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Remote sensing of atmospheric water vapour from Bhaskara II SAMIR data and its comparison with NOAA-7 water vapour data

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Abstract. Applying the method of 'statistical linear regression', atomspheric water vapour over oceanic areas has been estimated from the 19 GHz and 22 GHz data of the satellite microwave radiometer (SAMIR) system onboard the Bhaskara II satellite. In the absence of any simultaneous *in situ* measurements on water vapour over ocean, the SAMIR-derived water vapour data have been compared with like data from the NOAA-7 satellite. It is suggested that a positive bias seen in the SAMIR data could be due to calibration errors in the basic data. In view of the observed bias, the original regression equation is modified and then used to obtain water vapour distributions over ocean for winter and south-west monsoon seasons using SAMIR data of several orbits.

Keywords. Remote sensing; water vapour; Bhaskara II SAMIR; NOAA satellite.

1. Introduction

Microwave radiometry from space has long been recognised as a powerful tool for meteorological and oceanographic applications. Several satellites carrying multichannel passive microwave radiometers have been launched over the last 15 years and their data have been successfully used for a variety of geo-physical applications as reviewed by several workers (e.g. Swift 1980; Staelin 1981; Njoku 1982 and Hariharan and Pandey 1983).

One of the unique capabilities of passive microwave sensors in space is their ability to measure atmospheric water vapour and liquid water over the ocean, even in the presence of most types of clouds. Measurements at the weak water vapour resonance absorption frequency 22·235 GHz and at nearby frequencies allow us to determine the total atmospheric water vapour over ocean. This has been very well demonstrated through experiments on board the Nimbus series of satellites as well as the Seasat satellite (e.g. see Staelin *et al* 1976; Njoku and Swanson 1983).

The Bhaskara II satellite, which was launched on 20 November 1981 in a near circular orbit at an altitude of about 525 km, carried on board a 3-frequency passive microwave radiometer system SAMIR*, operating at 19·35 GHz, 22·235 GHz and 31·4 GHz. Table 1 gives some essential characteristics of the SAMIR system.

It may be noted here that the three SAMIR radiometers have a *common* footprint of ∼ 125 km diameter. The SAMIR system can be operated in two distinct modes called the *Normal* and *Alternate* modes. In the Normal mode the spin-axis of the spacecraft is maintained *perpendicular* to the orbital plane and consequently during each spin, observations by the three SAMIR radiometers are taken *along* the satellite ground trace at

*The acronym SAMIR is derived from *SA*tellite *MI*crowave *R*adiometer.

Table 1. Characteristics of the SAMIR system on board Bhaskara II.

System parameters	SAMIR radiometers R-1	R-2	R-3
Frequency (GHz)	31·4	19·35	22·235
RF bandwidth (MHz)	250	250	250
Integration time (ms)	300	300	300
RMS temperature sensitivity ΔT (K)	1	1	1
Spatial resolution (km)	125	125	125
View-angles with respect to nadir (normal mode)*	±2·8°, ±5·6°, 180° (zenith)		
View angles with respect to nadir (alternate mode)*	±2·8°, ±8·4°, ±14·0°, ±19·6°, ±25·2°, ±30·8°, ±36·4°, 180° (zenith)		

*Applicable to all the three radiometers.

four view angles with respect to the nadir direction. In the alternate mode, the spin-axis of the spacecraft is aligned *along a tangent* to the orbital plane at certain latitude and consequently the SAMIR radiometers scan *across* the satellite ground trace at a number of angular positions. In both these modes of operation the SAMIR system also measures the zenith cold sky temperature during each spin. The zenith measurement which corresponds to the lowest constant brightness temperature of ~ 3 K is used in the calibration scheme together with the pre-launch calibration data taken at different temperatures in the thermo-vacuum chamber. Although the temperature sensitivity of the SAMIR system is not adequate enough for measuring the 3 K radiation, the use of this measurement in the calibration scheme allows us to approximately account for the small variations in the gain of the radiometers. It is possible that this calibration procedure may introduce some unknown bias in the data.

Reviews by Pathak *et al* (1983) and by Hariharan and Pandey (1983) give further details of the SAMIR system and also describe several studies related to the application of the SAMIR data to meteorology and oceanography.

