Early prediction of onset of south west monsoon from ERS-1 scatterometer winds

U R RAO*, P S DESAI, P C JOSHI, P C PANDEY, B S GOHIL and B SIMON

*ISRO Headquarters, Antariksh Bhavan, Bangalore, India

Meteorology and Oceanography Group, Space Applications Centre (ISRO), Ahmedabad 380 053, India

Detailed analysis of the surface winds over the Indian Ocean derived from ERS-1 scatterometer data during the years 1993 and 1994 has been used to understand and unambiguously identify the onset phase of south-west monsoon. Five day (pentad) averaged wind vectors for the period April to June during both years have been examined to study the exact reversal of wind direction as well as the increase in wind speed over the Arabian Sea in relation to the onset of monsoon over the Indian west coast (Kerala). The related upper level humidity available from other satellites has also been analysed.

The results of our analysis clearly show a consistent dramatic reversal in wind direction over the western Arabian Sea three weeks in advance of the onset of monsoon. The wind speed shows a large increase coinciding with the onset of monsoon. These findings together show the dominant role of sea surface winds in establishing the monsoon circulation. The study confirms that the cross equatorial current phenomenon becomes more important after the onset of monsoon.

1. Introduction

The south-west monsoon is undoubtedly the most important summer circulation which affects practically all the countries in the Indian subcontinent. In the past, several studies have been made to explain different aspects of this circulation because of its paramount importance to agricultural planning. Of particular interest are the observational and theoretical attempts to understand the advancement of the monsoon from the equatorial Indian Ocean to the main continent (viz., Sikka and Gadgil 1980; Krishnamurti 1985).

The onset of monsoon in meteorological parlance has been generally associated with the heralding of monsoonal rains over the south-west coast of the Indian mainland in the state of Kerala (Ananthakrishnan *et al* 1967). Based on a comprehensive statistical analysis of over a hundred years of data on the onset of monsoon, Ananthakrishnan *et al* (1988) concluded that the average onset date is on 1st June, with a standard deviation of eight days. Significant changes, such as rapid increase in precipitation rate, increase in the vertically integrated humidity, and increase in the kinetic energy especially in the low level flows (Krishnamurti 1985), are known to occur in the large scale atmospheric structure over the monsoon region, coincident with the onset of monsoon. A large number of studies, based on both observational data and theoretical modeling, have been carried out in connection with the onset of monsoon (Joseph *et al* 1994). Soman and Kumar (1993) have summarized the space-time evolution of meteorological features associated with the onset by examining the conventional data for eighty years.

There have been many attempts to predict the onset date in terms of antecedent upper air circulation (Kung and Sharif 1980, 1982) and thermal features (Joshi *et al* 1985, 1990, 1994). The usefulness of satellite derived humidity data in characterizing the onset of monsoon is now well understood from the analysis of NOAA/TOVS data over a number of years. The mid-tropospheric water vapour over western Indian Ocean is known to increase about 8–10 days prior to the onset of monsoon (Simon and Joshi 1994). Gautam and Pandey (1994) examined the total

Keywords. Monsoon prediction; cross equatorial winds; ocean surface winds; scatterometer.

Proc. Indian Acad. Sci. (Earth Planet. Sci.), **107**, No. 1, March 1998, pp. 33–43

moisture burden in the atmosphere at the equatorial regions and the west coast of India and found a statistically significant increase (30–35%) in the weekly averaged moisture near the Indian coast accompanied by a sharp decrease (30–40%) in the moisture near the Somali coast around the time of the onset of the monsoon.

Despite many special campaigns, a complete picture of the monsoon circulation during onset time is still not well understood due to the paucity of surface and upper air data over the Arabian Sea and adjoining Indian Ocean. The long felt need for continuous monitoring of the winds over this region for understanding the circulation associated with the onset of monsoon has only been recently fulfilled with the availability of precision measurements of surface wind data over these regions from the scatterometer onboard ERS satellites. ERS data which are available even under cloud covered conditions, have already been used for understanding the movement of weather systems over the Indian Ocean (Joshi *et al* 1992; Bansal *et al* 1994). The present paper attempts at studying the spatio-temporal evolution of the wind field in the Arabian Sea and the Indian Ocean around the time of onset of monsoon for the two monsoon seasons during the years 1993 and 1994, for which data are available.

Both 1993 and 1994 were good monsoon years with the onset of monsoon over Kerala taking place on 28th May, four days prior to the normal onset date of 1st June. The monsoon rainfall over the entire country during June-September was 88 cm in 1993, which is normal, whereas it was 10% above the normal in 1994. The monsoon in 1993 advanced over the peninsular India and reached 20° North latitude by 12th June, even though its further advance over the north central region occurred with a delay of twenty days. In 1994, however, the central belt of India received almost continuous excess rain over the normal, even though eastern Indian region (Bihar, West Bengal states) and north-eastern States, which are traditional heavy rainfall areas, recorded slightly below normal rainfall. Section 2 describes the algorithm used for wind retrieval from ERS scatterometer data. In section 3 we present the results of our analysis of scatterometer data in relation to the onset of the monsoon, which we believe is the first definitive evidence showing clear and unambiguous association of surface winds with the onset of monsoon, which can be quantitatively used for the prediction of the onset.

2. Wind vector retrieval from ERS-1 scatterometer data

In the present study, the radar backscatter data of ERS-1 scatterometer has been used to derive the wind vectors over the Indian region. The radar scatterometer measures the energy backscatter by the ocean surface roughened by the action of the winds. The azimuthal harmonicity of the radar backscatter causes ambiguities in the wind directions derived from the radar data. The available fast-delivery copy of ERS-1 scatterometer data does contain the wind vectors along with the radar backscatter values but the directions are not ambiguity filtered. The ambiguity filtered wind vector fields have been retrieved from ERS-1 scatterometer data using the CMOD4 model functions. The retrieval algorithm used in the present study is based on the criterion of minimum wind speed standard deviation (Gohil and Pandey 1985) for prioritizing the solutions of wind vector. The directional ambiguities have been removed using the median filter with an optimum window (Gohil 1992). The authenticity of the derived wind parameters using the above algorithms has been established by comparing these with *in situ* spot observations over a period of one year (August 1992 – July 1993) in the Indian Ocean region (Gohil and Pandey 1995).

