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A study on the convective structure of the atmosphere over the West Coast of India during ARMEX-I

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सार – केरल में दक्षिण–पश्चिम मानसून (द. प. मा.) का आरंभ तीव्र संवहन से संबंधित है जिसके कारण भारत के पश्चिमी तट पर भारी वर्षा होती है। भारी वर्षा की घटनाएँ सामान्यतः मेसोस्केल संवहनीय तंत्रों से संबद्ध होती है जो अरब सागर में बड़े पैमाने पर सिनॉप्टिक तंत्रों में सन्निहित होती है। वर्षणीय कपासी मेघों में पानी की मात्रा में परितर्वन से संबद्ध ऊर्जा अंतरणों की अधिक मात्रा और क्षेाभमंडल में तीव्र ऊर्ध्ववाह और अधोप्रवाह के कारण ऐसे गहन और तीव्र कपासी संवहन का विस्तृत पैमाने के वायुमंडलीय तंत्रों की गतिकीय और ऊर्जा विज्ञान पर महत्वपूर्ण प्रभाव पड़ सकता है।

इस अध्ययन का मुख्य उद्देश्य आरमेक्स-I (अरब सागर मानसून प्रयोग) के दौरान भारत के पश्चिमी तट में वायुमंडल की संवहनीय संरचना (सक्रिय/निष्क्रिय) को समझना है। इस अध्ययन में मेघ समूह की औसत संरचना और पर्यावरण के साथ उसका परस्पर संबंध जानने का प्रयास किया गया है जिससे गतिमितीय और संवहनीय प्राचलों के निष्क्रिय से संवहनीय रूप में सक्रिय होने की प्रक्रिया में विविधता के अंतर का पता चलता है। चार तटीय स्थल केंन्द्रों नामतः मुंबई, गोवा, मैंगलोर और त्रिवेंद्रम तथा साथ ही ओ. आर. वी. सागर कन्या से प्राप्त किए गए उपरितन वायु प्रेक्षणों का उपयोग इन प्रेक्षण स्थलों द्वारा निर्मित बहुभुज के केन्द्र के संवहनीय और गतिमितीय दोनों प्राचलों का आकलन करने के लिए किया गया है। भारत के पश्चिमी तट से परे सक्रिय और निष्क्रिय सवंहनीय चरणों के दौरान समय औसत परिसंचरण गतिमितीय प्राचलों और ऊर्ध्वाधर वेग का इसमें विवेचन किया गया है। दक्षिण पश्चिम मानसून की प्रबल और कमजोर अवस्था के दौरान तापगतिकीय समीकरणों के अवशिष्टों के माध्यम से आभासी उष्मा और आभासी नमी में कमी का भी इसमें आकलन किया गया है।

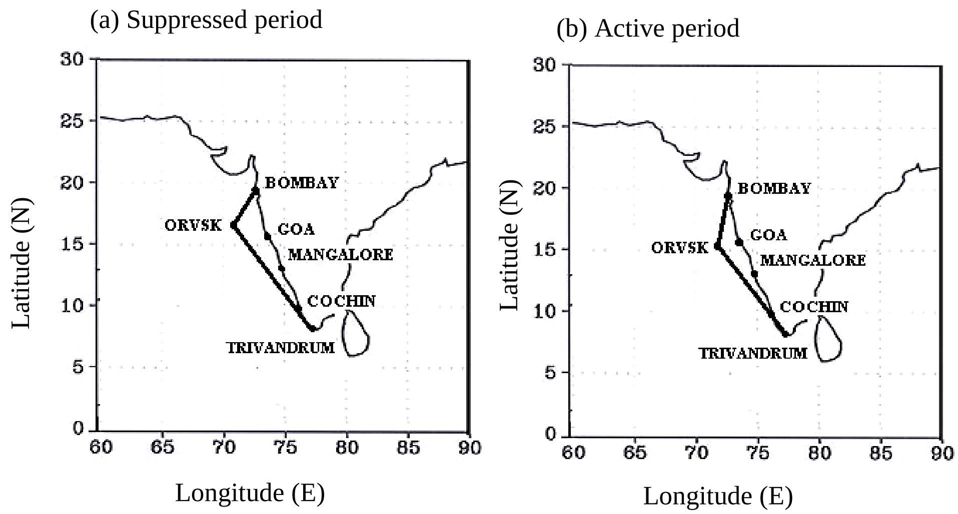
ABSTRACT. Onset of south west monsoon (SWM) over Kerala is associated with intense convection followed by heavy rainfall over the west-coast of India. The intense rainfall events are usually associated with meso-scale convective systems embedded in large scale synoptic system over the Arabian Sea. Such deep and intense cumulus convection can have an important effect on the dynamics and energetics of large-scale atmospheric systems, because of the large magnitudes of the energy transformations associated with changes of phase of water in precipitating cumulus clouds as well as the strong updrafts and downdrafts in the troposphere.

The prime objective of this study is to understand the convective structure (active/suppressed) of the atmosphere over the west-coast of India during ARMEX-I (Arabian Sea Monsoon Experiment). This study uses an approach to obtain the average structure of a cloud cluster and its interaction with the environment that enables in distinguishing the variation of kinematic and convective parameters from suppressed to convectively active process. Upper air observations obtained from four coastal land stations *viz*., Bombay, Goa, Mangalore and Trivandrum, alongwith that obtained over ORV Sagar Kanya are used to calculate both the convective and the kinematic parameters at the centre of the polygon formed by these observation locations. Time averaged circulation kinematic parameters and vertical velocity during active and suppressed convective phases off the west coast of India were discussed. The apparent heating and the apparent moisture sink are also estimated through residuals of the thermodynamic equations during intense and weak phases of SWM.

