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Temperature sounding of the atmosphere over the Indian region using satellite data

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सार—इनसैट मौसम विज्ञान आंकड़ा उपयोग केन्द्र (एम०डी०यू०सी०), नई दिल्ली में अमेरिका के ध्रुवीय कक्षा उपग्रहों से प्राप्त आंकड़ों के उपयोग द्वारा आंकड़ों को पुनः प्राप्त करने की परिज्ञप्ति की क्षमता का विकास किया गया है। तापमान परिज्ञप्ति के लिए विसकोन्सिन विश्वविद्यालय, अमेरिका द्वारा विकसित अंतर्राष्ट्रीय टी०ओ०वी०एस०संसाधन संवेष्टन (आइ०टी० पी० पी०) का उपयोग किया गया। एम०डी० यू० सी० में अग्रअंत्य संसाधन और पनः प्राप्ति एल्गोरिथ्म में 1000 एच०पी०ए० के विश्लेषण के आंकड़ों के निवेश के लिए एक साफ्टवेयर का विकास किया गया। भौतिक निकास पद्धति में समतापिक मंडल स्तर के एच० आइ० आर० एस० चैनलों के उपयोग द्वारा समाश्रयण आकलन उत्पन्न किए गए और एम० एस० यू० चैनलों का आरंभिक अनुमान के रूप में उपयोग किया गया। सतह के लिए दो विकल्पों, (1) जलवायुविक अनुमान, तथा (2) 1000 एच० पी० ए० विश्लेषणों का उपयोग किया गया।

इस शोध पत्र में 1989-91 की विभिन्न ऋतुओं में से 13 चुनी हुई तिथियों में भारतीय क्षेत्र में तापमान की पुनः प्राप्ति पर विचार किया गया है। उपग्रह पुनः प्राप्ति आंकड़ों के साथ व्यवस्थापित रेडियोसोंदे आंकड़ों की तुलना के परिणाम प्रस्तुत किए गए हैं। इन दोनों के बीच 700 से 150 एच०पी०ए० स्तरों तक अच्छी अनुरूपता है, जिसमें 3° सेल्सियस के अंदर आर० एम० एस० ई० त्रुटि है। जब क्षेत्रीय जलवायु को अनुमान के रूप में प्रयुक्त किया जाता है तो 850 एच०पी०ए० पर और सतह के समीप यह त्रुटि अधिक होती है। किंतु जब 1000 एच०पी० ए० विश्लेषण का उपयोग किया जाता है तो त्रुटि 3°-4° सेल्सियस के अंदर होती है।

ABSTRACT. Capability has been developed at the INSAT Meteorological Data Utilisation Centre (MDUC), New Delhi, for making sounding retrievals using data from the U.S. Polar Orbiting Satellites. The International TOVS Processing Package (ITPP) developed by the University of Wisconsin, USA, was used for making temperature soundings, software for front-end processing and input of 1000 hPa analysis data into the retrieval algorithm was developed at MDUC. In the physical retrieval method, regression estimates generated using stratospheric level HIRS channels and MSU channels were used as initial guess. For the surface, two options were used, (*i*) climatological guess, and (*ii*) 1000 hPa analysis.

The paper discusses temperature retrievals over the Indian region made on 13 selected dates from different seasons in 1989-91. Results of comparison of satellite retrievals with colocated radiosonde data are presented. There is good agreement between the two from 700 hPa to 150 hPa levels, with RMSE within 3° C. The error is higher at 850 hPa and near the surface, when climatology is used as surface guess, but is within 3°-4° C when the 1000 hPa analysis is used.

Key words — Bias, TOVS, Transmittance tuning, Physical retrieval, Gamma adjustment.

1. Introduction

Knowledge of temperature and humidity distribution in the vertical is essential for obtaining a complete three-dimensional picture of the atmosphere. The information is useful in aviation meteorology, for field initialisation in Numerical Weather Prediction (NWP) and in studies of earth-atmosphere radiation budget and global change. Soundings of the atmosphere by balloon-borne radiosonde instruments have increased our knowledge of the vertical structure of the atmosphere. These soundings are available on a limited scale over land areas and are practically absent over vast oceanic areas. The radiosonde data has inherent errors due to solar radiation in day-time and infrared cooling during night. Time lag in temperature and humidity sensors and errors in pressure measurement add to the problem (McMillin *et al.* 1988). Moreover, weather services, the world over, use different types of instruments and computation procedures, making the data inter-comparison further difficult.

On the other hand, earth satellites can provide repetetive globally consistent sounding capability on land and oceanic areas alike. Satellite soundings are available over a finer grid (approx. 80 × 80 km) but differ from the radiosonde in the scale in which they sample in the horizontal and vertical. While the radiosonde samples the local environment, the satellite profiles are averages of horizontal and relatively deeper layers of the atmosphere (Hayden *et al.* 1979). Absolute accuracy of satellite soundings is difficult to establish. Time-space colocation of the radiosonde with satellite profiles and the inherent errors in radiosonde data make the inter-comparison of these two systems of observations difficult. Refined retrieval procedures with improved instrumentation on board the future satellites will certainly help in making the satellite soundings more acceptable to the users.

