

On Some Aspects of Precipitation over Tropical Indian Ocean  
Using Satellite Data

M.R.Ramesh Kumar and O.P.Sreejith,  
Physical Oceanography Division,  
National Institute of Oceanography,  
Dona Paula, PIN – 403 004, Goa, India.

12 July 2004

Corresponding author address: Dr.M.R.Ramesh Kumar, Physical Oceanography Division,  
National Institute of Oceanography, Dona Paula, Goa- 403004. India.

E-mail: [kramesh@darya.nio.org](mailto:kramesh@darya.nio.org)

Running Title: On some aspects of precipitation over tropical Indian Ocean

## Abstract

The annual and inter-annual variability of precipitation over the tropical Indian Ocean is studied for the period 1979-1997, using satellite data from a variety of sensors. **The Climate Prediction Center Merged Analysis Precipitation (CMAP), Microwave Sounding Unit (MSU) estimates of rainfall had better correlation with the island rainfall data than the National Centers for Environmental Prediction/ National Centre for Atmospheric Research Reanalysis (NRA) estimates. A comparison of the mean annual rainfall by different estimates (CMAP, MSU, NRA and GPCP (Global Precipitation Climatology Programme)) showed significant differences with the CMAP, GPCP and MSU estimates depicting maximum off the Indonesian Islands whilst the NRA exhibited maximum in the southern part of the Bay of Bengal and equatorial Indian Ocean. A study of the inter-annual variability of the monsoon rainfall using the monthly CMAP data over the tropical Indian Ocean for different study areas, namely, Arabian Sea (AS), Bay of Bengal (BB), south Indian Ocean (SIO) and Indian Ocean (IO) showed significant differences during deficit (1979,1982,1986 and 1987), excess monsoon (1983 and 1988) years and also during ENSO years (1982,1987, 1992 and 1997). An analysis of the rainfall anomalies showed positive and negative anomalies in the northeastern Bay of Bengal during the summer season of deficit (1986) and excess (1988) monsoon years respectively, whilst the eastern equatorial Indian Ocean showed large positive and negative rainfall anomalies during the fall season of El Nino years, 1987 (deficit monsoon) and 1997 (normal monsoon) respectively.**

## 1. Introduction

As about 71% of the earth's surface is covered by oceans, an exact idea about the distribution and characteristics of precipitation is quite important for the earth's hydrological cycle. In spite of its importance, there is almost no information available about the amount of precipitation over the Oceans and most of the times the data over the coastal and island stations are interpolated to obtain the rainfall estimates over the nearby Oceanic regions or seas. Further, unlike many other air-sea interaction parameters, precipitation is highly discontinuous in both space and time, which makes the need for accurate measurement or estimate of precipitation over the Ocean vital for various air-sea interaction studies.

Precipitation over the Oceans in general can be estimated by the following methods:

- interpolation from coastal and island stations rainfall data
- point measurement with rain gauges over the ships, drifting and moored buoys
- areal precipitation estimation derived from frequency data of ship's observations
- areal precipitation measurement with a coastal radar or onboard a research vessel
- areal precipitation measurement with satellite infrared, microwave sensors and radars

Most of the earlier estimates of precipitation over the Oceans [Baumgartner and Reichel (1975)] were derived by direct interpolation of measurements from gauges at coastal and island stations. But the fact remains that most parts of the Oceans are far away from land based stations; and also there are significant differences between the precipitation processes over the land and seas.