The wind vector fields derived from scatterometer data collected over each pass of ERS-1 during the period April to June, for both 1993 and 1994 have been used to obtain the 5-day (pentad) mean wind vectors for 5° × 5° grids over the region from 40°E to 80°E longitude and 20°S to 25°N latitude. The variations of 5-day mean wind speed and direction over Arabian Sea in each of these grids have been examined in detail to study their behaviour during the onset, pre-onset and post-onset periods of the Indian monsoon during the years 1993 and 1994.

3. Results and discussion

3.1 *Scatterometer wind analysis*

The ERS-1 scatterometer derived winds have been vector averaged over 5° × 5° latitude-longitude boxes for five day periods (pentads) during the months of April to June of 1993 and 1994. The averaged wind vector for each of the pentads beginning with the pentad of April 6–10, for 1993 and 1994 are plotted in figures 1 and 2 respectively. The vectorial representation of pentad wind vectors, with the origin of each pentad vector coinciding with the end point of the previous pentad wind vector, provides a clear picture of the time sequence of the changing winds. The first five arrows starting from the beginning thus indicate the April wind vector followed by six vectors for the months of May and six pentads of June. The few data gaps, due to the non availability of satellite data, have been depicted by blunt head arrows of fixed length maintaining the direction of the previous pentad. The length of arrow in the vectorial representation indicates the magnitude of the mean wind speed in m/s and the direction of the arrow represents the direction of wind. Figures 1 and 2 clearly show the occurrence

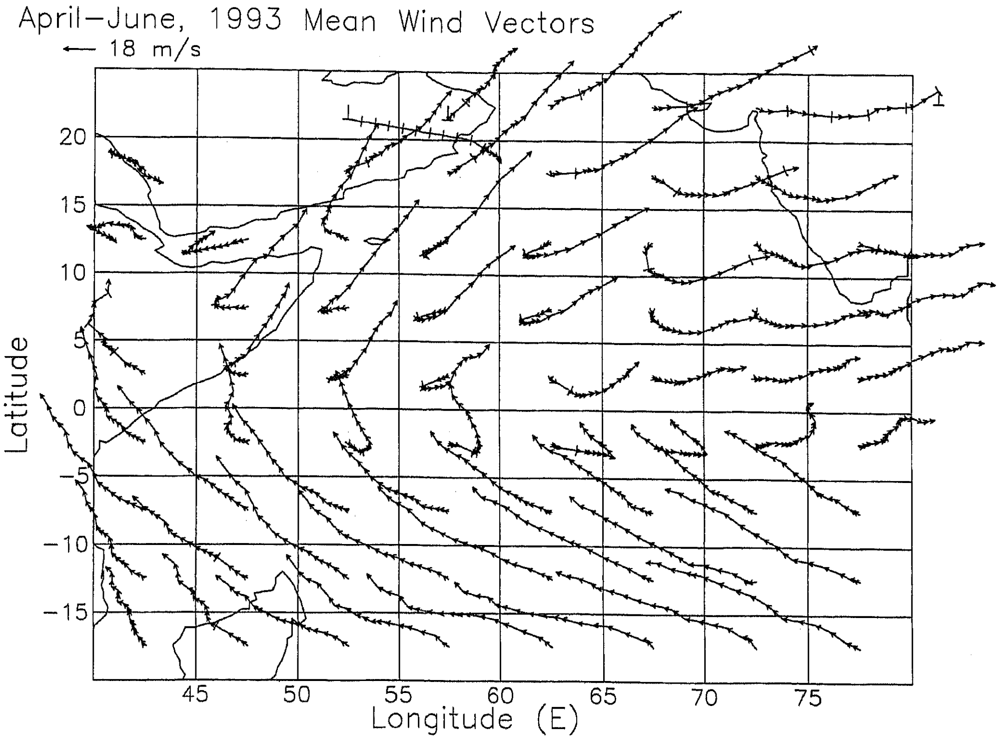

Figure 1. Pentad-wise average wind in the box during April – June, 1993. The first pentad is for April 6th – April 10th. A blunt arrow indicates no data in that pentad.

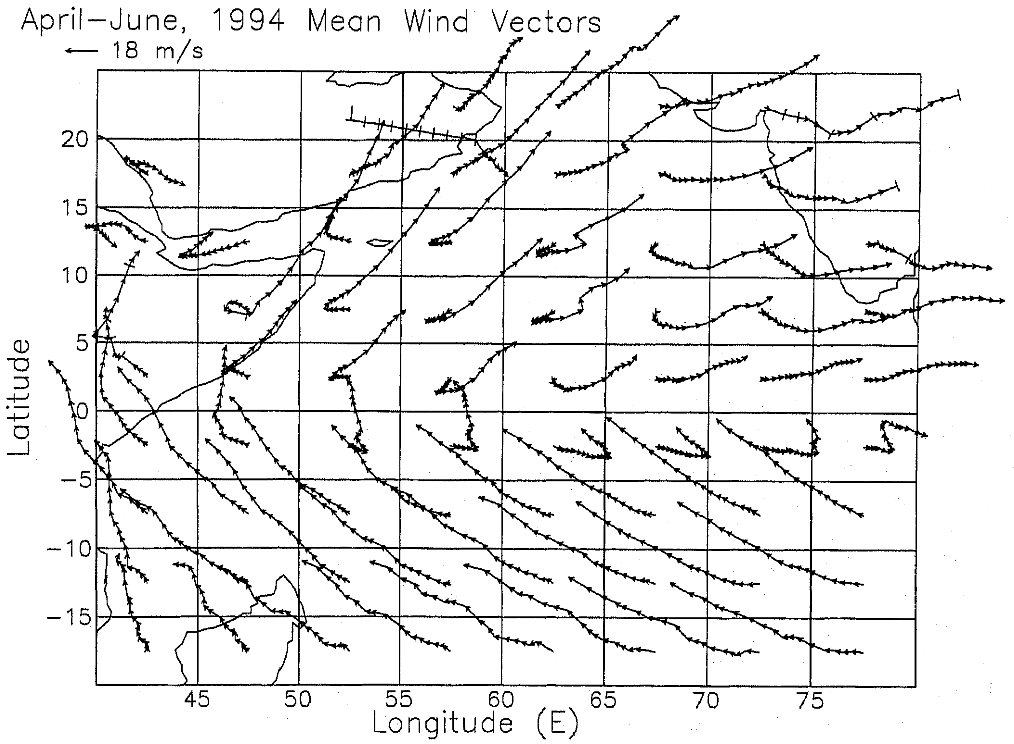

Figure 2. Same as in figure 1 but for 1994.