The work described in this paper is based upon the use of the International TOVS Processing Package (ITPP) of the University of Wisconsin, Madison, USA.

TABLE 1

Retrieval data used

S. No.	Date	Time (UTC)	Satellite	No. of retrieval
1	28 Aug 1989	0835	NOAA-11	340
2	28 Aug 1989	1344	NOAA-10	360
3	5 May 1990	0832	NOAA-11	371
4	6 May 1990	0821	NOAA-11	280
5	7 May 1990	0810	NOAA-11	290
6	4 Nov 1990	0830	NOAA-11	315
7	2 Dec 1990	0830	NOAA-11	345
8	23 Jan 1991	0856	NOAA-11	378
9	12 Apr 1991	0903	NOAA-11	322
10	4 Jun 1991	0912	NOAA-11	316
11	26 Jul 1991	0920	NOAA-11	358
12	30 Jul 1991	0120	NOAA-10	338
13	14 Aug 1991	0238	NOAA-10	335

The package was installed on S-1000 computer available at National Informatics Centre, New Delhi in 1987. A few test retrievals were made using statistical retrieval scheme. Updated version of the Wisconsin package (ITPP 3.3) was installed on VAX-8810 computer available at the National Centre for Medium Range Weather Forecasting (NCMRWF), New Delhi in 1989. However, the front-end processing software for data ingest was developed by the first author at the INSAT Meteorological Data Utilisation Centre, New Delhi. The code for surface data input for 1000 hPa temperature, geopotential and relative humidity was also added to the package from Wisconsin. Starting from March 1990, retrievals were made with frequency of about twice a week. Early results of the study are presented here. Figure 1 shows the data flow and the basic steps involved in the processing.

2. Satellite-based sounding technique

2.1. *Theory*

The narrow-band radiance measurements made by a satellite depend on: (a) surface skin temperature, (b) vertical temperature profile, and (c) vertical concentration profile of absorbing constituents like CO_2, water vapour and ozone. Satellite measured radiance in a spectral channel centred at wave number υ (nu) is given by the Radiative Transfer Equation (RTE) :

$$R(\upsilon) = \epsilon_s B\ (T_s, \upsilon, \theta)\ \tau_s\ (\upsilon, p_s) + $$

$$+ \int_{p_s}^{0} B(T_p, \upsilon, \theta)\ \frac{\partial \tau\ (\upsilon, p)}{\partial p}\ dp + Q$$

where,

ϵ_s — Surface emissivity,

Q — Reflection of downward atmospheric radiation, including reflected solar radiation,

B — Plank's function,

T_s — Surface skin temperature,

θ — View angle of the area from satellite,

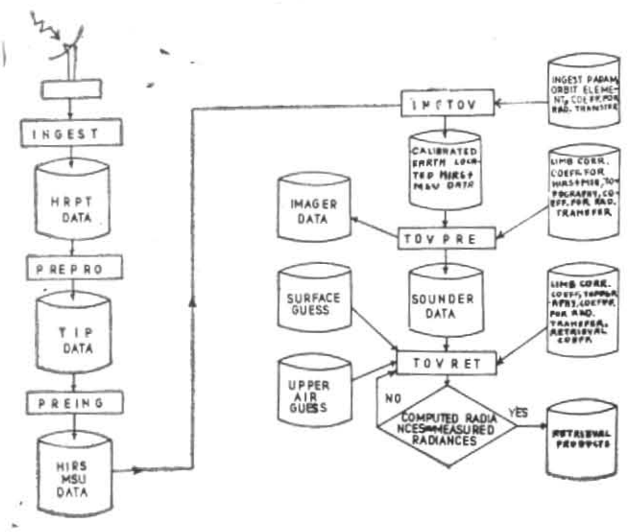

Fig. 1. Data flow and processing steps for physical retrieval

τ — Transmittance for channel from given level to top of atmosphere,

p_s — Surface pressure,

p — Pressure at given level,

T_p — Temperature at level p.

The first term on the right hand side of RTE is the surface contribution, while the second term is the integrated effect of the atmospheric layers. The third term is negligible in comparison with the first two for wavelengths longer than 5μm. The functions multiplying B in the integral term of RTE indicate the layer which contribute the maximum to the sensed radiance for a given channel. However, for each channel a considerable depth of the atmosphere contributes to the outgoing radiance (Hayden *et al.* 1979). Satellite based sounding of the atmosphere is thus an inverse problem which is further complicated by the fact that transmittances are not accurately known as a function of profiles of absorbing gases and temperature distribution in the vertical. It is not, therefore, possible to infer both the temperature profile and concentration profile from same set of measured radiances. In order to obtain accurate temperature sounding, it is necessary to conduct simultaneous measurements in water vapour and ozone absorption bands. Further, since there is large temperature dependence of thermal radiation at short wavelength, it is desirable to conduct at least a portion of measurements in the short wave spectral region from 3.5μm to 5μm (Smith *et al.* 1979).

