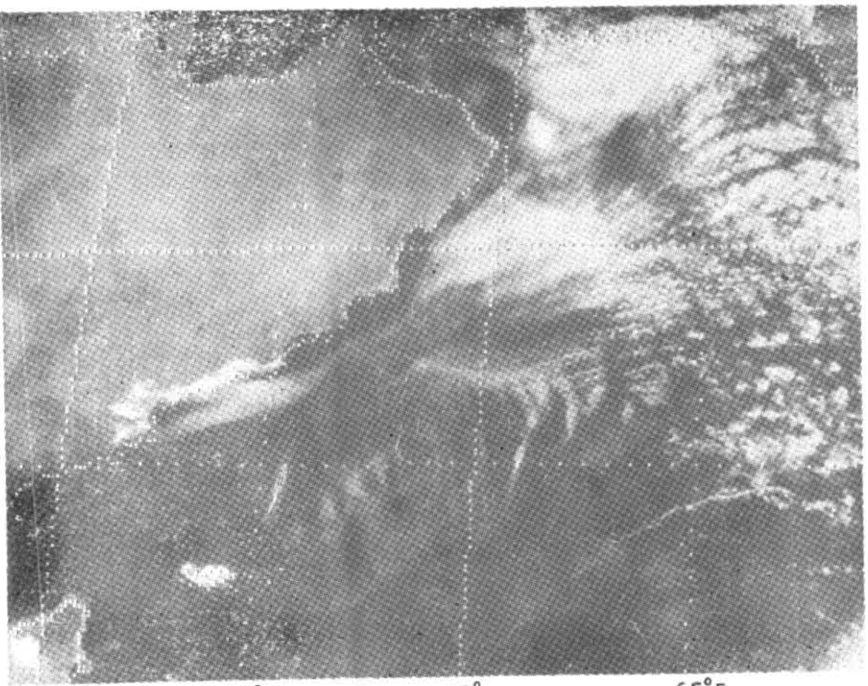

Fig. 1. INSAT-1B visible channel picture of 0600 GMT on 8 August 1985 showing the initial stage of development of wave pattern in the field of closed cellular clouds in the Arabian Sea northeast of Socotra

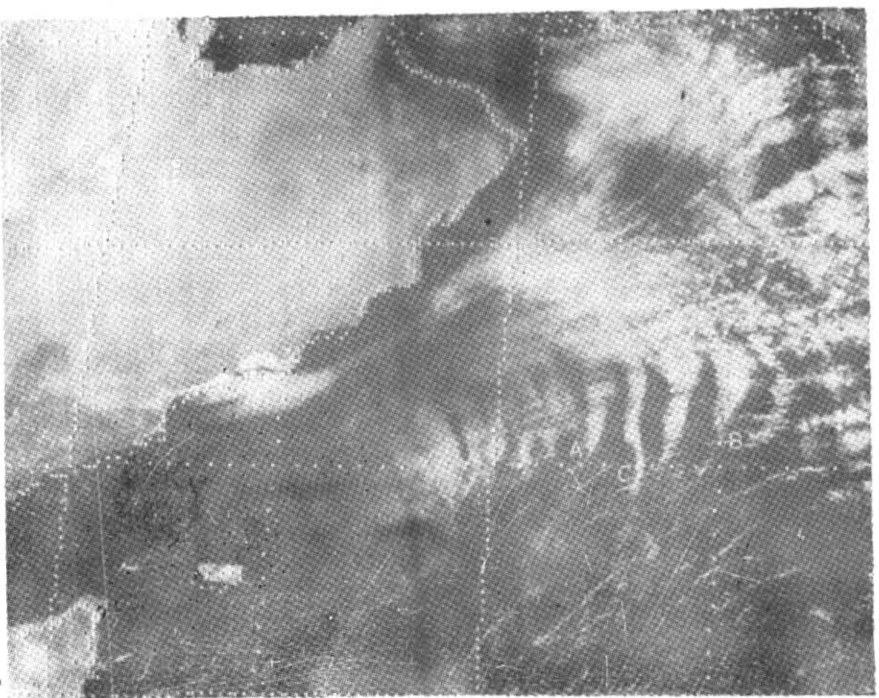

Fig. 2. INSAT-1B visible channel picture of 0900 GMT on 8 August 1985 showing the fully developed wave pattern in the Arabian Sea

