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# SEA SURFACE TEMPERATURES AROUND A TROPICAL CYCLONE FROM NOAA–5 SATELLITE DATA

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ABSTRACT

Sea Surface Temperatures (SST) over the Arabian Sea and Bay of Bengal as derived from the NOAA–5 Very High Resolution Radiometer (VHRR) data recorded at the Space Applications Centre, Ahmedabad during November 1978 are reported. The SST retrieval method and the atmospheric attenuation corrections are described. The results corresponding to four days around a cyclone are compared with available ship observations. Spatial variations of SST for two days around the cyclone are also presented.

## INTRODUCTION

Imageries produced by radiometers onboard meteorological satellites are being operationally used for short period forecasting. If there are no clouds in the field of view of the radiometer, the measurements in the infrared region (10.5–12.5 micron) can be effectively used to derive the Sea Surface Temperatures (SST).

The study and monitoring of SST's in India over large areas during pre-monsoon and pre-cyclone seasons can be used to understand the monsoon phenomenon, cyclogenesis and intensification.

Most of the reported measurements of SST on an operational basis over the globe are from the coarse resolution scanning radiometer data (Browner, Gohrband, Pischel, Signore and Walton, 1976; Smith, Rao, Koffler and Curtis, 1970). The Very High Resolution Radiometer (VHRR) data have been used on a few occasions (Breaker, Klein and Pitts, 1978; Tournier, 1977) to determine SST's at localised areas.

The VHRR data permits investigation of the small and medium scale features in the SST field. Under conditions of broken cloud, fairly common over the oceans, the VHRR with its much smaller instantaneous field of view greatly increases the proportion of cloud free areas viewed.

In this paper we present the SST derived from NOAA–5 satellite VHRR data over the Arabian Sea and the Bay of Bengal during November 1978. The details of the NOAA–5 VHRR data reception system at the Space Applications Centre, Ahmedabad have been described in an earlier communication (Rao, Narayanan and Sharma, 1980).

## RAW SST RETRIEVALS

### *VHRR-IR Data*

The VHRR is a line scan device. Global coverage is achieved from continuous horizon-to-horizon scanning combined with forward motion of the spacecraft. The spatial resolution is approximately 0.9 km at the sub–satellite point. Ground resolution worsens as the distance from the subsatellite point increases. The VHRR data received in analog from is digitised to 256 levels for further processing.

The temperature measurement accuracy of the radiometer expressed as Noise Equivalent Differential Temperature (NEDT) is estimated to be 0.5° for a 300°K scene. This value, representative only for the instrument, is further degraded by the additional noise generated by the transmission, reception and data processing. This system noise is considered to be random.

*Formatting of Blocks*

The raw retrievals are obtained from blocks of data rather than from individual pixels. Since the system noise is random, statistical techniques are used based on Gaussian distribution. The following considerations are important in determining the block size.

(a) The error in the estimate of the mean SST is inversely proportional to the square root of the number of pixels in the block. Hence block size should be sufficiently large.

(b) Temperature changes within a block should be very small. Also for good spatial resolution, the block size should be small.

(c) Requirements (a) and (b) are contradictory. In this study an optimum number of pixels per block has been taken so as to give a block of about 100 km on a side along the subsatellite track.

(d) At large zenith angles (>50°) a pixel and hence a block covers excessively large areas introducing unacceptable errors. Hence pixels with local zenith angles >50° should not be used.

Retrieving from blocks rather than pixels besides improving accuracy also enables to retrieve from partially cloudy scenes.

*Retrieval of Raw SST*

The retrieval technique is based on the assumption that the system noise is essentially Gaussian noise. For a uniform scene temperature and atmospheric attenuation, a histogram is constructed of all the pixels using the grey level as variate. The modal class of this histogram represents the actual raw retrieval. In this ideal case an arithmetic mean would have also served the purpose. But only histogram method enables retrieval when some pixels are cloud contaminated.

A Gaussian distribution with a mean $\overline{G}$ can be expressed as

$$\text{Frequency } F = A \exp[-B(G - \overline{G})^2]$$

This expression contains three constants A, B and $\overline{G}$. If $G_1$, $G_2$ and $G_3$ are grey levels with frequencies $F_1$, $F_2$, and $F_3$, $\overline{G}$ can be determined which is a grey level representing the raw SST of the block.

