

Sea surface temperature and boundary layer fluxes from ERS-1/ATSR data

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Dual angle and multi-spectral observations from ERS-1 ATSR can be utilized for corrections for sea surface temperature retrieval and to estimate the moisture and temperature structure of the lower boundary layer. The SST has been retrieved to a good level of satisfaction (0.5 K rms) while the surface humidity retrieved have been found to an accuracy of 10%. The feasibility of estimating the surface-air exchanges over the oceans has also been confirmed. Latent heat fluxes (LHF) for a limited region are derived using bulk aerodynamic formula. The comparison between satellite derived and ship derived LHF yields an RMS error of 34 watts m^{-2} .

Boundary layer fluxes form a very important input in understanding air-sea interactions. The parameters required for estimates of these fluxes are Sea surface temperature (SST), surface humidity (q_a) and wind speed (w). Since the numerical models require these estimates on larger temporal and spatial scales and ship observations over the oceans are inadequate, satellite retrievals for these parameters are necessary. Spaceborne observations do not measure these parameters directly, so indirect inference has to be made utilising the spectral response of suitable sensors. Sea Surface Temperature (SST) retrieval from satellite IR observations is always perturbed by the attenuation of the IR signal reaching the satellite sensor due to water vapor along with CO_2 and ozone gases present in the intervening atmosphere. Therefore, the major effort for retrieving the SST from satellite data is always concentrated towards a reasonable estimate of this perturbation. Several algorithms have been developed globally for SST retrieval using dual or triple window channels¹ or a combination of observations of the two sensors i.e. AVHRR and TOVS^{2,3} or using two satellite data⁴. The algorithm by McClain *et al.*¹, derived empirically for low water vapour regions, could not be applied to the regions like Indian Ocean where water vapour content is highly variable and its vertical distribution is random⁵. Although Mathur & Agarwal³ and

Schluessel *et al.*² suggested a method of collocating the AVHRR and TOVS to rectify such a problem, yet larger inaccuracies creep in due to collocation errors of AVHRR and TOVS data. An alternative approach to remove water vapour structural dependence can be combination of observations from mutually related optical view angles so that differential absorption due to different optical path lengths might lead to estimates for water vapour absorption effects. This technique has been applied in design of IR radiometer on ERS-1-ATSR (Along Track Scanning Radiometer). Unlike SST, estimates for surface humidity (q_a) by satellite is not easy since most of the designed spectral channels tend to saturate for water vapour variations near the surface. Some authors have tried to estimate q_a on monthly time scale by relating it with total precipitable water vapour. However, these calculations tend to break down in presence of stratifications in lower troposphere. ATSR being sensitive to lower troposphere in its forward scan (details in next section) provides a possibility of estimating q_a on instantaneous basis. A viable technique has been reported in this paper. Furthermore, an attempt is made to explore the potential of this sensor for the estimation of latent heat flux from ERS-1 data. The advantage of this estimation is accentuated by the fact that ERS-1 has a scatterometer which provides surface winds.

Materials and Methods

Radiance simulation of ERS-1/ATSR observations:

Physical basis

Assuming sea surface emissivity to be unity in IR range of electromagnetic spectrum, the simplest form of radiative transfer equation for a cloud free, plane parallel atmosphere with local thermodynamic equilibrium and using mean value theorem, can be written as

$$I(\nu) = \tau(\nu, p_0, \theta) B(\nu, T_s) + B_a(\nu, T) [1 - \tau(\nu, p_0, \theta)] \quad \dots (1)$$

where I is the radiance reaching at the satellite sensor, ν is the wave number, T_s is the surface temperature, p_0 is the surface pressure, τ is the transmittance, θ is the zenith angle and B is the Planck function. $B_a(\nu)$ is the mean atmospheric radiance, T is the mean atmospheric temperature, and for all the window channels the second term on R.H.S i.e. the atmospheric term is minimum for nadir looking observations. The radiative transfer calculations for ATSR spectral channels have been carried out by using LOWTRAN-7 package⁸ for a set of atmospheric profiles as discussed later in this section. For illustration of potential of ATSR data, we select a typical tropical atmosphere i.e. atmospheric profile with SST= 300 K and surface relative humidity= 70% corresponding to 35mm of total precipitable water. One can see (Fig. 1 for channel centered around 11 μm) that with increase in look-angle from 0° to 60°, the atmospheric absorption increases and at look-angle of 55°

