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Momentum exchange between cloud bands and the low level flow in the Arabian Sea

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सार – 24 जून 1979 को मुख्य रूप से NCAR के इलेक्ट्रा द्वारा एकत्रित किए गए आंकड़ों का प्रयोग करते हुए अरब महासागर में संवहनी स्तरों में संवेग फ्लक्सों $\overline{u'w'}$ और $\overline{v'w'}$ के उर्ध्वाधर वितरण को आकलित किया गया था। उपर्युक्त u वृद्धि की दिशा के साथ है और v, u दक्षिणावर्त के लम्ब में है। परिणामों से पता चलता है कि पूर्वी अरब सागर (पू.अ.सा.) में $\overline{u'w'}$ का उर्ध्वाधर वाहन 3 कि. मी. के नीचे प्रत्याप्रवण था। मध्य अरब सागर में (म.अ.सा.) $\overline{u'w'}$ का प्रदर्शन पूरे मेघ स्तर (पू.अ.सा. के समान) में उर्ध्वाधर संवेग प्रवण के विरुद्ध थे। संवेग फ्लक्स की उत्पत्ति के लिए प्रभावी बातें पू. म.सा. के समान ही थी। गतिक ऊर्जा अपांतरण के मूल्यांकन से पता चलता है कि बृहत मान प्रवाह गतिक ऊर्जा म.अ.सा. के ऊपर मेघ स्तरों से प्राप्त करता है, किन्तु पू.अ.सा. मेघ स्तरों को अपनी ऊर्जा स्थानांतरित कर देता है।

ABSTRACT. Vertical distribution of momentum fluxes $\overline{u'w'}$ and $\overline{v'w'}$ were computed in convective bands over the Arabian Sea, using the data gathered mainly by the NCAR's *Electra* on 24 June 1979. In the above u was along the direction of growth and v was orthogonal to u, right handed. The results revealed that, in the Eastern Arabian Sea (EAS) the vertical transport of $\overline{u'w'}$ was countergradient below 3 km. In the Central Arabian Sea (CAS), the $\overline{u'w'}$ profile was against the vertical momentum gradient throughout the cloud layer (similar to EAS). The dominant terms for the generation of momentum flux were the same as those in the EAS. An evaluation of the kinetic energy conversion showed that the large-scale flow received its kinetic energy from the cloud bands over the CAS but transferred its energy to the EAS cloud bands.

1. Introduction

The establishment of monsoon over the Arabian Sea in early summer takes usually the form of cloud bands. These cloud bands are oriented nearly parallel to the low level flow. They propagate slowly. In certain locations they propagate northnortheast and certain other locations southeast. According to earlier studies the cloud bands are typically of about 60 km in length separated by about 20 km. These bands could cause heavy rainfall over the west coast of India and are thus worth a thorough study. The purpose of this article is to present briefly the composite structure of cloud bands over the Eastern Arabian Sea (EAS) and Central Arabian Sea (CAS). The composite structure was mainly obtained on the basis of the NCAR's (sponsored by NSF) *Electra*'s slow response (one sample per second) data of u, v, w, T and q gathered as part of Summer Monsoon Experiment (SMONEX-79). The dropwindsonde observations and the neighbouring ship observations of u, v, T and q were also utilized. Under the assumption of two dimensionality and quasi-steady state these data were used to construct a two-dimensional (x-z, x- direction of growth of the band) composite structure. Some of the structures of u, v, cloud line, perturbation pressure, vertical velocity on a mesoscale ($\sim$6 km) are presented. The momentum fluxes $\overline{u'w'}$ and $\overline{v'w'}$ are shown along cross-sections in the EAS and CAS.

Prior investigators discussed the possible relationship between convection, inversion and the low level westerly jet stream (LLWJ). Our study presents detailed kinematic, and dynamic structures of bands. Utilizing these structures many key mechanisms of the kinetic energy transfer, generation of momentum flux etc can be discussed. In the current article we chose to examine quantitatively the interchange of kinetic energy between cloud bands and LLWJ in the EAS and CAS.