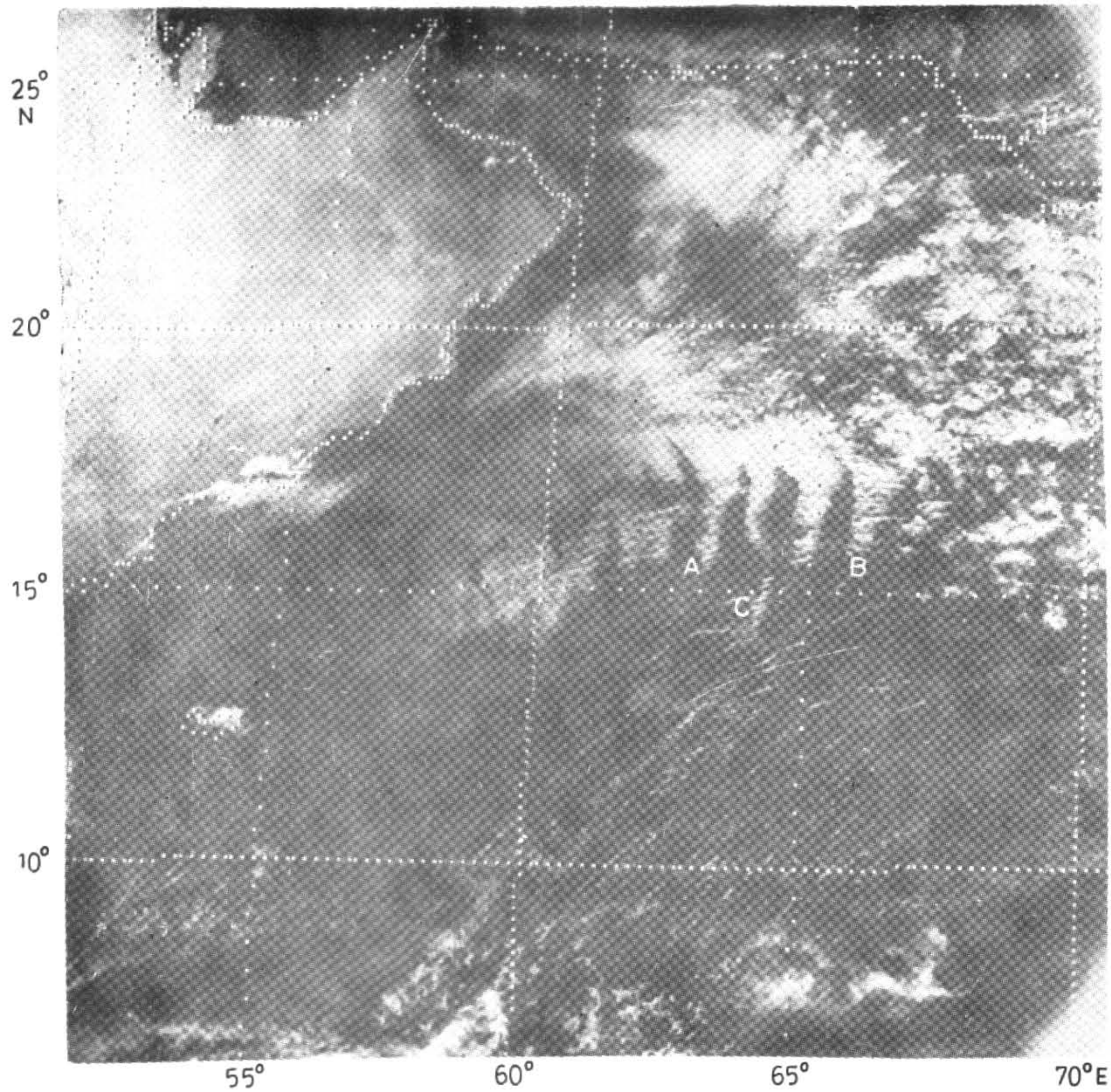

Fig. 3. INSAT-1B visible channel picture of 1000 GMT on 8 August 1985. Note the movement of bands A, B and C within the wave pattern since 0900 GMT (Fig. 2)

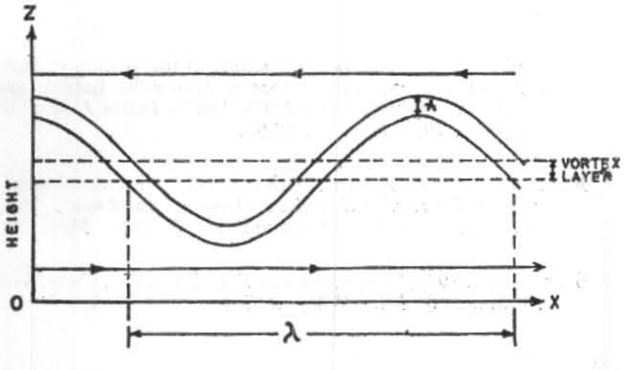

Fig. 4. A sinusoidal perturbation of the vortex layer of thickness '*h*' which may result in the formation of billows (*After* Scorer 1978)