(ATSR forward scan angle) it increases by a factor of 2. Similarly the total transmittance decreases from 0.51 at 0° to 0.2 at 55°. Further, if we look at weighting functions which are actually layerwise distribution of the atmospheric term in Eq. (1) (Fig. 2), it is clearly seen that the atmospheric layer contributing maximum for oblique view (i.e. the forward channel observations of ATSR) lie approximately within 2 km from the surface. Thus, it seems that ATSR forward scan observation may have the information regarding distribution of water vapor (which attenuates the IR signal). Hence, the differential absorption between near nadir and forward look angle observations of the sensor could provide the key to estimation of water vapor in the lower troposphere which, as pointed out earlier, can be used to retrieve specific humidity near surface.

Atmospheric structure used for radiance simulations

In order to incorporate atmospheric conditions prevailing over Indian Ocean into the radiance simulation, the data collected and analyzed by Ramage⁹ and Niemann¹⁰ is used for variation of relative humidity and temperature. The present study categorizes the climate over Indian Ocean mainly into three types of atmospheric profiles. The first type where relative humidity decreases linearly from surface to 200 mb with a near constant rate and temperature also decreases with a near constant

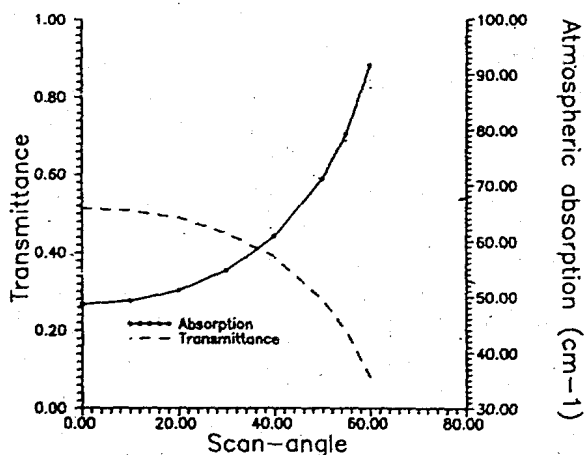


Fig. 1—Simulated Transmittance and Atmospheric absorption for ATSR window channel (11 μm) with respect to look angle of the sensor

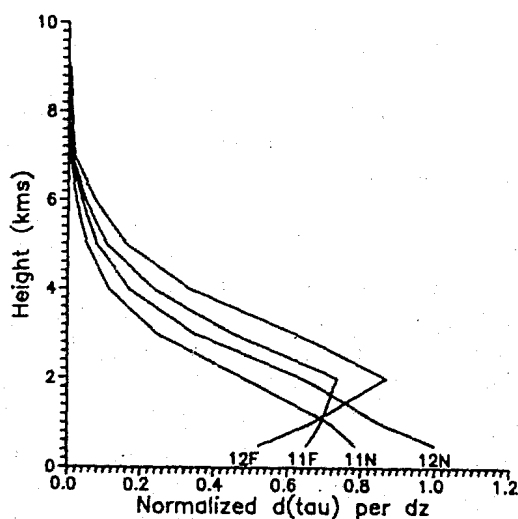


Fig. 2—ATSR window channels' weighting functions (N-refers to nadir and F-refers to forward view of ATSR, 11 and 12 refers to 11 μm and 12 μm channels respectively)

