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ORIGINAL PAPER

Simulation of rain-bearing summer monsoon systems along the west coast of India by use of ARMEX re-analysis

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Abstract Re-analysis, using surface, upper-air, and satellite observations specially collected during the Arabian Sea Monsoon Experiment-I (ARMEX-I), has been performed with a global data assimilation system at T-80/L18 resolution. Re-analysis was performed for the entire ARMEX-I period (15th June–16th August 2002). In this paper we discuss the results based on re-analysis and subsequent forecasts for two successive intensive observation periods associated with heavy rainfall along the west coast of India during 2–12 August, 2002. Results indicate that the re-analysed fields can bring out better synoptic features, for example troughs along the west coast and mid tropospheric circulation over the Arabian Sea. Simulated rainfall distribution using re-analysis as initial condition also matches observed rainfall better than data from the initial analysis.

Keywords ARMEX · Monsoon · Field experiment · Observations · Data impact

1 Introduction

Copious rainfall occurs over the west coast of the Indian peninsular region during summer monsoon season of India. Rainfall events along the west coast are mainly associated with convective systems embedded in large-scale flow over Arabian Sea. Within the season there are alternate spells of active and weak monsoon. Intense rainfall events over the west coast are usually associated with troughs along west

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coast (Rao 1976), strong cross-equatorial flow over the Arabian Sea (Findlater 1969), and mid-tropospheric cyclone (MTC) over the Arabian Sea near Gujarat and the Maharashtra coast (Miller and Keshavmurty 1968).

The Arabian Sea Monsoon Experiment (ARMEX) is one of the major field campaigns during recent years under the Indian Climate Research Programme (ICRP). It is a unique experiment and the first of its kind along the coastal region of the Arabian Sea. ARMEX-I was planned to study the convection associated with intense rainfall events on the west coast of India. One of the main objectives of the experiment was to achieve better understanding and modelling of the processes leading to the genesis, intensification, and propagation of convective systems over the eastern Arabian Sea associated with very heavy rainfall along the west coast of India (Sikka 2005). Satisfactory simulation of the mesoscale systems associated with heavy rainfall events along the west coast of India requires information about several aspects of the atmosphere including land–ocean–atmosphere interactions. The field campaign area of ARMEX covers approximately 200 km either side along the west coast of India and Laskhadweep Sea region. During this experiment extensive observations are taken from a variety of platforms, for example the conventional surface and upper-air network of India Meteorological Department (IMD), especially set up automatic weather stations (AWS), instrumented micro-meteorological towers, ships, buoys, and aircraft, etc. Five intensive observation periods (IOP) were related to heavy rainfall in some pockets over the west coast. During the IOP, the temporal frequency of observations from the regular IMD stations was also enhanced.

The ARMEX data centre was established at the National Centre for Medium Range Weather Forecasting (NCMRWF), India, in association with the Centre for Atmospheric Science, Indian Institute of Technology, Delhi and IMD, Delhi, with responsibilities to process, quality check, archive, and redistribute these especially collected observations (Rao 2005). A major task of the ARMEX data centre was to perform global re-analysis after ingesting these special observations and redistribute the results to other scientific organizations.

It is well known that the quality of any objective analysis of atmospheric fields depends on the density and the quality of the observations assimilated to produce the analysis. Data scarcity over the tropical oceanic region is one of the major problems associated with numerical weather prediction (NWP) over the tropics. Assimilation of any additional information over this region is therefore likely to provide better initial conditions (Basu and Das Gupta 2001, Das Gupta et al. 2003), which in turn would have positive effect on subsequent forecasts.

Carr et al. (1993), conducted observing system experiments (OSE) using a four-dimensional data-assimilation scheme based on Newtonian nudging with different types of in-situ observation during the summer monsoon experiment in 1979. The NWP model used in these experiments was a ten-level, limited area, primitive equation model. The result of this experiment was very encouraging, with improved forecasting of the monsoon onset vortex over the Arabian Sea during June 1979. The study revealed that the improvement was mainly because of temperature and humidity data from dropsonde, because these cover a substantial depth of the troposphere. Study of the effect of targeted observations (Langland et al. 1999) during the Fronts and Atlantic Storm-Track Experiment (FASTEX), 1997, revealed that the best 24-hour forecast improvement is achieved by using dropsonde and satellite wind data. It also revealed that assimilation of satellite wind data and ship-based soundings in areas of weak initial-condition sensitivity has a minimal effect on forecast error. The effect of the additional FASTEX radiosonde observations on the High-Resolution Limited-Area Model (HIRLAM) data-assimilation and forecasting system have been studied by Amstrup and Huang (1999). The study revealed that, although, on a daily basis, the extra data could have both positive and negative effects on the different meteorological variables considered, averaged over the whole period the effect is definitely positive, especially on upper model levels.