The present paper deals with the estimation of total atmospheric water vapour (WV) content over ocean through the 'statistical regression method' using the normal mode SAMIR data at 19 GHz and 22 GHz. The SAMIR derived WV data are compared with the near-coincident WV data of the NOAA-7 satellite for a sizable data base. The comparison with NOAA WV data allows us to apply necessary bias correction to the SAMIR WV data. Finally, the SAMIR data over a few orbits have been used to determine latitudinal distribution of WV over the Arabian Sea during the northern hemisphere winter and the south-west monsoon. Preliminary results of this analysis are given by Pathak (1983a).

2. Estimation of atmospheric water vapour

In order to estimate atmospheric WV from the SAMIR data we have used the 'statistical' approach which was first suggested by Grody (1976) and later used by Pandey *et al* (1981) for estimating atmospheric water vapour from Bhaskara I SAMIR data. In this method the expected brightness temperature over ocean is simulated for a statistically representative set of atmospheres for the region of interest, and a regression is then performed between the geophysical parameter (in the present case, water vapour) and the simulated brightness temperatures. The resulting equation is then later used independently to derive atmospheric WV over the ocean by using the observed brightness temperatures.

The brightness temperature $T_B(\nu)$ at frequency ν, observed over the ocean by a satellite-borne microwave radiometer for a non-scattering atmosphere in local thermodynamic equilibrium is given by

$$T_B(\nu) = \tau_\nu(0, \infty)[T_s\varepsilon_s(\nu) + (1 - \varepsilon_s(\nu))T_{sky}(\nu)] + T_{atm}(\nu) \tag{1}$$

where

$\tau_\nu(0, \infty)$ = total transmittance = $\exp\left[-\int_0^\infty \alpha_\nu(z)\,dz\right]$,

T_s = ocean surface temperature

$\varepsilon_s(\nu)$ = ocean surface emissivity at frequency ν,

$T_{sky}(\nu)$ = down-welling radiation

$= \int_0^\infty T(z)\alpha_\nu(z)\tau_\nu(0, z)\,dz + T_{cos}\tau_\nu(0, \infty)$,

$T_{atm}(\nu)$ = upwelling atmospheric radiation

$= \int_0^\infty T(z)\alpha_\nu(z)\tau_\nu(z, \infty)\,dz$,

$\alpha_\nu(z)$ = total absorption due to atmospheric constituents at altitude z,

$T(z)$ = temperature of a thin atmospheric layer at altitude z,

T_{cos} = cosmic background temperature ($\sim$ 2·8 K)

The emissivity of the ocean surface depends on the ocean surface temperature, salinity and surface roughness, which, in turn is related to surface winds as shown by Hollinger (1971).

The brightness temperatures over ocean for 19 GHz and 22 GHz were simulated for various atmospheric and surface conditions as observed during the MONEX-79 observation period, May–July 1979. For the above simulation, the MONEX data from 690 shipborne upsonde flights giving profiles of atmospheric water vapour and temperature over the Arabian Sea and the Bay of Bengal regions have been used, along with the ship's surface observations. Also included in these profiles are 48 non-precipitating cloud models having different amounts of liquid water (LW) at different altitudes. Absorption models for WV and LW as described by Pandey *et al* (1980, 1981) have been used. The effect of ocean surface wind speed on the ocean surface emissivity, $\varepsilon_s(\nu)$, is taken into account following the work of Wisler and Hollinger (1977), which considers effects due to surface wind through roughness and foam. The statistics of relevant atmospheric and oceanic parameters used for the simulation is given in table 2.

After simulating the brightness temperatures for 19 GHz and 22 GHz for different atmospheric profiles, a multiple regression was performed between the input WV values and the simulated brightness temperature values. This gave the following regression

Table 2. Statistics of the various geophysical parameters used in the simulation analysis.

Parameter	Minimum value	Maximum value	Standard deviation
Total water vapour (mm)	30	77	6
Liquid water content (kg/m^2)	0·06	6·54	1·27
Surface wind speed (m/s)	0·0	16·0	2·85
Sea-surface-temperature (K)	298	304	1

equation:

$$\text{WV} = 1{\cdot}26\, T_B(22) - 0{\cdot}75\, T_B(19) - 90{\cdot}65 \text{ mm}, \tag{2}$$

with an RMS error of about 2 mm.