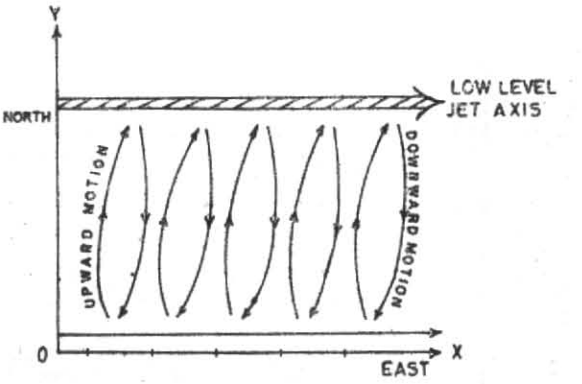

Fig. 5. A schematic of shallow secondary circulation cells projected in horizontal plane. The air parcels moving northward are simultaneously moving vertically upward. Similarly, air parcels moving southward are also moving downward.

The alternative mechanism, which probably explains the observed cloud pattern satisfactorily, envisages shallow secondary cells of motion produced by the relatively smaller vertical shear and the coriolis force (Scorer 1978). The secondary circulation in the y-z plane can exist when an air-stream is moving in x-direction with static stability β, such that the horizontal and vertical wind shears satisfy the criteria:

$$\left(\frac{\partial u}{\partial z}\right)^2 \geqslant g\beta\left(\left(1-\frac{\partial u}{\partial y}\right)\Big/ f\right) \qquad (4)$$

where, $\partial u/\partial y$ = horizontal shear

$\partial u/\partial z$ = vertical shear

$\beta = (1/\theta)\,\partial\theta/\partial z$ = stability parameter

f = Coriolis parameter (3.8×10^{-5} s^{-1} at Lat. 15°N)

When the relationship (4) is fulfilled, any parcel moving across the flow northward and upward will gain energy from the basic flow and its motion will be sustained. Same is the case for parcels moving southward and downward. Such a motion, confined in a plane normal to the basic flow, will have large horizontal dimension compared to its vertical extent and will constitute a "shallow secondary cell" of motion and is most likely to appear in the region where $\partial u/\partial y$ is positive, *i.e.*, anticyclonic (Scorer 1978). Putting the value of β obtained from the IIOE upper air data, *viz.*, 13.9×10^{-6} m^{-1} and assuming typically $\partial u/\partial y\sim\frac{1}{2}f$ in the anticyclonic shear region, we see that the above criteria are satisfied for vertical wind shear exceeding 8.3 ms^{-1} per km. Even when lateral shear is zero the critical vertical wind shear does not exceed 11.7 ms^{-1} per km. For larger lateral shear, *i.e.*, $\partial u/\partial y>\frac{1}{2}f$ the value of critical vertical wind shear is less than even 8.3 ms^{-1} per km. This value of wind shear is likely to be exceeded during the southwest monsoon season below 850 mb level due to appearance of the low level jet over the Arabian Sea.

In the cyclonic shear region $\partial u/\partial y$ is negative and its magnitude may be as high as 10 times the value of the coriolis parameter. In that case the minimum value of vertical wind shear, for which the secondary circulation may be self sustaining, is 38.7 ms^{-1} per km approximately. Even if the actual values of the lateral wind shear do not satisfy this condition on the cyclonic shear side, shallow secondary circulations can appear on the anticyclonic shear side where the condition (4) is satisfied with much smaller vertical shear $\partial u/\partial z$. Fig.5 shows a schematic of the secondary circulation cells, that formed within the field of horizontal and vertical wind shear, projected in the x-y plane. In case such a secondary circulation is present on the anticyclonic shear side, the aspect ratio of the secondary cells, *i.e.*, the height to the horizontal extent is given by:

$$\frac{c}{b}=\left[f\left(f-\frac{\partial u}{\partial y}\right)\Big/ 2g\beta\right]^{\frac{1}{2}}\approx\frac{f}{2\cdot(g\cdot\beta)^{\frac{1}{2}}}$$

Using the same values of β and $\partial u/\partial y$ we get $c/b\approx1.7\times10^{-3}$. Hence, if the horizontal extent of the secondary circulation is about 350 km then each parcel will get vertically displaced by about 0.6 km. The cellular circulation of individual cloud cells will be superposed on this secondary circulation. The presence of an inversion layer above the layer of small static stability will restrict the tops of cellular clouds to the bottom of the inversion.

One of the regions where the above kind of instability can occur is the exit region of the jet stream and the location of the present cloud pattern might be the region where the low level monsoon jet decelerates. Thus, most of the features of the cloud pattern can be explained by assuming that the clouds formed due to secondary circulation induced vertical velocity in a shallow layer of small stability topped by an inversion layer. The wave pattern, with cloud bands and intervening clear patches corresponding to the subsidence, was carried down wind by the low level jet.

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