Assimilation of special observations taken during Indian Ocean experiment, the Intensive field phase-1999 (INDOEX-IFP, 1999), also has resulted in a significant positive impact, especially on analyses over the oceanic region (Das Gupta et al. 2003).

A pilot study of re-analysis utilising upper-air observations during ARMEX-I with NCMRWF's operational global data assimilation system (GDAS) at T80/L18 resolution for July 2002 has been conducted by Das Gupta et al. (2005). Study revealed marginal improvement in analysis and subsequent forecasting over the Indian subcontinent. Re-analysis for the entire ARMEX-I period has subsequently been conducted using all the special observations collected during ARMEX-I; results relating to simulation of monsoon systems using re-analysed fields will be discussed in this paper. The Data used to generate re-analysis are discussed briefly and then the Global analysis-forecast system is described. The results are then presented and discussed and conclusions based on the results and discussion are presented in the last section.

2 Data

A variety of platforms were used to collect meteorological observations over the Arabian Sea and along the west coast of India, within 200 km of the coast, in the east–west direction, during ARMEX. The geographical distribution of some of these observations is shown in Fig. 1. They include surface observations and upper air observations from regular surface/upper-air stations of IMD along the west coast of India. Automatic Weather Stations (AWS) were also set up along the west coast of India. Upper-air temperature, moisture, and wind profiles with GPS-sonde from a coastal station at Dabolim (73.83° E, 15.38° N), Goa, operated by Directorate of Naval Oceanography and Meteorology (DNOM), the Indian Navy, were among the special observations collected during this period. The frequency of these upper air observations from Dabolim was twice a day (0000 and 1200 UTC) from 15th June to 15th August 2002 with two additional observations (0600 and 1800 UTC) during IOPs. Pilot balloon observations from three Indian Air Force (IAF) stations, Vadodara, Belgaum, and Sulur along the west coast of India, with a frequency of three observations per day (0000, 0600, and 1200 UTC) were also made available during this period. Upper air temperature, moisture, and wind profiles from ORV Sagar-Kanya (24th June–15th August 2002) over the Arabian Sea, with surface observations was one of the main sources of data over the Arabian Sea. Surface data over the Arabian Sea were also available from data buoys deployed by National Institute of Ocean Technology (NIOT) and Indian Naval ships INS-Hansa and INS-Sarvekshak. IAF also carried out special flights during IOP over the Arabian Sea. Apart