Key words − ARMEX, Convection, Arabian Sea.

1. Introduction

Onset of South West Monsoon (SWM) over Kerala is associated with intense convection followed by heavy rainfall over the west-coast of India. During SWM, there are spells of heavy rainfall alternate with spells having little or no rainfall. At times the rainfall is as high as 50 cm a day at some stations. These intense rainfalls are



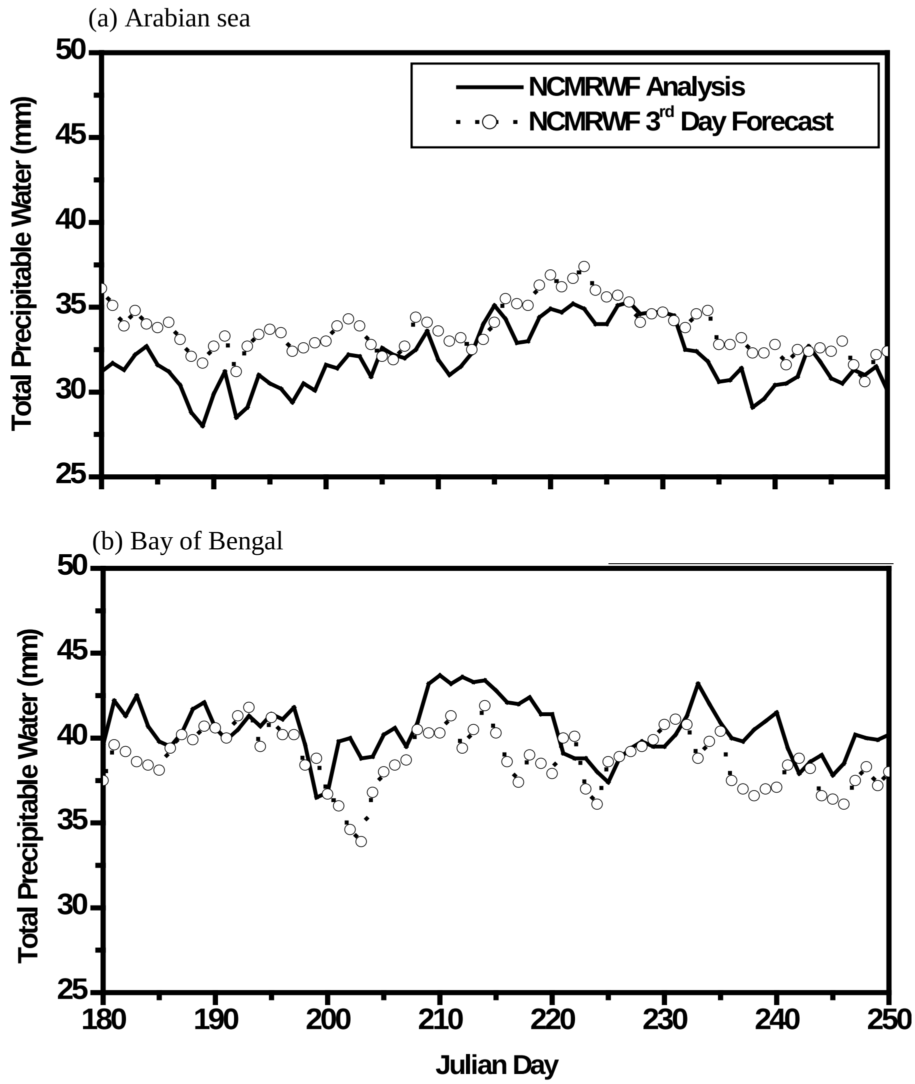
Figs. 1(a&b). Stationary position of ORV Sagar Kanya and the four land stations *viz*., Bombay, Goa, Mangalore and Trivandrum forming polygons during (a) Suppressed convection period and (b) Active convection period

usually associated with meso-scale convective systems embedded in large scale synoptic system over the Arabian Sea (Benson and Rao, 1987). These intense events are also associated with offshore troughs occurring over Arabian Sea (Rao, 1976). An understanding of the nature of the convective systems responsible for copious rainfall events over the west-coast of India is very much a pre-requisite for their prediction. Such deep and intense cumulus convection leading to heavy rainfall activity can have an important effect on the dynamics and energetics of large-scale atmospheric systems, because of the large magnitudes of the energy transformations associated with phase changes of water in precipitating clouds as well as during strong updrafts and downdrafts that often extend throughout the troposphere. The importance of deep cumulus clouds in the heat balance of the tropical atmosphere was first pointed out by Riehl and Malkus (1958). A number of research efforts had been carried out in the seventies during GARP Atlantic Tropical Experiment (GATE) to clarify the nature of the interaction between small-scale cumulus convection and large-scale circulation of the troposphere. Much attention had been given to the diagnostic study of the interaction processes, Yanai *et al.* (1973) for the determination of the bulk or averaged properties of populations of cumulus clouds from observations of large-scale meteorological variables. Ogura and Cho (1973) and Nitta (1975) have developed methods that have enabled the spectral distribution of cumulus mass flux for populations of cumulus clouds to be diagnosed from large-scale variables. In all of the studies having similar nature cumulus clouds have been modeled as a one-dimensional, steady-state entraining plume updraft.

