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# Retrieval of sea surface temperature from INSAT-IB radiometer measurements using a multi-channel simulation approach

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**सार** — वायुमंडलीय प्रभावों का विलोपन कर, उसी क्षेत्र पर विचार करते हुए विभिन्न उपग्रह रेडियो मीटर भ्रामिका चैनल द्वारा प्राप्त बहु चैनल समुद्र सतह के तापमान की पुन: प्राप्ति की तकनीक में दीप्त तापमान का प्रयोग किया गया। एकल अवरक्त भ्रामिका जैसे इनसेट-1बी वी. एच. ग्रार. आर. द्वारा उपग्रह रेडियो मीटर के साथ एम सी एस एस टी तकनीक का प्रयोग नहीं किया जा सकता है। प्रस्तुत शोधपत्र में वायुमंडलीय जल वाष्पन अंश के पदों में 10.5–11.5 और 11.5–12.5 $\mu$ बैंड प्रावली दो घटकों के विवरण के जोड़ के रूप में एकल चैनल 10.5–12.5 $\mu$ पर प्राप्त विकिरण को विभक्त करने के लिये पद्धति पर विचार किया गया, इसलिये एम सी एस एस टी पद्धति को अनुप्रयुक्त किया जाए यदि जल वाष्पन अंश ज्ञात अथवा माने गए हों। एम सी एस एस टी और एकल भ्रामिका कान्ति तापमान के बीच का अन्तर $T_{sw}$ और कुल वायुमंडलीय जलवाष्पन अंश के पदों पर परिभाषित किया गया है। वायुमंडलीय (आई आई ओ ई) जलवाष्पन आंकड़ों का प्रयोग करते हुए जनवरी और मई 1986 के अरब सागर, बंगाल की खाड़ी और हिन्द महासागर पर इनसेट-1 बी समुद्र सतह तापमान के समतापी वक्र प्रस्तुत किये गये। एन ओ ए ए पुन: प्राप्ति सुधार से तुलना ने अच्छी संगति दिखाई। यह पद्धति मेघ-मुक्त क्षेत्रों के लिये है।

ABSTRACT. In the multi-channel sea surface temperature (MC SST) retrieval technique, brightness temperatures obtained from different satellite radiometer window channels viewing the same area are used to eliminate the atmospheric effects. The MC SST technique cannot be used with satellite radiometers having a single infra-red window, *e.g.*, INSAT-1B VHRR. In the present paper, a method has been proposed to split up the radiance received over a single channel, 10.5-12.5 $\mu$, as a sum of two component radiances over 10.5-11.5 and 11.5-12.5 $\mu$ bands parametrically in terms of the atmospheric water vapour content, thus allowing the MC SST algorithm to be applied if the water vapour content is known or assumed. The difference between MC SST and the single-window brightness temperature ($T_{sw}$) is defined in terms of $T_{sw}$ and the total atmospheric water vapour content. Using climatological (IIOE) water vapour data, isotherms of INSAT-1B sea surface temperature over Arabian Sea, Bay of Bengal and Indian Ocean are presented for January and May 1986. Comparison with NOAA retrievals shows good agreement. The method is meant for cloud-free areas.

## 1. Introduction

In comparison with the complex derivation of many satellite data products, the retrieval of sea surface temperature over cloud-free areas is, theoretically speaking, a simple inversion process. In practice, however, a major difficulty arises from the fact that the 10.5-12.5 $\mu$ window, widely used in satellite radiometers, is not transparent in the perfect sense. The emission from the sea surface does undergo a residual attenuation on its way to the satellite through the atmosphere. As a result, the satellite brightness temperature is lower than the actual SST, the difference between them varying with location and season as the atmospheric water vapour makes the highest conribution. Over the tropics, the difference is generally 4°-8°C (Prabhakara *et al.* 1974) and in specific instances even 9°-10°C (Brandli *et al.* 1977). In the early years of development, efforts were made to parameterise the correction term $\triangle T$ as a function of SST, latitude and/or season (*e.g.*, Smith and Rao 1972). Later it became possible to evaluate the atmospheric attenuation from satellite soundings of temperature and water vapour fed into theoretical models which also incorporated effects of satellite earth geometry (*e.g.*, Maul and Sidran 1973).