of most significant changes in wind circulation (wind direction) over the western Arabian Sea in both the years unlike over the eastern Arabian Sea. In both the years we note the abrupt wind reversal over the Arabian Sea in all the grids north of 2.5° south latitude taking place in the sixth pentad (in 55° to 60°E, 0°–5°N region), i.e., during the period May 1st – 5th. It is to be noted that only data for 1993 and 1994 were available for full examination; 1993 was a normal monsoon year and 1994 was an above-normal monsoon year. The scatterometer data have now started coming and in future different monsoon years with differing monsoon activities may be possibly studied. Even though our inferences are based on two years data (1993, 1994), examination of the available scanty data of 1995, 1996 lead us to conclude that our observations based on the data of 1993, 1994 are essentially valid even for these later years.

In order to identify the unique significant features of the temporal and spatial variation of the wind profile over the Indian Ocean we have analysed the wind speed and direction for all the individual $5° \times 5°$ latitudinal and longitudinal boxes ranging between 40° to 80° East longitudes and 20°S to 20°N latitudes. Figures 3 and 4 show the wind speed and direction over the six boxes centered at 2.5°N and 7.5°N latitudes and 52.5°, 57.5° and 72.5° East longitudes for both 1993 and 1994, which are representative of the features over the Arabian Sea. It may be noted that the features of wind parameters in other boxes also show similar behaviour. In both the years the maximum change in wind direction is seen in the western Arabian Sea, the dramatic reversal in the wind direction taking place around 6th May, and about 20 days in advance of the onset of monsoon. There is a change in wind direction by 250° in the interval of one pentad over western Arabian Sea during the reversal phase. The wind speed on the other hand, shows rapid increase just around 28th May, coincident with the onset of the monsoon, the maximum increase in wind speed being recorded near the Kerala coast in both the years. The interesting feature to be noted is the abrupt reversal of wind direction taking place with the same lead time in both the years which in our opinion is the most significant precursor for prediction of the onset of monsoon about three weeks in advance. Equally significant is the observed abrupt increase in wind speed derived from the analysis of scatterometer data over the Arabian Sea during both the years, coinciding exactly with the onset of the monsoon. The wind speed changes from 3 mps to 13 mps in the interval of one pentad around the time of onset over the Kerala coast. While confirming the traditional meaning/definition of monsoon (Arabic 'Mausim' for season), our observation clearly pinpoints the area and the unique, unambiguous signatures accompanying the monsoon activity, the abrupt change in direction acting as a valuable precursor on which the monsoon onset prediction can be based and the significant change in the magnitude of the wind speed which denotes the actual onset of monsoon over the Kerala coast.

3.2 *Moisture changes during onset phase*

Simon and Joshi (1994) have shown that the humidity field over western Arabian Sea changes significantly nearly ten days in advance of the onset of monsoon over Kerala. The NOAA satellites provide the humidity in three broad regions of the upper atmosphere i.e., 1000–700 hpa, 700–500 hpa and 500–300 hpa. The interesting feature in the above study was that the noteworthy effects take place in the middle layer and that too over the western part of the Indian Ocean and not over the eastern Indian Ocean near the Kerala coast. The increased moisture content in the middle layers over the western Indian Ocean near Somalia coast has been explained as due to convection and lack of warm and dry upper-level northwesterlies from Saudi Arabia prior to the onset of monsoon, since the northwesterlies become dominant only towards the end of May. Gautam and Pandey (1995), based on the analysis of total precipitable water vapour over the Indian Ocean for four years (1980, 1981, 1984, 1988) were able to conclusively show an abrupt increase in the water vapor content by almost 30–40% near the Kerala coast around the time of onset of monsoon coincident with an equally abrupt decrease of similar magnitude in the water vapour content of the Somali coast. This is inspite of an increase in middle level moisture (700–500 hpa) about eight to ten days prior to the onset of monsoon followed by a decrease afterwards, reported by Simon and Joshi (1994) based on the analysis of five years of data during 1980–1985.

Figure 5(a) shows the plots of weekly averaged moisture content in 1980 for which the date of monsoon onset was 1st June. The moisture content values have been artificially shifted by four days in figure 5(b), to mimic the onset of monsoon to 28th May for easy comparison with the wind observations for 1993 and 1994. This procedure was adopted due to non-availability of moisture data for 1993 and 1994. In comparing the moisture load in 1980 with wind parameters in 1993 and 1994, we have assumed that the basic features of monsoon in these years are similarly connected which at least permits us to draw broad conclusions. Box 1 represents the area centred around 47.5°E and 2.5°N (i.e., Somali coast area). Box 2 represents the area centred around 72.5°E and 7.5°N (i.e., Kerala coast and nearby area). From the figures 5(a–d) it is clear that the crossover point where the water vapour near the Kerala coast begins to sharply increase to overtake the sharply decreasing water vapour in the Somali coast occurs about ten days earlier to the onset of the monsoon, consistent with the conclusion of Gautam and Pandey (1995) based on four years of data. Even more important, is the steady increase in the water vapour content over Kerala coast after the cross over point to reach its maximum peak value of about 55 mm as compared to the normal value of about 40 mm, soon after the onset of monsoon.