Only numerical models and satellites can provide the areal precipitation over the oceans but they also need to be calibrated against surface measurements. There are about 10,000 Voluntary Observing Ships over the globe, of these approximately 2000-3000 ships collect meteorological data at three hourly intervals (i.e 8 times in a day) on a routine

basis. If these ships are equipped with rain gauges then we would have enough sea truth rainfall data to calibrate the satellites [Indian National Satellite (INSAT), Defense Meteorological Satellite Program (DMSP) and Tropical Rainfall Monitoring Mission (TRMM)] as well as the models [National Centers for Environmental Prediction (NCEP), European Center for Medium range Weather Forecasting (ECMWF) and National Center for Medium Range Weather Forecasting (NCOMRWF)] estimates of precipitation. But the precipitation collected onboard the ships, especially on moving merchant vessels or research ships are strongly biased. The major sources of error in measurement of precipitation onboard a ship can be broadly classified as follows:

- Errors due to the disturbing effect of ship on the air flow
- Errors due to the creation of turbulent air flow by rain gauge and movement of the rain gauge which are caused by the ship's movements.
- Errors due to the effect of sea spray and dripping from superstructures
- Errors due to fair weather bias

Of all the above mentioned factors, it is the air motion around and over the ship that affects the precipitation measurements to the maximum extent. Thus, high wind speeds will effectively reduce the precipitation measured onboard a ship to almost half of the true rainfall. The next most important error, due to fair weather bias, arises due to the lack of precipitation measurements caused by the lows, depressions and cyclones, which most of the ships try to avoid. This problem is especially true in the case of the Bay of Bengal, which is frequented by lows, depressions and cyclones throughout the year.

Major drawbacks to studies of the rainfall over a particular area or region are the coverage of the instruments and their accuracy in measuring the areal extent and accumulation of rainfall. Over the oceans, where conventional instruments like rain gauges or weather radar may not exist, satellite sensors seem to be only source which can provide continuous data both in space and in time. Barrett and Beaumont (1994) have shown the potential for improving precipitation estimates using satellite data. One of the major needs envisaged by them was the need for calibration and validation of satellite algorithms intended for full operational use over the oceans where in-situ data are sparse. In the present study we have validated the CMAP (Climate Prediction Center Merged Analysis

Precipitation), National Center for Environmental Prediction (NCEP) and Microwave Sounding Unit (MSU) derived precipitation estimates for tropical Indian Ocean using island rainfall data. Further, we have also compared the different rainfall estimates (CMAP, GPCP, MSU and NRA) from different sensors and satellites. We have also looked into the inter-annual variability over different study areas during several contrasting monsoon years namely, 1979, 1982, 1986 and 1987 (deficit years) and 1983 and 1988 (excess years) and ENSO (1982, 1987, 1992 and 1997) years.

## **2. Data and Methodology**

**The Climate Prediction Center Merged Analysis Precipitation (CMAP) was obtained from Dr.P.Xie , NOAA, U.S.A. The CMAP is a gridded global monthly precipitation constructed on 2.5° X 2.5° latitude – longitude grid for the period 1979-1997. The sources include gauge observations, estimates of precipitation inferred from a variety of satellite observations, both microwave and infrared. The CMAP data provides two types of precipitation estimates; one based entirely on observations from rain gauges and satellite and second based on the model estimates also. For the present comparison, we have used the first precipitation estimates as it represents only observed data. More details of the CMAP can be had from Xie and Arkin (1997).**

**The Microwave Sounding Unit (MSU) based precipitation used here was obtained from JPL, Pasadena, U.S.A. It covers the global oceans from 60°S to 60°N and extend from 1<sup>st</sup> January 1979 to 31<sup>st</sup> May 1994. A precipitation index is first calculated from the anomalous temperature elevation in MSU channel (50.3 Ghz), where warming is mainly due to thermal emission by liquid water. This index is then calibrated into rainfall using observations from over 100 coastal and atoll gauges around the globe. More details of the MSU data can be had from Spencer (1993).**

**The Global Precipitation Climatology Project (GPCP) was established by the World Climate Research Program in 1986 to address the problem of quantifying the**

distribution of precipitation over the whole globe. The general approach of the project is to combine the precipitation information available from each source into a final merged product, taking advantage of the strengths of each type of data. The microwave estimates are based on the Special Sensor Microwave/Imager (SSM/I) data from the Defense Meteorological Satellite Program (DMSP, U.S) and the infrared estimates are primarily obtained from geostationary satellites operated by U.S, Europe and Japan and secondarily from polar orbiting satellites. More details of the GPCP can be had from Huffman et al., (1997). The pentad (i.e 5 day mean) data spans the period January 1979 to February 2002 and has a spatial resolution of 2.5° of latitude and longitude.