The most significant advance in satellite SST retrieval efforts was the development of the multi-channel sea surface temperature (MC SST) technique. Here the brightness temperatures obtained from different radiometric window channels viewing the same area are used to eliminate atmospheric effects, rather than evaluate them. Although the MC SST concept was mooted in the early seventies (Anding and Kauth 1970, Prabhakara *et al.* 1974), the operational application of the procedure became possible only after the launch of the NOAA-7 satellite in 1981, which carried a split-window radiometer (Mc Clain *et al.* 1983). On the assumption that two radiometer window channels have different attenuation effects and have corresponding brightness temperatures $T_1$ and $T_2$, it can be shown theoretically (Mc Millin and Crossby 1984) that :

$$SST = T_1 + K(T_1 - T_2) \tag{1}$$

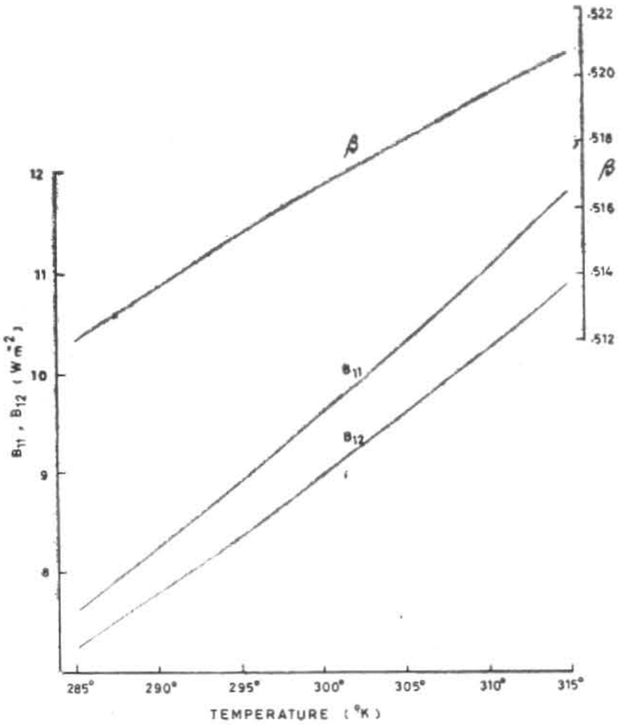


Fig. 1. Variation of black-body radiances [$B_{11}$, $B_{12}$ and ratio $\beta = B_{11}(B_{11}+B_{12})$ with temperature

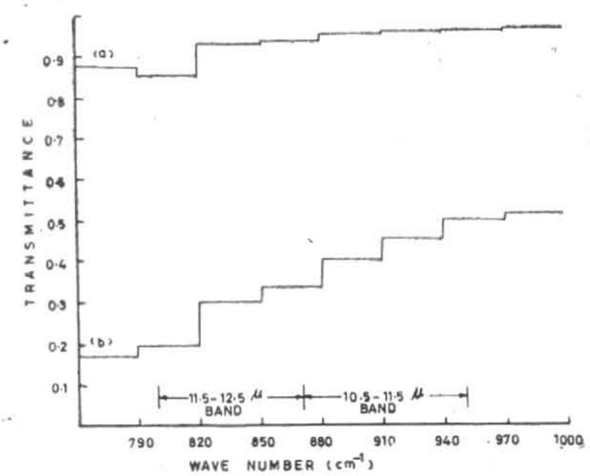


Fig. 2. Vertical path transmittance between surface and top of the atmosphere : (a) Dry atmosphere, 64° N, precipitable water 0.75 cm, (b) Moist atmosphere, 9° N, precipitable water 4.86 cm

(*After* Weinreb & Hill 1980)

