

Arabian Sea monsoon experiment: An overview

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सार — स्थल-महासागर-वायुमंडल क्षेत्रीय प्रयोगों में से एक अरब सागर मानसून प्रयोग (आरमेक्स) है जिसे भारतीय जलवायु-अनुसंधान कार्यक्रम के अन्तर्गत जून-जुलाई 2002 और मार्च-जून 2003 में कार्यान्वित किया गया है। आरमेक्स के व्यापक वैज्ञानिक उद्देश्य इस प्रकार हैं :-(i) मानसून अवधि के दौरान भारत के पश्चिमी तट पर तीव्र वर्षा की घटनाओं के साथ संबद्ध अपतटीय द्रोणी में निहित मेसोस्केल भ्रमिलों (अरब सागर संवहनी) का अध्ययन करना और (ii) अरब सागर उष्ण जलकुंड के विकास, अनुरक्षण और समाप्त होने तथा मानसून के आरम्भ होने की अवस्था का अध्ययन करना। इस प्रयोग के लिए परम्परागत मौसम मानीटरन प्रणालियों, मौसम उपग्रह प्रेक्षणात्मक प्रणालियों, पोतों, मौसम-महासागर प्लवों, स्वचालित मौसम केन्द्रों, धरातलीय स्तर पर मौसम वैज्ञानिक मीनारों और वायुयानों को अत्याधुनिक उपकरणों से लैस किया गया। इस शोध पत्र में आरमेक्स के वैज्ञानिक उद्देश्यों, कार्यान्वयन संबंधी नीति, स्रोत संघटन विस्तारित आधारभूत संरचना प्रेक्षणात्मक आँकड़ा मिलान अभिलेखागार और भाग लेने वाले वैज्ञानिकों द्वारा किए गए आरम्भिक विश्लेषण का सिंहावलोकन करने का प्रयास किया गया।

ABSTRACT. The Arabian Sea Monsoon Experiment (ARMEX) is one of the land-ocean-atmosphere field experiments implemented in June-July 2002 and March-June 2003 under the Indian Climate Research Programme. The broad scientific objectives of the ARMEX are (i) to study the offshore trough embedded mesoscale vortices (Arabian Sea convection) associated with intense rainfall events on the west coast of India during monsoon period, and (ii) to study the evolution, maintenance and the collapse of the Arabian Sea warm pool and onset phase of the monsoon. Conventional weather monitoring systems, weather satellite observational systems, ships, met-ocean buoys, automatic weather stations, surface layer meteorological towers and aircraft were deployed with state-of-the-art instrumentation for this experiment. This paper attempts to provide an overview of the ARMEX scientific objectives, implementation strategy, resource mobilization, infrastructure deployed, observational data collation, archival and initial analysis by the participating scientists.

Key words — ARMEX, Offshore trough, Heavy rainfall, Warm pool, Monsoon experiments, Sea surface temperature and Ocean-atmosphere coupling.

1. Introduction

Arabian Sea Monsoon Experiment (ARMEX) was the second large-scale land-ocean-atmosphere observational study proposed under the Indian Climate Research Programme (ICRP), coordinated by the Department of Science and Technology as nodal agency (DST, 1998). The atmosphere overlying the Arabian Sea prior to and during the southwest monsoon season (June-September) is complex as it contains air masses of different origin. In the lowest 1-2 km layer, air being warm and moist has maritime properties, whereas in 2-4 km layer air is of continental origin - very warm but dry. This can result in a strong inversion that inhibits cloud formation. However, Offshore Trough (OT) with possible embedded cyclonic vortex is an important weather system associated with organized convection over the Arabian

Sea during the southwest monsoon season, which is responsible for heavy rainfall along the west coast (George, 1956; Mukherjee and Shyamala, 1984). Vortices within the OT are mesoscale in character, with linear dimensions of the order of 100 km. Their presence is detected by weak southerly or easterly winds at coastal stations, as against the prevailing southwest monsoon winds over the Arabian Sea. Notwithstanding the small spatial dimensions of these vortices, they are effective in bringing about a spell of very heavy rain in their vicinity. The normal duration of the active phase of the trough is 1 to 5 days with embedded vortices lasting for about 12-24 hours and forming or reforming at different places within the OT as an individual vortex moves northward along the coast and collapses, giving birth to another vortex. The dynamics of these vortices has not been examined in much detail so far.