We also note that the water vapour content over the Somali coast and south of the Indian subcontinent, continue to be depressed at the low value of about

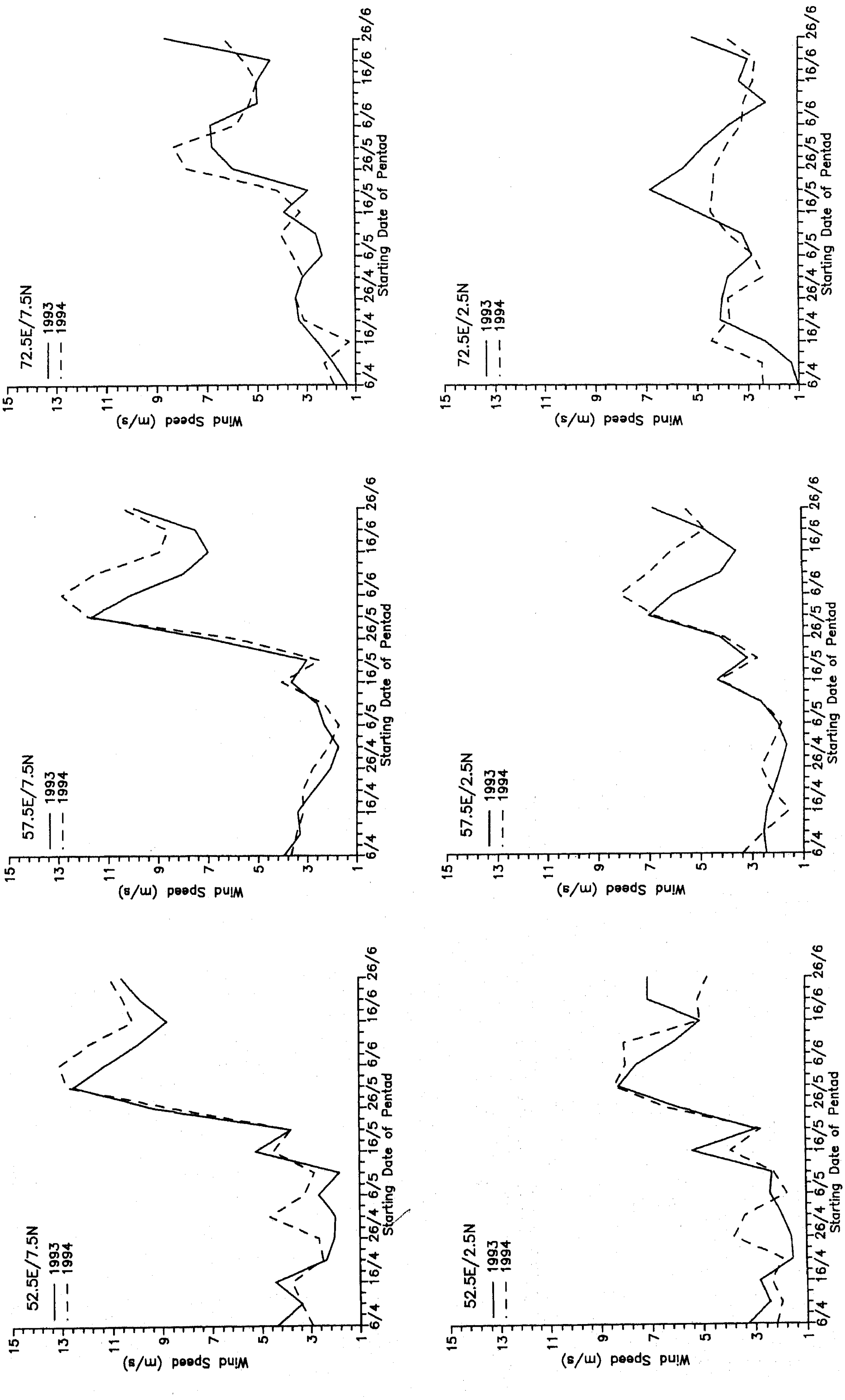

Figure 3. The wind speed changes during 1993 and 1994 in the selected six grids (the region corresponding to each grid is shown in the diagram).