lapse rate from surface to tropopause (100 mb). The temperature above the tropopause increases linearly up to 10 mb. This is the 'normal' profile. A temperature warming in the boundary layer (<1.5 km from surface) was introduced to depict the boundary inversion phenomenon normally observed in monsoon conditions over Arabian Sea and hence called 'inversion' profiles. This is taken as a typical example of atmospheric stratification. A total number of 110 'normal' and 110 'inversion' profiles were created by varying surface temperature and surface relative humidity. The radiative simulations were performed using these profiles for both the scan angle 0° and 55°. The emissivity of the ocean surface is calculated using method given by Zavody *et al.*¹¹ under normal sea conditions. The change in scan angle for nadir and forward scan due to across track scan has also been included by dividing the ATSR swath into 5 ranges of 50 pixels each on either side of the nadir pointing. The brightness temperatures thus obtained were assumed to be noise free i.e. having no measurement errors. This assumption was validated by introducing a random noise of 0.04 K in the simulated brightness temperatures as suggested by Barton *et al.*¹². The r.m.s error in estimating q_a from the relation thus obtained was marginally increased to 15.5% as against 14.7% in noise free case. The brightness temperatures for channel centering around 3.7 μm were not simulated because of its non functioning in ATSR. While simulating, the basic data set of surface meteorological parameters viz. SST, dry bulb and wet bulb temperatures and wind speed were taken from ship cruises' data for 220 locations in the Arabian Sea and Bay of Bengal for the month of January-March and October-December 1992 covering a wide range of annual variation in SST, humidity and air-sea temperature difference. The data were collected during the cruises of *ORV*

Sagarkanya and provided by National Institute of Oceanography, Goa, India.

Retrieval method for SST from ATSR

Agarwal *et al.*⁶ have studied in detail about the impact of atmospheric attenuation due to water vapour in tropical high humidity conditions over estimates for SST. They have found that a combination of dual wavelength as well as dual angle observations are necessary in order to get a fairly accurate water vapour correction in SST retrievals in tropical humid conditions. Hence, the following relation is suggested for SST retrieval,

$$\text{SST} = A_i + B_i [T(840, N)] + C_i [T(925, N)] + D_i [T(840, F)] + E_i [T(925, F)] \quad \dots(2)$$

where $i=1, 2, 3, 4$ or 5 depending upon pixel position across track distance; A, B, C, D and E are the corresponding regression coefficients, $T(840, N)$ is brightness temperature of channel centered around 840 cm^{-1} for scan at forward view angle. $T(925, F)$ corresponds to brightness temperature of channel at wavenumber 925 cm^{-1} for scan at forward view angle. The relationship has a least r.m.s. error (0.2 - 0.3 K) and a very high level of significance (goodness of fit > 0.9). The complete set of regression coefficients is given in Table 1. The proposed SST retrieval technique was applied to an actual ATSR brightness temperature data set for March 3, 1992, April and May 1994, obtained from RAL, UK. Before applying the regression coefficients for retrieving SST, each set of data is subjected to cloud checks (based upon difference in nadir and forward scan observations of 925 cm^{-1} channel and the difference in nadir observations of 925 cm^{-1} and 840 cm^{-1} channel). Collection of nadir and forward scan pixels has been performed by RAL, UK. While processing 'ATSR.IBT' data product, we have assumed that there is no earth

Table 1—Regression coefficients for SST retrieval

Set	Across track distance(km)	Coefficients				
		a	b	c	d	e
1	(0-50)	-7.3283	7.5337	-5.7105	-4.5381	3.7396
2	(51-100)	-5.8402	7.0078	-5.4961	-3.7695	3.2784
3	(101-150)	-6.4659	6.7292	-5.2795	-3.4781	3.0512
4	(151-200)	-7.1492	6.6502	-5.2121	-3.3928	2.9798
5	(201-256)	-6.5522	6.5350	-5.1330	-3.2660	2.8872