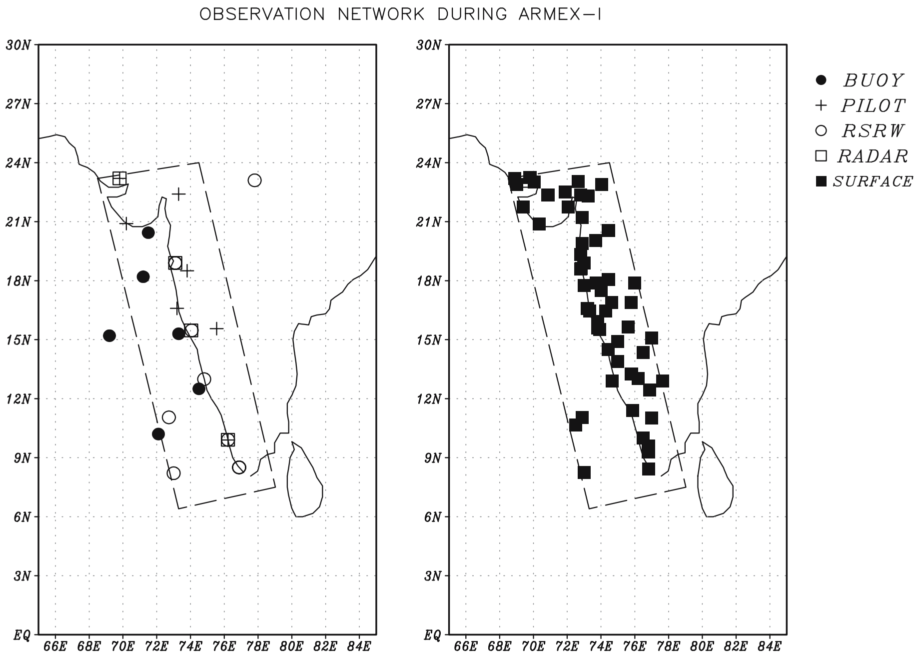

Fig. 1 Observation network (conventional) during ARMEX-I

from the operationally archived observational data sets at NCMRWF, all these especially collected observations were assimilated to generate re-analysis. Re-analysis also used high-density water vapour channel winds from METEOSAT-5 (63° E) and Quickscat surface winds at 75 km resolution. Some of these specially taken upper-air observations were validated against IMDs regular observational data sets (Das Gupta et al. 2005) and found to be satisfactory; all these special data sets, with other archived observations, were, however, also passed through quality-control procedures during assimilation.

Data used in the operational assimilation system of NCMRWF were:

(a) surface observations from land stations and voluntary observing fleet over the sea (SYNOP/SHIP);
(b) drifting and moored buoy observations (BUOY);
(c) upper air profiles of temperature, moisture, and wind (RS/RW and Pilot Balloon);
(d) satellite observed cloud motion vectors (CMV) from a variety of geo-stationary satellites;
(e) derived temperature and total precipitable water from NOAA 15 and 16 satellites;
(f) upper level wind and temperature reported by aircraft; and
(g) surface wind speed from polar orbiting DMSP (Defense Meteorological Satellite Programme, USA) satellites.

3 Global analysis-forecast system

The Global Data Assimilation system (GDAS) operational at NCMRWF is a six-hourly intermittent three-dimensional scheme. At NCMRWF meteorological observations from all over the globe are assimilated four times a day, at 0000, 0600, 1200, and 1800 UTC. The assimilation scheme uses all data collected within ±3 h of the assimilation time and received within a specified cut-off period (~12 h for 0000 UTC). All the data are passed through comprehensive quality-control scheme (Collins and Gandin 1990). A six-hour prediction from Numerical Weather Prediction (NWP) model (T80/L18), with a previous initial condition, valid for the current analysis time is used as the background field, or the first guess for the analysis. The analysis scheme used in GDAS is based on the concept of the Spectral Statistical Interpolation (SSI) technique developed originally at National Center for Environmental Prediction (NCEP), USA (Parrish and Derber 1992). The analysis is performed in spectral space at vertical sigma levels; the analysis variables are the sigma level spectral coefficients of the empirical orthogonal functions (EOFs) of vorticity, mixing ratio, unbalanced part of divergence, temperature, and logarithm of surface pressure. The balanced parts of the different variables are computed using a quasi-geostrophic linear balance relationship (Haltiner and Williams 1979). The forecast model (Kanamitsu 1989) operational at NCMRWF is a global model which uses the spectral method for expansion of variables in a series of spherical harmonics. The forecast model variables are surface pressure, layer temperature, specific humidity, divergence, and vorticity, all of which are currently expanded in a series of up to 80 waves. In the vertical, the atmosphere is sliced into 18 unequally spaced sigma layers, of which approximately 12 are within the troposphere and the rest are in the stratosphere.

Re-analyses were generated by assimilating all the special observations from ARMEX, as discussed in the section Data, with other conventional and non-conventional data sets from the operational archive of NCMRWF for the period 1st June to 16th August 2002. Five-day forecasts were also made for every day, using 0000 UTC re-analysis of that day as initial condition. There were a total of five IOPs during ARMEX-I associated with heavy rainfall in some pockets over the west coast of India. Of these five IOPs there were two consecutive IOPS in quick succession during 2–11 August 2002. Results based on analyses and forecasts (henceforth referred to as ARMEX) and thus generated using ARMEX data for IOP periods 2–4 August and 7–11 August have been discussed here.