It is evident that large amount of latent heat is liberated in cumulus clouds and the released heat is transported upwards but how this heat is used in warming/cooling the large-scale environment, needs further exploration (Mohanty *et al*. 2003). Therefore, the need of the hour is to have a better understanding of the physical processes to improve the cumulus parameterization schemes. The prime objective of this paper is to study the structure of the atmosphere during convectively active and suppressed periods observed during Arabian Sea Monsoon Experiment (ARMEX) 2002. During ARMEX – I in 2002, special high-resolution upper air observations giving vertical profiles of temperature, humidity, zonal and meridional wind were taken on board Oceanographic Research Vessel (ORV) Sagar Kanya, using Vaisala sondes. The kinematic and convective budgets of an environment during ARMEX-I are grouped in A/B Scale (GARP). In this paper the profiles of kinematic parameters *viz*., mean zonal and meridional wind and vertical velocity along with its daily variability and profiles of convective parameters *viz*., apparent heat source and apparent moisture sink have been computed for the both convectively active and suppressed periods during ARMEX-I.

2. Data and synoptic situation

Upper air data consisting of 12 hourly (0000, 1200 UTC) observations over Arabian Sea on board ORV Sagar Kanya and from land stations *viz*., Mumbai (19.11° N, 71.85° E), Goa (15.48° N, 73.81° E), Mangalore (12.95°N, 74.83° E) and Trivandrum (8.48° N, 76.95° E) are used



Figs. 2(a&b). NCMRWF general circulation model analysis and forecast values of Total Precipitable Water (TPW) content over (a) Arabian Sea and (b) Bay of Bengal

in this study. These five stations, one ocean based and four land based stations, together form a polygon column of atmosphere representing the B-Scale, as defined during GATE. The selection of the polygon is due to the prevalent convective activity and associated rainfall over this regime along the west coast of India during south west monsoon (SWM). Two specific cases were taken for the study. The first case represents a convectively suppressed period starting from 1 - 10 July 2002 and the second, a convectively active period from 1 - 10 August 2002. In both of these periods of study the west coastal land stations being fixed, the position of ORV Sagar Kanya was changed. Figs. 1 (a&b), depicts respectively the two polygons that represent the convectively suppressed period (ORV Sagar Kanya at 16.94° N, 71.19° E) and the active period (ORV Sagar Kanya at 15.34° N, 72.18° E).

July 2002 has been one of the driest July months on record and the All India monsoon rainfall was 49 % below normal value. The wind anomaly at 850 hPa indicates absence of monsoon trough line over the Indo Gangetic plains. It also indicates weaker low-level Somali Jet and weaker South East (SE) trades in the Southern Indian Ocean west of 70° E. The Arabian Sea and the Indian Ocean is cooler by 1-2° C. At 700 hPa the entire central

Asian region around Iran and neighbourhood is cooler by 1° C. At 150 hPa, the Indian subcontinent continues to be cooler by 1° C and weaker tropical easterly jet stream is noticed (ARMEX- Weather Summary).

In August 2002, the monsoon trough line makes its appearance at 850 hPa, showing a remarkable revival in the SWM wind, the monsoonal westerlies being stronger closer to the equator. Figs. 2 (a&b) show the averaged total precipitable water (TPW) content obtained from National Centre for Medium Range Weather Forecasting – General Circulation Model (NCMRWF-GCM) analysis and 3rd day forecast respectively over Arabian Sea (0-19.5° N, 55-75° E) and Bay of Bengal. Both NCMRWF-GCM analysis and forecast show a considerable dip in TPW value during 1-10 July 2002 and a gradual revival during 1-10 August 2002. National Oceanic and Atmospheric Administration (NOAA) supported Cooperative Institute for Research in Environmental Sciences derived outgoing long-wave radiation (OLR) values show that during convectively active period the OLR values are almost 50 Wm^{-2} lower than that during suppressed phase.

The study here uses an approach to obtain the average structure of a cloud cluster and its interaction with the environment. The high degree of organization of convective clouds into clusters during active monsoon period (1-10 August 2002) suggests their likely association with large-scale wave disturbances. In this paper the objective is to compute both, the convective and the kinematic parameters at the centre of the polygons. The high-resolution upper-air data obtained on board ORV Sagar Kanya during ARMEX was a real boon for this study. A linear interpolation technique was used to interpolate some of the data at regular intervals of 50 hPa from 1000 to 100 hPa. The missing observations were replaced by fitting a linear regression equation in time and space. The data sets were also processed for internal consistency. The horizontal derivatives *viz.*, $\nabla \cdot V$, $\nabla \times V$ etc. are obtained from regression coefficients (Mohanty and Das, 1986).

3. Methodology

3.1. *Vertical velocity and divergence*

The estimation of vertical velocity (ω) is usually done by kinematic, adiabatic or vorticity technique. The errors in the wind measurement are one of the several reasons that bring inaccuracy in the estimation of divergence. The vertical velocity ω_k at any level k, then, becomes successively less acceptable as k increases, due to errors in the estimation of divergence and thus, it may not satisfy the upper boundary condition. O'Brien (1970) gave a more realistic correction in the computation of vertical velocity and divergence, which is employed in this paper.