Absorption bands of CO_2 centred near 15μm (longwave IR) and 4.3 μm (short wave IR), of O_2 near 5 mm (micro-wave) provide temperature sounding capability from surface to stratosphere. Absorption bands of water vapour centred near 6.7μ m and of ozone near 9.7μm enable estimation of moisture profile from surface to 300 hPa and total ozone respectively.

2.2. *Sounding data from satellites*

Currently, only U.S. Geostationary Satellite 'GOES' with VISSR Atmospheric Sounder (VAS) and polar orbiting satellites of TIROS series with TOVS give sounding capability. GOES does not cover the Indian

TABLE 2

Instrument characteristics

Parameters/ Instrument	No. of channels	No. of steps	Scan time for line (sec)	Res. at SSP (km)	Cross track scan (deg)	Scan direction
AVHRR	4 or 5	2048	1/6	1.1	±55	Anti sun to sun
HIRS	20	56	6.4	17.4	±49.5	Sun to anti sun
MSU	4	11	25.6	109.3	±47.35	-Do-
SSU	3	8	32	147.3	±40	-Do-

Ocean area. A number of user countries use TOVS data for deriving atmospheric soundings. A pair of two operational satellites (currently NOAA-10 and NOAA-11) orbiting the globe in sun-synchronous inclined polar orbit give global sounding capability every six hours. The data transmission from these satellites is in two modes: (*i*) Direct-Sounder Broadcast (DSB) transmitting 8-bit deep TIROS Information Processor (TIP) data, and (*ii*) HRPT data stream, where TIP data is multiplexed with Advanced Very High Resolution Radiometer (AVHRR) imagery data. Sounding retrievals are made using TIP data which includes besides other information, data from: (*i*) 20-channel High Resolution Infrared Radiometer Sounder (HIRS/II), (*ii*) 4-channel Microwave Sounding Unit (MSU), and (*iii*) 3-channel Stratospheric Sounding Unit (SSU) (Smith *et al.* 1979). The resolution, number of spots, scan direction and line time of HIRS, MSU, SSU are given in Table 2.

In the US, only HIRS and MSU data are currently being used for making soundings. Data are calibrated and earth located and MSU data, being of coarser resolution are mapped on to high resolution HIRS data by distance-weight interpolation technique (Kelley *et al.* 1983).

2.3. *Retrieval schemes*

Currently three schemes are in vogue for making sounding retrievals:

(*i*) Statistical retrieval scheme,

(*ii*) One-step physical retrieval scheme,

(*iii*) Physico-statistical retrieval scheme.

The University of Wisconsin has developed a software package (Smith *et al.* 1985) which gives an option for statistical retrieval or one-step physical retrieval. Chedin and his team in Cedex, France developed a package for physico-statistical retrieval (Chedin *et al.* 1984).

2.3.1. *Statistical retrieval scheme*

The scheme has been explained by Smith and Woolf (1976), Smith *et al.* (1979), and McMillin (1978) and Le Marshall and Schreiner (1985). This is the simplest technique requiring minimum of computing power as it does not attempt to solve the RTE. A large dependable radiosonde data-set and radiance measurements colocated in space and time are regresssed and set of regression coefficients is generated. These coefficients with measured radiances subsequently help in estimating sounding information. The coefficients are to be periodically updated, say once every week, to account for any gradual changes in channel characteristics or air-mass composition.

The scheme, however, has the following limitations :

(a) Radiance data has to be limb corrected. Since at different times, the same area may be viewed at different angles, the emitted radiances have to pass through varying depths of the atmosphere, while radiosonde data over the area is from a near vertical column. The correction is accomplished by using limb correction coefficients which introduce errors (Le Marshall and Schreiner 1985).

(b) Emissivity of land departs from unity by an unknown amount, which may be appreciable for microwave window channel. This depends on soil moisture contents (Smith *et al.* 1985). This limitation is common to all methods.

(c) Surface elevation is not considered in the solution and this introduces errors in retrievals over highly variable terrain (Smith *et al.* 1985, Le Marshall *et al.* 1989).

(d) Retrievals from cloudy scene can be made after computing clear column radiances from contaminated field, using the so called N^* technique (McMillin 1978, Aoki 1982) which has its own limitation.