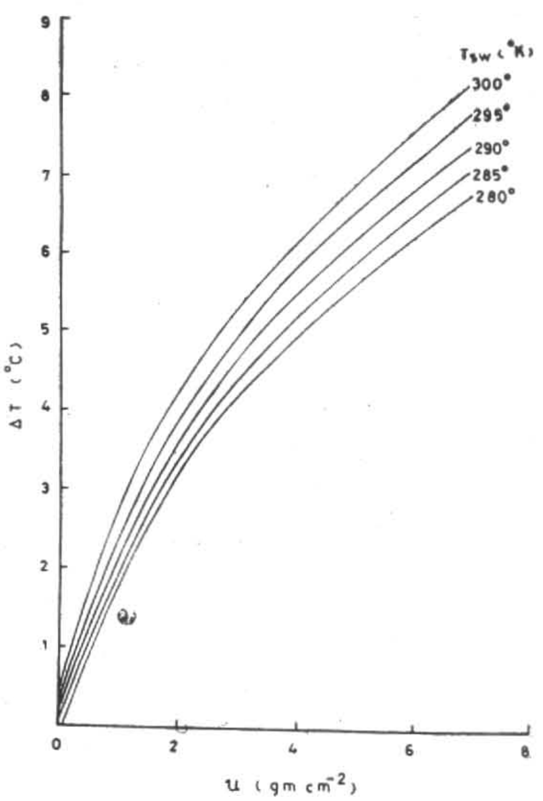


Fig. 3. Correction $\triangle T$ to be applied to single window brightness temperature $T_{sw}$ as a function of water vapour optical depth $u$

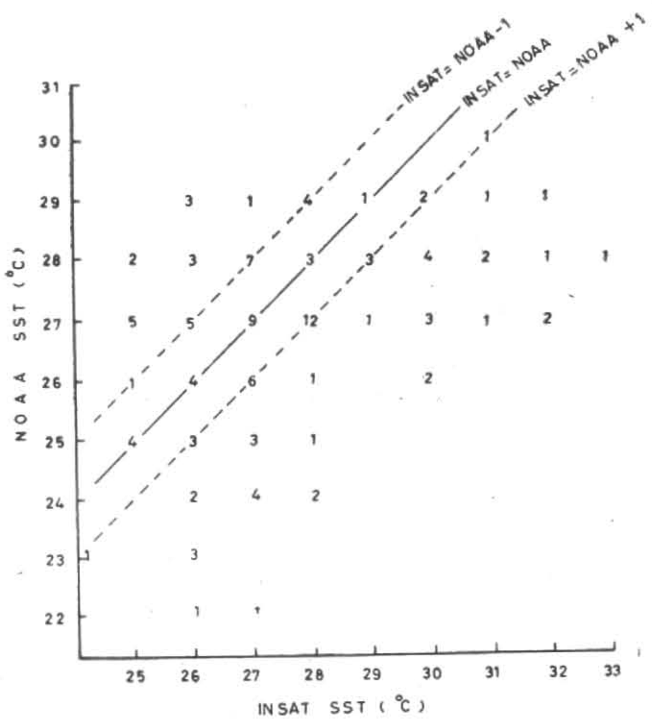


Fig. 4. Scatter plot of NOAA SST *vs* INSAT SST. Figures represent number of co-located retrieval of given pair of SST values out of a total of 117

Where, $K$ is a constant, although a more rigorous approach would involve a quadratic (Mc Millin 1980).

The algorithms actually used by NOAA for global MC SST retrievals, based upon the above principle, have been further refined by involving brightness temperatures of three channels, *viz.*, 3.55-3.93$\mu$ ($T_{3.7}$), 10.3-11.3$\mu$ ($T_{11}$) and 11.5-12.5$\mu$ ($T_{12}$) and by incorporating bias corrections with reference to drifting buoy match-ups (Strong and Mc Clain 1984):

$$\text{MC SST (Day)} = 1.0346 \quad T_{11} + 2.58\,(T_{11} - T_{12}) - 283.21 \qquad (2)$$

$$\text{MC SST (night)} = 1.0170\; T_{11} + 0.97\,(T_{3.7} - T_{12}) - 276.58 \qquad (3)$$

where all brightness temperatures are in °K and MC SST is in °C. Comparisons with special XBT measurements have shown that MC SSTs are accurate to within 0.5°C in the range of 20°-28°C (Hawkins 1986).

None of the currently operational meteorological satellites, excepting those of the United States, have more that one infrared window channel. For example INSAT-1B has a 10.5-12.5 $\mu$ i-r channel and a 0.55-0.75 $\mu$ visible channel. The atmospheric attenuation has therefore, to be estimated indirectly by one of the pre-MC SST methods.

In the present paper the authors have evolved a new method of apportioning the radiance received by a single radiometer channel of 10.5 -12.5$\mu$ into two components so as to simulate a split-window (10.5 - 11.5 $\mu$ and 11.5-12.5 $\mu$). By simulating two brightness temperatures from one measured value, the MC SST algorithm can be applied in the estimation of SST. This split-up is, of course, parametric, as a function of the atmospheric water vapour content, which should be known or assumed. Correction curves have been developed to estimate SST from the INSAT single-window brightness temperature as a function of atmospheric water vapour. Mean monthly SST maps obtained by applying climatological values for the water vapour correction, are presented in this paper for January and May 1986.