4 Results and discussion

4.1 Synoptic condition

The first IOP in August 2002 was declared for 2–4 August, when the monsoon was very active over Maharashtra and Karnataka coast yielding widespread rainfall amounting to 1–9 cm of rain along this coast. In the lower level a trough of low pressure lay along south Maharashtra to Kerala coast on 2nd August, which subsequently extended to the entire coast on 4th August. A cyclonic circulation was also noticed over the east central Arabian Sea off the Maharashtra coast (Hatwar et al. 2005). Figure 2 depicts 850 and 700 hPa winds from RS/RW and pilot balloon

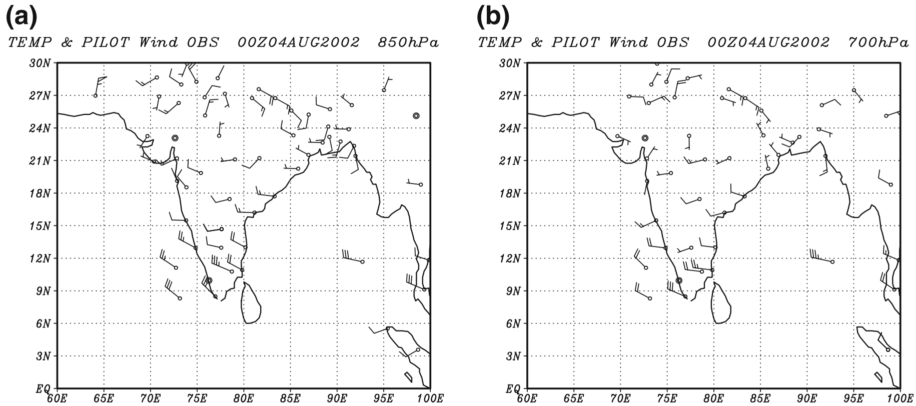

Fig. 2 RS/RW and pilot balloon wind observations at 0000 UTC on 4th August 2002 (**a**) 850 hPa (**b**) 700 hPa

observations for 0000 UTC on 4th August 2002. One can notice the north-north-westerly winds along the west coast at 850 hPa (Fig. 2a), which also reveal the presence of a trough along the west coast at that level. Similarly at 700 hPa level (Fig. 2b), wind turning over the Maharashtra coast (between 15° N and 21° N) also reveals the presence of cyclonic circulation over the Maharashtra coast at that level.

Analysed wind fields for re-analysis (ARMEX), operational analysis (OPER), and their difference (ARMEX–OPER) at 850 and 700 hPa at 0000 UTC on 4th August 2002 are depicted in Fig. 3. At the 850 hPa level one can notice the northerly

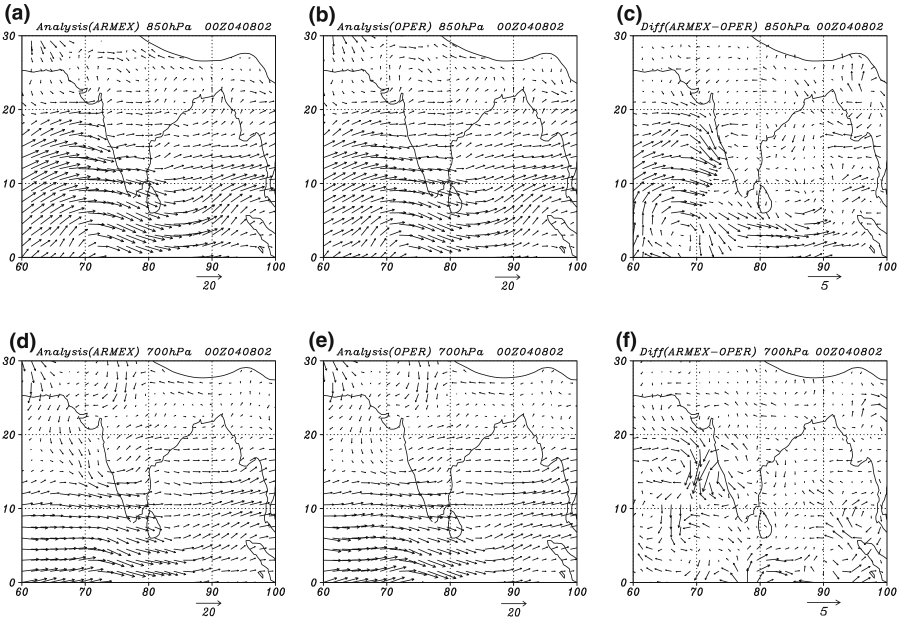

Fig. 3 Analysed wind fields at 850 and 700 hPa at 0000 UTC on 4th August 2002 for ARMEX, OPER, and their difference (ARMEX-OPER)