3.2. *Convective parameters*

In the study of convection, the dry static energy (*S*), moist static energy (*S*e), the saturation moist static energy (*S*es) and the equivalent potential temperature (θe) are very useful parameters. These variables are explained in Mohanty *et al*. (2003). The moist static energy remains conserved during both dry and moist adiabatic processes. Observed estimates of the horizontal and vertical advections of temperature and moisture may be combined with their observed temperature and moisture tendencies to produce residuals in the budgets of thermodynamic and moisture continuity equation, denoted by the apparent heat source (Q_1) and moisture sink (Q_2), which are defined as (Yanai *et al*., 1973)

$$Q_1 \equiv \frac{\partial \overline{S}}{\partial t} + \overline{V} \cdot \nabla \overline{S} + \overline{\omega} \frac{\partial \overline{S}}{\partial p} \quad (1)$$

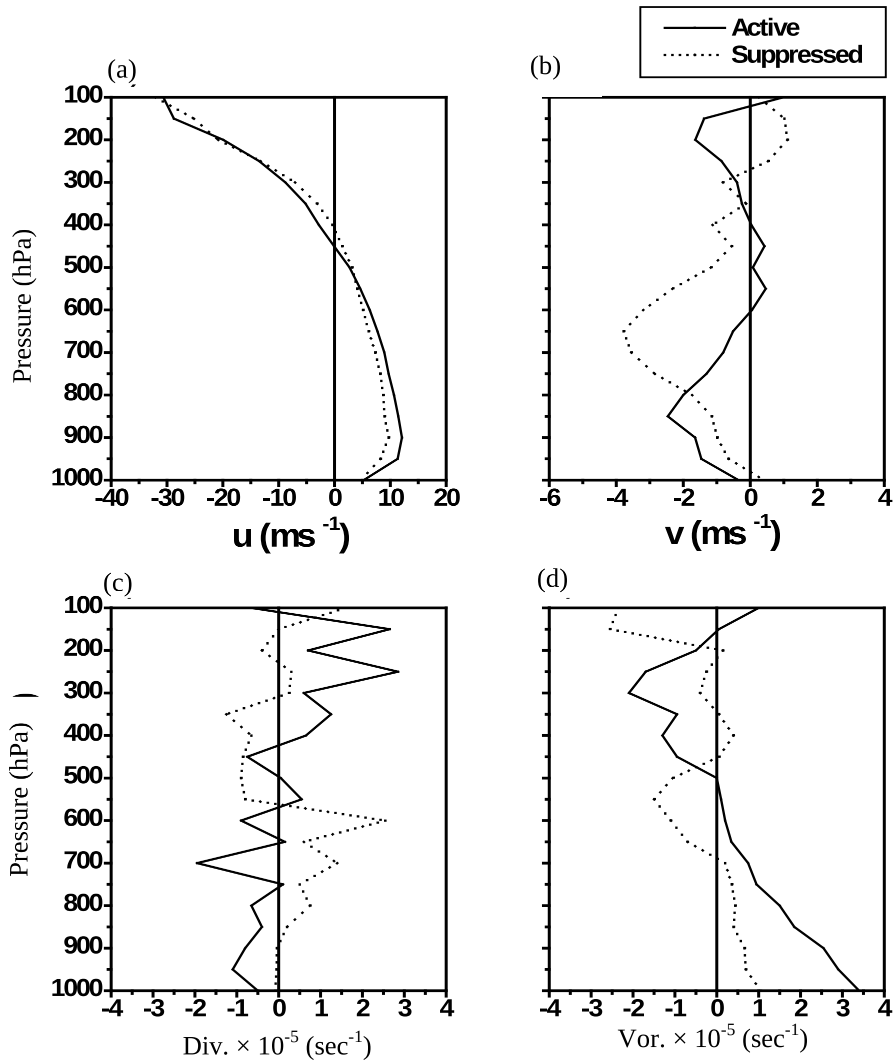
$$Q_2 \equiv -L\left[\frac{\partial \overline{q}}{\partial t} + \overline{V} \cdot \nabla \overline{q} + \overline{\omega} \frac{\partial \overline{q}}{\partial p}\right] \quad (2)$$

Here, *V* is the horizontal velocity, ∇ the horizontal gradient operator, ω the vertical velocity, *p* the pressure, *L* the latent heat of condensation. The over-bar denotes a large-scale horizontal average.

4. Results and discussion

4.1. *Mean variations of kinematic parameters*

The mean profiles of zonal (*u*) and meridional (*v*) wind, divergence and vorticity at approximately the centre of the polygon during convectively active and suppressed periods are presented in Figs. 3(a-d). All of these profiles represent a 10-day averaged picture. General observation of average *u*-profile Fig. 3(a) depict westerlies in the lower levels and easterlies in the upper levels during both the periods. However, maximum wind speeds of the order of 12.5 ms^{-1} at around 900 hPa while during the suppressed convection period wind speeds were less than 10 ms^{-1}. The westerlies in both cases decrease gradually above 500 hPa to become easterlies that attain a maximum speed of nearing 30 ms^{-1} at around 100 hPa level. Such a structure that is observed in *u* wind profile is typical to that noticed of SWM, where the westerlies are overlain by