3. Comparison between SAMIR and NOAA water vapour data

In order to validate the SAMIR WV content obtained on the basis of the regression equation (2) derived above, we require a large data base of near-coincident *in situ* observations on WV over oceanic areas. For the present case, we do not have such *in situ* data and we have, therefore, chosen near-coincident WV data from NOAA-7 satellite for the purpose of comparison with the SAMIR WV data. This choice is based on an earlier study (Pathak 1983b), wherein it was demonstrated that the TIROS-N/NOAA WV data show excellent agreement with the *in situ* WV data from aircraft (dropsondes) and ships (upsondes) during MONEX-79 (May–July 1979) with RMS errors of 2–3 mm, even on a day-to-day basis. Cadet (1983) has also compared TIROS-N WV data with the corresponding MONEX-79 data from ships (upsondes) and found very good agreement between the two.

The TIROS-N/NOAA series of operational meteorological satellites carry a high resolution infrared sounder (HIRS) from which the amount of precipitable water (water vapour) in three broad layers (surface–700 mb, 700–500 mb and 500–300 mb) is available. The water vapour amounts for these three layers are combined to obtain the total WV in the atmosphere, which is then compared with the SAMIR WV data. Water vapour above 300 mb is implicitly neglected; this is generally $\leqslant$ 1 mm.

The NOAA satellite provides WV data on a global scale with a spatial resolution of $\sim$ 17 km for each observation. Being an infrared sensor, HIRS does not provide WV data for cloudy atmospheres. In contrast, however, SAMIR allows WV retrieval even for moderate cloud covers. For the present analysis, the NOAA-7 'finished product' data tapes for the period January–June 1982 have been obtained from the NOAA Environmental Data and Information Service, USA.

Total WV content from the SAMIR data has been calculated using (2) by considering observations only over open ocean. In order to avoid effects due to high emissivity of land, SAMIR data within $\sim$ 200 km of the coast were not used in the analysis. No correction for the antenna pattern has been applied to the brightness temperature data. Njoku *et al* (1980) have shown that for reasonably homogeneous areas (such as over open ocean well away from major land areas), the errors introduced by neglecting sidelobes effect is not significant. Thus, for the present analysis where we have considered data only over open oceans, the antenna pattern correction may not be important. Internal consistency of the SAMIR data is checked by comparing brightness temperature (T_B) data at closely spaced beam centre positions. This is illustrated in figure 1 which shows T_B data corresponding to all four view angles for 19 GHz and 22 GHz, over the ocean, plotted as a function of latitude. It can be seen from this figure that a number of clusters, each having four data points, corresponding to four closely spaced beam centres, occur along the ground trace. From such a plot, mutual consistency of T_B values in each cluster helps in deciding the quality of the data. Secondly, wildly fluctuating T_B values can be easily identified and eliminated. For calculating WV from the SAMIR data, T_B values in each cluster were first averaged. This helped in reducing the error in the basic data.

For comparison with the NOAA WV data, spatial separation between SAMIR beam-centre position and NOAA observation position is restricted to 1° in latitude and 1° in longitude. This criterion is based on the fact that the spatial resolution of SAMIR is a circle of ~ 125 km diameter which is comparable to 1° ≈ 110 km. Time difference, Δt, between SAMIR and NOAA observations is limited to within 8 hr. For the complete data set, Δt has the following statistics:

$$\Delta t \leqslant 6\text{ hr}—65\%;\ 6 \leqslant \Delta t \leqslant 7\text{ hr}—23\%;\ 7 \leqslant \Delta t \leqslant 8\text{ hr}—12\%.$$

The comparison is made for spot values of NOAA WV data without any spatial or temporal averaging. Figure 2 shows the extent of the geographical region over which

