MAUSAM, **56**, 1 (January 2005), 89-96

551.558.1 : 551.577 (267.37)

Convection inhibition energy of the inversion and the suppressed rainfall over the Arabian Sea during July 2002

G. S. BHAT

Centre for Atmospheric and Oceanic Sciences

Indian Institute of Science, Bangalore, India

e mail : bhat@caos.iisc.ernet.in

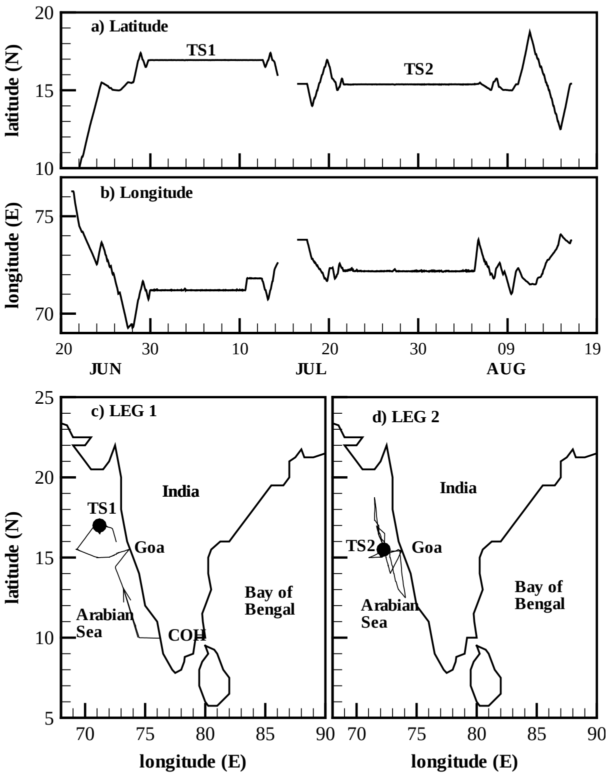
सार – जुलाई के महीनों में, जब मानसून की वर्षा सबसे अधिक होती है, वर्ष 2002 के दौरान समूचे भारत में वर्षा अद्वितीय रूप से सामान्य से 49 प्रतिशत कम थी। इस शोध पत्र में ओ. आर. वी. सागरकन्या से एकत्रित किए गए आँकड़ों का उपयोग करते हुए जुलाई 2002 के दौरान भारत के पश्चिमी तट से 100–200 कि.मी. दूर अरब सागर में फैली हुई सतही और उपरितन वायु की अवस्थाओं को बताया गया है। तट से दूर जहाज पर मापी गई वर्षा की कुल मात्रा जुलाई माह में 30 मि.मी. से कम थी। अध्ययन क्षेत्र में गहन संवहन के विकास के लिए सतही अवस्थाएँ सहायक थीं। रेडियोसौन्दे प्रोफाइलों से ऊर्ध्वाधर में जटिल ऊष्मीय संरचना का पता चला है और अधिकांश दिनों में दो सुस्पष्ट प्रतिलोमन, एक 800 हैक्टापास्कल के निकट और दूसरा 500 हैक्टापास्कल के निकट विद्यमान थे। उस समय गहन मेघों के बनने के लिए उष्मा अवरोध सहित निचले प्रतिलोमन की विशेषताएं विद्यमान थीं। इससे यह पता चला है कि जुलाई के पूर्वाद्ध के अधिकांश दिनों में निचले प्रतिलोमन स्तर में संवहन अवरूद्ध उष्मा स्थिरोष्म रूप से वायु की राशि की नमी में निष्प्रभावित वृद्धि की तुलना में अपेक्षाकृत अधिक रही और जिससे मेघों की ऊर्ध्वाधर वृद्धि अवरूद्ध हुई। जुलाई का उत्तरार्द्ध कुतूहल उत्पन्न करने वाला रहा है और निष्क्रिय वर्षा के लिए एक से अधिक कारक उत्तरदायी रहे हैं।

ABSTRACT. All India rainfall was an unprecedented 49% below normal in the peak monsoon month of July in the year 2002. Surface and upper air conditions that prevailed over the Arabian Sea 100-200 km off the west coast of India during July 2002 are described here using the data collected from ORV Sagar Kanya. The total amount of rainfall measured on the ship away from the coast was less than 30 mm in July. The surface conditions were conducive for the development of deep convection in the study area. Radiosonde profiles reveal a complex thermal structure in the vertical and on a majority of the days two prominent inversions were present, one near 800 hPa and the other near 500 hPa. The characteristics of the lower inversion, including the energy barrier that it created for the development of deep clouds is presented. It is shown that on most days during July first half, the convection inhibition energy in the lower inversion layer was much more than that an air parcel ascending moist adiabatically could overcome and the vertical growth of clouds was stunted. The second half of July is intriguing and more than one factor seems to have contributed to suppressed rainfall.

