CALCULATION OF UPDATED COEFFICIENTS FOR ATMOSPHERIC TEMPERATURE RETRIEVAL

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ABSTRACT

In order to calculate updated coefficients for atmospheric temperature retrieval from satellite sounding data and radiosonde data, it is necessary to form statistical samples of real radiance and radiosonde data match-ups. A procedure is presented here for the data matchups. And a method of eigenvectors of statistical covariance matrices is used to produce updated coefficients for atmospheric temperature retrieval. The updated coefficients produced are tested using radiance observations from NOAA-7 satellite. Comparisons of these real-time retrieved data with radiosonde data show that the atmospheric temperature profiles retrieved have an accuracy of RMS 2—3 degrees (°C). In addition, the error sources are also discussed.

I. INTRODUCTION

At present, the statistical regression method (Smith et al.[1], 1970) is still a main method to process the meteorological satellite operational vertical sounder data. The advantages of this method are: 1) it requires only relative calibration of satellite sounding instruments; 2) it is not necessary to calculate atmospheric transmittances, so that much more computer time can be saved. However, the accuracy of retrievals for the statistical regression method depends on the accuracy of regression coefficients to a great extent. In order to obtain accurate atmospheric temperature retrieval profiles, which can satisfy operational requirements, it is necessary to use recent radiosonde data and satellite sounding data[1)] (usually 14 days' data) to update retrieval coefficients once a week. This is the so-called updating of coefficients for atmospheric temperature retrieval. In this paper, a technique is presented to match radiosonde temperature data with TIROS Operational Vertical Sounder (TOVS) brightness temperature data, which are used for generating updated coefficients. Also, an algorithm is developed for the calculation of updated coefficients. Finally, the accuracy of temperature retrieval obtained using updated coefficients is discussed. Some test results are shown at the end of this paper.

II. BACKGROUND

For a nonscattering atmosphere in local thermodynamic equilibrium, the radiative transfer

1) The radiosonde data refer to the data of 15 mandatory levels (i.e., 10, 20, 30, 50, 70, 100, 150, 200, 250, 300, 400, 500, 700, 850, 1000 hPa) and several other significant levels. The satellite sounding data refer to retrieved temperature profiles which consist of 40 pressure levels (0.1, 0.2, 0.5, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 7.0, 10, 15, 20, 25, 30, 50, 60, 70, 85, 100, 115, 135, 150, 200, 250, 300, 350, 400, 430, 475, 500, 570, 620, 670, 700, 780, 850, 920, 950 and 1000 hPa) and clear radiances (or brightness temperatures) for TOVS channels (see Table 1) which are obtained by combining the information from a box of 3×3 individual High-Resolution Infrared Sounder (HIRS/2) fields of view (Smith et al.[2] 1979).

equation may be expressed as

$$I(\nu,\theta)=B[\nu,T(p_s)]\tau(\nu,\theta,p_s)-\int_0^{p_s}B[\nu,T(p)]\left(\frac{\partial\tau(\nu,\theta,p)}{\partial p}\right)dp, \qquad (1)$$

where $I(\nu, \theta)$ is the spectral radiance at a particular wavenumber ν for a zenith angle of observation θ, $B[\nu, T(p)]$ is the Planck function at wavenumber ν and temperature T, and $\tau(\nu, \theta, p)$ is the transmittance of the atmosphere from the pressure level p to the top of the atmosphere along the observation direction. The subscript s refers to surface values, either ground or cloud top. Eq. (1) is the Fredholm's linear integral equation of the first kind. Since the atmospheric temperature profiles being calculated are discrete random variables, the problem of solving integral equation (1) (usually called the retrieval problem) can be written in matrix notation, i. e.

$$\mathbf{t}_B=\mathbf{H}\mathbf{t}, \qquad (2)$$

where $\mathbf{t}_B$ denotes a vector of TOVS-observed brightness temperature, $\mathbf{t}$ denotes a vector of atmospheric temperatures, capital letter **H** denotes a matrix of TOVS weighting functions. If **H** is a square matrix, the direct solution of Eq. (2) for the temperature profiles is

$$\mathbf{t}=\mathbf{H}^{-1}\mathbf{t}_B. \qquad (3)$$

Usually, this solution is unstable (Twomey[3], 1977) due to the influence of unknown observation errors, because **H** is nearly singular owing to strong overlapping of the weighting functions.