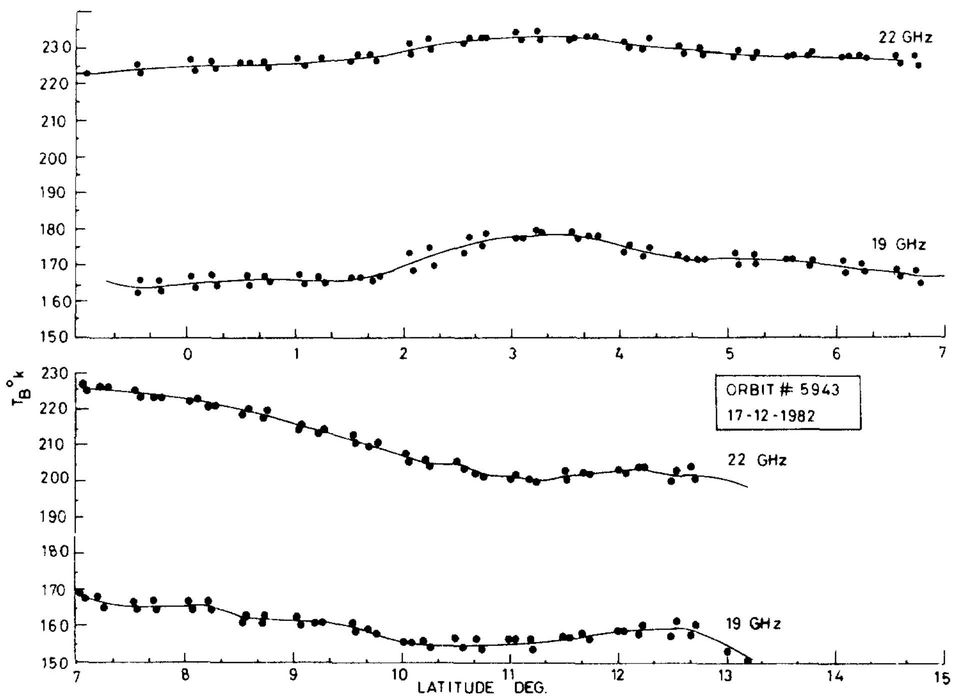

Figure 1. Brightness temperature (T_B) for 19 GHz and 22 GHz of SAMIR over ocean plotted as functions of latitude for orbit no. 5943.

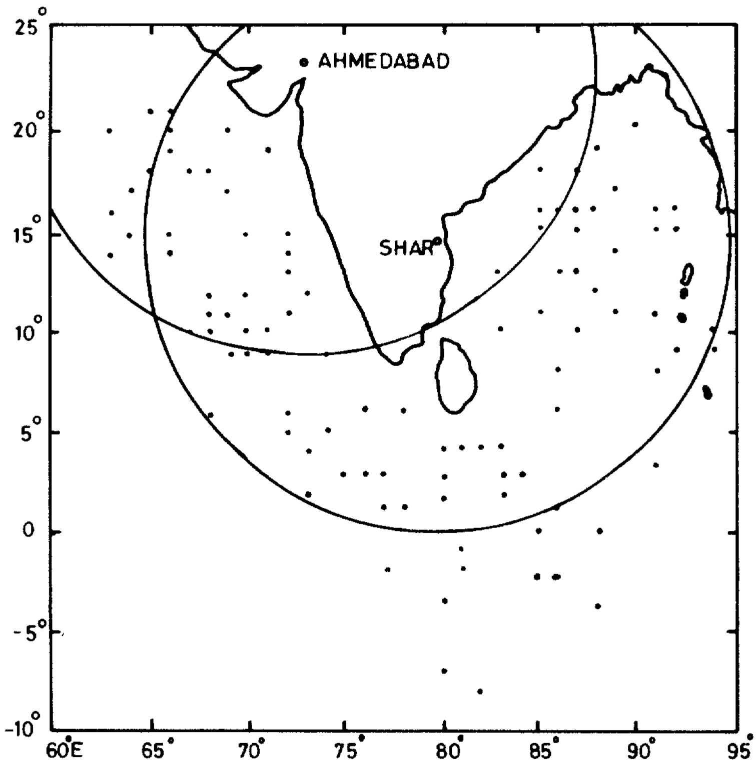

Figure 2. Geographical locations of the SAMIR derived water vapour data which are compared with the nearby NOAA water vapour data. The two circles represent the radio-visibility zones of the two ground stations (Ahmedabad and Shar) at 10° elevation.

the SAMIR and NOAA WV data have been compared. Although NOAA provides global data on WV, the coverage of Bhaskara II SAMIR data is restricted to the tropical Indian region north of the equator (see figure 2) mainly by the radio-visibility zones of the SHAR and Ahmedabad ground stations which receive the SAMIR data in *real* time. However, on board recording of SAMIR data has, at times, provided coverage over the southern latitudes also. Such on board recorded data have, in fact, been used in the present comparison to a limited extent.