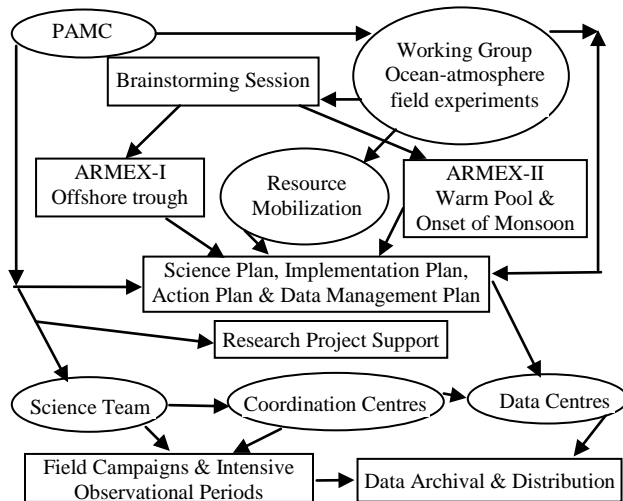


Fig. 1. Interactive system of working in planning and implementation of ARMEX

Similarly, a pool of warm waters [Sea Surface temperature (SST) $>28^{\circ}\text{C}$] with a well defined three-dimensional structure in the South Eastern Arabian Sea (SEAS) has been recognized as an important boundary condition (Seetaramayya and Master, 1984; Shankar and Shetye, 1997; Rao and Sivakumar, 1999), which in some years triggers the onset of the monsoon and the formation of the monsoon onset vortex (Krishnamurti *et al.*, 1981). The coupling of the atmosphere to the warm pool (WP) needs to be understood because it is observed that frequently, intense large scale convection occurs over this region. The linkage between the transient cold SSTs, driven by coastal upwelling and strong surface wind mixing and weakening of the monsoon in the eastern Arabian Sea on intra-seasonal time scale has not been well established so far. Issues involved are complex and multi-disciplinary in nature, the need for co-operative efforts of the scientific groups and organizations in the country, working on monsoon-climate related problems was thus recognized. Thus, ARMEX is aimed at elucidating the linkages between the *in-situ* atmospheric and oceanic processes in the Arabian Sea region and the variations in the monsoon climate over the Indian sub-continent. The ARMEX operational area covers about 200 km either side along the west coast of India and Lakshadweep Sea region.

2. Planning and objectives of the ARMEX field phase

Detailed planning and implementation of ARMEX field experimental campaigns was carried out with the active support of all concerned departments/institutions/scientists associated with the research, development and prediction of the monsoon in an interactive way (Fig. 1). Recognizing the complexity of

the experiment and constraints in the availability of resources, the Project Advisory and Monitoring Committee (PAMC) recommended towards implementing ARMEX in two phases, during June-August 2002 and during March to June 2003. Accordingly, detailed implementation and action plans (DST, 2002; DST, 2003) were prepared by the 'Working Group on Ocean-Atmosphere Field Experiments', under the overall guidance of PAMC and an inter-departmental committee on ICRP. An ARMEX-Science team and ARMEX-weather advisory group provided the necessary guidance during various stages of implementation of the field campaigns. ARMEX-Operations co-ordination centre from India Meteorological Department (IMD), New Delhi & Mumbai provided the overall operational co-ordination during the field campaigns. DST has supported several research projects to various scientists/institutions, to procure the required additional instruments, calibration & installation and additional human resources to systematically monitor, analyses the observations and modelling to meet the objectives. The detailed scientific objectives of two-phases of ARMEX are as follows.