The NCEP/NCAR Reanalysis (NRA) uses the medium range forecast (MRF) T62 model and in-situ observations to make fine estimates of various atmospheric parameters (Kalnay et al., 1996). The NCEP reanalysis used in this study consists of monthly field of precipitation. The values of variables derived from the reanalysis have varying degrees of influence from observations and models. The precipitation rate are solely affected by the model physics and no observations have gone into it. More details of the dataset can be had from Kalnay et al., (1996). The details of various data sets used in the present study are given in table 1.

### 3. Results and Discussion

#### 3.1. Validation of the precipitation estimates

The mean monthly NCEP, CMAP, MSU, and MSU (daily) derived precipitation estimates have been validated using the monthly mean and daily rainfall of four island stations: Aminidivi (11°N, 72°E) and Minicoy (8°30'N, 73°E) in the Arabian Sea, and Port Blair (11°30'N, 93°E) and Car Nicobar (9°N; 93°E) in the Bay of Bengal. From figure 1 it is obvious that the daily MSU estimates ( $r=0.41$ ) are least correlated with the island rainfall as compared with the monthly data of NCEP ( $r=0.54$ ), CMAP ( $r=0.72$ ) and MSU ( $r=0.70$ ). In a recent study, Ramesh Kumar et al (2004) have

looked into the correlation between the island station data and the satellite data on different spatial ( $0.25^\circ \times 0.25^\circ$  to  $2.5^\circ \times 2.5^\circ$ ) and temporal (daily to monthly) scales, and they found that even though, the correlation is quite low between the daily island station data and the satellite estimates, it improved substantially with the pentad data especially in the case of GPCP ( $r=0.62$ ) as compared to TMI ( $r=0.37$ ) or NRA ( $r=0.44$ ) data.

### 3.2. Comparison with earlier estimates

Figure 2 gives the mean annual rainfall (in mm) for the Indian Ocean using the CMAP, GPCP, MSU and NRA for the period January 1979 to December 1993. Even though there is a reasonable agreement as far as the broad tropical Indian Ocean rainfall features are concerned, namely the minimum of the Arabian and east African coasts ( $<500$  mm), and the maximum value near the Indonesia in the equatorial belt where rainfall exceeds 3000 mm, in most of the cases, the NRA shows significant differences, namely, it shows the maximum in the southern Bay of Bengal and equatorial Indian Ocean. The maximum differences between CMAP and other estimates are most prominent in the Bay of Bengal region and in the Indonesian island Ocean region ( $>500$  mm). Janowiak and Arkin (1991) obtained similar results for eastern equatorial Indian Ocean for the differences between the Geostationary Meteorological Satellite (GMS) and the polar orbiting satellite (NOAA 11) for the month of January 1989. They found maximum differences between the two estimates just south of the equator (6 mm/d). NCEP and MSU mean annual patterns presented a different view especially of the Indonesian Islands with the MSU values being the lowest.

Barrett et al. (1994), while interpreting the result of the first Precipitation Inter comparison project (PIP-1), found that in the case of inter comparison based on the monthly rainfall totals it is difficult to pinpoint reasons for the differences in the performance of the algorithms and their estimates (e.g., due to the algorithm physics, features of data used in

the analysis, screening logic, calibration, conversion of instantaneous rain rates to monthly totals, etc.).