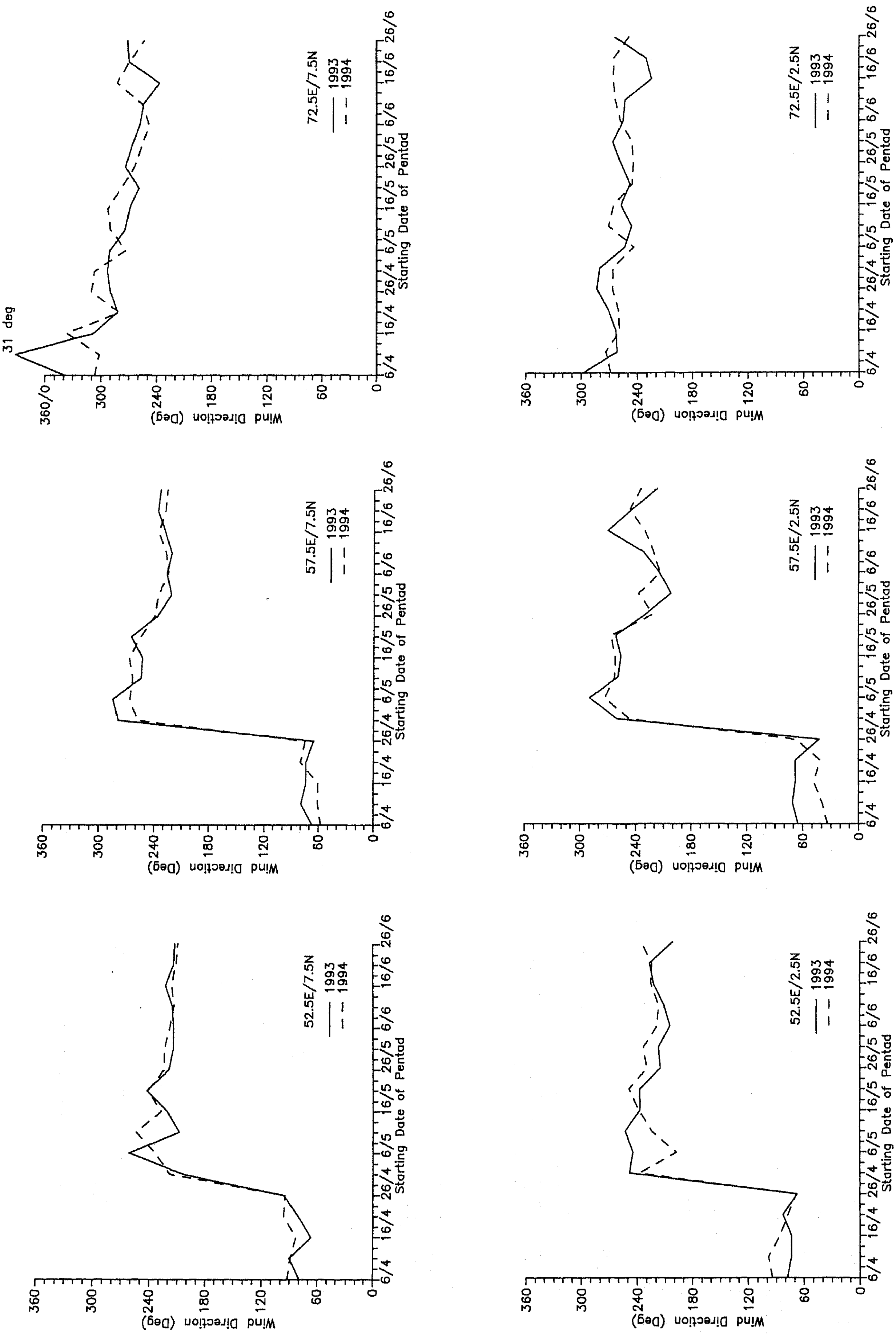

Figure 4. Same as in figure 3 but for wind direction.

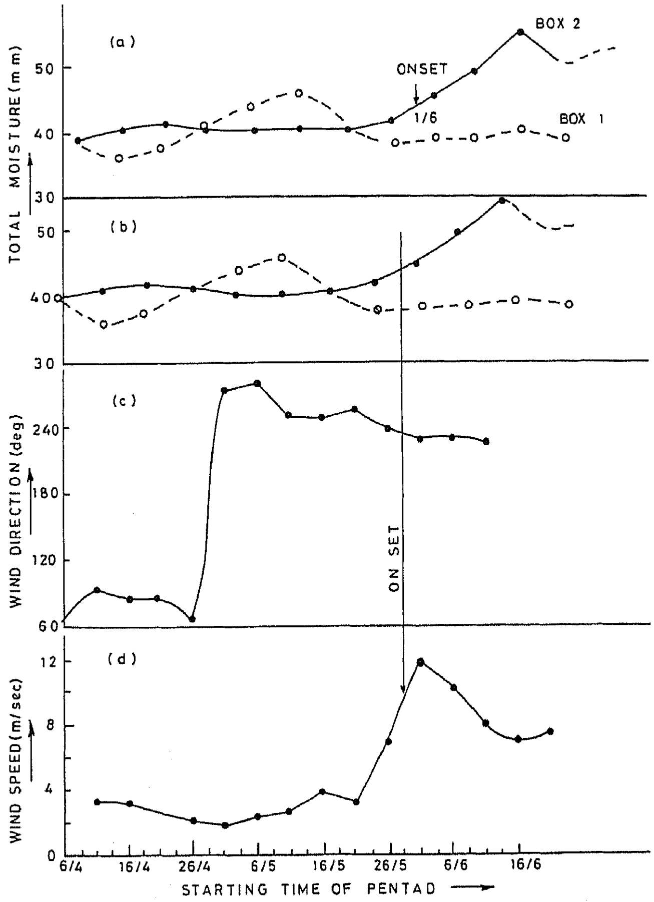

Figure 5. (**a**) Total moisture over box 1 (dashed line) and box 2 (continuous line) centered at 47.5°E and 2.5°N for the year 1980. (**b**) Same as in (a) but shifted by three days. (**c**) Wind direction at 72.5°E and 7.5°N for the year 1993. (**d**) Same as in (c) but for wind speed.

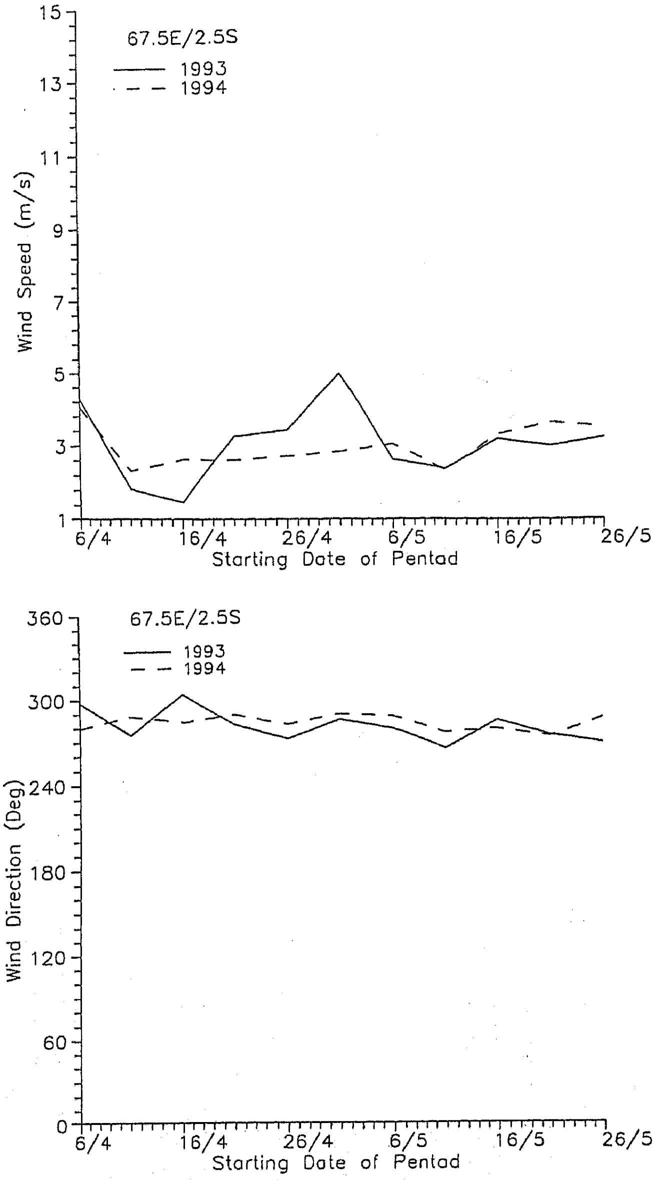

Figure 6. Wind speed and direction for 1993 and 1994 for the grids centered at 67.5°E and 2.5°S.