## 2. Black-body radiances

The black-body radiance, as defined by the Planck function at temperature $T$ (°K) and wave number $\nu$ (cm$^{-1}$) is given by :

$$B(T, \nu) = \frac{C_1 \nu^3}{e^{C_2 \nu / T} - 1} \qquad (4)$$

where $C_1$ and $C_2$ are constants of value $1.1911 \times 10^{-5}$mW m$^{-2}$ st$^{-1}$ (cm$^{-1}$)$^{-4}$ and 1·438833°K cm respectively.

For a given temperature $T$, the integrated black body radiance over a window region extending from wave numbers $\nu_1$ to $\nu_2$ is :

$$\bar{B}(T) = \int_{\nu_1}^{\nu_2} B(T, \nu)\, d\nu = \int_{\nu_1}^{\nu_2} \frac{C_1 \nu^3}{e^{C_2 \nu / T} - 1} \qquad (5)$$

If $\triangle\nu = \nu_2 - \nu_1$ is a small interval and we denote $\nu_0 = \dfrac{\nu_1 + \nu_2}{2}$

we can evaluate $\bar{B}(T)$ as :

$$\bar{B}(T) = \frac{C_1 \nu_0^3}{e^{C_2 \nu_0 / T} - 1} \triangle\nu \qquad (6)$$

This is justified by the fact that even at 280°K, Wien's displacement law gives $\lambda_{max} = 10.35\,\mu$, so that the 10.5-12.5 $\mu$ range is in the monotonic part of the $B$-$\nu$ curve. Taking 10.5$\mu$ and 11.5$\mu$ as the limits of the 11$\mu$ window, 11.5 $\mu$ and 12.5 $\mu$ as those of the 12 $\mu$ window we can derive $\bar{B}(T)$ for each. These two parameters are called $B_{11}$ and $B_{12}$ hereafter and are understood to be functions of $T$.

The integrated black-body radiance $B_{sw}$ in a single window extending from 10.5 to 12.5 $\mu$ should be a sum of $B_{11}$ and $B_{12}$, *viz.*,

$$B_{sw} = B_{11} + B_{12} \qquad (7)$$

We define

$$\beta = \frac{B_{11}}{B_{sw}} = \frac{B_{11}}{B_{11} + B_{12}} \qquad (8)$$

All $B$'s are radiances leaving the surface, hence $\beta$ is a function of the real surface temperature, *i.e.*, SST in our case. It is seen that (Fig. 1), $B_{12}$ is always less than $B_{11}$, the difference $B_{11} - B_{12}$ increasing with temperature. The ratio $\beta$ is slightly higher than 0.5 and also increases with temperature. Actually $T_{11}$ in Eqn. (2) corresponds to 10.3-11.3 $\mu$ which has slightly higher attenuation effect than 10.5-11.5 $\mu$. However, the ratio $\beta$ is not seriously affected as $B_{11}$ appears in both numerator and denominator.

## 3. Split-window simulation

The split-window simulation approach, introduced in this paper, essentially consists of expressing a radiance $R_{SW}$ actually received by the radiometer channel 10.5-12.5 $\mu$ as a sum of two values $R_{11}$ and $R_{12}$ corresponding to 10.5-11.5 $\mu$ and 11.5-12.5 $\mu$ components respectively. In other words, we have to select the proper ratio $\rho$, where,

$$\rho = \frac{R_{11}}{R_{sw}} = \frac{R_{11}}{R_{11} + R_{12}} \qquad (9)$$

In the ideal case where the atmospheric attenuation is zero, the three corresponding brightness temperatures $T_{SW}$, $T_{11}$ and $T_{12}$ should all be equal to SST and the ratio $\rho$ should be equal to $\beta$ (SST). In the real atmosphere, $\rho$ must have values higher than $\beta$ (SST), depending upon the degree of atmospheric attenuation, because the transmittance in the 10.5-11.5 $\mu$ band is always greater than that in the 11.5-12.5 $\mu$ band. This is obvious from Fig. 2 which shows transmittances at 30 cm$^{-1}$ wave number interval in the water vapour window region, for model atmospheres representing 64°N and 9°N latitudes, having precipitable water vapour of 0.75 and 4.86 cm respectively, as per Weinreb and Hill (1980).