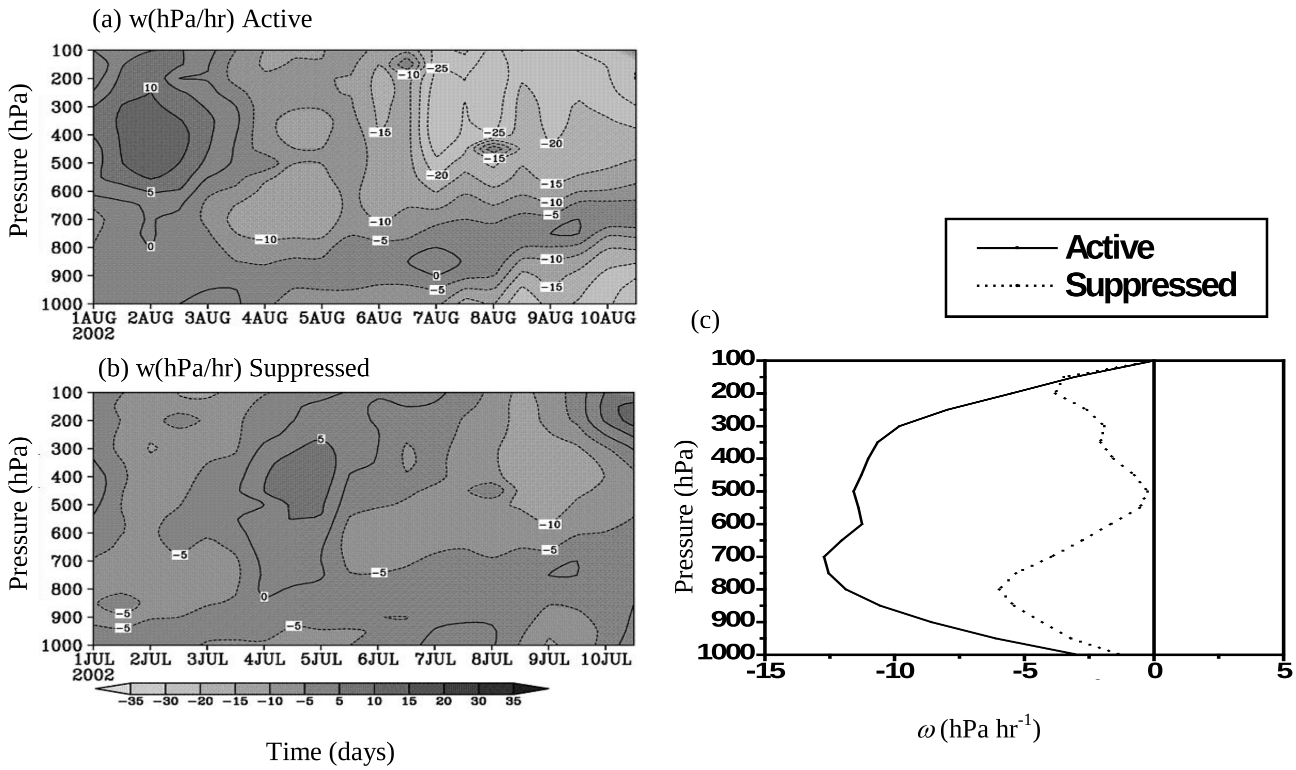


Figs. 3(a-d). 10-Day mean variations of vertical profiles of (a) zonal (*u*) (b) meridional (*v*) wind, (c) divergence and (d) vorticity during convectively active (1-10 August 2002) and suppressed period (1-10 July 2002)

easterlies in the upper levels. Betts (1976) had stated that such a profile of wind often leads to shear formation, which is favourable in the development and sustenance of convection.

Analyzing *v* wind profile it is observed that predominantly northerly winds Fig. 3(b) prevail during both active and suppressed periods at around 850 hPa (~2.5 ms^{-1}) and 650 hPa (~3.5 ms^{-1}) respectively. At upper levels nearing 100 hPa both the periods show a tendency towards southerly component of *v* wind. A relative reversal of *v* wind in the boundary layer below 800 hPa is observed during the convectively active period.

Figs. 3 (c&d) depicts the averaged profiles of divergence and vorticity during active and suppressed periods of convection respectively. An increase in mass convergence at lower levels over the oceans leads to an increase in convective activity. Such a phenomenon can be clearly seen in Fig. 3(c), where low-level (1000-750 hPa) mass convergence indicates an increased convective activity, while near zero mass convergence up to 900 hPa and divergence up to 500 hPa is noticed during convectively suppressed period. During the active convection phase, this lower level convergence in overlain by upper level divergence above 400 hPa with two maxima around 250 and 150 hPa respectively that could



Figs. 4(a-c). Daily variations of vertical velocity during (a) active (b) suppressed periods and (c) 10-day mean profiles of ω during both active and suppressed conditions