Key words − ARMEX, Monsoon, Tropical convection, Atmospheric inversion.

1. Introduction

The first phase of the “Arabian Sea Monsoon Experiment (ARMEX-I)”, was carried out during June-August 2002. Objectives of ARMEX included understanding these very heavy rainfall events and the associated offshore convective systems. The area of intense observations was the region within 200 km from the west coast of India employing land, ocean and space based platforms. Land observations were enhanced by installing 10 automatic weather stations along the west coast and ships were deployed for monitoring conditions over the Arabian Sea (AS) including ORV Sagar Kanya that spent nearly two months over the sea. There have been observational experiments conducted over AS in the past, *e.g.*, the International Indian Ocean Expedition of mid 1960s (IIOE, *e.g.*, Colon 1964), Indo-Soviet Monsoon Experiment of 1973 (ISMEX-73, *e.g.*, Pant 1982), Monsoon experiments of 1977 (MONSOON-77, *e.g.*, Pant 1982) and 1979 (MONEX-79, *e.g.*, Krishnamurti 1985). It is worth noting here that in contrast to the earlier field experiments where a broad area over AS was explored, the emphasis in ARMEX was on time series observations within 200 km from the Indian coast in the eastern AS.



Figs. 1(a-d). Cruise track and time series positions of ORV Sagar Kanya. (a) Latitudinal position with time, (b) Longitudinal position with time, (c) cruise track during leg 1 (21 June – 14 July) and (d) cruise track during leg 2 (17 July – 16 August). The time series durations are : TS1 from 30 June - 10 July and TS2 from 22 July - 5 August 2002

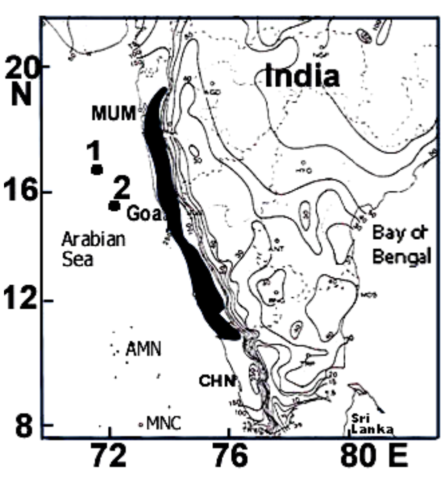
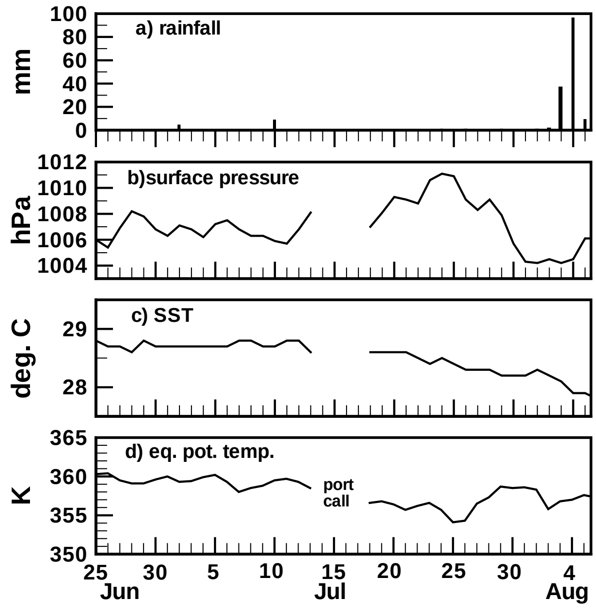


Fig. 2. June-September rainfall on the west coast of India (adapted from Rao 1976). Areas receiving more than 250 cm rain are shaded dark. Filled circles in the Arabian Sea denote the ship position during the time series observations during ARMEX-I