Thus, the attenuation effect can be parameterised if a relationship can be established between the ratio $\rho$ and the atmospheric moisture content, which is the prime cause of atmospheric attenuation in the 10.5-12.5 $\mu$ window region. This was accomplished in the manner described ahead.

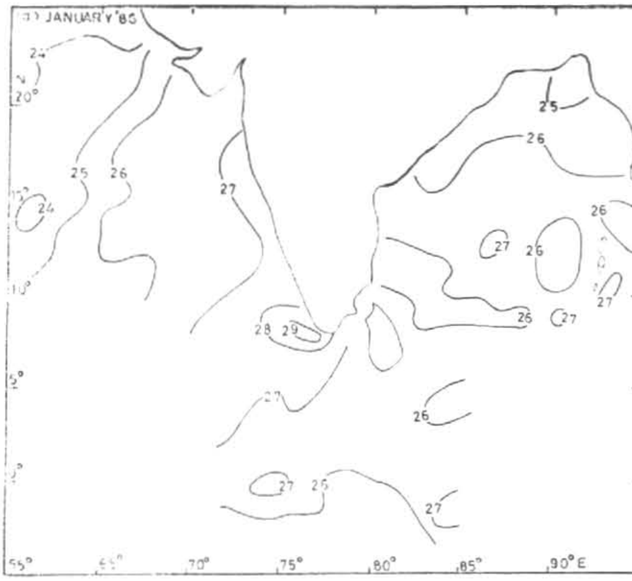


Fig. 5. Isotherms of mean monthly INSAT SST (°C) for January 1986

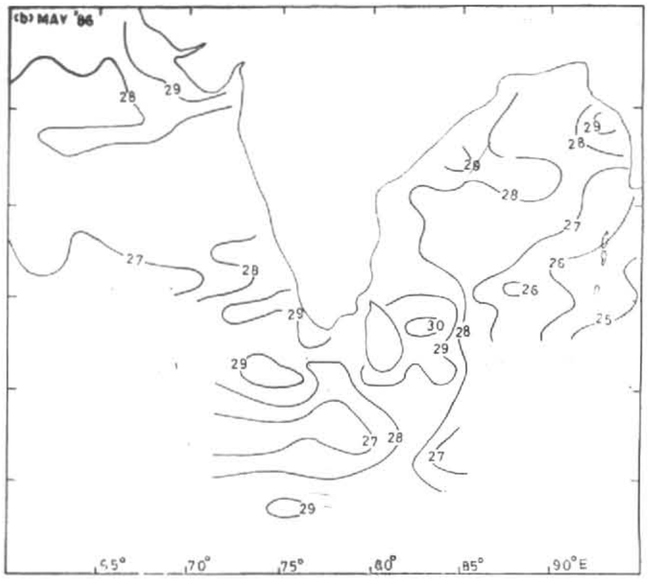


Fig. 6. Isotherms of mean monthly INSAT SST (°C) for May 1986

For different values of brightness temperature $T_{SW}$, ratio $\rho$ was varied in small steps of 0.001 from $\rho=\beta$ to $\rho=\beta+0.01$. In each case, $R_{sw}$ was accordingly apportioned into $R_{11}$ and $R_{12}$ from which $T_{11}$ and $T_{12}$ were derived as brightness temperatures. The NOAA MC SST Eqn. (2) was applied to $T_{11}$ and $T_{12}$ and MC SST derived. The difference $\triangle T_{11}$=MC SST$-T_{11}$ was next obtained for each value of $\rho$ for different values of $T_{sw}$.

Sidran (1980) applied temperature-dependent transmission functions to model atmospheres representing various values of total precipitable water vapour and solved the radiative transfer equation. The effect of varying the emissivity of the sea surface between 0.99 and 1.00 was also considered but found to be insignificant. For the 10.4-11.3 $\mu$ channel, the difference $\triangle T_{11}$ between SST and the brightness temperature $T_{11}$ has been plotted by Sidran for water vapour concentrations ranging from 0 to 5 gm cm-2 and SST of 299 to 302.5°K. Although Sidran has adopted fixed combinations of water vapour and SST, in the tropics we may not be deviating too far from her SST range. However, it must be mentioned that Sidran has assumed a negative correlation between water vapour and SST, which may be too restrictive in the tropics.

By combining Sidran's relationship between $T_{11}$ and the water vapour amount with our relationship between $T_{11}$ and $\rho$, it became possible to evaluate the ratio $\rho$ for any given optical depth and temperature.