*Calibration*

The complete calibration procedure relating grey level counts on the imagery (or CCT) to physical temperatures has been described in an earlier communication by Narayanan and Rao (1981). In determining SST's in blocks of 100 scan lines, the appropriate calibration corresponding to those particular 100 lines are used and not an average calibration for the whole imagery. This ensures minimum calibration errors, i.e., less than 0·3°C.

## ATMOSPHERIC ATTENUATION CORRECTION

It has been estimated that attenuation due to the atmospheric constituents, water vapour, carbon dioxide, ozone and aerosols contribute to the corrections to be applied to the estimated sea surface temperatures. Among these, water vapour is most significant and the correction may be as high as 10°C for temperature retrievals from the 10–12 micron region.

The true SST ($T_S$) and the raw retrieved SST ($T_R$) are related by the following expression:

$$B(T_R) = B(T)\Upsilon_s + \sum_{i=1}^{n} B(T_i)(\Delta\Upsilon)_i$$

where $(\Delta\Upsilon)_i = \Upsilon(Z_{i+1}) - \Upsilon(Z_i)$

$B(T)$ = Planck's function

$Z_i$ = Atmospheric vertical height, divided into 'n' slabs

$\Upsilon(Z_i)$ = Atmospheric transmittance at height $Z_i$, integrated over the wavelength interval under consideration.

Given the temperature and humidity profiles, transmittances can be calculated as a function of wavelength at every height level of the atmosphere (Selby and Mc-Clatchey, 1975; Selby, Shettle and McClatchey, 1976). Thus knowing the retrieved raw SST and the atmospheric structure the true SST can be determined.

## DATA

All estimates of SST were made around two cyclones, one over the Arabian Sea and the other over the Bay of Bengal. Fig. 1 shows four infrared imageries of the cyclone in the Arabian Sea and one IR imagery of the cyclone in the Bay of Bengal. There are about 500 scan lines per cm along the vertical axis and about 500 pixels per cm along the horizontal axis (each of about 0·9 km at ssp). One SST retrieval per block of 100 lines × 100 pixels has been made over a few completely clear areas of each imagery. The central scan line number and pixel number of these blocks are listed in Table II alongwith the results.

For November 6, 1978 blocks of 100 × 100 pixels were constructed over the whole observational area and histograms obtained for SST retrieval. Adopting a suitable objective quality control criterion, SST for clear area blocks were determined and contours drawn. No attempt has been made to retrieve SST from partly cloudy areas.

(*a*) Nov. 6, 1978 (13°N, 72°E

(*b*) Nov. 9, 1978 (18°N, 63°E)

(*c*) Nov. 10, 1978 (22°N, 64°E)

(*d*) Nov. 11,1978 (23°N, 67.5°E)

(*e*) Nov. 23, 1978 (8.5°N, 83°E)

*Fig. 1.* Infrared imageries of Arabian Sea *(a–d)* and Bay of Bengal *(e)* cyclones.

## RESULTS

The mean monthly climatological humidity and temperature profiles over Andaman Islands (representative of Bay of Bengal) and Minicoy Islands (representative of Arabian Sea) were used to calculate the atmospheric correction effects in the SST determinations. The corresponding corrections for different look angles and as a

*Table I.* Radiometric Temperature *vs* SST· for typical months for different look angles.

| Month | SST | Minicoy Islands | | | Port Blair Islands | | |
|---|---|---|---|---|---|---|---|
| | | $\theta = 0°$ | $\theta = 25°$ | $\theta = 45°$ | 0° | 25° | 45° |
| Jan | 305 | 300.3 | 299.9 | 299·0 | 300·6 | 300·4 | 299·6 |
| | 300 | 295·1 | 294·7 | 293·8 | 295·7 | 295·3 | 294·5 |
| | 295 | 290.0 | 289·6 | 288.6 | 290·5 | 290·2 | 289·3 |
| July | 305 | 298·7 | 298·2 | 297.0 | 296·5 | 295·8 | 294·4 |
| | 300 | 293·5 | 293·0 | 291·8 | 291·2 | 290·6 | 289·1 |
| | 295 | 288·9 | 288·4 | 287·3 | 287·4 | 286·8 | 285·4 |
| Nov | 305 | 299·3 | 298·9 | 297·8 | 298·8 | 297·3 | 295·8 |
| | 300 | 294·2 | 293·7 | 292.5 | 292·7 | 292·1 | 290·7 |
| | 295 | 289·2 | 288.7 | 287·5 | 287·8 | 287·2 | 285·9 |
| Saturated | 305 | 290·6 | 289·7 | 287·7 | | | |
| WV at all | 300 | 289·6 | 288·8 | 287·2 | | | |
| Heights | 295 | 287·8 | 287·3 | 285·9 | | | |

function of actual scene temperature are tabulated in Table I· Included in this table is also the correction corresponding to a saturated water vapour profile at all heights·