36 mm even after the crossover. Similar observations have been reported by Simon and Joshi (1994), who find that the moisture content in the middle level over the Somali coast is significantly lower at the time of the onset of monsoon over the Kerala coast. Increased moisture content over the Kerala coast, a prerequisite for the onset of monsoon, clearly seems to be a strong function of the increase in wind speed over the entire Arabian Sea all the way up to the Kerala coast.

Contribution of cross equatorial flux to the moisture content over the western coast of India during monsoon continues to remain a highly debatable point with a number of authors such as Pisharoty (1965) and Ghosh *et al* (1978) not favouring the hypothesis of cross equatorial contribution and an equal number of authors such as Saha and Bavadekar (1973), Holland and Sikdar (1979) and Cadet and Reverdin (1981) favouring the importance of cross-equatorial flux. Most of these studies are for the post-onset period, wherein the monsoon circulation is fully developed over the Indian subcontinent. In the following we investigate the cross equatorial exchange in the pre-onset period.

Boogard and Rao (1984) have estimated the cross equatorial flux based on special observations taken during MONSOON 1977. Rao *et al* (1978) also computed the trajectories over the Indian Ocean. Hastenrath *et al* (1991) studied the cross hemispheric exchange from the point of view of examining the underlying ocean currents. They find that the monsoonal reversals of wind stress forcing, which are most noticeable in the northern Indian Ocean and the equatorial zone and more moderate in the southern part of the basin, have diverse consequences for the various current systems. These studies reveal that the southeasterlies of the southern hemisphere change to southwesterly over northern hemisphere just after crossing the equator. These developments are due to both dynamical and kinematical reasons. The coriolis force is considerable in magnitude to the south,

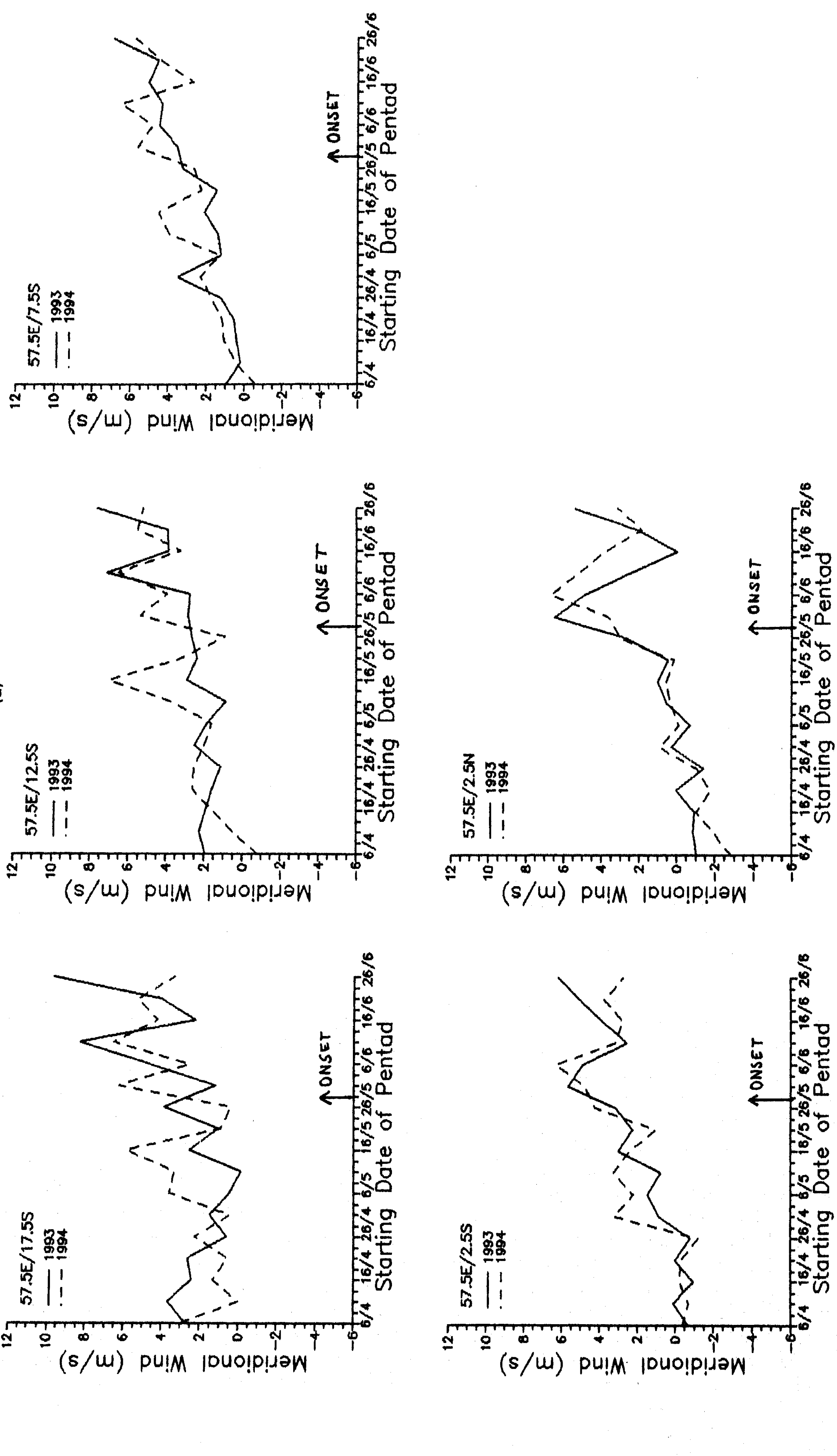

Figure 7. (Continued)