### 3.3. Annual Cycle

**We have prepared the climatological seasonal mean maps of Indian Ocean rainfall for the period January 1979 to December 1997 using the CMAP data (figures 3). An analysis of the seasonal mean rainfall shows the following features:**

**a) There is little or no precipitation over the northern and western Arabian Sea and northern Bay of Bengal during the winter season (December to February). The south equatorial band extending from Madagascar to Indonesia is quite prominent and strong during this season (winter). Martin et al. (1993) have provided a detailed description of all the various bands, namely, the north equatorial band, the south equatorial band, the India band, the central band and the eastern band.**

**b) The onset of summer monsoon over the Arabian Sea is evident from the dramatic increase in rainfall over the eastern Arabian Sea from spring (March to May) to Summer (June to August), which coincides with the onset of summer monsoon over the Kerala coast. In summer season all the rainfall bands described by Martin et al., (1993) are observed namely the south equatorial band, north equatorial band, India band and central band.**

**c) The rainfall decreases rapidly over the Arabian Sea by fall, coinciding with the withdrawal of the summer monsoon from the Indian subcontinent, but in the case of Bay of Bengal, rainfall persists in the southern parts due to the presence of lows, depressions and cyclonic storms during the fall season.**

**The eastern and central bands are seen in all seasons except winter during the study period. The India band is present only during the summer season and it more or less coincided with the monsoon trough (ITCZ) during most of the years.**



In order to look into the temporal distribution of rainfall, we have plotted the climatological monthly mean rainfall for four different regions, namely, Arabian Sea ( $8^{\circ}$ - $26^{\circ}$ N;  $40^{\circ}$ - $77^{\circ}$ E), Bay of Bengal ( $8^{\circ}$ - $26^{\circ}$ N;  $77^{\circ}$ - $100^{\circ}$ E), south Indian Ocean ( $0^{\circ}$ - $30^{\circ}$ S;  $40^{\circ}$ - $100^{\circ}$ E) and the whole Indian Ocean ( $30^{\circ}$ S- $26^{\circ}$ N;  $40^{\circ}$ - $100^{\circ}$ E).

Figure 4a gives the monthly mean rainfall over the Arabian Sea (AS) and Bay of Bengal (BB). From the figure it can be seen that BB rainfall (solid line) is substantially higher (about two to three times) than the AS rainfall (dashed line). The rainfall peaks in the month of June in the AS (there is a sharp increase in rainfall from May to June) with the onset of the southwest monsoon over Kerala coast, whereas it peaks a month later in the BB. This agrees very well with the earlier results of Ramesh Kumar and Prasad (1997), who obtained similar results using INSAT data.

Figure 4b gives the monthly mean rainfall over the SIO and IO as a whole. From the figure, it can be seen that, SIO (solid line) receives minimum rainfall during the northern hemispheric summer months, namely, June, July and August. It receives the maximum rainfall during the northern hemispheric winter months, January and February. In the case of IO (dashed line), it receives the maximum rainfall during the summer monsoon season (June, July and August) and minimum during the spring month of March.

#### 3.4. Inter-annual variability of rainfall over tropical Indian Ocean from different estimates:

In order to look into inter-annual variability the oceanic rainfall over the study area for the study period (1979-1997), we have analyzed the monthly time series data for the Indian Ocean region using the CMAP data. During the study period, there were four deficit monsoon years (1979, 1982, 1986 and 1987) and four El Nino years (1982, 1987, 1992 and 1997) and two excess monsoon years (1983 and 1988). In order to look into the inter-annual variability of the rainfall, we looked at the annual

rainfall of four regions, namely, the Arabian Sea ( $8^{\circ}$ - $26^{\circ}$ N;  $40^{\circ}$ - $77^{\circ}$ E), Bay of Bengal ( $8^{\circ}$ - $26^{\circ}$ N;  $77^{\circ}$ - $100^{\circ}$ E), south Indian Ocean ( $0$ - $30^{\circ}$ S;  $40^{\circ}$ - $100^{\circ}$ E) and the Indian Ocean as a whole ( $30^{\circ}$ S- $26^{\circ}$ N;  $40^{\circ}$ - $100^{\circ}$ E).