2.1. ARMEX-I : Offshore trough

During the summer monsoon, copious rainfall occurs over the west coast of India. On occasions, the rainfall is exceptionally heavy, exceeding 20 cm per day. These events are believed to be due to mesoscale convective systems, known as offshore troughs which are generally embedded in synoptic or larger scale convective systems over the Arabian Sea. The scientific objectives of ARMEX-I : Offshore trough are to examine the nature of the systems responsible for these events include : (i) Genesis, intensification and propagation of convective systems over the eastern Arabian sea leading to very heavy rainfall events along the west coast of India, (ii) Variation of air-sea fluxes, vertical stability and wind shear associated with these systems, (iii) Impact of the SST field including wind-induced upwelling on convective systems, (iv) Spatial and temporal variation of off-shore trough and its relationship with the convection on the eastern Arabian Sea and (v) Modelling of the off-shore mesoscale convection.

2.2. ARMEX-II : Warm pool dynamics and onset of monsoon

Very little is known about the mechanisms responsible for the warm pool, evolution of its formation, maintenance and collapse, though plausible mechanisms have been suggested (Rao and Sivakumar, 1999; Shankar and Shetye, 1997). Also, noted the SEAS (Lakshadweep Sea) is the location where the monsoon onset vortex forms. The onset of the summer monsoon over Kerala is

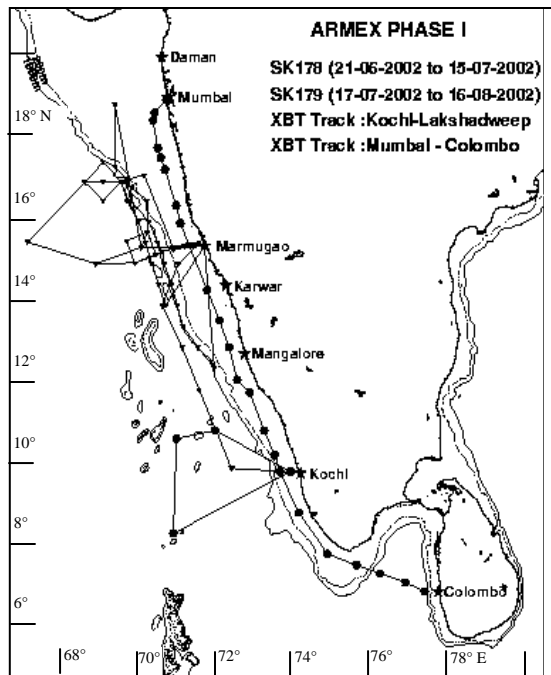


Fig. 2. Region of intensive observations and ORV Sagar Kanya cruise tracks and XBT surveys during ARME X-I observational campaigns

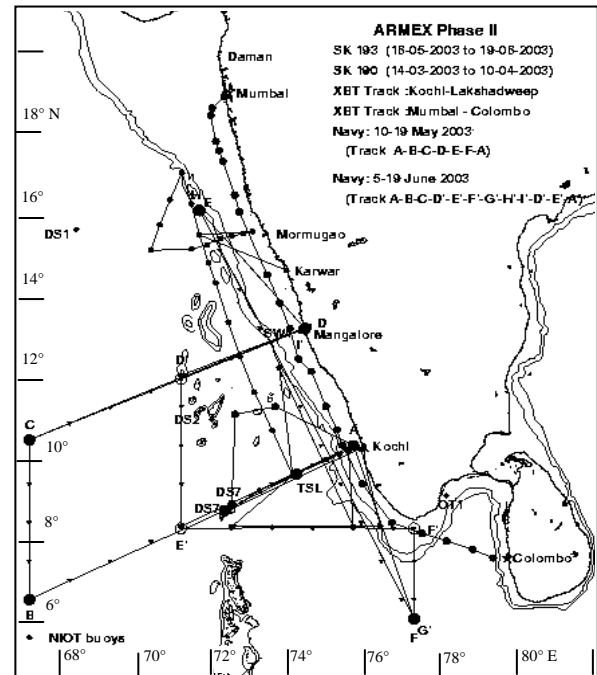


Fig. 3. Region of intensive observations, ORV Sagar Kanya and Naval ships cruise tracks and XBT surveys during ARME X-II observational campaigns

often, but not always, associated with the formation of this vortex. Research objectives of the ARME X-II were centered on : (i) Life cycle of the north Indian Ocean WP and SST high over SEAS with its spatiotemporal structure *vis-à-vis* the Indian Ocean WP, (ii) Nature and strength of inversions in the atmosphere over SEAS during the growing, mature and collapsing phases of the WP, (iii) Components of surface fluxes and air-sea interaction processes in the Lakshadweep Sea, (iv) The role of WP over Lakshadweep Sea in the process of onset of monsoon over Kerala and (v) Role of aerosols in modulating SST (Aerosol climate forcing) over the WP.