components in ARMEX analysed winds along the west coast of India between 10° N and 20° N, whereas winds over the same region in OPER are more zonal. The trough along this region is clearly seen in the difference plot (ARMEX–OPER). The difference plot also shows that the changes in wind analysis because assimilation of ARMEX observations are mainly restricted to over the Arabian Sea adjoining the west coast of India and the Indian Ocean region. As expected, the impact of ARMEX data is comparatively small over the other Indian land mass. At the 700 hPa level the trough along the west coast is more organized and stronger in ARMEX reanalysis than in OPER.

The next IOP in August 2002 was declared for 7–11 August, when the monsoon again became active over the entire west coast yielding heavy rainfall (maximum rainfall reported 28 cm) along the coast. Between 5th and 6th August the monsoon was relatively weak along the west coast of India yielding scattered rain (1–5 cm) along the coast. These consecutive active and weak phases of the monsoon along the west coast are usually captured in the day-to-day variation of the kinetic energy over the Arabian Sea at the 850 hPa level (Basu et al. 1999). Figure 4a depicts the variation in the kinetic energy m^2s^{-2} averaged over the Arabian Sea (55° E–75° E and 0°–19° N) at 0000 UTC on 1–12 August 2002 for ARMEX and OPER. The strong and moderate phases of the monsoon along the west coast is clearly revealed from the analysed kinetic energy of ARMEX, whereas the variation for OPER is smooth, showing no signals indicating the different phases of the monsoon. The daily variation of net tropospheric moisture (NTM) over the same region (Fig. 4b) are clearly captured in both analyses, however.

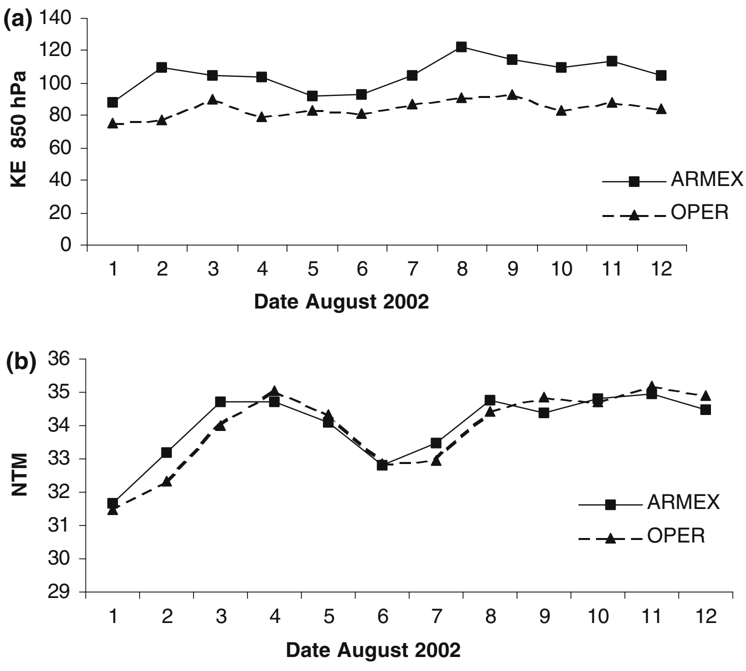

Fig. 4 (**a**) Daily variation of kinetic energy (m^2s^{-2}) over the Arabian sea at 850 hPa for ARMEX and OPER analyses at 0000 UTC on 1–12 August 2002. (**b**) Same as (**a**) except for net tropospheric moisture