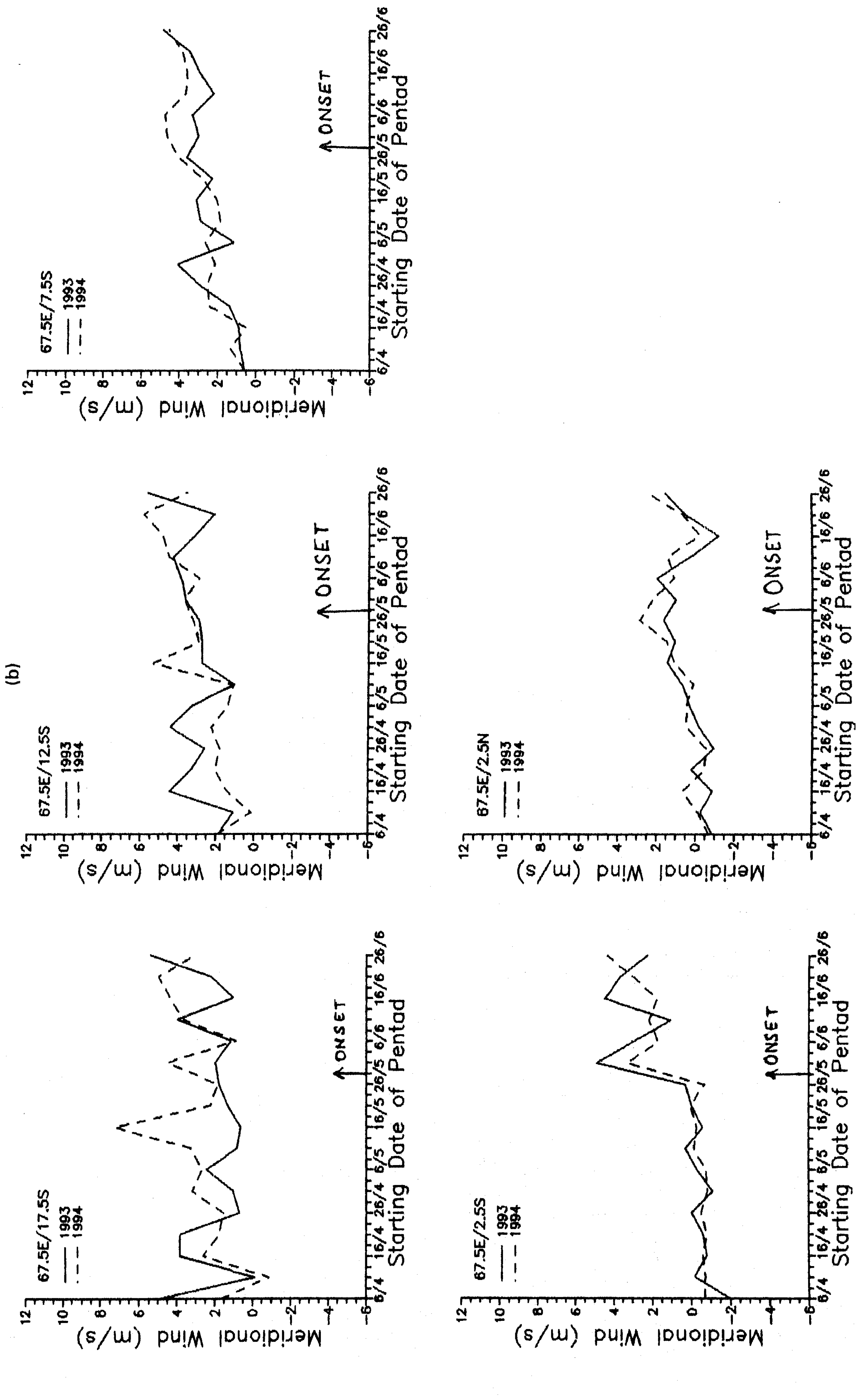

Figure 7. Variation of meridional component of scatterometer derived winds at five degree intervals along (a) 57.5°E and (b) 67.5°E longitudes for 1993 and 1994.

decreases and becomes zero right on the equator, and increases again to the north. Similarly the dynamical factors are like 'low' over India and 'high' to the south. Figure 6 shows the wind direction and wind speed plotted for 1993 and 1994 over 67.5°E longitude, 2.5°S latitude which clearly points out that the wind vector, even though showing marginal increase in speed, remains practically unidirectional (120°) blowing continuously towards the African coast even at the time of the monsoon onset. Comparison with the behaviour of wind vector at northern latitudes for the same period (figures 3 and 4) brings out the significant fact that the change in wind direction or wind reversal which is the precursor to the onset of monsoon is limited to the grids north of 2.5°S latitude. We have carefully examined the data for all the grids south of 2.5°S latitude for both 1993 and 1994 and find that the sea surface wind over the entire Indian Ocean south of 2.5°S latitude remains unidirectional blowing towards the African coast during the entire period unlike over the Arabian Sea at latitudes of 2.5°N and above, where the dramatic reversal in wind direction about twenty days prior to the onset of monsoon is a consistent phenomenon. The scatterometer observations thus conform well with other special observations made for the wind pattern around the equator. Together with the evidence of moisture content in the southern ocean continuing to remain at practically a constant low level, the scatterometer results provide evidence to show that the contribution of the cross equatorial current is comparatively less important to the onset of the south-west monsoon. This can also be seen in figure 7, where the meridional component of the surface wind at 67.5°E and 57.5°E longitudes and 2.5°N, 2.5°S, 7.5°S, 12.5°S and 17.5°S latitude is plotted. It is interesting to note that the contribution of cross-equatorial flow (about 20% as reported by others) during the onset phase is not significantly different from that during the pre-onset phase, even though it increases significantly – nearly by a factor of two – after the onset, which is consistent with earlier observations (Boogard and Rao 1984).

4. Conclusions

The surface wind vector field provided by the ERS satellite scatterometer has the unique capability of monitoring the onset of monsoon over the Indian Ocean. The analysis of winds for two years, i.e. 1993 and 1994 shows that the wind reversal over the western Arabian Sea occurs consistently three weeks in advance of the onset of monsoon which can be taken as a reliable precursor for the prediction of the onset of monsoon. The study also shows that the wind direction in the southern part of the Indian Ocean during this entire period remains unidirectional, blowing towards the African coast. The cross hemispheric exchange becomes more important in the post-onset period. The large increase in the wind speed following the wind reversal and coincident with the onset of the monsoon is another very significant finding which clearly brings out the dominant role of the sea surface winds over the Arabian Sea in determining the onset and intensity of south west monsoon.