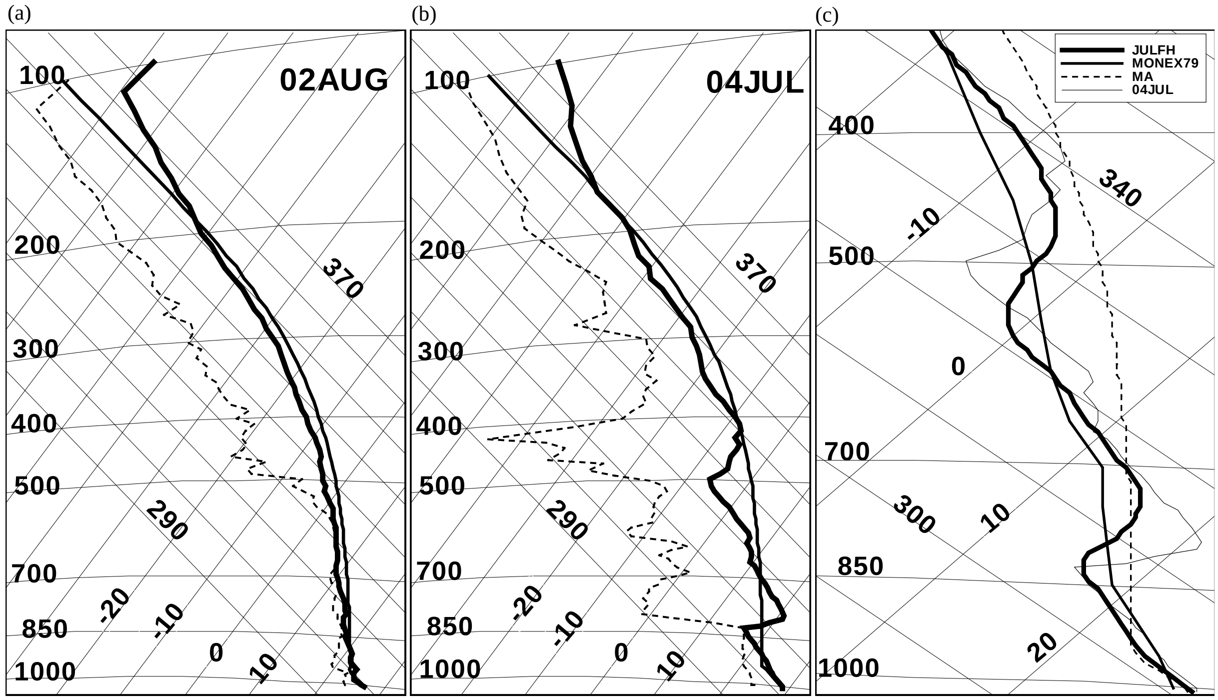


Figs. 3(a-d). Temporal variation of rainfall, surface pressure, sea surface temperature (SST) and surface air equivalent potential temperature. Values shown are daily averages

Nature had other designs and the all India monsoon rainfall was 49% below its long term average in July 2002 with the largest deficits occurring in the western parts of India. 2002 monsoon was a major failure and neither any heavy rainfall event occurred where ORV Sagar Kanya was located nor an offshore trough developed in its vicinity. Thus, the data collected from ORV Sagar Kanya are not that useful for the study of original ARMEX objectives as such. However, this data set is very valuable as 2002 July was a very rare case and the data collected helps us in understanding the conditions that prevailed over the eastern AS during one of the worst monsoon years. In the present study, surface and upper air conditions observed from ORV Sagar Kanya over AS during July 2002 are described.

2. Ship location and data

The Indian research vessel ORV Sagar Kanya was deployed over the eastern AS from 21 June to 16 August with a port call in between during 14-17 July. Fig. 1 shows the cruise track. The cruise comprised of sections parallel to and normal to the coast and time series observations. The ship was positioned for time series observations at 16.9° N & 71.2° E from 30 June - 10 July and at 15.5° N & 72.2° E from 22 July to 5 August 2002. The ship location was chosen to be in close vicinity of the heaviest rainfall belt on the west coast (Fig. 2). The surface variables were continuously monitored and high resolution GPS radiosondes (Vaisala model RS80-15G) were launched (2-4 per day) to monitor the upper air



Figs. 4(a-c). Skew *T*-log p diagram of the ARMEX soundings. The continuous thick and thin lines in (a) and (b) correspond to air temperature and surface air moist adiabat respectively and the dashed line is dew point temperature. For ease of comparison, 4 July sounding is reproduced in (c). See text for further details regarding (c)

conditions. The details pertaining to the sensors installed on board ORV Sagar Kanya can be found in Bhat *et al*. (2001).

3. Surface and upper air conditions

Temporal variations of daily rainfall, surface pressure, sea surface temperature (SST) and surface air equivalent potential temperature (θ_e) are shown in Figs. 3(a-d). In the first two weeks of July, the total rainfall measured on board the ship is 13 mm and that during the second half of July is even smaller (rainfall measured at the port is not shown). Surface pressure showed a decreasing trend during 28 June – 4 July and 7 – 11 July; shallow convective cloud activity increased around these periods, however, cumulonimbus clouds and organized deep convective systems did not develop. The rising pressure from 17 – 24 July suggests that this period was becoming unfavourable for the development of convection. SST was well above the convection threshold of 28° C for the Indian Ocean (Gadgil *et al*. 1984) during July. The surface air was warm and moist and its θ_e was in 353-360 K range, sufficiently high to support deep convection in the tropical atmosphere (Betts and Ridgway 1988). Therefore, the surface thermodynamic conditions were conducive for supporting deep convection and there were no inhibitors among the surface variables/ parameters that could completely suppress deep convection over the AS during July 2002.