The Indian sub continent receives substantial amount of rainfall during the summer monsoon season and it exhibits significant differences during contrasting monsoon years, namely, deficit and excess monsoon years. Table 2 gives the times series of the annual values for entire study period. From the table it can be seen that the Arabian Sea received the minimum rainfall in the deficit year of 1986, (i.e. one year prior to the deficit and El Nino year of 1987), whereas it received the maximum rainfall in the El Nino year of 1997. In fact, the year 1997 was one of the strongest El Nino years of the last century. Both the southern Indian Ocean and Indian Ocean received the minimum rainfall during the El Nino year of 1997 and maximum in 1983 (an excess monsoon year). In the case, of Bay of Bengal, it received minimum in 1982 ( a deficit and El Nino year) and maximum rainfall in 1990.

Further, to look into detailed spatial distribution of the seasonal rainfall anomalies for different conditions, we have prepared rainfall anomaly maps for a deficit monsoon year (1986), a deficit and El Nino year (1987) an excess monsoon year (1988) and a normal and El Nino year (1997). Here the anomaly refers to the mean seasonal value minus the long term climatological mean (1979-1997). Figure 5 gives the rainfall anomalies for the deficit monsoon year, 1986. From the figure it can be seen that there are large positive anomalies in the northeastern Bay of Bengal in summer. In Fall, there is a small negative anomaly near the Indonesian islands. Figure 6 gives the rainfall anomalies in the case of a deficit and El Nino year (1987). The interesting aspect is that there are no large positive rainfall anomalies, unlike in 1986 over the head or north east Bay of Bengal in summer season. But there are large positive rainfall anomalies during the fall season in the eastern Indian Ocean region. In the case of an excess year (1988), there are large negative rainfall anomalies in the north eastern Bay of Bengal during the summer season, i.e. just

the opposite of what happens during a deficit year (1986). The most interesting result is for the year, 1997 which incidentally was the strongest El Niño of the century, but the Indian subcontinent received normal monsoon rainfall. The large positive anomalies near the Indonesian islands and equatorial Indian Ocean region, during the winter, turn into small negative anomalies by spring and turn into large negative anomalies by summer and very large negative anomalies by Fall.

#### **4. Conclusions**

a) The observed island rain gauge data correlated very well with monthly CMAP, MSU estimates ( $r=0.72$ ,  $r=0.70$  respectively) and to lesser extent with the NCEP ( $r = 0.54$ ) and MSU daily values ( $r=0.41$ ) and is statistically significant at the 0.001 level.

b) A comparison of the annual mean rainfall estimates also showed significant differences, with the NRA estimates depicting the maximum rainfall rates over the southern BB and equatorial Indian Ocean, whilst the other estimates (CMAP, GPCP and MSU) showed the maximum off the Indonesian islands.

c) A comparison of the inter-annual variability of the monsoon rainfall over the tropical Indian Ocean showed significant differences over different study areas, namely, AS, BB, SIO and IO during deficit (1979, 1982, 1986 and 1987), excess (1983 and 1988) and ENSO (1982, 1987, 1992, 1997) years.

d) Large positive rainfall anomalies occurring in the northeast Bay of Bengal in summer season of a deficit monsoon (1986) turned into large negative anomalies in an excess monsoon year (1988). Similarly, large positive and negative anomalies were observed over the eastern equatorial Indian Ocean during the fall season of the El Niño years, 1987 (deficit monsoon year) and 1997 (normal monsoon year) respectively.

## **Acknowledgements**

The GPCP data was obtained from the Global Precipitation Climatology Project of the World Data Center for Meteorology, Asheville, U.S.A. Ferret software was used for the analysis of the various datasets. The authors are grateful to an anonymous reviewer for his useful suggestions in improving the manuscript. This is NIO contribution number 3911.