Figure 3 shows a scatter diagram between the near-coincident SAMIR and NOAA WV data. The SAMIR data used here correspond to about 100 orbits during the period January–June 1982. The range of NOAA WV values used here is 20–50 mm which is slightly different from that used for the simulation analysis in §2. The total number of data points is 200 while the correlation coefficient is 0·98. The least squares fit line is given by the following equation

$$\mathrm{wv}_{\mathrm{SAMIR}} = 1{\cdot}04\,\mathrm{wv}_{\mathrm{NOAA}} + 9{\cdot}85\ \mathrm{mm}. \tag{3}$$

The RMS error is ~ 5 mm, which is calculated on the basis of the scatter of the data. The important point to note is that there is a *positive bias* of about 10 mm on the SAMIR WV axis, while the slope is very close to 1. Figure 4 shows a histogram of the observed bias in the SAMIR WV values with respect to the NOAA WV data.

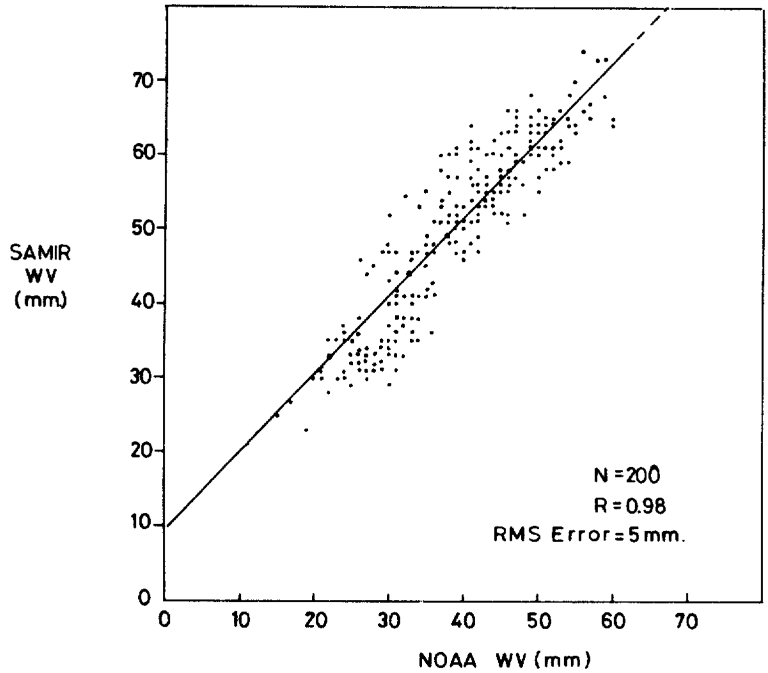

Figure 3. Scatter plot between SAMIR and NOAA water vapour data. N denotes the total number of data points while R is the correlation coefficient.

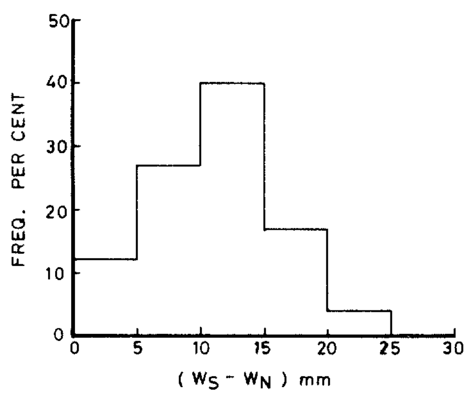

Figure 4. Histogram of the bias between the SAMIR and NOAA water vapour data (W_s = SAMIR WV, W_N = NOAA WV, in mm).

4. Discussion and conclusion

The above analysis clearly shows that based on the present regression equation (2) SAMIR WV is always *over-estimated* by about 10 mm in comparison with the NOAA WV data. However, the RMS error of 5 mm is in good agreement with the Seasat results of 4 mm (Njoku and Swanson 1983). The observed positive bias may be due to (a) some biases introduced in the basic SAMIR data through the calibration procedure and (b) uncertainty in the values of atmospheric transmittances and inadequacy in the model connecting sea-surface wind speed and ocean surface emissivity, as used in the simulation analysis in §2. It should be noted here that uncertainties related to both the factors in (b) will be of a variable nature. It is, therefore, more likely that the constant bias observed in the SAMIR WV data could probably arise from the calibration procedure. It may be pointed out here that in many microwave remote sensing satellites such post-launch adjustments/corrections in the calibration constants or bias corrections in the geophysical parameters have to be effected based on the results of verification programmes (e.g. Staelin *et al* 1976; Lerner and Hollinger 1977; Pandey and Kakar 1983 etc.). In the present case, it is found that slight changes in the T_B values can bring down the WV values as calculated from (2). For example, a reduction of 5°K in the 22 GHz T_B values and an equal increase in 19 GHz T_B values would result in an overall reduction of ~ 10 mm in the SAMIR derived WV values. Rather than effecting such arbitrary adjustments in the T_B data, we use (3) and introduce the bias correction,