It can be concluded from this table that a correction of 5–10°C will be required to be taken into account for correcting for the raw SST's under varying conditions of humidity, look angle etc·

Fig· 2 shows a few typical examples of histograms obtained from the imageries· Raw SST's were calculated from these blocks by the procedure outlined above· These results are presented in Table II·

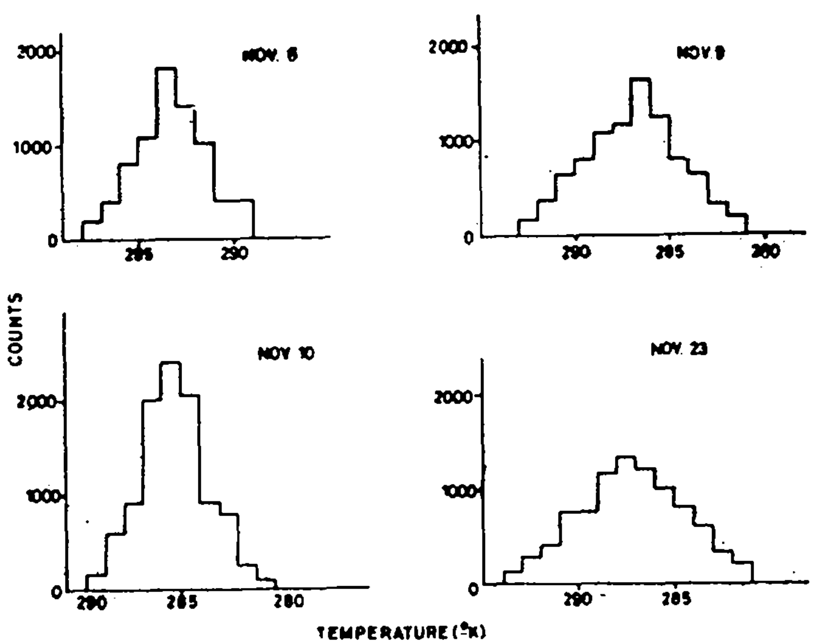


*Fig. 2.* Histograms for raw SST retrieval.

*Table II.* SST results from satellite and ships·

| Block Central Line No. | Block Central Pixel No. | Latitude (°N) | Longitude (°E) | Raw SST | Corrected SST °K | Corrected SST °C | Ship value (°K) (within 500 km radius) |
|---|---|---|---|---|---|---|---|
| *1) Nov. 9, 1978* | | | | | | | |
| 1950 | 2050 | 15 | 70 | 286.8 | 295·8 | 22·8 | |
| 1950 | 2150 | 15 | 71 | 287·0 | 296·0 | 23·0 | 27·5 |
| 1950 | 2250 | 15 | 72 | 286·8 | 295·8 | 22·8 | |
| *2) Nov· 10, 1978* | | | | | | | |
| 1850 | 2700 | 14 | 60 | 286·0 | 295·5 | 22·5 | |
| 1850 | 2400 | 15 | 57 | 286·5 | 296·0 | 23·0 | 27·0 |
| 1850 | 2500 | 15 | 58 | 286·5 | 296·0 | 23·0 | |
| *3) Nov. 23, 1978* | | | | | | | |
| 1950 | 2950 | 4 | 92 | 289·3 | 298·1 | 25·1 | |
| 1950 | 3050 | 3 | 93 | 289.3 | 298·1 | 25·1 | 28·0 |
| 1950 | 3150 | 5 | 90 | 289·0 | 297·8 | 24·8 | |

Note: 1) SST corrected for water vapour attenuation and look angles.
2) Nov. 6 and Nov. 11 results not included in this table.