Figs. 4(a-c) show the vertical profiles of temperature on 2 August, 4 July and the average for the period 28 June-13 July (JULFH), respectively. The 2 August profile [Fig. 4(a)] has a shallow mixed layer (about 40 hPa deep) with high humidity levels (indicated by the closeness of dry bulb and dew point temperatures) upto 500 hPa. Convective clouds were developing on this day and it started raining on 3 August. Thus 2 August profile shows the conditions during the growing stages of convection. The 4 July profile is very different and several distinct layers are seen [Fig. 4(b)]. The temperature lapse rate is close to the dry adiabatic upto 850 hPa level (suggesting a deep atmospheric mixed layer) followed by a rapid increase in the potential temperature (θ) immediately above indicating the presence of an inversion. The inversion is sharp, dew point temperature decreased rapidly with height in the inversion and the corresponding values of relative humidity decreased from over 90% near the base of the inversion to less than 25% at its top. Temperature and humidity structures in this inversion are akin to the soundings belonging to the dry (air) intrusion category observed during TOGA COARE (Lucas and Zipser 2000). Further up, the lapse rate between 600 hPa and 500 hPa levels resembles those normally found in the

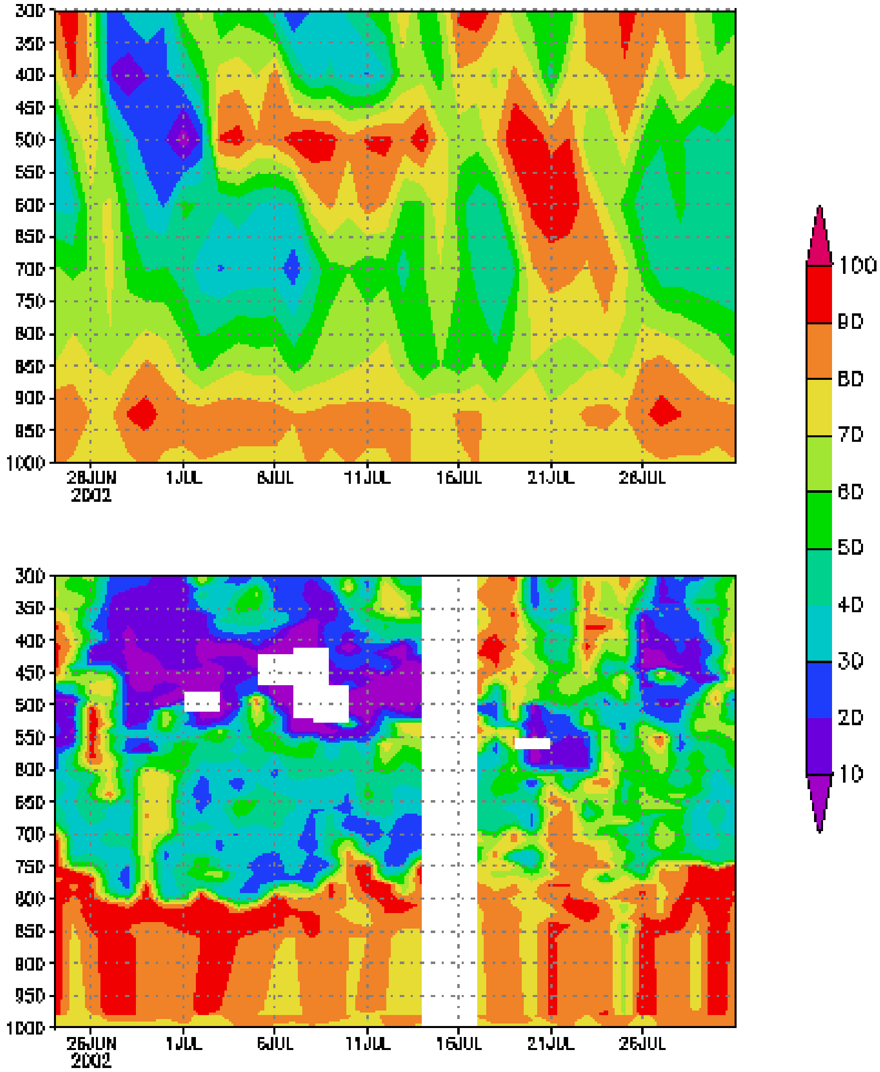
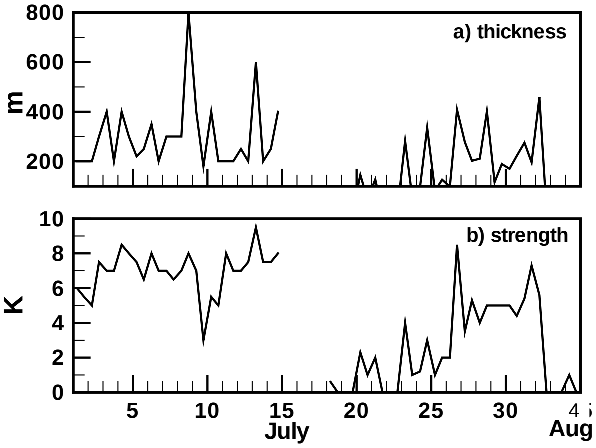