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**Table:1 Details of various datasets used in the present study.**

Data	From	To	Temporal Resolution	Spatial Resolution
MSU	January 1979	May 1994	Daily	1.0° X 1.0°
GPCP	January 1979	February 2002	Pentad	2.5° X 2.5°
CMAP	January 1979	December 1997	Monthly	2.5° X 2.5°
NRA	January 1979	December 1997	Monthly	2.5° X 2.5°

**Table 2: Annual Rainfall (mm) over Arabian Sea, Bay of Bengal, south Indian Ocean and Indian Ocean for the study period (1979-1997).**

Year	Arabian Sea	Bay of Bengal	South Indian Ocean	Indian Ocean	Remarks
1979	529.5	1644	1702	1486	Deficit
1980	467.1	1898	1677	1468	
1981	521.7	1815	1594	1421	
1982	483.5	1506	1708	1469	Deficit, El Nino
1983	533.8	1796	1922	1630	Excess
1984	427.1	1711	1745	1515	
1985	407.7	1863	1695	1492	
1986	388.8	1781	1632	1437	Deficit
1987	404.3	1791	1665	1448	Deficit El Nino
1988	504.1	1924	1752	1574	Excess
1989	446.2	1558	1686	1445	
1990	416.8	1959	1647	1461	
1991	429.0	1738	1601	1414	
1992	501.9	1665	1702	1463	El Nino
1993	513.6	1767	1592	1448	
1994	529.1	1873	1600	1496	
1995	467.9	1865	1708	1519	
1996	579.2	1926	1656	1499	
1997	583.7	1710	1411	1372	El Nino



## Figure Captions

Figure 1: Scatterplot of observed island raingauge data of four stations versus the  
 a) NCEP (monthly) b) CMAP (monthly) c) MSU (monthly) d) MSU (daily)

Figure 2: The mean annual precipitation rates ( in mm / year, with contours at 500 mm interval) over the tropical Indian Ocean  
 a) CMAP b) GPCP c) MSU d) NCEP

Figure 3: The seasonal mean rainfall over the tropical Indian Ocean ( in mm / month with contours at 200 mm)  
 a) Winter b) Spring c) Summer d) Fall

Figure 4a: Annual cycle of the rainfall (mm) over the Arabian Sea (solid) and Bay of Bengal (dashed)

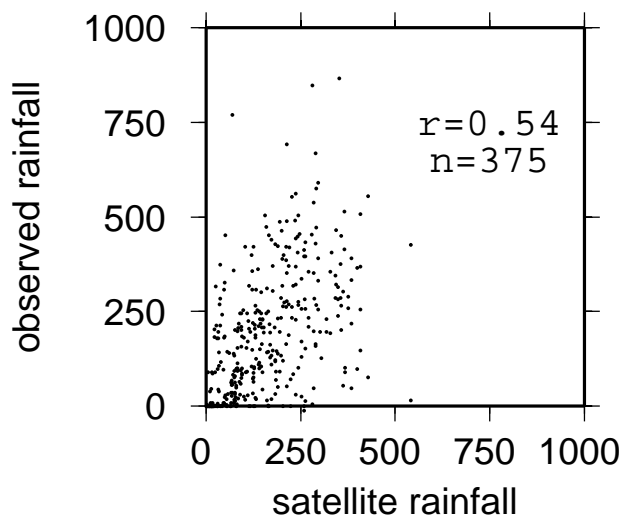
Figure 4b: Annual cycle of the rainfall (mm) over the south Indian Ocean (solid) and Indian Ocean (dashed)

Figure 5: The seasonal mean rainfall anomaly over the tropical Indian Ocean ( in mm / month with contours at 200 mm) for a deficit monsoon year, 1986.  
 a) Winter b) Spring c) Summer d) Fall