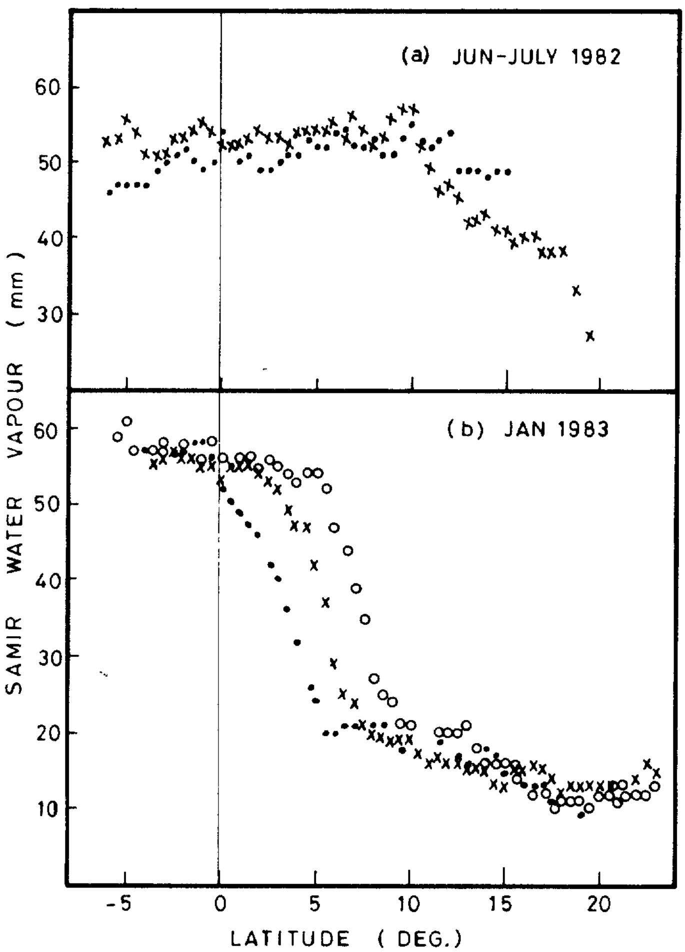

Figure 5. Latitudinal distributions of SAMIR WV over the Arabian sea for (**a**) two orbits during June–July 1982 and (**b**) three orbits during January 1983. Data for different orbits are shown by different symbols.

modifying the original regression equation (2) as follows:

$$\text{WV} = 1{\cdot}21\,T_B(22) - 0{\cdot}72\,T_B(19) - 96{\cdot}63\,\text{mm} \tag{4}$$

In the present work, we have used NOAA WV data in place of *in situ* data. It is therefore, important to consider the limitations of the NOAA data. The main limitation of the NOAA WV data is that the WV values are available only for clear (cloud-free) areas, whereas for cloudy areas no retrieval of WV is possible. Thus, the present comparison of SAMIR WV with the NOAA WV data can be considered essentially for a cloud-free atmosphere. The extension of the bias-corrected modified regression equation (4) to cloudy regions would perhaps require further validation through *in situ* measurements of WV by radiosondes. Another important limitation of the NOAA WV data, as noted by Gruber and Watkins (1979), is that there is an underestimation of WV for deep moist layers and an overestimation for a relatively dry layer. If this feature is indeed present in the present NOAA data, it might have affected the slope of the regression line in figure 3 to some extent. However, we do not have any means to check this effect in the present analysis.