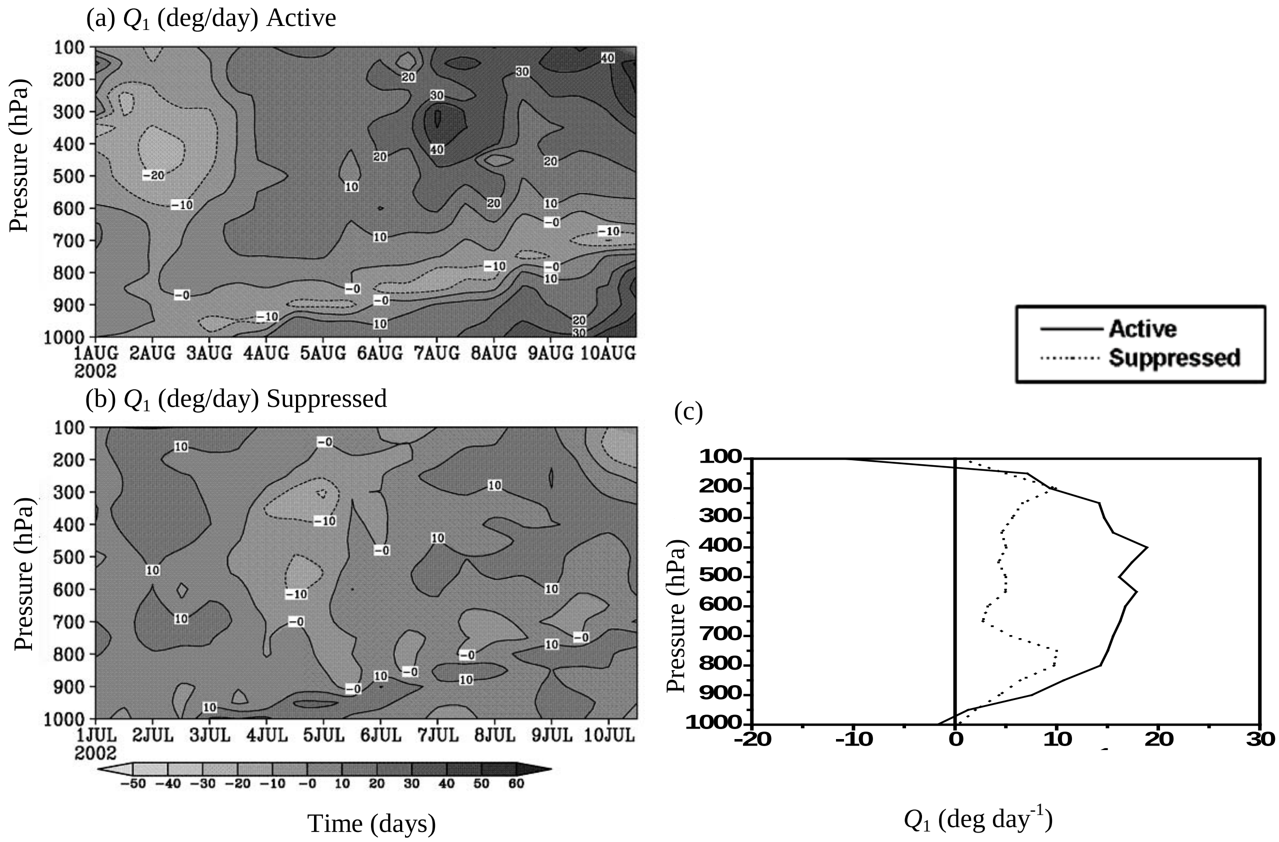
be attributed to the upper level cross equatorial return flow. The suppressed period showed a major portion below 500 hPa associated with divergence of mass. Also a strong convergence was observed above 500 hPa and below 300 hPa in the upper layers with maximum value at 350 hPa. This was similar to the profile obtained during a decaying phase of convection obtained over GATE by Nitta (1977).

Fig. 3 (d) shows the averaged vertical profiles of vorticity. A very strong cyclonic flow is observed during the convectively active episode extending up to almost 500 hPa. Above 500 hPa between 500 & 200 hPa, negative vorticity was found during this period, attributing to an anticyclonic flow. The profile of vorticity during the convectively active period is similar to the profiles of transition from the suppressed to a convectively active phase. The vorticity field shows a very good correspondence with the divergence field seen in Fig. 3(c), which in principle relates to the fact that positive vorticity is usually accompanied by a negative divergence/ convergence field.

4.2. *Daily and mean variations of vertical velocity*

During the active period [Fig. 4 (a)], continuous rising motion can be observed during 3-10 August 2002, affirming the revival phase of SWM from a prolonged break like condition. When closely observed five distinct pockets (*viz*., 4^{th}, 6^{th}, 7^{th}, 8^{th} and 9^{th} August 2002) of rising motion could be noticed. The rising motion gets intensified on an active convection day and as the day progresses, on an average two maxima are observed around 700 and 500 hPa in the forenoon. The maximum vertical velocity observed on 4^{th}, 6^{th}, 7^{th}, 8^{th} and 9^{th} respectively are 10, 15, 20, 30 and finally 10 hPa hr^{-1}. During the suppressed period [Fig. 4 (b)], such an intensified rising motion as encountered of active convection episodes are not seen. However, at the lower levels nearing 850 hPa, rising motion of very low magnitude (< 10 hPa hr^{-1}) is observed.