From the histograms one can ascertain the accuracies in the retrieval of raw SST's· We consider our estimates of raw SST to be about 1–2°C accurate in clear sea areas (except for November 23) based on the histograms·

Column 6 of Table II indicates the corrected SST's incorporating atmospheric attenuation effects· Fig· 3 presents the SST contour on November 6 around the cyclone area derived by the present method·

Fig· 4· presents a computer printout of SST map on Nov· 11 depicting spatial variation in temperature at 20 × 20 km$^2$ resolution· The high level clouds in the cyclone and adjoining areas are assigned a single character and the land sea areas assigned different characters each corresponding to specific value of temperature· Each

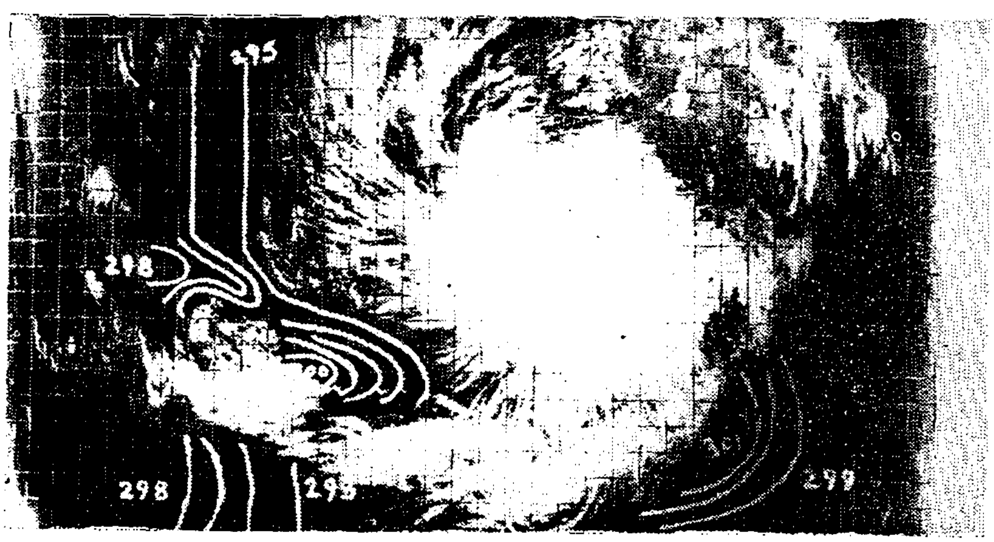


*Fig. 3.* SST contours–Nov. 6, 1978.

character represents an area of about 400 km². The land-sea boundary and low level cloud systems over the sea are also delineated.

### COMPARISON WITH SHIP OBSERVATIONS AND SOURCES OF ERRORS

Fig. 5 shows the map of India wherein the available meagre ship observed SST are plotted alongwith the satellite-derived values for each date of observation. It can be seen from the figure that even the individual ship observations themselves are differing by as much as 2–3°C in a few cases. Another point to note is that the satellite derived values correspond to the sea surface whereas the ship observations correspond to the immersion temperature. The latter is known to be about 0.6°C higher than the former (Saunders, 1967).

In Table II column 8 the mean of the ship observed SST within about 500 km radius of the satellite derived values (where possible) are listed for comparison for