location error. The SST thus obtained at each pixel is compared with near simultaneous ship observations. Ship and satellite observations were assumed to be simultaneous if they are separated by not more than 1° in space and 6 hours in time. Ship observations (Bucket temperature) taken during the cruises of research vessels *Sagarkanya*, and *Sagarsampada* were provided by National Institute of Oceanography (NIO), Goa while the ship observations dated 3 March 1992 were provided by Royal Observatory, Hong Kong. SST was also estimated from the regression coefficients as described by Zavody *et al.*¹¹ and Barton *et al.*¹² using the simulated ATSR data and we found that these coefficients have a cold bias of 0.3 to 0.6 K depending upon the total water vapour content in the atmosphere.

Retrieval method for surface humidity

Some authors^{14,15} have tried to relate near surface humidity (q_a) with the total precipitable water on monthly time scale with the help of radiosonde observations on climatic level within accuracies of the order of 0.8 g kg^{-1} . The method's error of estimation increases when applied to instantaneous measurements^{16,17} which will lead to very large error in estimating evaporative flux. Even a region wise empirical fit has not proven very fruitful. The reason is that the atmospheric boundary layer normally is decoupled from the higher troposphere because of increased stability in the region just above the boundary layer. Taylor¹⁸ and Marchuk¹⁹ have shown that total precipitable water can not be used as a predictor for q_a because of poor correlation between the two (Fig. 3). The difference in brightness temperatures for nadir and forward scan represents the water vapour content near surface. In order to minimize the temperature effect these differences were normalized by introducing a function σ such that

$$\sigma_c = (T_{n,c} - T_{f,c}) / (T_{n,c} + T_{f,c}) \quad \dots (3)$$

where T denotes the simulated brightness temperature, subscript n or f refers to nadir or forward scan angle observation and c refers to 840 cm^{-1} or 925 cm^{-1} channel. The differential absorption term so constructed, then, can be used as a tracer for estimating surface humidity. Correlation of σ with ship observations of surface humidity has

been shown in scatter plots (Figs 4, 5) and lead to conclusions that σ 's (both σ_1 corresponding to 925 cm^{-1} and σ_2 corresponding to 840 cm^{-1}) are very well correlated with q_a . The correlation coefficients are found to be better than 0.7 in both cases. A least square regression fit was found:

$$q_a = a + b \sigma_1 + c \sigma_2 \quad \dots (4)$$

where

$$a = 17.69, b = 0.0026106, c = -0.0048342$$

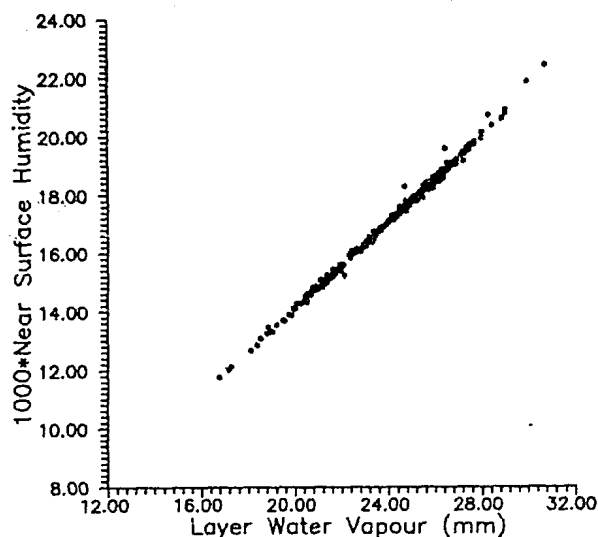


Fig. 3—Scatter plot showing the correlation between near surface humidity and lower (below 3 km) layer water vapour content.