2.3.2. *One-step physical retrieval scheme*

The scheme attempts to solve the RTE in perturbation form. It gives in a single step, the temperature, moisture and surface skin temperature (Smith *et al.* 1985). RTE in perturbation form can be written as :

$$\delta T^* = \epsilon_s \, \delta T_s f_s \tau_s - \int_{p_s}^{0} \delta U \left[\frac{\delta T}{\delta p} \cdot \frac{\partial \tau}{\delta U} f \right] dp + \int_{p_s}^{0} \delta T \left[\frac{\partial \tau}{\partial p} - \frac{\partial \tau}{\partial T} \right] f dp$$

$$\text{where, } f = \frac{\partial B}{\partial T} \Big/ \frac{\partial B}{\partial T^*}$$

T, U, p, B represent temperature, precipitable water, pressure and Planck's function respectively, τ is transmittance, T^* is the brightness temperature which is computed from the satellite-measured radiance by inversion of Planck's law assuming emissivity as 1, s denotes the surface.

The method attempts to solve simultaneously for temperature, moisture profiles and surface skin temperature using all radiance information available. This

TABLE 3

Retrieval pairs in the vicinity of radiosonde stations

Pressure level (hPa)	Delhi (14 Aug' 91) NOAA-10				Jodhpur (4 Jun' 91) NOAA-11			
	28.3°N, 76.9°E	28.0°N, 76.7°E	Avg.	RS	25.9°N, 73.2°E	26.6°N, 73.4°E	Avg.	RS
1000	34.1	33.9	34.0	—	33.3	34.1	33.7	—
850	23.9	23.6	23.7	23.4	28.7	30.1	29.4	27.4
700	11.8	11.4	11.6	12.2	16.1	15.7	15.9	17.4
500	-0.5	-0.9	-0.7	-0.5	-1.2	-2.4	-1.8	-4.7
400	-9.0	-9.3	-9.1	-12.5	-11.5	-12.2	-11.9	-8.9
300	-21.7	-21.7	-21.7	-29.1	-25.3	-25.0	-25.1	-24.3
250	-32.5	-32.5	-32.5	-37.5	-36.1	-35.3	-35.7	-32.7
200	-46.4	-46.3	-47.3	-50.3	-49.5	-48.5	-49.0	-41.7
150	-63.6	-63.6	-63.6	-65.1	-67.9	-67.1	-67.5	-53.7
100	-78.6	-78.7	-78.7	-77.1	-85.0	-85.1	-85.0	-65.9
70	-71.2	-71.4	-71.3	-65.1	-74.1	-74.2	-74.1	-67.3
50	-60.1	-60.2	-60.1	-54.5	-59.4	-59.2	-59.3	-52.1

TABLE 3 (*Contd.*)

Pressure level (hPa)	Nagpur (4 Jun' 91) NOAA-11				Bombay (4 Jun' 91) NOAA-11				Bombay (26 Jul' 91) NOAA-11			
	21.2°N, 79.0°E	20.9°N, 79.7°E	Avg.	RS	19.4°N, 72.3°E	18.6°N, 73.2°E	Avg.	RS	18.7°N, 72.5°E	19.2°N, 73.2°E	Avg.	RS
1000	21.9	24.3	23.1	—	26.8	25.5	26.1	—	26.6	24.1	25.3	—
850	19.3	20.1	19.7	29.8	19.8	22.5	21.2	24.2	15.2	18.1	16.7	18.2
700	15.0	15.6	15.3	15.4	13.6	14.2	13.9	15.2	7.4	9.2	8.3	11.4
500	1.6	0.5	1.1	-2.7	-1.1	-1.7	-1.4	-5.5	-5.6	-4.5	-5.1	-3.5
400	-10.1	-10.7	-10.4	-13.1	-10.9	-11.9	-11.4	-14.5	-15.1	-13.5	-14.3	-12.3
300	-24.9	-25.5	-25.2	-27.5	-25.0	-26.2	-25.6	-28.1	-28.2	-26.6	-27.4	-26.9
250	-36.2	-36.5	-36.3	-37.9	-35.8	-36.8	-36.3	-38.3	-37.7	-36.6	-37.1	-26.9
200	-49.4	-49.6	-49.5	-49.5	-49.1	-49.7	-49.4	-50.5	-49.5	-49.3	-49.4	-48.7
150	-68.3	-67.2	-67.7	-63.7	-66.8	-67.2,	-67.0	-64.9	-63.4	-64.3	-63.9	-64.1
100	-86.6	-86.6	-86.6	—	-85.5	-85.7	-85.6	-83.3	-76.0	-79.0	-77.5	—
70	-76.3	-77.3	-76.8	—	-77.3	-77.3	-77.3	-80.3	-70.4	-72.4	-71.2	—
50	-60.9	-62.1	-61.5	—	-62.3	-62.0	-62.1	-68.3	-60.6	-60.0	-60.3	—

alleviates the problem of dependence of measured radiances upon the three parameters. The inherent advantage of this technique is that it includes explicit treatment of surface temperature, emissivity (for IR 0.95 for land and 0.98 for sea, for MSU it is computed using MSU channel 1 data), surface elevation and non-nadir radiances (Fleming and McMillin 1977, Le Marshall and Schreiner 1985, Le Marshall *et al.* 1989). In reality as there are many possible profiles consistent with the measured radiances (Eyre 1990), the initial guess has to be made judiciously. A guess condition could be numerical forecast, climatology or a regression estimate obtained by using stratospheric level HIRS channels and MSU channels as they are not much affected by clouds.