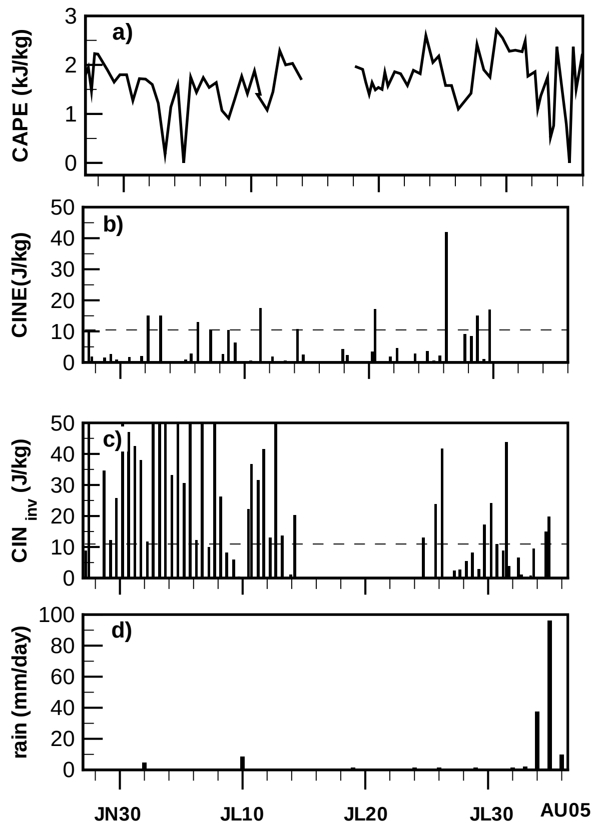
Fig. 5. Time height variation of relative humidity over the ship locations. Top and bottom panels are based on NCEP reanalysis and ship radiosonde data respectively

atmospheric mixed layer. A second inversion layer (with a sharp increase in θ and low humidity) is observed between 500 hPa and 400 hPa. 4 July sounding was not an isolated case, and a persistent inversion prevailed in the first half of July. The drastic decrease in relative humidity across the inversion can be used to locate and characterize the inversion from radiosonde data. Time-height variation of relative humidity shown in Fig. 5 reveals a persistent inversion occupying the layer of the atmosphere around 800 hPa on most days during the first half of July. For the lower inversion layer, inversion thickness (height across which temperature increased) and inversion strength as measured by the increase in θ across the inversion layer are shown in Figs. 6(a&b). Inversion thickness typically varied in 200-400 m range. Strength of the inversion varied from 2 K to 9 K with an average around 7 K during July first half. Except on a couple of occasions, inversion strength was weaker during July second half. The average temperature profile for the July first half [Fig. 4(c)] carries clear signatures of the inversions. Inversions around 800 hPa and 500 hPa are prominent in the average temperature profile also.

NCEP reanalysis data is widely used at present for a variety of purposes including monsoon studies. In order to see how well NCEP reanalysis data reproduced the inversion features, the variation of relative humidity based on NCEP reanalysis data for the grid box where the ship



Figs. 6(a&b). Characteristics of July 2002 inversion. (a) Thickness; (b) Strength