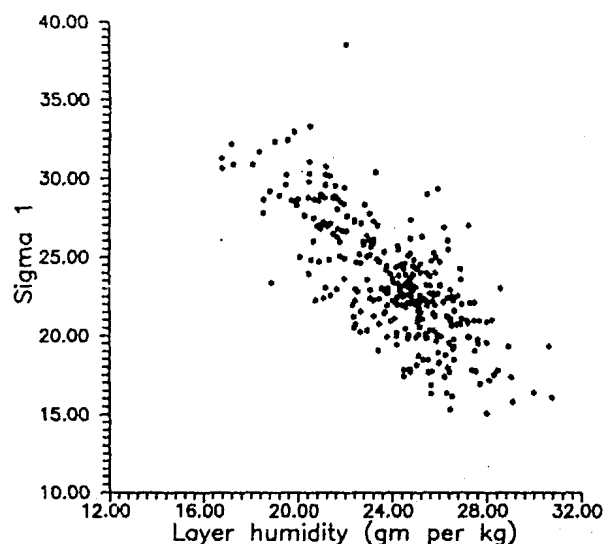


Fig. 4—Scatter plot showing the variation of σ_1 with respect to q_a (multiplied by 1000)

For finding the rms error in the regression analysis an independent data set (which was not used in establishing the relationship) of 210 tropical atmospheres was generated by taking another set of surface meteorological data collected by ships. The rms deviation was found to be 3 g kg^{-1} while the percentage rms error was 14.7. In order to validate the q - σ relation, we obtained an actual ERS-1/ATSR data dated 3-3-1992 from Rutherford Appleton Laboratory U.K. The q_a has been computed using the above relation. Table 2 shows the comparison between q_a derived from ATSR data

and those derived from corresponding simultaneous ship observations. All those ship observations which were taken within "6 hours of the satellite pass were assumed to be simultaneous.

Retrieval method for latent heat flux

Latent heat flux can be computed using the Bulk aerodynamic formula:

$$E = D C_d U (q_a - q_s) \quad \dots (5)$$

where E is evaporative flux [$\text{kg(m}^2\text{s)}^{-1}$], D is surface air density (kg m^{-3}), C_d is water vapour flux transfer

Table 2—Comparison between q_a derived from ATSR data using the proposed relation and q_a derived from ship observations (in brackets)
[Values of q_a in gm kg^{-1} are multiplied by 1000 for convenience]

	108	108.5	109	109.5	110	110.5	111
11.0		22(*)	24(*)	31(19)	13(*)	16(19)	15(19)
10.5		23(*)	31(18)	22(17)	15(19)	16(*)	15(18)
10.0		25(*)	25(*)	16(11)	17(20)	16(18)	15(*)
9.5		16(*)	15(20)	16(20)	17(18)	17(*)	14(*)
9.0		17(16)	16(19)	18(27)	17(*)	19(*)	16(*)
8.5		15(18)	17(19)	18(18)	17(*)	19(*)	16(*)
8.0							

*denotes nonavailability of ship data.

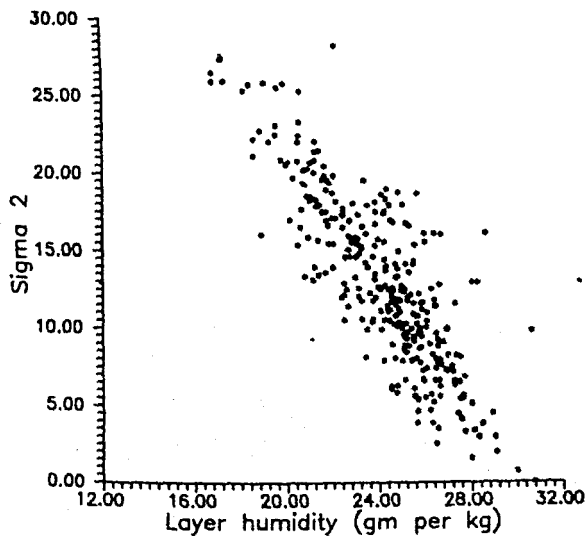


Fig. 5—Scatter plot showing the variation of σ_2 with respect to q_a (multiplied by 1000)