The bias-corrected modified regression equation (4) has been used along with an expanded SAMIR data set (without reference to NOAA data) to determine latitudinal gradient of total WV over the ocean for two typical time periods. Figure 5 shows

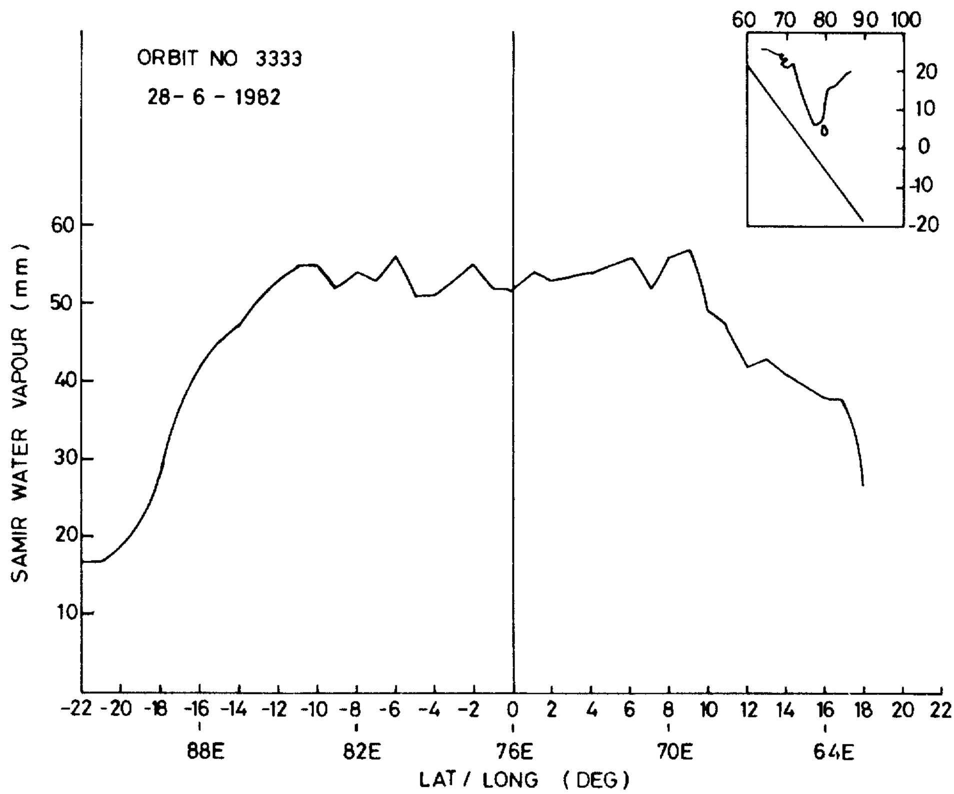

Figure 6. Latitudinal distribution of SAMIR WV over a large part of the Arabian Sea and southern Indian Ocean region obtained through onboard recording of the SAMIR data during a single orbit in June 1982. Approximate ground trace of the orbit is shown in the inset.

latitudinal gradients of total water vapour for two days in June–July 1982 during the south-west monsoon period and three days in January 1983 which is during the northern hemisphere winter. Both of these latitudinal distributions are mainly over the Arabian Sea region. It can be clearly seen that there is a marked difference between the two distributions. Whereas for the June–July period, the total wv is high (~ 50 mm) and practically constant from the equator to ~ 10°N, the January distribution shows a very sharp latitudinal gradient, with wv decreasing by almost a factor of four from the equator to 20°N. Both these distributions are consistent with the climatologically expected behaviour of wv during the south-west monsoon period and during the dry conditions of the northern winter (Peixoto and Oort 1983). Similar results were also reported on the basis of the Nimbus-5 data by Staelin *et al* (1976). Figure 6 shows the total wv distribution determined from the SAMIR data of orbit 3333 on 28 June 1982, wherein the data were recorded onboard the Bhaskara II satellite. This allowed mapping of wv over a large part of the Indian Ocean and Arabian Sea from 22°S to 18°N. This distribution shows high wv concentration (~ 50 mm) on either side of the equator from 10°S to 10°N and a sharp fall thereafter in both the hemispheres. In conclusion, it can be stated that the present comparison between SAMIR and NOAA WV data has been useful, in identifying a large positive bias in the SAMIR wv data, which could arise due to calibration errors.

After correcting for the observed bias, the wv values estimated from the SAMIR data are found to be consistent with the expected seasonal behaviour. It may be useful to further analyse the SAMIR data to decide whether there are any changes in the observed bias. Also, a few island and coastal stations radiosonde data, would be useful in deciding how the bias is spread between SAMIR and NOAA.

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