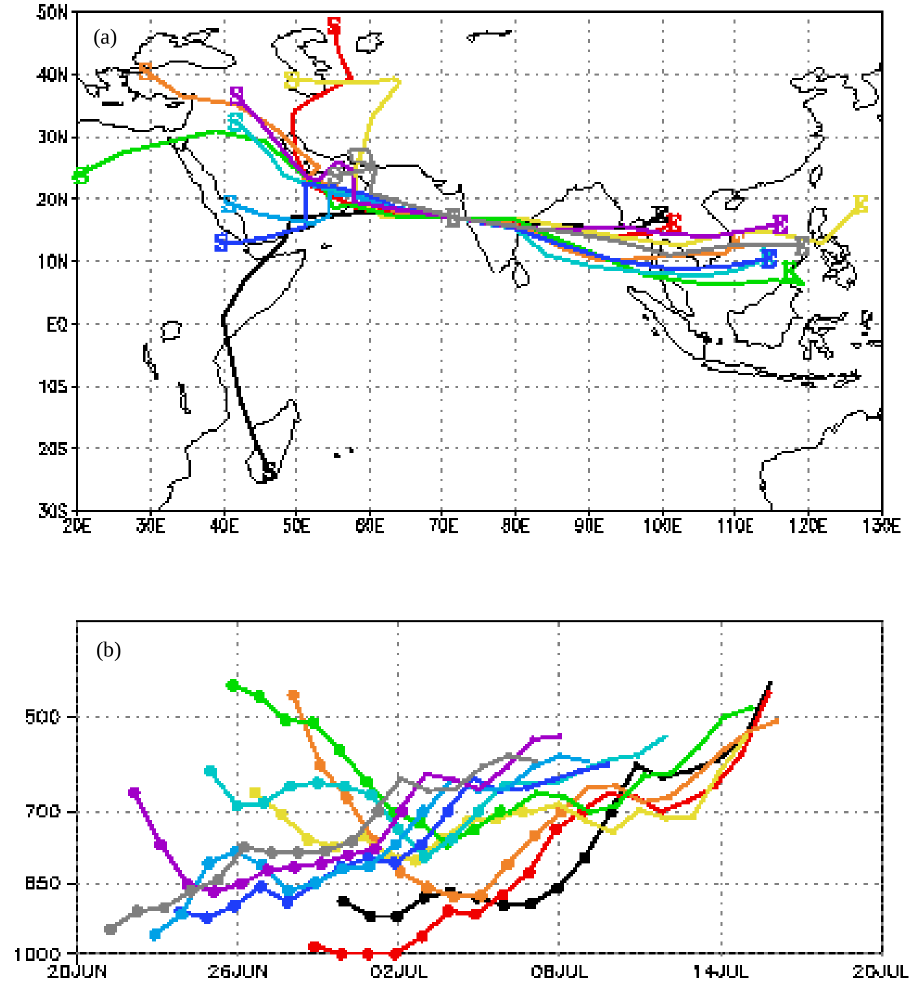


Figs. 7(a-d). Variation of CAPE and CINE of the surface air, CIN_{inv} and daily rainfall. The rainfall shown is the rainfall in the preceding 24 hours at 0830 hr (IST) local time on that day

was located is shown in the top panel in Fig. 5. NCEP data shows a layer of dry air around 700 hPa level. Remembering that no upper air observations over the eastern Arabian Sea (in the area of ship location) went into the reanalysis, it is remarkable that some gross features of humidity field are captured by the reanalysis. However, the values of mid tropospheric relative humidity are generally larger than those observed and are highly overestimated around 500 hPa level. Differences between the reanalysis and observed profiles arise both due to model limitations and the coarse resolution of reanalysis data. Features of the inversion could be captured in detail because high vertical resolution (better than 5 hPa) radiosondes were used. A coarse resolution radiosonde, having a vertical resolution of 50 hPa for example, would have underestimated the strength and sharpness of the inversion since the inversion depth was often less than 50 hPa.

Temperature inversion over the AS has been reported from earlier observational experiments also where it was noted that strong low level temperature inversion occurs in the western AS due to warm continental air from deserts of east Africa and west Asia flowing over the cool maritime air of AS (Colon 1964, Ghosh *et al*. 1978). The inversion weakens and lifts up eastward of 60° E and vanishes beyond 70° E (Colon 1964). These results are based on a few number of soundings (especially eastward of 70° E) from IIOE and ISMEX-73 experiments. MONEX-79 had a good coverage of the eastern AS and the year 1979 in which it was carried out was also a deficit monsoon year. In Fig. 4(c) average MONEX-79 sounding for days without offshore convection (based on Table 4 of Grossman and Durran 1984) is compared with JULFH sounding measured during ARMEX. The atmospheric mixed layer is more stable in the MONEX-79 profile, but further up, there is no indication of a prominent inversion that can compare in strength with those observed in the JULFH profile. Therefore, a strong persistent inversion observed in July 2002 over AS eastward of 70° E seems unusual.

It is observed from Fig. 4 that the air parcel lifted moist adiabatically from the surface is negatively buoyant initially but attains a positive buoyancy if moved further up. The corresponding negative area on the tephigram between the moist adiabat (MA) and the environmental temperature (T_e) profiles represents the energy barrier that the parcel has to overcome before it can ascend on its own and is known as the convection inhibition energy (CINE, *e.g.*, Williams and Renno 1993). If the parcel overcomes CINE, it becomes positively buoyant for a considerable depth above for normal tropical soundings and the positive area between MA and T_e lines on the tephigram gives the convective available potential energy CAPE (Williams and Renno 1993). It is observed from Fig. 4(b) that for the 4 July sounding, the parcel lifted from the surface has a positive buoyancy before the inversion, however, the parcel temperature is lower than



Figs. 8(a&b). Back and forward trajectories of the air at 700 hPa level calculated using NCEP reanalysis data. Period 1-10 July 2002. (a) Top - horizontal trajectories and (b) Bottom - vertical trajectories

that of its ambient air for a considerable depth inside the inversion. The second negative area, which is even larger than the lower negative area (*i.e.*, CINE), represents the convection inhibition energy due to the inversion and is denoted by CIN_{inv} henceforth.