Table 1. Characteristics of TOVS Channels

HIRS Channel Number	Channel Central Wavenumber	Central Wavelength (μm)	Principal Absorbing Constituents	Level of Peak Energy Contribution (hPa)
1	668	15.00	CO_2	30
2	679	14.70	CO_2	60
3	691	14.50	CO_2	100
4	704	14.20	CO_2	400
5	716	14.00	CO_2	600
6	732	13.70	CO_2/H_2O	800
7	748	13.40	CO_2/H_2O	900
8	898	11.10	Window	Surface
9	1028	9.70	O_3	25
10	1217	8.30	H_2O	900
11	1364	7.30	H_2O	700
12	1484	6.70	H_2O	500
13	2190	4.57	N_2O	1000
14	2213	4.52	N_2O	950
15	2240	4.46	CO_2/N_2O	700
16	2276	4.40	CO_2/N_2O	400
17	2361	4.24	CO_2	5
18	2512	4.00	Window	Surface
19	2671	3.70	Window	Surface
20	14367	0.70	Window	Cloud

MSU Channel Number	Frequency (GHz)	Principal Absorbing Constituents	Level of Peak Energy Contribution (hPa)
1	50.31	Window	Surface
2	53.73	O_2	700
3	54.96	O_2	300
4	57.95	O_2	90

Extending Eq. (3) to cover the entire statistical samples yields

$$\mathbf{T}=\mathbf{A}\mathbf{T}_B, \tag{4}$$

where **A** is defined as a coefficient matrix that gives a statistical optimum solution for atmospheric temperature profiles in a statistical sense of simultaneously observed radiances and temperature profiles.

In Eq. (4)

$$\mathbf{T}=(t_{ik}), \quad \begin{pmatrix} i=1,2,\cdots,N \\ k=1,2,\cdots,K \end{pmatrix} \tag{5}$$

is a $N\times K$ matrix of atmospheric temperature departures from the mean temperature of sample set; K is the total number of temperature profiles in the statistical samples; and N is the number of quadrature pressure levels at which atmospheric temperature is retrieved. The elements of matrix **T** are

$$t_{ik}=t'_{ik}-\frac{\sum_{k=1}^{K} t'_{ik}}{K}.$$

Similarly

$$\mathbf{T}_B=(b_{jk}), \quad \begin{pmatrix} j=1,2,\cdots,M \\ k=1,2,\cdots,K \end{pmatrix} \tag{6}$$

is a $M\times K$ matrix of simultaneously observed brightness temperature departures from their respective mean values of sample sets, where M is a number of TOVS channels being selected, and K is the total number of TOVS observed brightness temperature sets in the statistical samples. The elements of matrix $\mathbf{T}_B$ are

$$b_{jk}=b'_{jk}-\left(\sum_{k=1}^{K} b'_{jk}\right)\Big/K.$$

And matrix **A** is a $N\times M$ coefficient matrix, i. e.,

$$\mathbf{A}=(a_{ij}), \quad \begin{pmatrix} i=1,2,\cdots,N \\ j=1,2,\cdots,M \end{pmatrix}.$$

If **A** and $\mathbf{T}_B$ are known, using Eq. (4), the optimum solution **T** can be obtained. Therefore the key point is to generate the coefficient matrix **A** by use of the statistical samples determined by real brightness temperature and radiosonde data matchups.

III. DETERMINATION OF STATISTICAL SAMPLES

When temperature retrieval coefficients are to be calculated, good statistical samples should be chosen. Because the quality of the statistical samples will directly affect the accuracy of the temperature retrievals. However, determination of good and representative statistical samples is a complex procedure. This procedure consists of three parts, that is, satellite sounding data and radiosonde data matching, statistical sample filtering, and statistical sample sorting.