If satellite soundings are to have a visible impact in NWP models, transmittances have to be known accurately. Tuning of transmittance will account for airmass, view angle and cloudiness variation. Transmittances are computed using time-space colocated radionsonde data and radiances (Fleming and McMillin 1977, McMillin and Fleming 1976, McMillin *et al.* 1979).

In the operational technique, model transmittances are used for an initial guess and transmittances are subsequently adjusted (Goldberg and Fleming 1991, Smith *et al.* 1974) for an improved guess, since they depend on temperature profile as well as concentration profile, till the computed radiances from improved guess coverage to measured radiances.

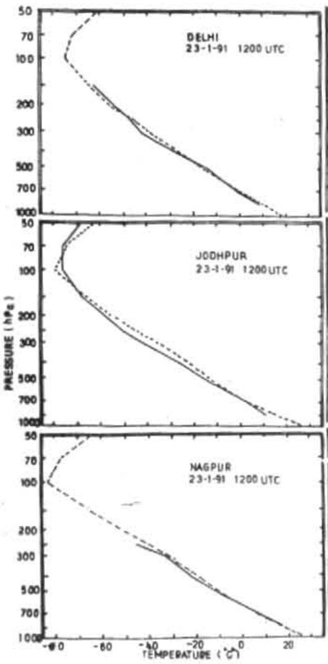

Fig. 2. Comparison of radiosonde (solid line) and satellite retrievals (dashed line) for winter season

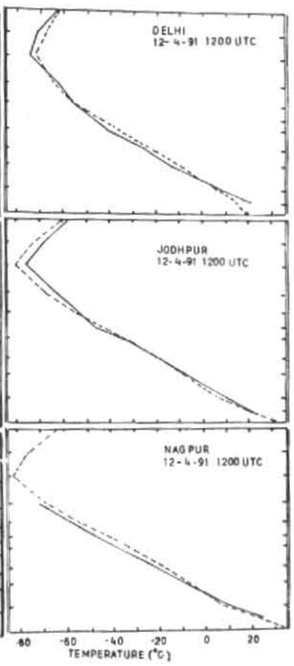

Fig. 3. Same as Fig. 2 for summer season

Any physical inverse solution to RTE requires accurate forward computation of outgoing radiance. To this end, it is desirable to identify various sources of error in the forward problem, such as :

(a) Poorly colocated radiosonde and radiance data,

(b) Non-availability of radiosonde data (RAOB) above 20 hPa,

(c) Insufficient stratification of radiosonde data requiring extrapolation up to 0.1 hPa.

2.3.3. *Physico-statistical retrieval scheme*

This scheme uses the inversion technique to make retrievals, but the initial guess is made through statistical approach. The algorithm was developed by Chedin *et al.* (1984) and is based on the following considerations :

(a) Better parameterisation of physical processes in the radiance computation.

(b) Transmittances are computed using line by line approach for large number of cases of RAOB once for all and stored. It provides an efficient way to account for suitable transmittance for a given guess condition. Any finer variation, however, can be adjusted using bias approach.

(c) Optimisation of initial guess for faster convergence to iterative solution.

The scheme which is also known as Improved Initialisation Inversion (3I) method, is based upon creating once and for all, the synthetic TOVS Initial Guess Retrieval (TIGR) data set comprising a large number of atmospheric conditions covering tropics and higher latitudes. Also archived parallely are :

(a) Computed values of transmittances for all channels for 40 layers (surface to 0.05 hPa) using fast line by line computation code.

(b) Computed values of radiances and associated brightness temperatures.

(c) Two Jacobian matrices representing partial derivatives of brightness temperature with respect to temperature and moisture.

(d) Means of radiance, temperature and covariance matrices.

These computations are made for various values of zenith angle, emissivity and surface pressure. Latitude plays an important role in the general or mean aspect of atmospheric temperature profile. TIGR data set is, therefore, organised in subsets according to latitude (tropics, mid-latitudes and pole), sec θ (for 10 different view angles θ), pressure (p_s= 1023 hPa to p_s= 725 hPa in steps) and emissivity of surface.

The algorithm proceeds in two steps. In the first step, initial guess is obtained by comparing observed radiance with those archived in TIGR data set, choosing the closest one which minimises the objective function (Chedin *et al.* 1984)

$$d^2_{i_1,\, i_2} = \frac{1}{n}\sum \left[T_{i_1}(k) - T_{i_2}(k)\right]^2 \Big/ S_k$$

where,

$d_{i_1,\, i_2}$—denotes the distance between two situations i_1 and i_2

n—the number of channels selected,

T—the brightness temperature of channel k for the situation,

S_k—the variance of $T(k)$ over sample of m situations

This ensures a more realistic initial guess from the observed radiance data. In the second step the archived transmittances and Jacobians associated with the guess are used to converge to a solution consistent with initial guess.