Values of CAPE, CINE and CIN_{inv} for the surface air along with the daily rainfall amounts are shown in Figs. 7(a-d). CAPE is calculated for the pseudomoist adiabatic process (Williams and Renno 1993) and when the inversion is present, CAPE shown corresponds to the positive area above the inversion. The average value of CAPE is about 1.5 kJ kg^{-1}, which, considering that convection was not active during this period is on the low side. For example, the values of CAPE over the Bay of Bengal at comparable values of SST were around 3 kJ kg^{-1} during the break monsoon conditions (Bhat 2001). In general, values of CAPE in 2-3 kJ kg^{-1} range is common for the tropical soundings (Williams and Renno 1993). The value of CINE [Fig. 7(b)] is small and only on few occasions it exceeded 10 J kg^{-1} and is somewhat on the lower side when compared to the Bay of Bengal (Bhat 2001) and TOGA-COARE soundings (Kingsmill and Houze 1999). CIN_{inv} [Fig. 7(c)] was more than 10 J kg^{-1} for most soundings in the first half of July. CIN_{inv} is an energy barrier and a rising parcel of cloud air has to overcome this barrier in order to penetrate the inversion and grow further up. At a height of around 2 km above the surface where the inversion was present, only source of energy available for the parcel to overcome CIN_{inv} over the tropical oceans is the kinetic energy of its vertical velocity. The vertical velocities in the tropical convective clouds are small - in the lowest 2 kilometers it is less than 5 m s^{-1} and values in 1-3 m s^{-1} range are more common (Lucas and Zipser 1994). (The corresponding value of maximum kinetic energy is less than 12.5 J kg^{-1}). Therefore, when values of CIN_{inv} were more than 10-12 J kg^{-1}, it was not possible for a cloud to penetrate the inversion. In fact, CIN_{inv} exceeded 10 J kg^{-1} on most days during July first half [Fig. 7(c)]. In fact, those who were on board the ship (the author being one among them) could see shallow cumulus clouds most of the time in July, but very rarely cumulus congestus and cumulonimbus clouds.

4. Discussions

The observations persistently showed dry and warm air in the inversion layer. The question is where this air originated. AS is surrounded by the desserts in the west and north and the entire region is very hot and dry during the boreal summer. Under very strong land heating, the boundary layer is expected to be deep (~2 km or deeper). It is possible that hot thermals that ascended in the land boundary layer moved over cool and moist marine air over the AS. This mechanism can produce a dry and warm layer of air above the marine boundary layer and the inversion observed in the western Arabian Sea is attributed to this. There is another possibility as well. In the outflow from deep convective cloud systems originating in the upper troposphere, moisture has been condensed out and removed. This air has high potential temperature and if forced to subside a great distance in the vertical then also a strong inversion can result. Back trajectory analysis using NCEP reanalysis data was carried out to explore which of the two mechanisms were operating during July and where the inversion air originated. Results for the first 10 days of July 2002 are shown in Figs. 8(a&b). In the lower panel in Fig. 8(b), filled circles are placed at a time interval of 1 day and the last circle on a line gives the day on which the air was over the ship at 700 hPa level. S and E refer to starting (10 days before) and end [10 days later or trajectory rose above 600 hPa (*i.e.*, underwent deep ascent in Cb clouds) whichever is earlier] points. The position B off the west coast of India where all trajectories meet is the ship location. It is observed [Fig. 8(a)] that air at 700 hPa over the ship location originated in the deserts of east Africa, west Asia and sometime also farther north. The vertical trajectories [Fig. 8(b)] show that on some days, air ascended from the boundary layer whereas on other days it descended from above.

It may be noted here that several tropical cyclones (typhoons) formed over the west Pacific and south China Sea in July 2002 (www.solar.ifa.hawaii.edu/Tropical/tropical.html). The forward trajectories observed in Fig. 8(a) reveal that the air over the AS moved over the south China Sea/west Pacific ocean where it ascended in deep clouds. Thus, water evaporated over the AS was feeding the west Pacific typhoons. Whether increased cyclone activity over the west Pacific facilitated the intrusion of dry continental air over the eastern AS suppressing the monsoon or a weak monsoon allowed the typhoons to flourish by feeding them with warm and moist air from the Indian Ocean or it was a mere coincidence needs to be explored.