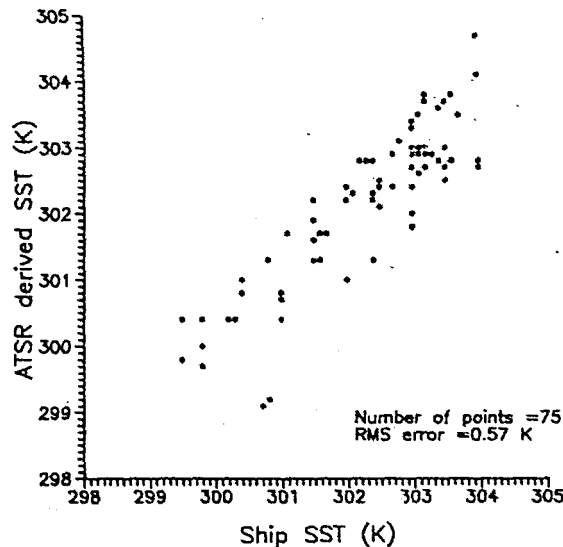


Fig. 6—Comparison of ATSR derived SST and Ship SST

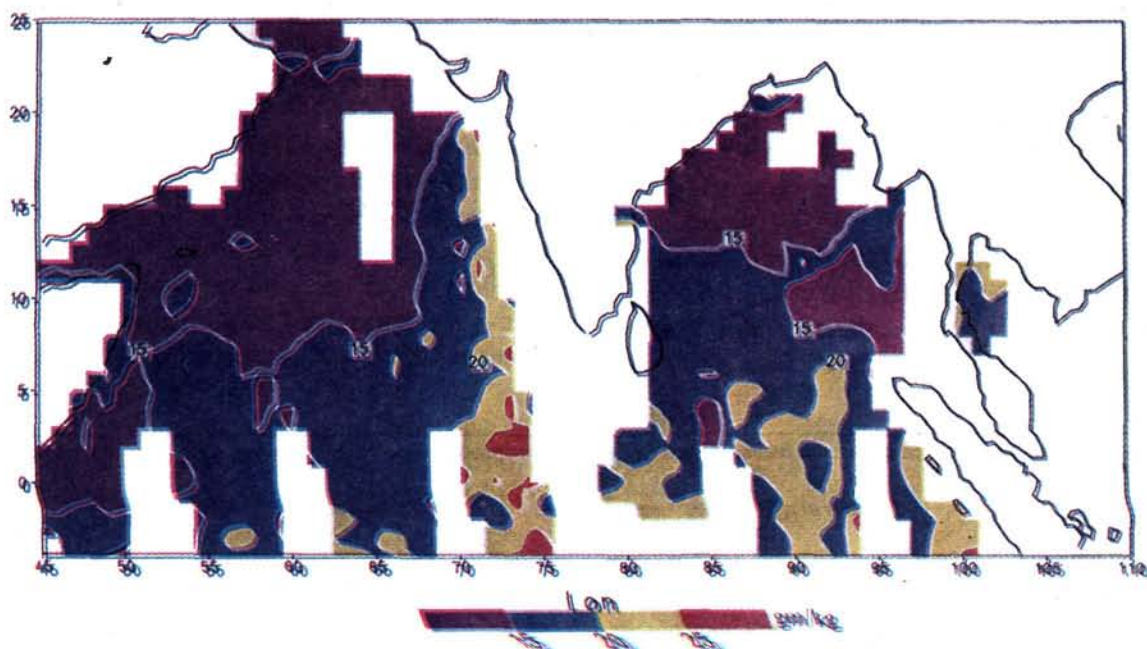


Fig. 7—Sea Surface Temperature contours derived from ATSR (1-15 April 1994)