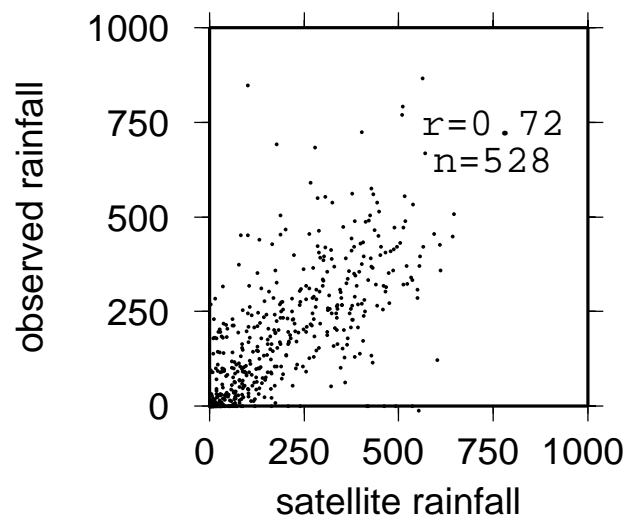
Figure 6: The seasonal mean rainfall anomaly over the tropical Indian Ocean ( in mm / month with contours at 200 mm) for a deficit monsoon and El Nino year, 1987.  
 a) Winter b) Spring c) Summer d) Fall

Figure 7: The seasonal mean rainfall anomaly over the tropical Indian Ocean ( in mm / month with contours at 200 mm) for an excess monsoon year, 1988.  
 a) Winter b) Spring c) Summer d) Fall

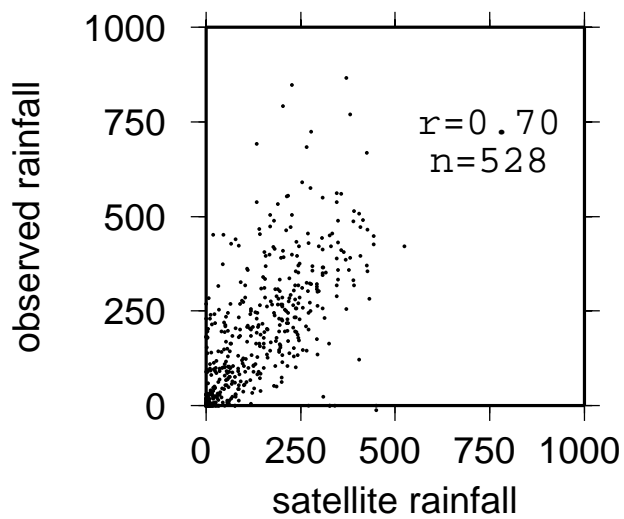
Figure 8: The seasonal mean rainfall anomaly over the tropical Indian Ocean ( in mm / month with contours at 200 mm) for a normal monsoon and El Nino year, 1997.  
 a) Winter b) Spring c) Summer d) Fall



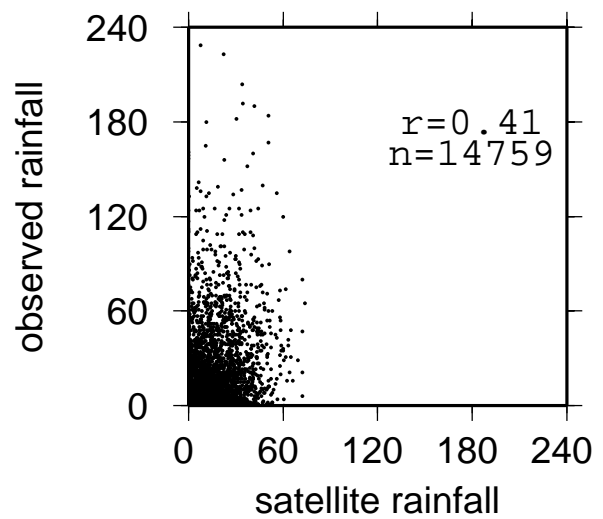
NCEP (monthly)



CMAP (monthly)



MSU (monthly)



MSU (daily)