The time averaged (10-day) profile of vertical velocity, during both the periods are given in Fig. 4(c). At 700 and 500 hPa, the two maximum values 12.5 and 11 hPa hr^{-1} was observed during active convection period,



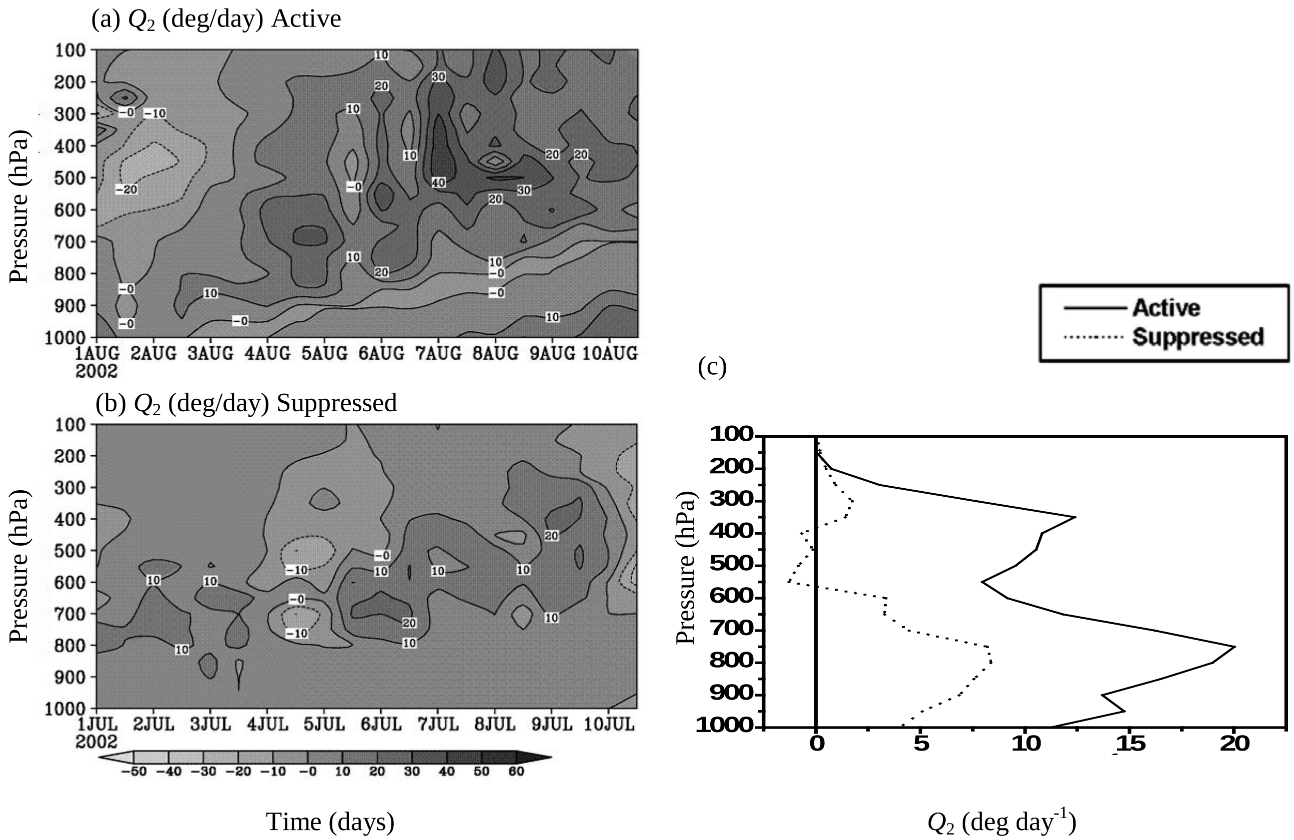
Figs. 5(a-c). Daily variations of apparent heat source (Q_1) during (a) active (b) suppressed periods and (c) 10-day mean profiles of Q_1 during both active and suppressed conditions

which confirms the intensity of rising motion. The averaged profile during suppressed period too depicts rising motion below 500 hPa, however the magnitude of maxima observed were well below 25% of that seen during active convection period.

4.3. *Daily and mean variations of convective parameters*

4.3.1. *Apparent heat source (Q_1)*

Figs. 5(a-c) illustrates the apparent heating observed during convectively active [Fig. 5(a)] period, suppressed period [Fig. 5(b)] and an averaged [Fig. 5(c)] picture depicting the heating trend during both of these periods of distinct convective scenario. Looking at an overall picture, a continuous heating trend is observed from 4th August 2002, with pockets of maxima located around 1000-800 hPa and 700-150 hPa [Fig. 5 (a)]. Pockets of cooling are also noticed between 950-850 hPa. This cooling may be due to evaporation of rain drops. Observations also indicate that during the convectively active period the sea surface temperature (SST) was above 28° C (ARMEX data) and surface winds were of the order of 20-25 knots. The maximum heating rate of 50° C day^{-1} was seen around 350 hPa level on 7th August 2002 (0000 UTC). A secondary maximum (~20° C day^{-1}) was also found at lower levels nearing 950 hPa on 8th August 2002 (1200 UTC). This could be possibly due to the contribution of the sensible heat flux from the land stations. Fig. 5 does not show very sharp changes from heating to cooling between 1000 and 500 hPa, however maximum cooling observed over the period was between 950 and 700 hPa. The periods of maximum heating are usually associated with the passage of cloud clusters over the polygon (Krishnamurti *et al*. 1979; Sikka and Grossman 1980; Mohanty *et al*. 2003). This heating may be due to the release of latent heat in cumulus clouds and its upward transport by eddies. The distribution of OLR from NOAA shows considerable reduction in magnitude (~190 Wm^{-2}) during the active period when compared to the suppressed period (~255 Wm^{-2}). Also the active convective episode rainfall is the out come of several processes in the atmosphere and the most important one is the