Dramatic changes in the humidity field observed earlier and in the surface wind field observed here occur around the same area, even though initiation of these phenomena have different lead times with respect to the onset of monsoon over Kerala. This region is also the place of formation of strong low level Somali jet responsible for a considerable inter-hemispheric exchange of moisture. The Somali jet gradually builds up. The strengthening of wind starts taking place after the wind reversal from north-easterly to south-westerly and reaches its peak value at the time of the onset of monsoon. This can be then confirmed from significant increase in wind-speed and mid-tropospheric humidity.

While our results are based mainly on the analysis of two years of scatterometer data, the unambiguous changes consistently observed over these two years give credence to our conclusions. Further confirmation of these conclusions from the analysis of scatterometer data over a longer period of time would definitely help in establishing the parameters which can unambiguously define the onset of monsoon in an objective and quantitative manner as compared to the present method based purely on the measurement of rainfall over the Kerala coast. With the planned launch of new satellites carrying scatterometers onboard, it should be possible to confirm our conclusions and better understand the monsoon onset.

References

Ananthakrishnan R, Acharya U R and Ramakrishnan A R 1967 On the criteria of declaring the onset of the south west monsoon over Kerala; *IMD, Forecasting manual*, **iv** 18.1

Ananthakrishnan R 1988 The onset of the south west monsoon over Kerala: 1901–1980; *J. Climate* **8** 283–296

Bansal R K, Krishnan R, Kishtwal C M, Simon B, Joshi P C and Narayanan M S 1994 Impact of ERS-1 scatterometer data on the analysis and prediction of a severe cyclonic storm in the Bay of Bengal; *Vayu Mandal* **24** 59–66

Boogard H M E van De and Rao G V 1984 Mesoscale structure of the low-level flow near the equatorial east African coast; *Mon. Weather Rev.* **112** 91–107

Cadet D and Riverdin G 1981 The monsoons over the Indian Ocean during the summer 1975, Part I: Mean Fields; *Mon. Weather Rev.* **09** 148–158

Gautam N and Pandey P C 1995 Fluctuations in satellite-derived moisture fields over the Indian Ocean and their possible linkage with the onset of monsoon over India; *Indian J. Radio Space Phys.* **24** 107–112

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

Gohil B S and Pandey P C 1985 An algorithm for retrieval of oceanic wind vectors from the simulated SASS normalized radar cross-section measurements; *J. Geophys. Res.* **90** 7307–7311

Gohil B S 1992 Extraction of ocean surface wind field from simulated ERS-1 scatterometer data; *Inter. J. Remote Sensing* **13** 3311–3327

Gohil B S and Pandey P C 1995 An atlas of surface wind vectors in the seas around India during August 1992–July 1993 from ERS-1 scatterometer; *Special publication, ISRO-SAC-SP-76–95*, Indian Space Research Organisation, Bangalore, India

Hastenrath S and Greichar L 1991 The monsoonal current regimes of the tropical Indian Ocean: Observed surface flow fields and their geostrophic and wind-driven components; *J. Geophys. Res.* **96** 12619–12633

Holland M R and Sikdar D N 1979 The moisture budget over north-eastern Arabian Sea during pre-monsoon and monsoon onset; *Mon. Weather Rev.* **111** 2255–2268

Joseph P V, Eischied K E and Pyle R J 1994 Interannual variability of the onset of the Indian summer monsoon and its association with atmospheric features, El Nino, and Sea Surface Temperature anomalies; *J. Climate* **122** 81–105

Joshi P C and Desai P S 1985 The satellite determined thermal structure of heat low during Indian south-west monsoon season; *Adv. Space Res.* **5** 57–60

Joshi P C, Simon B and Desai P S 1990 Atmospheric thermal changes over the Indian region prior to the monsoon onset as observed by satellite sounding data; *Inter. J. Climate* **10** 49–56

Joshi P C, Simon B, Narayanan M S, Rizvi S R H and Bansal R K 1992 Preliminary analysis of circulation over the Indian Ocean and adjoining regions using ERS-1 surface winds in the NCMRWF data assimilation system; *ESA SP-359* 107–111

Joshi P C and Simon B 1994 NOAA/TOVS derived upper tropospheric temperature changes associated with the onset of monsoon over Kerala coast; *Mausam* **45** 155–160

Krishnamurti T N, Philip A, Ramanathan Y and Richard P 1981 On the onset vortex of the summer monsoon; *Mon. Weather Rev.* **109** 344–363

Krishnamurti T N 1985 Summer monsoon experiment – a review; *Mon. Weather Rev.* **113** 1590–1626

Kung E C and Sharif T A 1980 Regression forecasting of the Indian summer monsoon with the antecedent upper air conditions; *J. Appl. Meteorol.* **19** 370–380

Kung E C and Sharif T A 1982 Long range forecasting of the Indian summer monsoon onset and rainfall with upper air parameters and sea surface temperature; *J. Meteorol. Soc. Japan* **60** 672–682

Pisharoty P R 1965 Evaporation over the Arabian Sea and Indian south-west monsoon; *Proceedings of Symposium on meteorological results of IIOE*, Bombay

Rao G V, van De Boogard H M E and Bolhofer W C 1978 Further calculations of sea level air trajectories over the equatorial Indian Ocean; *Mon. Weather Rev.* **106** 1465–1475

Saha K R and Bavadekar S N 1973 Water vapour budget and precipitation over the Arabian Sea during the northern summer; *Quart J. Meteorol. Soc.* **99** 273–278

Sikka D R and Gadgil S 1980 On the maximum cloud zone and the ITCZ over Indian longitudes in the south-west monsoon; *Mon. Weather Rev.* **108** 1840–1853

Simon B and Joshi P C 1994 Determination of moisture changes prior to the onset of monsoon over Kerala using NOAA/TOVS satellite data; *Meteorol. Atmos Phys.* **53** 223–231

Soman M K and Kumar K K 1993 Space-time evolution of meteorological features associated with the onset of Indian Summer monsoon; *Mon. Weather Rev.* **121** 1177–1194