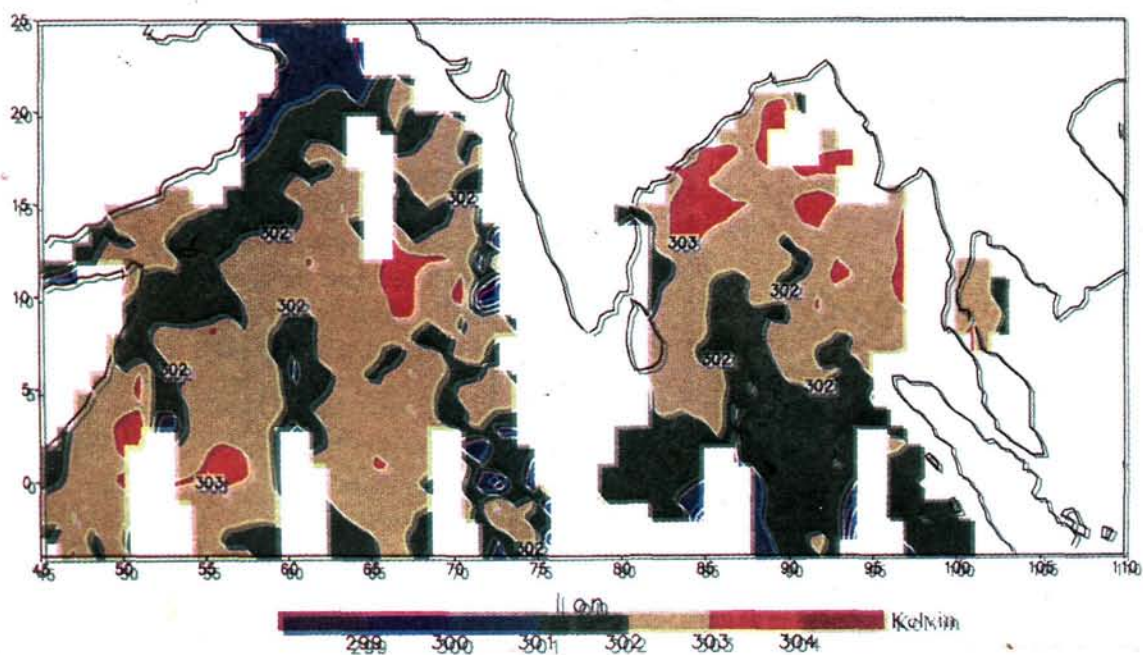


Fig. 8—Surface humidity contours derived from ATSR (1-15 April 1994)

coefficient, U is the wind speed (m s^{-1}) at 10 m height, q_s is saturation specific humidity (kg^{-1}) at sea surface temperature and q_a is specific humidity at wind observational level. The wind speed can be obtained from satellite borne scatterometer on ERS-1. For spot comparison, we have used ship data. For preparation of detailed distribution maps, data from satellite wind measurements are used.

Results and Discussion

Sea surface temperature

The comparison between ATSR SST and ship SST (Fig. 6) shows that most of the time (44 out of 75) the difference lies between -0.5 to 0.2 K. The overall r.m.s error of the comparison is 0.57 K. We have also produced fortnightly average SST maps (Fig. 7). Although theoretically dual angle technique for retrieving SST looks very promising and in the present scenario, ERS-1 can cater to such a technique, yet the technique has to be used after a lot of preprocessing and analytical efforts. For example, geometric distortion in the image due to the conical scanning of ATSR and due to obliqueness of the Earth when the scanner's view angle is 55° , needs to be corrected carefully. Navigation of ATSR images earlier^{20,21} can be a good tool to calculate latitude and longitude corresponding to ATSR scan line and pixel.

Similarly the corrections arising out of the Roll, Pitch and Yaw steering of the satellite will certainly make the retrieval algorithm more complex but accurate.