Figs. 6(a-c). Daily variations of apparent moisture sink (Q_2) during (a) active (b) suppressed periods and (c) 10-day mean profiles of (Q_2) during both active and suppressed conditions

condensation of water vapour in cumulonimbus clouds (Bhat *et al.*, 2002). Here, it is also noted that the latent heat released during condensation when a 10 cm rainfall is observed compounds to an increase in the temperature column of air from surface to the troposphere by more than 25° C. Not much of a cooling is noticed in the upper levels during the active period. The observed heating rate per day is in good agreement with the results obtained by Mohanty and Das (1986), except for slight variations in the magnitude owing to the difference in the intensity of convective activity.

During the suppressed convection period [Fig. 5(b)], a much diminished heating rate (~ 10° C day^{-1}) but with a larger pocket of cooling is noticed. This period compounds to warmer lower troposphere, colder mid-troposphere and a warmer layer near tropopause, which are in agreement with the general features of tropical convective atmosphere (Emmanuel, 1994; Houze, 1993). A maximum cooling of -10° C day^{-1} is observed between 600 & 300 hPa (1200 UTC, 4th July 2002). However, an apparent heating of around 10° C day^{-1} is noticed during 1-3 July and 6-10 July 2002 in different pockets within these periods. The maximum cooling observed is due to evaporation of moisture in the dryer atmosphere and is consistent with Q_1 profile.

Fig. 5 (c) shows the time averaged vertical profile of Q_1 during active and suppressed convection. During active period Q_1 increases with height to give two maxima respectively at 550 hPa (18° C day^{-1}) and 400 hPa (19° C day^{-1}). In the suppressed period a much diminished heating profile is noticed throughout the vertical column of the atmosphere. The dominant cooling effect during this period (1-10 July 2002) nullifies the apparent heating from some pockets in the time averaged Q_1 profile.

4.3.2. *Apparent moisture sink (Q_2)*

Fig. 6(a) shows heating due to apparent moisture sink Q_2 during the active convection period. This figure clearly depicts that the time of maximum drying coincides with the time of maximum apparent heating. All those pockets of apparent heating mentioned in section 4.3.1 correspond well with apparent drying. Maximum drying (40° C day^{-1}) is observed at 0000 UTC of 7th August 2002 between 500 & 400 hPa. A secondary maximum (~ 30° C day^{-1}) was observed at 1200 UTC on 8th August 2002. Barring 1-3 August 2002, from 4-10 August 2002 the continuous drying process, correspond well with Fig. 5 (a). During suppressed convection period [Fig. 6(b)] drying is comparatively less compared to that observed in active convection period. Negative values (~10° C day^{-1}) of Q_2 are dominant during 4-5 July 2002 that correspond well with the apparent cooling observed during same period in Fig. 5(b). Positive values of Q_2 could be due to the presence of deep convective cloud system developed in the Arabian Sea during the convectively active period. Similar observations were also made during BOBMEX (Bhat *et al.*, 2002), where the system could not intensify further and decayed therein.

The averaged profiles of Q_2 during both active and suppressed periods are presented in Fig. 6(c). A maximum drying of 20.5° C day^{-1} at 750 hPa was noticed during the active convection period. The suppressed period do not show continuous moistening except a little between 550 and 400 hPa. This may be due to the dryer atmosphere after evaporation at those levels. Also it is well known that clouds have tops mainly below 500 hPa and a majority of them have at around 700 hPa, while atmosphere is dry above 500 hPa. However the amount of drying observed during the suppressed period is very less compared to that observed during active convection period.

5. Summary and conclusions

In the present study the time averaged vertical profiles of zonal and meridional winds, divergence and vorticity, vertical velocity, apparent heat source and moisture sink during active and suppressed periods of convection over the Arabian Sea during ARMEX 2002 have been discussed. Alongwith the time averaged profiles, day-to-day variations of vertical velocity, Q_1 and Q_2 were also examined. During convective activity a strong low-level mass convergence is observed compared to the suppressed period. Strong winds in the vertical are one of the dominant factors that persist during active convection period that helps in the development and sustenance of meso-scale convective systems. The maximum rising motion coincides with times of maximum convergence and it is noticed to be almost always between 0000 and 1200 UTC. The general trend of warming in the lower troposphere and few pockets tending to have cooler environment in the upper troposphere is noticed during the active period.

The release of latent heat is one of the major contributing entities towards large-scale heating of the atmospheric column. Part of the heating is also contributed by the vertical transport of heat by eddies. The apparent heat source during active convection over the Arabian Sea increases with height to maximum values of 18° C day^{-1} at 550 hPa and 19° C day^{-1} at 400 hPa. During the suppressed period, the heating is much diminished and larger pocket of cooling is noticed. The apparent heating whatsoever observed could be due to the presence of stratus/stratocumulus clouds. The maximum drying experience (20.5° C day^{-1} at 750 hPa) due to Q_2 during the convectively active episode could be attributed to the net condensation and vertical transport of moisture by eddies. The level of apparent moisture sink occurs at a relatively lower level than compared to the apparent heat source and also the drying is relatively less during the suppressed convection period.

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