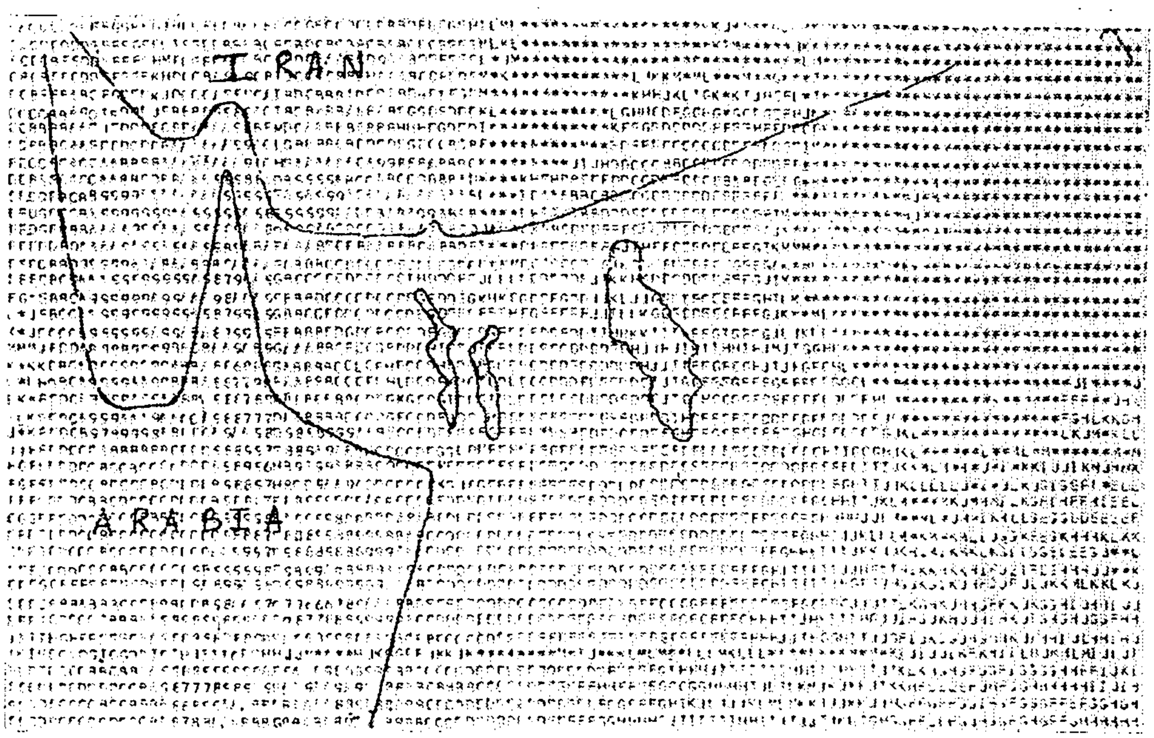


*Fig. 4.* Computer printout depicting raw SST spatial variation.

| *Character* | *Raw Temp (°K)* | *Feature* |
|---|---|---|
| 8 | 293·2 | ↑ |
| A | 291·2 | LAND |
| C | 289·3 | ↓↑ |
| E | 287·3 | SEA |
| G | 285·3 | ↑↓ |
| I | 283·2 | LOW CLOUDS |
| K | 281·1 | \| |
| M | 279·0 | ↓ ↑ |
| * | <277·8 | HIGH CLOUDS |
| | | ↓ |

all days except Nov. 6 as on this day, horizontal SST gradients of nearly 1°C per 100 km have been observed (Fig. 3) and at such close intervals ship data were not available.

Yet another point to note in these comparisons is that the ship data and the satellite-derived data are not colocated and also they belong to different times. Hence a point-to-point comparison between the two sources of observations are difficult, more so when horizontal gradients of temperature are significant.

It is noticed that the satellite-derived values in the present study are less by about 2-3°C from the nearest ship values in some cases. Part of this could be explained by the fact that the processing has been performed near cyclone areas where water vapour profile/content assumed from climatological data might be less than those actually prevailing. Even otherwise, since variability of water vapour in the atmosphere is comparable to its mean value, the climatological set of information is inadequate for applying the corrections. The water vapour information has to be derived from simultaneous and independent measurements, as is possible during the MONEX for a near 1°C SST accuracies.

Thus, the errors associated with estimates of satellite SST are strongly linked to cloud cover (in our present case they do not exist, unless very low level clouds had obscured our measurements) and the amount of water vapour in the atmosphere, indicating that present methods for correcting for these types of contamination are inadequate. The errors also depend on the number of observations that have