3. Temperature retrievals over Indian region

MDUC New Delhi has a facility for reception of High Resolution Picture Transmission (HRPT) data. Pre-processing of HRPT data is done on PDP 11/70 computer system. This data is then copied on 1600 BPI magnetic tape. The retrievals are made using VAX-8810 computer in NCMRWF, New Delhi. While capability exists for making retrievals using statistical or one step physical retrieval scheme, retrievals are made using physical retrieval option because of its advantages over statistical approach, such as use of appropriate surface emissivity values, capability of adjustment of transmittances (Le Marshall *et al.* 1989, Goldberg and Fleming 1991, and Smith *et al.* 1974) and removal of biases. Gamma adjustment to transmittances and biases supplied with Wisconsin package have been used. These have to be generated for Indian region to account for local condition and degradation of sensors. The retrievals were made for mainly NOAA-11 afternoon (92 passes) with fewer cases of NOAA-10 morning,

TABLE 4

Comparison of radiosonde observation with colocated retrievals from NOAA-10 and NOAA-11

Pressure level (hPa)	Nagpur (28 Aug'89) (12 UTC)			Lucknow (28 Aug'89) (12UTC)			Guwahati (28 Aug'89) (12 UTC)		
	NOAA-11 (09 UTC)	RS (12 UTC)	NOAA-10 (14 UTC)	NOAA-11 (09 UTC)	RS (12 UTC)	NOAA-10 (14 UTC)	NOAA-11 (09 UTC)	RS (12 UTC)	NOAA-10 (14 UTC)
1000	—	—	—	—	—	—	—	—	—
850	21.7	20.6	19.5	17.4	20.2	17.2	22.7	22.0	24.7
700	12.0	9.6	10.0	10.2	13.6	10.5	11.9	13.0	14.7
500	—3.0	—1.5	—3.8	—2.6	—3.3	—2.4	—2.2	0.6	—0.5
400	—13.8	—9.1	—13.6	—12.0	—13.5	—11.6	—11.7	—9.3	—10.9
300	—28.7	—24.9	—27.8	—25.7	—24.5	—24.6	—25.1	—24.1	—25.6
250	—39.4	—35.1	—38.3	—36.2	—31.7	—35.1	—35.7	—33.7	—36.1
200	—51.7	—48.5	—51.0	—49.0	—41.5	—47.5	—48.5	—45.9	—48.4
150	—65.8	—65.1	—66.1	—64.3	—55.7	—64.5	—65.2	—60.9	—62.2
100	—77.7	—	—79.4	—78.1	—	—78.8	—80.4	—	—75.2
70	—	—	—	—	—	—	—	—	—
50	—	—	—	—	—	—	—	—	—

evening (16 passes) of ten minutes duration. The passes covered Indian region, Bay of Bengal and part of Arabian Sea. Satellite soundings were made for 300 (±50) boxes of size about 80 km square for a single satellite pass. In the absence of surface or 1000 hPa data as initial guess, climatological data interpolated to latitude was used as provided in Wisconsin package. For first guess upper air data, regression estimates obtained from 3 stratospheric level HIRS channels and 3 MSU channels were used. However, the regression coefficients used for the purpose were the ones provided in the package. Whenever NWP generated analysis was available, 1000 hPa geopotentials, temperatures and relative humidity values were used as initial surface guess. Choice of guess for upper air data was restricted to regression estimates only rather than analysis because of requirement of guess up to 0.1 hPa while analysis was available only up to 50 hPa.

3.1. *Early results of work*

Any validation of satellite soundings against RAOB has inherent problems due to limited knowledge of transmittances, surface emissivity assumed, satellite sensor degradation and resolution of the two systems. When channel radiances are computed from RAOB, they show a systematic bias with colocated satellite measured radiances (Le Marshall *et al.* 1989). While model transmittances can be computed from large dependable match-up set of RAOB and colocated satellite measured radiances finer tuning on season-to-season basis can be done using Gamma (γ) adjustment (Goldberg and Fleming 1991, Smith *et al.* 1974). Such seasonal match-up will also help in computing channel biases. Appropriate values of Gamma (γ) and biases can then be used to improve the satellite retrievals. However, for the Indian region, determination of biases and Gamma computation become difficult because of lack of sufficient RAOB information from stratosphere.