Surface humidity

The comparison between ship derived and ATSR derived surface humidity (Table 2) shows that in most of the cases (12 out of 19) the difference in computed q_a and observed q_a is between 2.5 and 5.0 and there are 4 cases where the difference is in between 0 and 2.5 . On the other hand the number of cases where the difference exceeds 5 are only 3. The r.m.s error of the comparison is 5 g kg^{-1} i.e. within 15% . Based upon the above q_a estimation, we have also generated fortnightly averaged contour maps for the Indian Ocean. A typical contour map is shown in Fig. 8. Although such a small statistics of validation with only a single orbit data is not sufficient for establishing a relationship, yet the results certainly show a strong possibility of retrieving the information regarding boundary layer specific humidity on instantaneous basis which at present is very difficult as far as satellite data is concerned. Furthermore, unlike the conventional method of estimating q_a , the proposed relation does not depend upon the retrieval of total integrated water vapour estimation and hence the possibility of error is decreased.

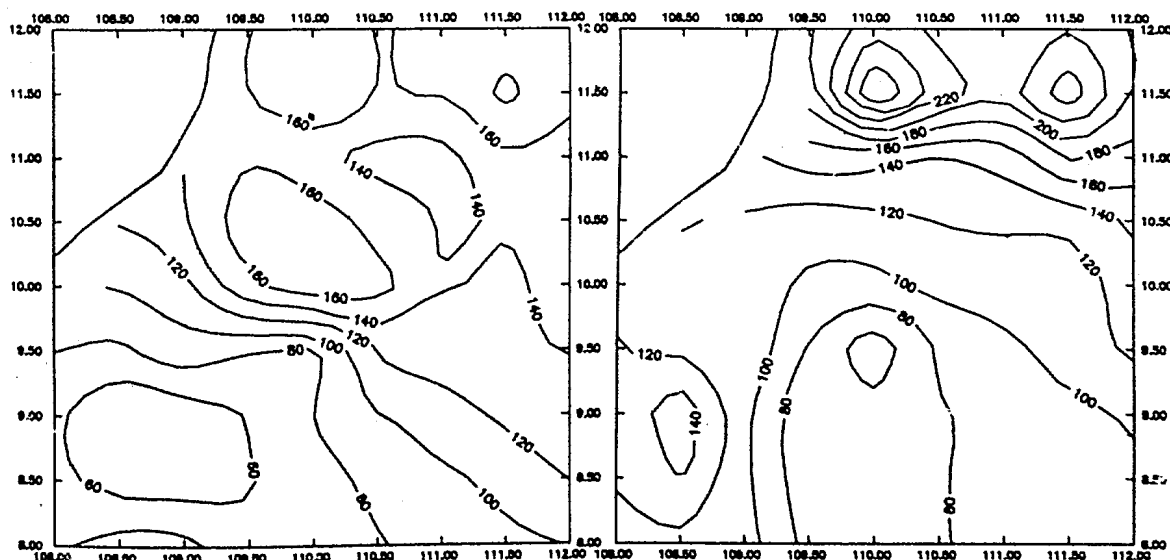


Fig. 9—Contour plot of Latent Heat Flux (watts m^{-2}) derived from — A) ATSR SST and q_a and B) from Ship data

Latent heat flux

With the SST and q_a derived from the above proposed retrieval methods, we have estimated the latent heat flux (LHF) over a limited region for which we could get the simultaneous wind observations using bulk aerodynamic formula. The wind measurements have been taken from colocated deck level ship observations. This LHF has been compared with the ship derived LHF. Figure 9 shows the contour maps of the ATSR derived LHF and ship derived LHF. It was found that rms error in calculating LHF from ATSR data is 34 watts m^{-2} if we ignore the points very close to the coastline. If these points are also included the rms error increases to nearly 81 watts m^{-2} . The possible reason for such a large anomaly may be the land surface affect in estimating q_a . In order to have a totally satellite based estimation of LHF, one should have winds derived from ERS-1 scatterometer, but this data could not be acquired for the desired period. Therefore the wind measurements from ship have been taken to demonstrate the potential of ATSR data in estimating LHF with a good level of accuracy. The main concern for LHF estimation on instantaneous basis is concerned.

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