During IOP of 7–11 August 2002, very heavy rainfall occurred over Gujarat, Maharashtra region, mainly associated with an MTC over the Arabian sea at 68° E south of Gujarat (Mohanty et al. 2002). Figure 5a and 5b depict the Meteosat-5 high-density water vapour channel middle tropospheric level wind observations for 1800 UTC on 7th August and 0000 UTC on 8th August 2002. Although there were no wind observations over the north–east Arabian Sea region at 0000 UTC on 8 August (Fig. 5b), north–easterly and south–westerly winds are apparent over the Arabian Sea off the Gujarat coast at 1800 UTC on 7 August 2002. Global analysis of NCEP has also captured this MTC at the 500 hPa level (Routray et al. 2005). Analysed wind fields for ARMEX and OPER at 500 hPa at 0000 UTC on 8 August 2002 are shown in Fig. 6. MTC over the Arabian Sea, south west of the Gujarat coast (highlighted within a box) is analysed in ARMEX re-analysis (Fig. 6a), in contrast with a broad trough analysed over that region in OPER (Fig. 6b). The improvement seen in re-analysis for this particular case could be the consequence of assimilation of METEOSAT-5 water vapour channel wind observations in the 1800 UTC assimilation cycle of August 7, thereby modifying the guess field used in the assimilation cycle at 0000 UTC on August 8.

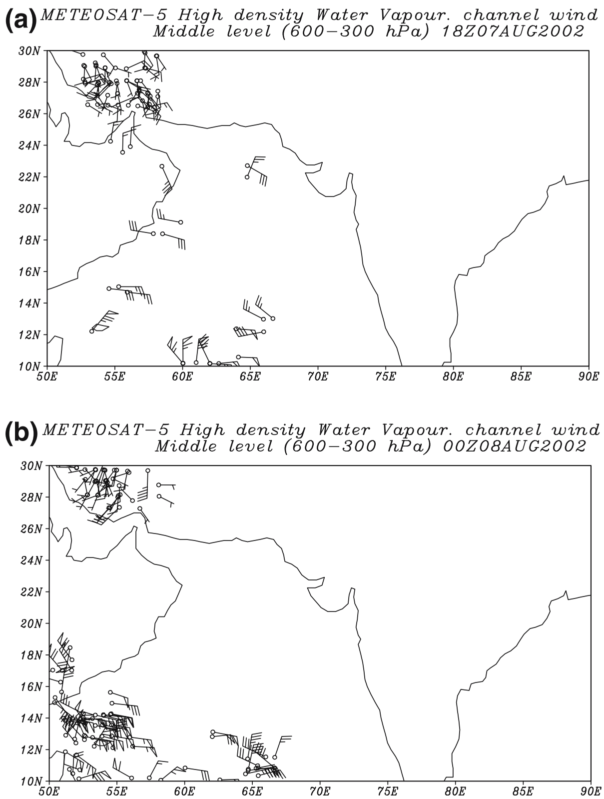

Fig. 5 Meteosat-5 high-density water vapour channel wind observations, middle level (600–300 hPa) (**a**) at 1800 UTC on 7th August 2002 (**b**) at 0000 UTC on 8th August 2002

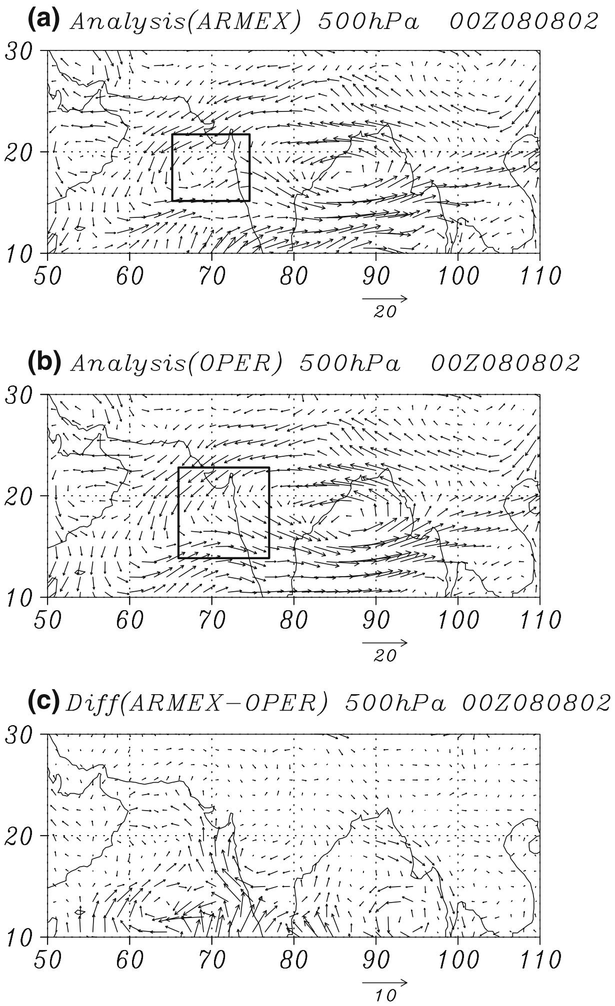

Fig. 6 Same as for Fig 3 but for the 500 hPa level at 0000 UTC on 8th August 2002