2. Synoptic situation, data collection and accuracy

The synoptic situation for 24 June 1979 was discussed in general terms by Sikka and Grossman (1980) and Meyer and Rao (1985). The cloud bands appeared in the EAS between 00 and 05 UTC from a disorganized cloud mass which was detected at 00 UTC of 24 June. The more intense convection appeared to be organized into four bands at 06 UTC parallel to LLWJ. These bands dissipated by 13 UTC. The *Electra* flew across the bands at different elevations. The bands moved slowly and appeared to show only gentle development. Thus the quasi-steady and two-dimensional assumption of these bands appear to be reasonable.

Fig.1 shows the *Electra* and *P3* flight tracks (for details of the track and the elevations where the *Electra* observations were made ; *see* Meyer and Rao 1985).

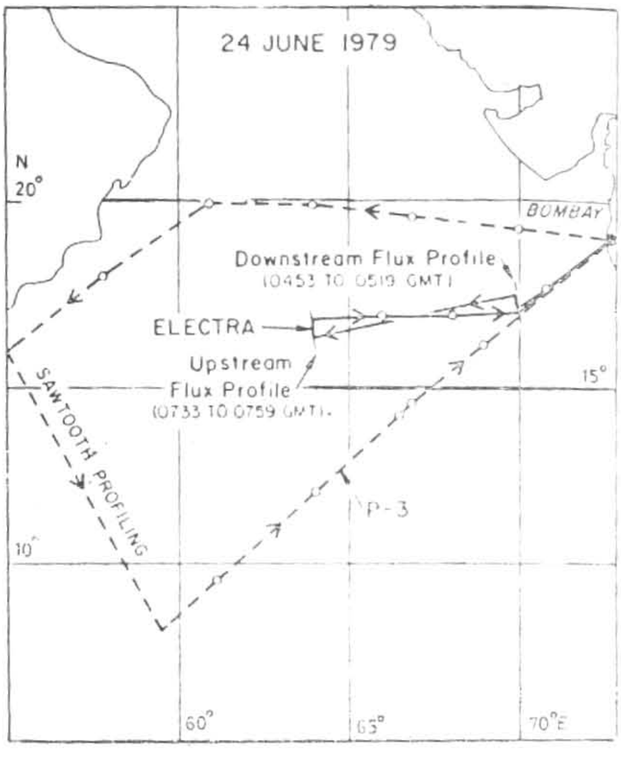

Fig. 1. Plan view of NCAR *Electra* and NOAA *P*-3 flight track for 24 June 1979 (*from* Grossman and Durran 1984)

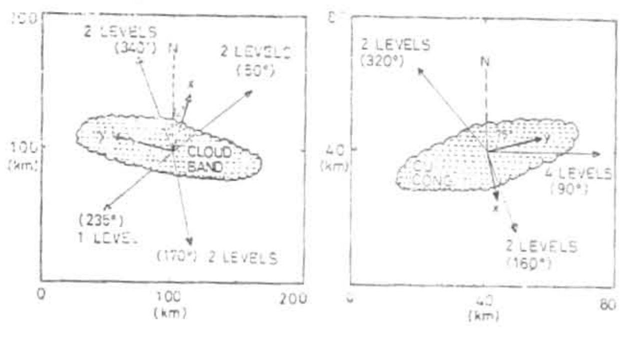

Fig. 2. (*Left*) Composited westnorthwest-eastsoutheast oriented cloud band in the eastern Arabian Sea on 24 June 1979. The x-axis points toward the direction of propagation. This composite was propagating 12 northnortheast. The levels where reconnaissance missions occurred are also shown with the heading angle orientation.

(*Right*) Same as *Left* except the composited cloud band is rotated pointing southsoutheast.

Fig. 2(L) shows the coordinate axes for a study of the bands in the EAS. The z-axis was rotated clockwise 12° from the north. The *Electra* penetrated the bands at 320, 580, 1000, 1610, 2840, 3170 and 4900 m from different directions as indicated. The characteristics and error estimates of the *Electra* instrumentation were discussed by Meyer and Rao (1985).

Fig. 2(R) shows the coordinate axes for a study of the bands in the CAS. The x-axis was rotated 165° clockwise from the north. The *Electra* penetrated the cloud bands at 90, 300, 960, 1590, 1930, 2580, 2890 and 3120 m from different directions as indicated.