Satellite retrievals made from thirteen passes spread over different seasons (Table 1) have been discussed in the present attempt and they fairly represent the quality of satellite soundings in general. The comparison of satellite retrievals with colocated RAOB (± 3 hour, ±0.5° Lat./Long.) are shown as pressure-temperature plot in Figs. 2-5. RAOB are plotted as solid line while satellite retrievals are shown as dashed line. In case more than one retrieval are available close to a RAOB, average is taken as a representative of satellite sounding. It was difficult to find RAOB colocated with satellite retrievals for single pass a day. Delhi, Jodhpur, Nagpur, Lucknow, Guwahati were chosen to represent inland stations, while Bombay and Calcutta were selected to represent maritime stations. These

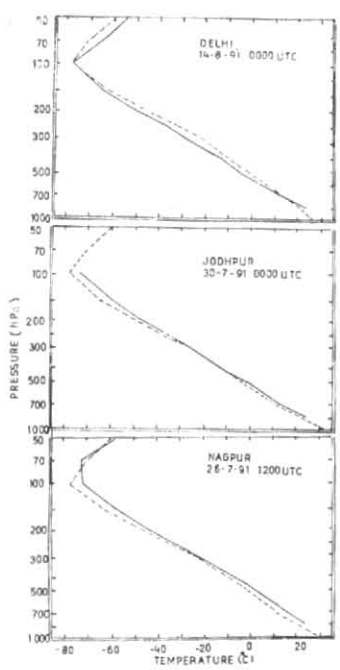

Fig. 4. Same as Fig. 2 for monsoon season

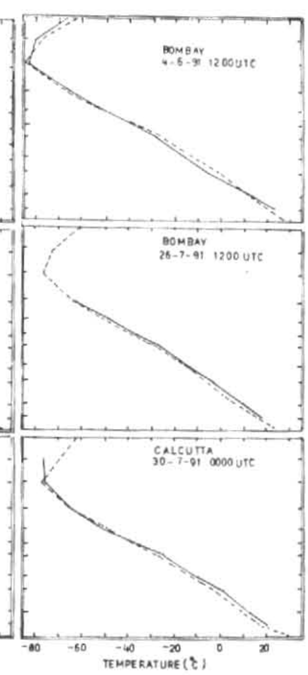

Fig. 5. Same as Fig. 2 for monsoon season

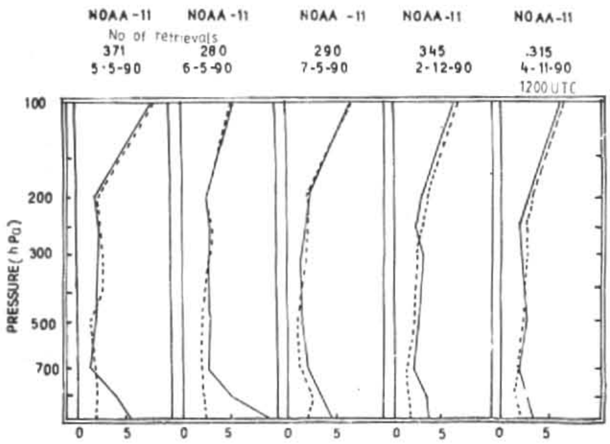

Fig. 6. RMSE (°C) in satellite retrievals with climatology as surface guess (solid line) and analysis as surface guess (solid line) and analysis as surface guess (dashed line)

seven stations have Weather Bureau type Radio Theodolite (WBRT) equipment and provide data of confidence.

Fig. 6 shows levelwise Root Mean Square Error (RMSE) for satellite retreivals, taking upper air analysis (1000 hPa—50 hPa) for that day as standard, solid line shows RMS when climatological data was used as surface guess. Dashed line shows RMSE when 1000 hPa geopotentials, temperature and humidity values from previous days' analysis were used as first guess. Table 3 shows the inter-comparison of two nearby satellite retrievals within 0.5 degree of RAOB. As a test case, a few retrievals were made using NOAA-11 afternoon pass and NOAA-10 evening pass on the same day. The inter-comparison of retrievals from two satellites with RAOB for 1200 UTC is shown in Table 4.

3.2. *Discussion*

3.2.1. *Comparison of pressure-temperature plots*

3.2.1.1. *Winter season*

Fig. 2 shows pressure-temperature plots for Delhi, Jodhpur and Nagpur on 23 January 1991. Satellite soundings are generally warmer, being appreciably so for Jodhpur between 500 hPa and 300 hPa and near surface.

3.2.1.2. *Summer season*

Fig. 3 shows pressure-temperature plots for Delhi, Jodhpur and Nagpur on 12 April 1991. Satellite soundings are close to RAOB for Jodhpur up to 200 hPa, at higher level satellite soundings are colder by 3° to 5°C. In case of Delhi and Nagpur, satellite temperatures are generally warmer by 2° to 4° C between 400 hPa and 250 hPa. In case of Delhi, satellite temperatures are appreciably colder near surface and warmer above tropopause.

3.2.1.3. *Monsoon season*

Fig. 4 shows pressure-temperature plots for Delhi (8 August 1991), Jodhpur (30 July 1991) and Nagpur (26 July 1991). Satellite temperature for Delhi are 3° to 5°C colder near surface and above tropopause and generally warmer at other levels. Those for Jodhpur and Nagpur are generally colder from surface to 100 hPa.

Fig. 5 shows pressure-temperature plots for Bombay (4 June 1991 and 26 July 1991) and Calcutta (30 July 1991). Satellite soundings, in general, are close to to RAOBs. In case of Bombay (4 June 1991) these are warmer in the middle troposphere and colder up to middle troposphere in other two cases.