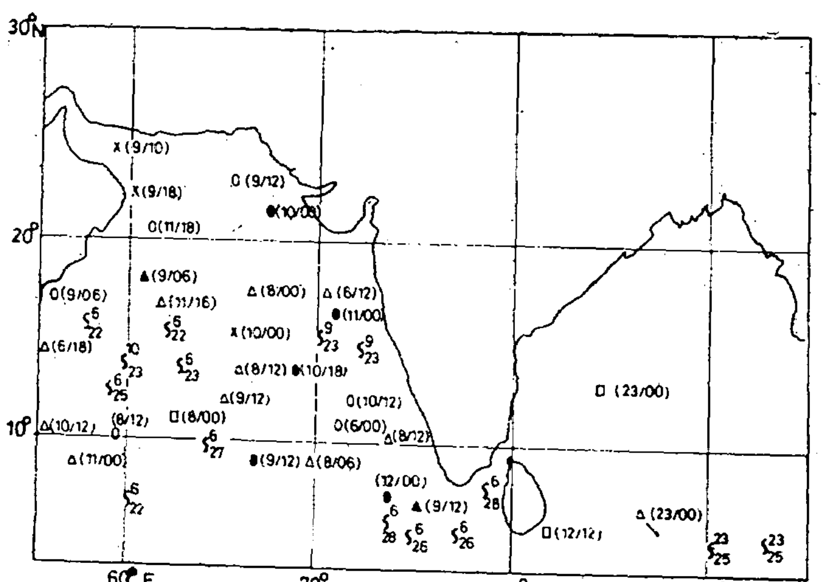


*Fig. 5.* SST from satellites and ships.

Ship symbols: × – 25°C, 0 – 26°C, ● – 27°C, △ – 28°C, ▲ – 29°C, □ – 30°C

Number in bracket denote date/time.

Satellite symbol: e.g. $\int_{27}^{6}$ — denotes retrieval on Nov. 6 and a value of 27°C.

gone into the satellite estimate of SST (Barnett, Patezert, Webb and Bean, 1979). Theoretical studies (Braun, 1971; Maul and Sidram, 1973) suggest that theoretical limits on satellite accuracy are ∾2–3°C. On observational side a recent study by Browner, Gohrband, Pichel, Signore and Walter (1976) shows global daily mean difference between satellite and ship reports of SST ranging from − 0.92 to +0.39°C.

Besides, in the present study, as in many other studies also, the sources of errors listed in Table III have not been taken into account.

## DISCUSSION AND CONCLUSIONS

Observations from aircraft of SST in Hurricane Ela (1978) on three successive days made with AXBT's and an airborne IR radiometer has shown that surface cooling ∾3–4°C occurs in 12 hr in a region beyond the radius of maximum winds on the right of the storm track. Cooling continued for more than a day after the storm forcing had ceased. It has been shown (Black, 1980) from these and other recent tropical cyclone observations that the magnitude of the surface cooling depends strongly upon the hydraulic Mach Number (the ratio of the storm speed to the first mode internal wave speed).

Considering the above new findings and the sources of error discussed earlier, the overall agreement between the NOAA–5 satellite-derived and ship observations are considered reasonable for individual measurements around cyclones when no averaging is done nor when actual atmospheres are known. Dalu, Prabhakara, Lo and Mack's (1979) recent study has shown that for arriving at a near 1°C accuracy, two channels in the 11 to 13 window region will be necessary, as will be incorporated in the later TIROS–N/NOAA satellites.

*Table III.* Sources of error not taken into account in this study.

| Source of error | Remarks |
|---|---|
| *Atmospheric* | |
| 1 Absorption by $CO_2$, $O_3$, and aerosols | Small; usually neglected. |
| 2 Absorption by ice crystals near tropopause | Not observable in visual VHRR. |
| 3 Scattering by dust particles and gases | Negligible at 11·5 micrometres. |
| 4 'Skin' *vs.* immersion temperature | Skin temperature reported to be about 0·6°C cooler than immersion temperature (Saunders, 1967). |
| 5 Nonunity surface emissivity | Reported values all exceed 0·98. |
| 6 Sea state | May affect emissivity. |
| *Sensor system* | |
| 7 Aging of radiometer | Could change responsivity. |
| 8 A/D quantization error | Small for 8 bit data (VHRR), |
| 9 System noise | Noise specs should be available from prelaunch data. |
| a) Radiometer noise | |
| b) Satellite electronics noise. | Space view value should represent a measure of system noise. |
| c) Ground system noise. | |
| 10 Calibration errors | Occasional disagreement between housing thermistors. |

The present method, however, offers the capability of delineating spatial SST variations over large areas on a day-to-day basis. From these results it is seen that the cyclone of Arabian Sea had moved from an environment of higher SST to one of lower SST, which could have also contributed to its weakening, besides it (cyclone) having been embedded in the dry westerlies on Nov. 10/Nov. 11 and thus decreasing in intensity.

With improved sensors in the TIROS-N satellite and with better, closely spaced ground truth and near-simultaneous water vapour estimates available during MONEX, our efforts are now to improve the accuracies of the satellite derived SST values.

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