In the following mean motion along the flight legs within cloud bands is obtained by averaging over 54 km distances over EAS and 40 km over the CAS. The power spectrum of kinetic energy over the EAS revealed a dominance of scale of about 6 km. Furthermore, the updraft core strength and coverage showed that the measured momentum flux was associated with cores of scale less than 6 km agreeing with the GATE results of Zipser *et al.* (1981) and LeMone (1983). These evidences supported the construction of a composite cloud band in the mesoscale. A one minute running mean of u, v and w over distances of 54 km for EAS and 40 km for CAS was performed at different elevations. The distinguishing mark of the cloud band was the leading edge (*see* LeMone 1983 for a definition of the leading edge). The slope of the cloudline was estimated as 58° in the EAS and 70° in the CAS from the vertical by using the IR measured temperatures at various elevations.

3. Cross-sectional structures

Fig. 3 shows the u-component within a cloud band in the EAS along x-axis which is the direction of propagation of a band (*see* Fig. 2L). The slant line denotes the cloud's leading edge. Similar cross-sections for v in the EAS and u and v in the CAS were also constructed but not shown.

The momentum fluxes $\overline{u'w'}$ and $\overline{v'w'}$ were directly calculated from the *Electra* measurements of u, v and w. Contaminated data, which accounted for only 3% of leg, was ignored. Another source of error was the possibility that the measured mean vertical velocity was biased by the encounter of a few large events but Zipser and LeMone (1980) found this possibility to be less frequent. The leg-to-leg differences inside and outside the active regions of the cloud (LeMone 1983, LeMone *et al.* 1984) were also another source of error. This error was reduced by partitioning the fluxes into active and non-active regions and normalizing all averages to correspond to 54 km over EAS and 40 km over CAS.

Fig. 4 shows $\bar{u}$ (positive along x-direction which is northnortheastward) averaged for each flight leg across the composited cloud band in the EAS. Similar profiles for $\bar{v}, \bar{w}$ in the EAS and $\bar{u}, \bar{v}$ and $\bar{w}$ for the CAS cloud bands were derived but not shown.

Fig. 4(R) shows the vertical profile of $\overline{u'w'}$ and $\overline{v'w'}$. The $\overline{u'w'}$ is negative below 3 km and is against the gradient of $\bar{u}$. Such countergradient momentum transport was noticed in the GATE cloud systems earlier by LeMone (1983). She postulated a mso-low pressure centre in the cloud which would draw air and cause this type of momentum transport. The $\overline{v'w'}$, however, is along the gradient of $\bar{v}$ (the profile of $\bar{v}$ not shown). The corresponding profiles of $\overline{u'w'}$ and $\overline{v'w'}$ in the CAS are similar but they are positive.

Fig. 5 shows the mesoscale velocity w_m along x-axis (positive northnortheast). This vertical velocity is obtained by integrating two-dimensional anelastic continuity equation :

$$\frac{1}{\rho}\left(\frac{\partial(\rho\, w_m)}{\partial z}\right) = -\frac{\partial u_m}{\partial x} \qquad (1)$$

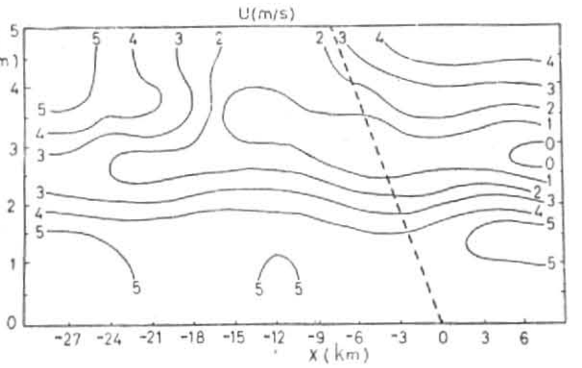

Fig. 3. Cross-section of the composite mesoscale u field along the x-axis (positive northnortheast) over the eastern Arabian Sea. Slant line (about 58° from the vertical) denotes the cloud's leading edge. The vertical exaggeration is 4 to 1.