1. *Satellite Sounding Data and Radiosonde Data Matching*

For a given time and location (altitude/longitude) of the satellite sounding data, the procedure of searching for the correspondent radiosonde data and putting them together is called matching. Usually, the coverage of satellite data is uniform, and the observations can be obtained about 14 times a day. But the distribution of radiosonde stations is non-uniform, the stations being much more over the land than over the oceans, over middle-latitude regions than over high- and low-latitude regions. Moreover, the radiosonde observation data can be obtained only twice a day (00 and 12 GMT) at each station. Thus for the given satellite sounding data at particular time and location, it is difficult to find the radiosonde data at identical time and spatical location. For this reason the matched time and space windows are determined based on the density of distribution of radiosonde stations, space resolution of satellite sounding data (about 80 km) and observation times. Table 2 shows the space and time windows for each sub-latitude zone. In Table 2, the region (70°—0°N) is determined by the receiving area at the Beijing Meteorological Satellite Ground Station. From Table 2, it can be seen that space window 1°×1° is used for subzones 1 to 6. But in subzone 7, there are fewer radiosonde stations, so that 1.5°×1.5° space window is used.

Table 2. The Matched Space and Time Windows for Satellite Sounding Data and Radiosonde Data

No.	Subzone (°N)	Space Widow	Time Window* (hr)
1	70—60	1°×1°	±6
2	60—50	1°×1°	±6
3	50—40	1°×1°	±6
4	40—30	1°×1°	±6
5	30—20	1°×1°	±6
6	20—10	1°×1°	±6
7	10—0	1.5°×1.5°	±6

*In fact, interpolation is made between 00 and 12 GMT.

Suppose that radiosonde data are available at 00 and 12 GMT. Given a time and location of the satellite sounding data, the procedure will automatically search for the correspondent radiosonde data according to matched space and time windows shown in Table 2. The searching procedure is as follows:

(1) *Matched time window test*

If satellite observation time is in a matched time window or, in other words, if it satisfies the relationship

$$t_{r1} \leqslant t_s \leqslant t_{r2},$$

where t_{r1} denotes the preceding radiosonde observation time (i. e., 00 GMT), t_{r2} the succeeding one (i. e., 12 GMT), and t_s the time of satellite observation. In this case, the satellite sounding data and the radiosonde data are called time-matched. Otherwise, they are not matched.

(2) *Matched space window test*

Given a location of satellite sounding data (i. e., latitude/longitude), the subzone where it is located can be determined. After that, a procedure can automatically search for a radiosonde data station which is the closest to the satellite sounding data point in distance based on the satellite sounding data location and matched space window of the particular subzone. Since the earth is an ellipsoid, the effect of the earth's curvature should be considered in calculating distances between the satellite sounding data point and the radiosonde station. Fig. 1 shows the geometrical relation between a satellite sounding point and a radiosonde station. In Fig. 1, S (a, b) denotes a satellite sounding point, where a and b are latitude and longitude respectively, and R (c, d) for those of radiosonde. If W represents a matched space window for a particular subzone where satellite sounding point is located, then the matchup conditions between S and R are

$$|a-c|\leqslant W$$

and

$$g=\{[(b-d)\cos a]^2+(a-c)^2\}^{1/2}\leqslant W,$$

where g is the distance between S and R.

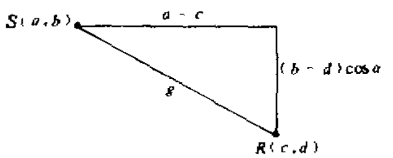

Fig. 1. The geometrical relation between a satellite sounding point and a radiosonde station.

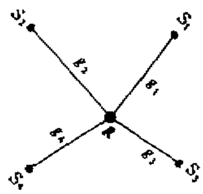

Fig. 2. Satellite sounding points matched with a radiosonde station.

Finally, the satellite sounding data and the preceding and succeeding radiosonde data that have passed both tests (1) and (2) are put into one record and saved as a matched sample.