3. Design and Implementation of ARME X

The design of ARME X-I was based on our understanding about the fluctuating regime of the monsoon over the Arabian Sea and the SST and ocean circulation features in the offshore region of the west coast of India and SEAS. Conventional IMD stations (Thiruvananthapuram, Cochin, Mangalore, Karwar, Ratnagiri, Goa, Mumbai, Ahmedabad, and Minicoy & Amini Islands) in the ARME X operation area and weather satellite observational systems, ORV Sagar Kanya, ships of the Indian Navy and the Indian Coast Guards, network of met-ocean buoys (DS1, DS2, DS6, DS6A, DS7, DS7A, SW3 and SW4), automatic weather stations, surface layer meteorological towers for measuring fluxes, wind profiler

and aircraft missions by Indian Air Force (IAF) were deployed for this experiment. The region covered was the east Arabian Sea off the west coast of India. Fig. 2 provides the details of the ship cruise tracks of ORV Sagar Kanya (SK 178 during 21 June to 15 July 2002 and SK 179 during 17 July to 16 August 2002), XBT (Expandable Bathy Thermograph) surveys between Mumbai-Colombo using commercial ships and between Kochi-Lakshadweep islands using passenger ships (MV Tipu Sultan and MV Bharat Seema) during April to August 2002. Naval Hydrographic vessels INS Sarvekshak (during 15 June - 11 July) and INS Jamuna (during 15 July to 14 August 2002) carried out hourly surface meteorological observations during intensive observational periods (IOPs) and synoptic surface observations, sea surface temperature and CTD observations as per schedule. Also the Coast Guard vessels were used to collect data on ocean surface conditions and meteorological parameters.

The design of the ARME X-II observational phase stems from our present understanding derived from sea surface temperature (SST) records and satellite altimetry about the formation and persistence of the WP region in the SEAS. In order to quantify these processes, measurements were continued between Mumbai and Colombo at monthly interval and between Cochin and Lakshadweep Islands at 15-day interval. The observational network thus provided special observations

on the evolution of the structure of the WP and the atmospheric regime over the WP and the adjoining coastal areas. Details of the ship cruise tracks of SK190 during 12 March to 10 April 2003 and SK193 during 16 May to 19 June 2003 and Naval Oceanographic vessels INS Matunga during 10-19 May 2003, INS Investigator during 5-19 June 2003 and XBT surveys are provided in Fig. 3.

As per the implementation strategy, executed the ARMEX-I OT observational campaign during 15 June to 15 August 2002 and ARMEX-II: Warm pool and onset of the monsoon during 14 March to 10 April 2003 and 15 May to 19 June 2003. During this observational period, there were six (6) intensive observational periods to obtain more detailed data of the critical events. During this period, further efforts were put to collect additional data necessary to investigate the dynamics of the atmospheric processes associated with the convective activity.

3.1. Scientific experiments

A number of specific, intensive observations (some time every two hours) were carried out to quantify different components of the atmosphere, physical and chemical oceanography, from a depth of 1000 meters in the ocean to about 20-25 km in the upper atmosphere using state-of-the art instrumentation in the Arabian Sea and along the west coast of India. The time series measurements at 74° 30' E, 9° 13' N (TSL) was chosen to lie within the climatological high in SST in the region to ensure a high probability that it would fall in the zone of SST high and provided high-resolution temporal coverage and the sections sampled the spatial variability across the WP. The observations at TSL major time series extended over a period of 15 days in each cruise during 2003. It also falls on the Kochi–Minicoy XBT section, along which an XBT line once almost every fortnight is being run under the ARMEX programme. Time series measurements for about 4 days were also carried out near the buoys (DS6, DS7 & DS7A) to study the role of advection in the heat budget of the surface layer of the SEAS. Atmospheric profiles (two profiles in general and four profiles during IOPs) were taken within the study region, including over the ocean, to investigate the dynamics of the convective processes and associated rainfall variability. Fluctuations in the structure of atmospheric and marine boundary layers and WP dynamics were monitored. Also continuous measurements of atmospheric fluxes over land and fluxes within the marine boundary layer at stationary position of the Sagar Kanya during the observational period were undertaken. The composition of aerosols, rainfall chemistry, atmospheric electricity and clouds were also observed. Modeling different aspects of atmospheric