Finally, we considered about 300 combinations of the single-window brightness temperature $T_{SW}$ and the water vapour optical depth $u$ with $T_{sw}$ varying between 280° and 300°K and $\mu$ ranging from 0 to 7 gm cm-2. For each case, $R_{SW}$ was computed from $T_{SW}$ and split into $R_{11}$ and $R_{12}$ as per the values of $u$ determined from $u$ and $T_{SW}$. From $R_{11}$ and $R_{12}$ the brightness temperatures $T_{11}$ and $T_{12}$ were obtained and Eqn. (2) applied to get MC SST. The correction $\triangle T$= MC SST$-T_{sw}$, was obtained as a function of $T_{sw}$ and $u$, and is presented as a family of curves in Fig. 3. The curves do not show $\triangle T=0$ for $u=0$, because of an empirical factor in the MC SST algorithm, and also due to aerosol and other corrections.

#### 4. INSAT-1B sea surface temperatures

4.1. *Retrieval procedure*

INSAT-1B data is received and processed every three hours at the Meteorological Data Utilisation Centre (MDUC), New Delhi. INSAT-1B has only one infrared channel of 10.5-12.5 $\mu$ with a resolution of 11 km at the sub-satellite point (0°, 74°E). Atmospheric attenuation over the tropical oceanic regions is known to be large, and unless properly accounted for, the SST's would be in error. Software was, therefore, developed at MDUC, based upon the consideration explained in this paper, to derive INSAT-1B SSTs over three sectors of approximately 14°×14° Lat. Long. extent, covering the Arabian Sea, the Bay of Bengal and the Indian Ocean, north of 3°S. Routine derivation of SST over these three sectors commenced at MDUC in September 1985, on an experimental basis, at 0300 and 0600 GMT daily.

The software, divides each sector into 225 (15×15) boxes and the warmest brightness temperature $T_{sw}$

amongst all the pixels in a box is chosen to minimise cloud contamination. Boxes which wholly cover coastal land areas are not used for further processing. Among the boxes which are over sea areas, those having $T_{sw}$ less than 280°K or larger than 300°K are not considered for SST derivation. Cloudy areas are thereby avoided. For computing the correction term $\triangle T$ from Fig. 3, the precipitable water vapour is required to be known. This information was derived from the monthly maps of the IIOE atlas of Ramage *et al.* (1972). Since the viewing angle of the satellite radiometer increases with distance from the sub-satellite point and the water vapour content of the atmosphere pertains to the atmospheric column, we have to take into account the increased attenuation along a slant path. For this purpose, the increase in the path length is computed from simple geometric consideration involving the latitude and longitude of the place viewed and the height of the satellite.

Having derived the corrected SSTs (as $T_{sw}+\triangle T$), the software applies a gradient check to the SST field in the east-west and north-south directions. If a box has an SST which differs from adjacent boxes by more than 2°C, it is rejected. This condition may not, however, be applicable in regions known to have steeper gradients such as in the vicinity of the Somali coast.

4.2. *Comparison with NOAA SSTs*

In view of the extensive clouding which prevails during the Indian southwest monsoon season and largely inhibits derivation of SST, the two months of January and May 1986, representative of winter and pre-monsoon conditions, were chosen for detailed analysis. Since the SST retrieval philosophy described in this paper seeks to simulate the MC SST technique, the SST values reported for the Indian Ocean region by NOAA over the Global Telecommunication System were used as a standard for comparison. The variable time of observation of polar-orbiting satellites and the sparseness of the NOAA SST reporting grid, made it difficult to find coincident NOAA and INSAT SSTs. However, 117 pairs of values, which were fairly co-located in time (mostly $\pm$6 hours) and space (generally $\pm$1° Lat./Long.) were picked up from the GTS information stream and the MDUC SST retrievals. Fig. 4 is a kind of scatter diagram based upon these 117 cases, showing how far the INSAT SSTs agree with NOAA SSTs. Since the comparison is between values expressed in nearest whole numbers, the usual dots in a scatter diagram have been replaced by a numerical figure indicating number of pairs of SSTs. The numbers lying along the central line indicate cases of equal values of INSAT and NOAA SSTs. In general, it is noticeable that there are more situations in which INSAT SST is higher than NOAA SST than the other way round. Out of the total population of samples studied, three-fourth of the samples agreed with $\pm$2°C while half agreed within $\pm$1°C.