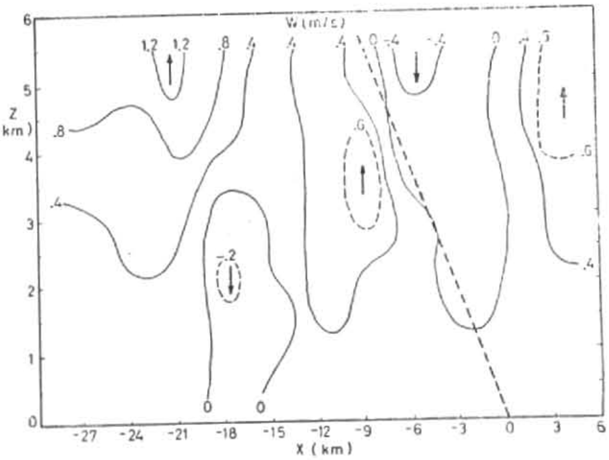

Fig. 5. Cross-section of the mesoscale vertical velocity w_m along x-axis (positive northnortheast) calculated from two-dimensional continuity equation and u_m (Fig. 4) over the eastern Arabian Sea. Slant line (about 58° from the vertical) denotes the leading edge. The vertical exaggeration is 4 to 1.

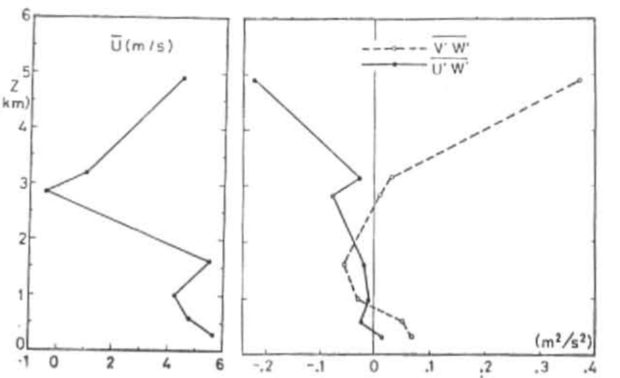

Fig. 4. (*Left*) Vertical profile of wind component $\bar{u}$, averaged in flight leg at each level across the composited cloud band in the eastern Arabian Sea on 24 June 1979. $\bar{u}$ is positive northnortheast, in the direction of band motion (*see* Fig. 2L)

(*Right*) Profiles of the vertical flux of horizontal momentum $\overline{u'w'}$ (solid line) and $\overline{v'w'}$ (dashed line) over the eastern Arabian Sea on 24 June 1979

In the finite difference analogue $\triangle z = 500$ m and $\triangle x = 3000$ m, u_m and w_m are the mesoscale winds and $\bar{\rho}$ is the level averaged air density obtained from the adjacent ship polygon in early June 1979.

Highlights of this figure are the ascent at 3.5 km. Air entered the cloud composite through the front of the leading edge between 2 and 4 km. Deep ascent is experienced behind the leading edge. The ascent itself is associated with a low pressure centre in the perturbation pressure p' field (not shown). Some descent is shown about 18 km in the back at an elevation of 1.5 km where the LLWJ is located. This vertical velocity pattern compared favourably with the leg averaged aircraft observed vertical velocity.

The transfer of kinetic energy from a convective system to a large scal system was studied by Sun (1978) for moist convection. Tne relevant formulas are:

$$(\bar{K}, K')_u = -\overline{u'w'}\,\frac{\partial \bar{u}}{\partial z} \qquad (2)$$

and

$$(\bar{K}, K')_v = -\overline{v'w'}\,\frac{\partial \bar{v}}{\partial z} \qquad (3)$$

These equations are evaluated from data.

It was found that in the EAS below 2.5 km the large scale (LLWJ) is supplying KE to the convective cloud bands and consequently suffered a decrease in intensity. Winds in general weakened as the west coast is approached.

It was noticed that in the CAS the transfers were stronger than those in EAS. The LLWJ located at 1 km was receiving KE from convection. This agrees with the observation that winds in CAS were intense. This cloud system in turn, must have received its energy from the sea surface and from the latent heat release.

4. Further work

The above study pointed at the importance of momentum flux in cloud bands. Since the LLWJ is usually strong around 1.5 km elevation and develops strong shears the kinetic engery exchange between cloud bands and LLWJ must go on steadily. The key factors responsible for the up or downward momentum fluxes in cloud bands should be investigated in the manner of LeMone (1983) from all available observations. The direction of propagation of these bands, their orientation with respect to LLWJ, their development in the vertical, the role of dry air travelling in the middle levels from the neighbouring desert locations and the role of inversion over the western Arabian Sea in this developmental processes must be investigated. Some of these problems are currently being investigated at St. Louis University.

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