processes, oceanic processes and the ocean-atmosphere coupling processes were undertaken. Also, utilized the opportunity to investigate the ocean surface waves and the acoustic propagation in the waters of the Arabian Sea.

3.2. Infrastructure deployed

In order to meet the scientific objectives, various land-based, ocean-based and space-based observational platforms/system were utilized. During the observational campaigns of ARMEX several aspects of the convection, intra-seasonal variability of the monsoon and land-ocean-atmosphere interactions were monitored by variety of slow and fast response sensors from land-based, ocean-based, and space-based platforms. The land-based platforms includes all the Radiosonde (RS) and Radar Network of IMD along the west coast of India, Synoptic stations maintained by IMD, IAF, Agromet stations, etc., atmospheric flux measurements (sensors mounted on a Boom on ORV Sagar Kanya and Micrometeorological towers at Goa, Mangalore and Tarapore), ten automatic weather stations (AWS) and a Lidar. Ocean-based platforms consisted of Ships (Sagar Kanya, vessels of Indian Navy and Indian Coast Guard), shallow and deep water Buoys, CTD profiles, XBTs, lowered and vessel mounted ADCP, Moorings, AWS on ships). In addition to the existing Buoy network in the Arabian Sea, a close network of four data buoys (DS6, DS6A, DS & DS7A) were deployed off Minicoy Island. The DS7A was deployed with thermister chains and current meters. It may be noted that one of the met-ocean buoy (DS 7) had stopped functioning by the beginning of April, where as DS7A continued to function till 18 May 2003. However, vital sub-surface data from the current meters attached to DS7A were lost during the field phase and could not be recovered. ORV Sagar Kanya was specially equipped with high resolution GPS radiosondes, atmospheric fluxes, radiation, underwater radiation profiles (SATLANTIC meter), atmospheric chemistry & aerosols. In addition, composition of aerosols, SO₂ and black carbon concentrations and mass distribution and of atmospheric ions, conductivity and electric field were continuously monitored. One IAF Aircraft was suitably modified to take observations on aerosols, cloud microphysics, *in-situ* meteorological data (temperature, wind and humidity) during the sorties. Digital video pictures of the clouds during the Aircraft sorties were also obtained. All the available satellite pictures (Infrared and Visible) from INSAT and METEOSAT have been obtained and archived.

4. ARMEX data management

During the four SK cruises surface meteorological parameters and air-sea fluxes were recorded continuously

using automated weather stations, radiometers and other equipments. Vaisala Sonde (Digicora) ascents were made to probe the atmospheric column up to 20 to 25 km height. About 251 upper air profiles were obtained during these cruises using the hydrogen filled balloons. SBE 9/11 plus CTD system was operated at 366 stations and also operated the SBE 19 plus SEACAT profiler covering section perpendicular to the coast and time series locations. Water column samples were obtained towards analyzing for nutrients, oxygen content and nitrous oxide. Continuous measurements were also made on atmospheric ions, conductivity and electric field throughout the cruise. In addition, the air samples were collected at regular intervals to measure cloud condensation nuclei, mass distribution of aerosols and suspended particulates. Rainwater samples were collected to analyze the wet deposition. The data thus generated cover weak, break and active monsoon conditions. Detailed analysis of this unique dataset is expected to improve our understanding of the monsoon phenomenon in general and that of intense rainfall events over the west coast of India in particular.