4.2 Rainfall prediction

Merged satellite and rain-gauge rain observations are good for validation of model predictions. One such rainfall observation is from the Tropical Rainfall Measuring Mission (TRMM). TRMM 24-hourly accumulated daily rainfall data at 25 km resolution were also acquired during ARMEX-I. Although the global model at T80/L18 resolution is not usually able to predict high variations in rainfall, it is able to predict the widespread rainfall activity associated with large scale flow. Keeping these limitations in mind an attempt was made to validate the predicted rain by both ARMEX re-analysis and OPER analysis against observed TRMM rain. Figure 7 depicts TRMM 24-hourly accumulated rain observations (cm) valid for 0300 UTC on 6th August 2002 with 24-hourly accumulated rain for 72 h predictions (Day-3

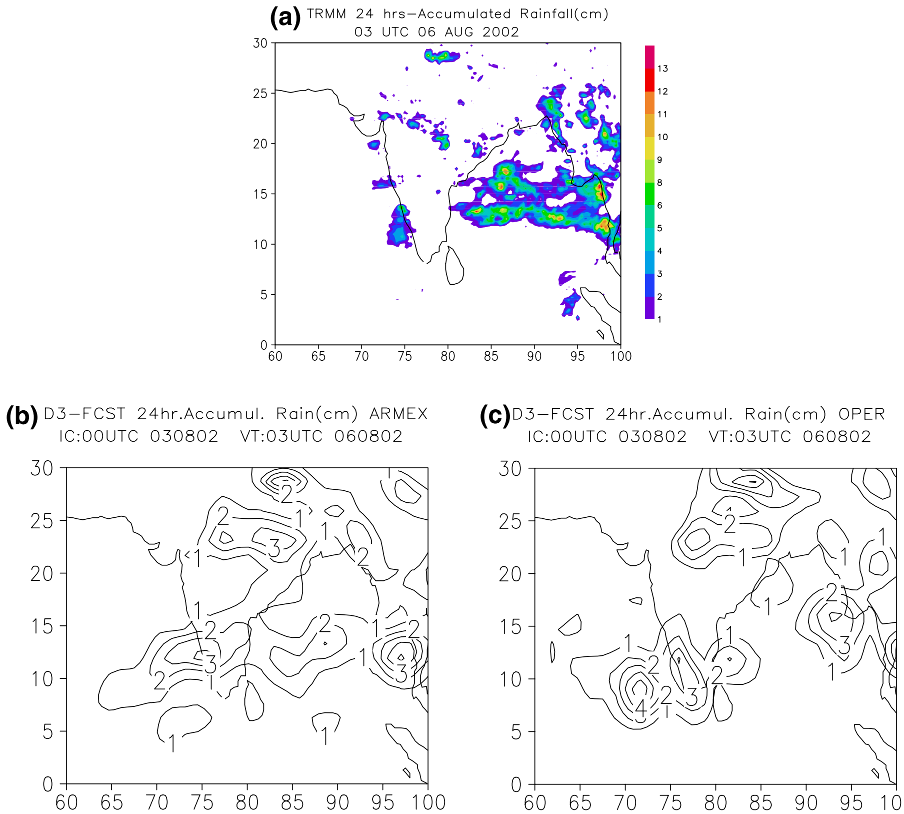

Fig. 7 (**a**) 24 hourly accumulated TRMM rainfall observation (cm) valid for 0300 UTC on 6 August 2002 and 72 h predicted rain (cm) for (**b**) ARMEX and (**c**) OPER

forecast) based on initial condition for 0000 UTC on 3 August 2002 and valid for 0300 UTC on 6 August 2002 for ARMEX and OPER.