In this comparison, MC SST values, were decoded from the GTS stream instead of directly using MC SST maps such as those presented by Viswambharan *et al.* (1986). The maps are actually 7-day composite fields. Over areas which might have remained covered with clouds during most of the compositing period, the isotherm analysis is not truely representative. Moreover, it is not possible to isolate the bogusing, if any, from the maps above. Hence, the above method was preferred.

The NOAA-INSAT differences are of the same order of magnitude as reported by Legeckis *et al.* (1980) in a comparison between NOAA-5 VHRR and GOES VISSR retrievals of SST, over the Gulf of Maine. The two radiometers had the same channel width, 10.5-12.5 $\mu$ but different resolutions and filter responses. When the 1 km VHRR data were degraded to match the 8-km VISSR resolution the brightness temperatures were found to agree within $\pm$1°C. When the temperatures were corrected for attenuation, VISSR SSTs were found to be lower than the VHRR SSTs by 2°-3°C, due to differences in the calibration and response function.

Studies made for the Arabian Sea with data for MONEX-1979 (Pathak 1982, Agarwal 1983) also suggest that there was a consistent underestimation of SST by the NOAA scheme for high values of atmospheric water vapour content, prior to the introduction of MC SST.

4.3. *Monthly averages of SST*

For the months of January and May 1986, the daily INSAT SSTs were averaged for each of the 15$\times$15 boxes of the Arabian Sea, Bay of Bengal and Indian Ocean sectors. Isotherms of mean monthly SST derived therefrom are shown in Figs. 5 and 6.

As evident from these analyses, the SST gradient is appreciable over Arabian Sea in January (Fig. 5) and the isotherms have a nearly northeast-southwest orientation. The isotherms over the Bay of Bengal are aligned more latitudinally. The warmest SSTs are found off the Kerala coast and decrease to the north and south of it. These features agree well, both qualitatively and quantitatively, with the SST blended analysis for January 1986 published by the Climate Analysis Centre, Washington D.C. (CAC) and also with the climatological SST chart of Reynolds (1982) based upon surface marine data for January.

In May (Fig. 6), INSAT SSTs are again high to the west of Kerala, but in addition, the warm zone extends to the east of Sri Lanka, also. Equally warm SSTs are found over the area of Arabian Sea to the west of Gujarat and Saurashtra coastline. While in January, SST over the Arabian Sea is generally less than 27°C, in the month of May it is mostly above 27°C. Gradients are steep over the Bay of Bengal in May, with SSTs as low as 25° over the Andaman Sea and increasing northwards and westwards of the area. As against this, Reynold's climatological SST is mostly 28°-29°C over the Indian seas, while the CAC map for May 1986 shows SSTs of the order of 29°-30°C. Gradients of SST are weak in both the maps. The MC SST map for the week ending 20 May 1986 reproduced by Viswambharan *et al.* (1986) shows closed 30° isotherms over southeast Arabian Sea and the Andaman Sea, MC SST being 28°-29°C elsewhere in the area of interest. The INSAT SSTs thus appear to be 1°-2°C lower, in general, as compared to other maps. However, they are 1°-2°C higher to the east of Sri Lanka and 3°-4°C lower in southeast Bay of Bengal.

The discrepancies between INSAT and other SST maps can be attributed to several sources. First of all, in the daily INSAT SST retrievals, climatological monthly atmospheric water vapour amounts have been used. The pitfalls in the use of climatological water vapour are well-known (Prabhakara *et al.* 1974). The situation may improve if NOAA water vapour amounts transmitted over GTS are utilised on a day-to-day basis, but this information is not sufficient for making spatial analysis over our area of interest. The climatological maps of Ramage (1972) could also be augmented with reference to recent MONEX observations, but the latter are for the monsoon season and mainly over the Arabian Sea.

Another important aspect to be considered is that the NOAA MC SST retrieval scheme incorporates exhaustive tests to ensure that only cloudfree areas are processed. The five channels of the NOAA AVHRR and their high resolution make this possible. With the INSAT VHRR resolution of 11 km in the infra-red, sub-pixel clouding and uniform low-level stratus clouds could contaminate the retrievals and cause a lowering of the SST values.

### 5. Concluding remarks

The SST retrieval scheme described in this paper as applied to INSAT single-channel infra-red radiance data, has yielded results which are comparable in accuracy with observations made by NOAA satellites using the MC SST approach. Monthly averages of SSTs derived from INSAT for January and May 1986 are seen to be in good agreement with climatological charts. The INSAT SST data set thus appears to be a valuable source of information in an important but otherwise data sparse area.