Comparison shows satellite retrievals generally warmer than RAOBs during winter and summer, being relatively drier seasons and colder during monsoon season. Relatively larger variation between satellite soundings and RAOBs can be due to: (a) inaccuracies in RAOBs, (b) bias between the two systems of measurement, and (c) dependence of transmittances on profiles of temperature and moisture. In the present study, RAOB data has been taken for stations having WBRT equipment providing data of confidence.

Although the results indicate a tendency of the satellite retrievals to be colder/warmer than the RAOBs depending upon season, much more data will have to be used to work out a bias correction for applying to the retrievals.

Model transmittances and Gamma (γ) adjustment factors provided in the Wisconsin package have been used. These have to be tuned for Indian region.

3.2.2. *Comparison of retrieval errors*

Fig. 6 shows the levelwise RMSE in the satellite retrieval for the afternoons on 5 to 7 May, 2 December and 4 November 1990. The RMSEs were computed using analysis of the current day as the standard. Solid line shows RMSE when surface guess was climatological data, while dashed line shows RMSE when previous day's analysis was used as surface guess. RMSE were computed for all the retrieved profiles levelwise, comparing the retrievals within $\pm 0.5°$ of analysis data available at 1° Lat./Long. grid.

The plot for climatology as surface guess (solid line) shows RMSE to be 4° to 8°C at 1000 hPa for the month of May, reducing to 3°C during November-December. RMSE, however, remained within 3° C up to 200 hPa and thereafter increased to 7°C for all cases. When the 1000 hPa analysis was used as surface guess, there was improvement in all the cases in lower levels but no significant change above 200 hPa.

3.2.3. *Inter-comparison of retrievals from neighbouring areas*

Table 3 shows comparison of two retrievals within 0.5° Lat./Long. of radiosonde station for Delhi (14 August 1991), Jodhpur, Nagpur, Bombay (4 June 1991) and Bombay (26 July 1991). It is seen that the neighbouring pairs of satellite retrievals are consistent amongst themselves from 850 hPa to 50 hPa. When compared to colocated radiosonde data, the differences are within 3° to 5°, except in isolated cases.

3.2.4. *Inter-comparison of radiosonde data with retrievals from NOAA-10 and NOAA-11*

As a test case, retrievals were made from NOAA-10 (nominally at 1400 UTC) and NOAA-11 (nominally at 0900UTC) for 28 August 1989. The colocated retrievals (±3 hours from radiosonde observation of 1200 UTC and ±0.5° Lat. / Long.) and radiosonde data for the day are shown in Table 4. In spite of the 5-hour difference in satellite passes, the retrievals from the two satellites agree well. This shows that retrievals are independent of the satellite. Compared with radiosonde data, for Lucknow and Guwahati, the values at lower levels agree generally within 3.

4. Concluding remarks

Early results of the work indicate that :

(a) There is good agreement of satellite retrievals with radiosonde data between 700 hPa and 150 hPa.

(b) The difference is large above 150 hPa where satellite retrievals are generally colder than radiosonde data by about 6° to 8°C.

(c) The agreement from surface to 850 hPa is poor specially in case of summer afternoon retrievals.

It is proposed to use 1000 hPa analysis of geopotentials, temperature and humidity as initial surface guess when the same is operationally available. The use of this data is seen to have a positive impact on the retrievals.

Transmittances depend on profiles of moisture and ozone and on temperature profile weakly though. Excessive hot lower levels in summer afternoons and season-to-season moisture variation may be the cause of larger variation in satellite soundings and RAOBs. Model transmittances provided in the package were computed using a mean profile of temperature and moisture. In case a more realistic first guess temperature, moisture profile is used, the transmittances can be dynamically tuned taking into account difference in guess temperature-moisture profile and mean profile and using dry/wet transmittance approach (Goldberg and Fleming 1991). One or two iterations generally will permit convergence of the improved guess profiles of temperature, moisture to actual profiles. Satellite measured channel radiances can be tuned by removal of biases (measured *vs* computed). These tuned radiances when used in the inversion of radiative transfer equation will yield more realistic satellite soundings.

In this study, the first guess temperature profile was taken from the regression estimates using 3 stratospheric level HIRS channels, and 4 MSU channels and synthetic coefficients provided in the Wisconsin package. The periodically updated coefficients for Indian region can give better regression guess. It is, therefore, proposed to periodically update these coefficients. As an alternative approach, one may use upper air analysis extrapolated for 40 layers from surface to 0.1 hPa as first guess to improve the retrieval at all the levels.

With the proposed improvements, the technique can provide better retrievals at 80 km square grid over land and oceanic areas alike. When the proposed HRPT reception and processing capability comes up at Madras, NWP modellers will have a significant volume of sounding information over a fine grid covering large oceanic areas which are currently devoid of it (barring standard GTS soundings).

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