Rain below 1 cm is not plotted in observed and predicted rain plots. On 6th August 2002 the monsoon was not very active over the west coast. The rainfall zone with maxima of 4 cm along the Karnataka coast is seen in the TRMM rain observation (Fig. 7a). Both ARMEX and OPER predictions showed rain over the south peninsula along the west coast but the region of rain with the OPER prediction (Fig. 7c) is more extended toward the south, i.e. over the Kerala coast, whereas rain with the ARMEX prediction (Fig. 7b) is mainly concentrated over the Karnataka coast and a contour of 4 cm is also seen over the coast at 11° N. Another maximum of rain (5 cm) is seen in the OPER prediction over the south central Arabian Sea centred at approximately 72° E/8° N, whereas there is no rain over that region in the TRMM observation. Although the ARMEX prediction also showed some rain over that region the amount is less than that in the OPER prediction and closer to that observed. A small patch of rain is seen over Arabian Sea just off the Maharashtra coast in the TRMM observation. This patch is not predicted by ARMEX whereas in the OPER prediction a 1 cm contour is seen near that region. On 6th August copious rainfall occurred over the central Bay of Bengal (BOB). An east–west band of rain over BOB along 13° N is seen in the TRMM observation with maximum of

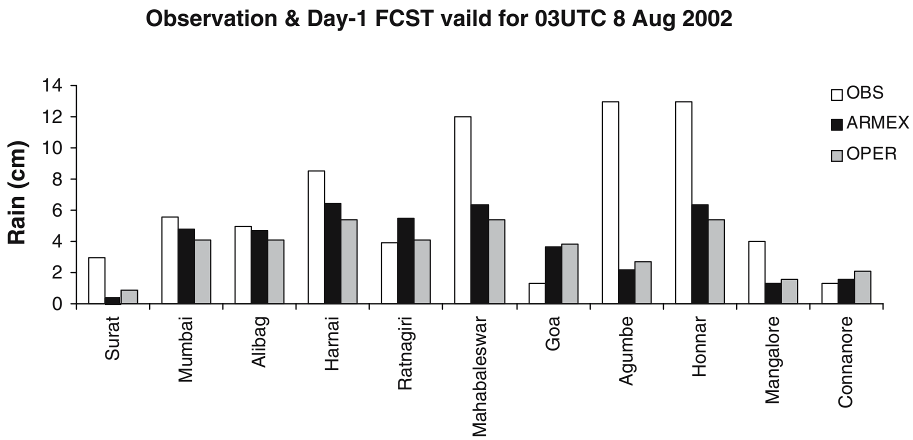

Fig. 8 Rainfall observations, with Day-1 forecast valid for 0300 UTC on 8 August 2002, for ARMEX and OPER along the west coast of India

12 cm. Although the predictions from both ARMEX and OPER could not predict this large amount of rainfall, the orientation of the rain band over BOB in ARMEX is closer to the TRMM observation. In general, it is seen that OPER predictions produce more rainfall in the south-east and central Arabian Sea which are not seen in TRMM observations whereas ARMEX predicted more concentrated rainfall near the coast,which is in better agreement with observations.

In Fig. 8 observed rainfall at different stations along the west coast of India are plotted with predicted rainfall (Day-1) valid for 0300 UTC on 8th August 2002. For most of these 11 stations, i.e except for Goa Ratnagiri and Connanore, model-predicted rainfall with both ARMEX and OPER analyses is always less than observed rainfall. Although the model cannot predict large amounts of rainfall, for most of the stations the amount predicted by ARMEX is more than that predicted by OPER. Differences between predicted and observed rainfall for both ARMEX and OPER were subjected to a *t*-test. It was found that the mean difference between predicted and observed rainfall for these eleven stations is slightly less for ARMEX (2.49 cm) than for OPER (2.82 cm). This difference between the means is significant at the 95% level, which shows that rainfall predicted by ARMEX is closer to observed rainfall than that predicted by OPER.

5 Conclusion

ARMEX re-analysis could capture some of the rain-bearing systems over the west coast of India which are not captured in the operational analysis. The re-analysis is able to capture the MTC and lower level trough over the west coast of India. It showed the realistic variation of kinetic energy consistent with active and weak phases of the monsoon. Slight improvement in rainfall prediction was also noticed after assimilation of ARMEX observations. Because of the low resolution of the model, however, subsequent prediction for such systems resulted in marginal improvement only. A higher-resolution model with this improved initial condition may capture the rainfall distribution better.

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