During 18-24 July, inversions were either weak or absent, CINE was low and CAPE values were around 2 kJ kg^{-1}, but deep clouds did not develop. A positive CAPE is a necessary but not a sufficient conditions and dynamics (large scale low level convergence in particular) has to be favourable for deep convection. Rising surface pressure (Fig. 3) suggests that large scale conditions were becoming unfavourable for convection during 18-25 July. The surface pressure started continuously falling from 25 July and deep clouds developed and produced 145 mm rainfall in the first week of August. The reappearance of inversion, though not as strong as that during the first half of July (Figs. 5, 6 & 7), perhaps delayed the rains till 3 August.

5. Conclusions

The surface and upper air data collected from ORV Sagar Kanya have been analyzed to elucidate the conditions that prevailed over the eastern Arabian Sea during July 2002. The total rainfall measured over the AS in the region 100-200 km off the west coast of India was less than 30 mm in the peak monsoon month of July for the year 2002. A sequence of events seems to have led to this abnormally deficit rainfall. The following are the main conclusions

(*i*) The surface conditions were conducive for the development of deep convective clouds.

(*ii*) During the first half of July, a strong atmospheric inversion between 800 hPa and 700 hPa was present on most days. The convection inhibition energy of the inversion was far too large for the clouds to penetrate.

(*iii*) The second half of July is intriguing – it looks like the large scale dynamics and atmospheric inversion acted in series to extend the dry spell.

(*iv*) The inversion air descended from the upper troposphere on some days and originated in the boundary layer of the deserts of east Africa and west Asia on other days.

(*v*) Values of CAPE over the Arabian Sea during July 2002 were low (~1.5 kJ kg^{-1}) compared to typical values observed over the warm tropical oceans (2-3 kJ kg^{-1}).

Acknowledgements

This work is supported by a grant from the Department of Science and Technology, New Delhi, Govt. of India and I thank the agency. I thank Prof. Sulochana Gadgil and Prof. J. Srinivasan for the encouragement and many useful discussions and Mr. Vinayak Bhat for the back trajectory analysis and diagrams. I thank the National Centre for Antarctic and Ocean Research for making available ORV Sagar Kanya for ARMEX and the ship crew and scientists on board for their help in collecting the data.

References

Betts, A. K. and Ridgway, W., 1988, "Coupling of the radiative, convective and surface fluxes over the equatorial Pacific", *J. Atmos. Sci*., **45**, 522-536.

Bhat, G. S., 2001, "Near surface atmospheric characteristics over the North Bay of Bengal during the Indian summer Monsoon", *Geophys. Res. Lett*., **28**, 987-990.

Bhat G. S, Gadgil, S., Harish Kumar, P. V., Kalsi, S. R., Madhusoodanan Murty, V. S. N., Prasada Rao, C. V. K., Ramesh Babu, V., Rao, L. V. G., Rao, R. R., Ravichandran, M., Reddy, K. G., Sanjeeva Rao, P., Sengupta, D., Sikka, D. R., Swain, J. and Vinayachandran, P. N., 2001, "BOBMEX - the Bay of Bengal Monsoon Experiment", *Bull. Amer. Meteor. Soc*., **82**, 2217-2243.

Colon J. A., 1964, "On interactions between the southwest monsoon current and the sea surface over the Arabian Sea", *Indian J. Met. Geophys*., **15**, 183-200.

Gadgil, S., Joseph, P. V. and Joshi, N. V., 1984, "Ocean atmosphere coupling over monsoonal regions", *Nature*, **312**, 141-143.

Ghosh S. K., Pant, M. C. and Dewan, B. N., 1978, "Influence of the Arabian Sea on the Indian summer monsoon", *Tellus*, **30**, 117-125.

Grossman R. L. and Durran, D. R., 1984, "Interaction of low-level flow with the western ghat mountains and offshore convection in the summer monsoon", *Mon. Wea. Rev*., **112**, 652-672.

Kingsmill, D. E. and Houze, R. A. Jr., 1999, "Thermodynamic characteristics of air flowing into and out of precipitating convection over the west Pacific warm pool", *Quart. J. Roy. Meteor. Soc*., **125**, 1209-1229.

Krishnamurti, T. N., 1985, "Summer monsoon experiment – A review", *Mon. Wea. Rev*., **113**, 1590-1626.

Lucas, C. and Zipser, E. J., 1994, "Vertical velocity in oceanic convection off tropical Australia", *J. Atmos. Sci.*, **51**, 3183-3193.

Lucas, C. and Zipser, E. J., 2000, "Environmental variability during TOGA COARE", *J. Atmos. Sci.*, **57**, 2333-2350.

Pant M. C., 1982, "Some characteristic features of the low-level jet field over the Arabian Sea during the Indian summer monsoon", *Mausam*, **33**, 1, 85-90.

Williams, E. and Renno, N., 1993, "An analysis of the conditional instability of the tropical atmosphere", *Mon. Wea. Rev.*, **121**, 21-36.