A variety of operational and specialized data sets were collected during ARMEX period about the surface and upper atmospheric parameters, surface fluxes, outgoing long-wave radiation, satellite derived rainfall, short and long-wave radiation, subsurface vertical profiles of temperature and salinity, ocean currents, and atmospheric chemistry near the ocean surface. All the observational data sets related to atmosphere were collated and quality checked at ARMEX data Centre at NCMRWF, New Delhi and subsurface oceanographic data sets at INCOIS (Indian National Centre for Ocean Information Services), Hyderabad. The atmospheric data consists of all meteorological data including surface, radiosondes, towers, AWS, Wind Profiler, atmospheric aerosols, cloud characters and atmospheric electricity. Further, model analysis of NCMRWF, NCEP and gridded data sets are available for modelling studies. Some of the quality checked data sets were made available to the Indian scientific community for detailed analysis. The weather summaries during the ARMEX period were prepared and distributed (Mohanty, *et al.*, 2002, 2003). The initial results were discussed at a ARMEX data analysis workshop held during 23-24 December 2003 at NIOT, Chennai.

ARMEX data policy envisages that the participating scientists in collecting new datasets are free to exchange their data with other ARMEX participants. Quality checked atmospheric data would be distributed at the end of one-year from the completion of field phase through data Centre. Sub-surface oceanographic data could be exchanged among the Indian researchers with an undertaking for self use only and data would not be

exchanged with any foreign scientist, without prior permission. All land-atmospheric data sets would be in Public domain at the end of two years of field phase.

5. Discussion and conclusion

Some of the scientific issues associated with the monsoon variability are (a) dynamics of local atmospheric convection leading to intense rainfall events along the West Coast of India, (b) existence of 'Offshore trough' with embedded vortices and its spatial and temporal association with synoptic scale settings, (c) formation of stable layer in the Arabian Sea role of remote forcing, (d) evolution and collapse of the WP region in the SEAS, (e) air-sea coupling at high SSTs and pre-onset atmospheric conditions, (f) intense convection over SEAS and monsoon onset over Kerala coast, (g) role of aerosols over the Arabian Sea during the pre-monsoon on the rainfall variability over the land during monsoon season and (h) modeling the land-ocean-atmosphere interactions. In order to improve our scientific understanding on the above stated issues, large scale field observational campaigns were conceived and most of the available national resources were mobilized to implement the program. The observational network operational during the field campaigns provided special observations on the land-ocean-atmosphere coupled system during the northward propagating phase of convective regime along the west coast, the evolving stages of the OT and the formation and structure of offshore vortices, if any, embedded in the trough. The network also provided special observations on the structure of the WP and the atmospheric regime over the WP and the adjoining coastal areas. Thus, ARMEX is one of the well designed multi-disciplinary, multi-institutional participatory land-ocean-atmosphere interactions study over the north Indian Ocean, successfully implemented during 2002 and 2003. As many infrastructure facilities as possible were deployed to meet the objectives of ARMEX. Successful collection of observational datasets was possible due to the contributions and dedicative efforts of each and every person associated with ARMEX in meeting the time-bound requirements of the implementation plan. Quality checked ARMEX data sets were widely distributed among the participating scientists/organizations towards detailed analysis/modeling to answer many of the scientific questions leading to ARMEX.

The initial analysis of the data could establish the existence of the OT, its oscillation on the intraseasonal scale and is dictated by the cross equatorial flow which triggers the intense rainfall (Sanjeeva Rao and Sikka, 2005). Ocean-atmospheric exchanges under the warm ocean surface fuel convective episodes resulting in cooling of the SST suggesting ocean's role in regulating

the monsoon and in turn being impacted by it. Mesoscale modeling of the phenomena would be capable of simulating formation of OT and embedded vortex with additional data, which has potential for operational extreme weather forecasts of onset of deep convective episodes. Similarly existence of barrier layer, occurrence of temperature inversions in the sub-surface waters of the Lakshadweep Sea and their west ward spread indicates the oceanic process play an important role in the WP dynamics (Shankar *et al.*, 2004). Further, systematic analysis of ARMEX datasets, as discussed in this special issue of MAUSAM, provide an enhanced understanding of the atmospheric processes, oceanographic processes and the coupled land-ocean-atmospheric processes towards better prediction capabilities of the monsoon variability over India.

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