It is also recommended that later designs of the INSAT VHRR should be augmented with one or two additional thermal infra-red channels to enable SST retrievals similar to those attempted by Bates and Smith (1985) with the GOES VAS sounder data. Till then, INSAT single-channel observations used along with information on atmospheric water vapour, preferable from NOAA satellites, may be useful in the manner described in the present paper.

### References


Agarwal, V.K., 1983, "Remote sensing of sea surface temperature from multi-channel infra-red satellite observations", *ISRO Tech. Rep.* No. *ISRO-SAC-TR*-32-83, 54

Anding, D. and Kauth, R., 1970, "Estimation of sea surface temperature from Space", *Rem. Sens. Environ* **11**, pp. 217-220.

Bates, J.J. and Smith, W.L., 1985, "Sea surface temperature: Observations from geostationary satellites", *J. geophys. Res.*, **90**, pp. 11609-11618 (C6).

Brandli, H.W., Reinke, D., and Irvine, L.E., 1977, "Sea surface emission temperatures from Defence Meteorological Satellites", *J. Phys. Oceanography*, **7**, pp. 302-304.

Hawkins, J.D., 1986, " Satellite SST accuracies", Field Workshop, on Intercalibration of conventional and Remote Sensed SST Data", Report No. 16, WMO-TD No. 95, pp. 44-47.

Legeckis, R., Legg, E. and Limeburner, R., 1980, "Comparison of polar and geostationary satellite infra-red observations of sea surface temperatures in the Gulf of Maine", *Rem. Sens. Environ*, **9**, pp. 339-350.

Maul, G.A. and Sidran, M., 1973, "Atmospheric effects on ocean surface temperature sensing from the NOAA satellite scanning radiometer", *J. geophys. Res.*, **78**, pp. 1909-1916.

Mc Clain, E.P., Pichel, W.G., Walton, C.C., Ahmed, Z. and Sutton, J., 1983, "Multichannel improvements to satellite-derived global sea surface temperatures", *Adv. Space Res.*, **2**, pp. 43-47.

Mc Millin, L.M., 1980, "The split window retrieval algorithm for sea surface temperature derived from satellite measurements" in *Remote Sensing of Atmospheres and Oceans* (Ed : A Deepak), pp. 437-455.

Mc Millin, L.M. and Crossby, D.S., 1984, "Theory and Validation of the multiple window sea surface temperature technique", *J. geophys. Res.*, **89**, pp. (C3) 3655-3661.

Pathak, P.N., 1982, "Comparison of sea surface temperature from TIROS-N and ships in the Indian Ocean during MONEX (May-June 1979)", *Rem. Sens. Environ.*, **12**, pp. 363-369.

Prabhakara, C., Dalu, G. and Kunde, V.G., 1974, "Estimation of sea surface temperature from remote sensing in the 11 to 13 $\mu$m window region", *J. geophys. Res.*, **79**, pp. 5039-5044.

Ramage, C.S., Miller, F.R. and Jeffries, C., 1972, "*Meteorological Atlas of the International Indian Ocean Expedition*", **1**, National Sci. Found., Washington D.C., p. 144.

Reynolds, R.W., 1982, "A monthly averaged climatology of sea surface temperature", *NOAA Tech. Rep.* No. *MWS* 31, 53 pp.

Sidran, M., 1980, "Infrared sensing of sea surface temperature from space", *Rem. Sens. Environ.*, **10**, pp. 101-114.

Smith, W.L. and Rao, P.K., 1972, "The determination of sea surface temperature from satellite window radiation measurements", *Proc. First Symp. Temp. Instrumentation Soc. of America*, pp. 2251-2257.

Strong, A.E. and Mc Clain, E.P., 1984, "Improved ocean surface temperatures from space—Comparison with drifting buoys", *Bull. Amer. met. Soc.*, **65**, pp. 138-142.

Viswambharan, N.K., Shubha, S. and Gangadhara Rao, L.V., 1986, "Remote sensing of sea surface temperature through infra-red radiometry—A review", *Sadhana* (*Academy Proc. Engg. Sci.*), **9**, pp. 281-297.

Weinreb, M.P. and Hill, M.L. 1980, "Calculations of atmospheric radiances and brightness temperatures in infra-red window channels of satellite radiometers", *NOAA Tech. Rep.* No. *NESS* 80, 40 pp.