2. *Statistical Sample Filtering*

In section 1, matched samples are searched and collected, but the quality of the matched samples is still uncertain. Therefore, in order to save good samples and reject bad ones, it is necessary to pass several other tests.

(1) *Radiosonde data quality test*

Generally speaking, radiosonde data quality is rather good, but it is almost impossible that there is no error among them due to communication error or other unexpected reasons. Thus, it is not easy to get good data at any time. For this reason, it is very important to do the quality tests for the radiosonde data. At present, many radiosonde stations can obtain data up to about 70 hPa; only a few stations can sound up to about 10 hPa. Therefore, we only check the data at each level below 100 hPa.

(a) *Check temperatures of* 10 *lower mandatory levels* (*i. e.*, 1000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 hPa)

If there are two adjacent levels at which sounding data are missed below 100 hPa for a matched sample, then the matched sample is rejected in order to ensure the continuity among pressure levels. If only one level data are missed among several pressure levels, then the data of that level are interpolated by the data of the two adjacent levels. The interpolation formula is

$$T_j = T_{j+1} + r\ln(P_j/P_{j+1}), \quad j=2,3,\cdots,9,$$

where $r=(T_{j-1}-T_{j+1})/\ln(P_{j-1}/P_{j+1})$ is called slope. T_j is the atmospheric temperature at jth level, P_j the pressure at jth level. If the number of levels with data is less than 6 for a matched sample, then the matched sample is rejected.

(b) *Compare radiosonde data with satellite sounding data*

There is no way to directly compare satellite sounding data with radiosonde data, because both data have different observation time and sounding levels. In order to make them compatible, the interpolation algorithm is used to yield new radiosonde data at the satellite observation time. The following formula

$$T = T_1(1-f) + fT_2$$

is applied, where $f=(t_s-t_{r1})/(t_{r2}-t_{r1})$ is called time interpolation factor; T_1 is the preceding radiosonde data, T_2 the succeeding radiosonde data, t_s the satellite observation time, t_{r1} and t_{r2} the preceding and succeeding radiosonde observation time respectively (here $t_{r2}-t_{r1}=12$ hr), and T the calculated radiosonde data at t_s. Then an interpolation formula similar to that in section (a) is used to interpolate radiosonde data into the satellite sounding levels. The radiosonde data should include the 15 mandatory levels and the significant levels. Upon completing the above two steps, the radiosonde data can be compared with satellite sounding data level by level.

(i) Compare near-surface temperatures

Suppose that T_S is the near-surface temperature of a satellite sounding, and T_R is the near-surface temperature of radiosonde data for a matched sample, if

$$T_S - T_R < -5\ \mathrm{K},$$

then the matched sample is rejected.

(ii) Compare temperature at each level below 100 hPa

Suppose that T_{sj} is the satellite sounding temperature at the jth level and T_{rj} is the radiosonde temperature at the same level for a matched sample, if

$$|T_{sj} - T_{rj}| > 10\ \mathrm{K},$$

then the matched sample is rejected.

(2) *Delete duplicate matched samples*

If there are more than one satellite sounding matched with the radiosonde data of a given station at the same time (see Fig. 2), these matched data are called duplicate samples. In Fig. 2, it can be seen that the radiosonde station R is matched with four satellite sounding points simultaneously. In this case, it is necessary to calculate distances g_i (i=1,2,3,4) for each pair of matched samples. Then the one with the shortest distance is saved, and the others are rejected. However, the duplicate samples for zone 1 (70°—50°N) (see Table 3) are not deleted because there are only a few samples in that zone.

TABLE 3. Latitude Zones and a Number of Daily Standard Samples Used to Generate Updated Coefficients for the Temperature Retrieval

No.	Zones (°N)*	No. of Daily Standard Samples
1	70—50	35
2	60—30	35
3	30—0	35

*The boundaries of each zone are determined according to the standard of the National Earth Satellite Service, U. S. A. (i. e., 90°—60°N, 60°—30°N, 30°N—30°S, 30°—60°S, 60°—90°S). Because there are a few samples in the zone of 70°—60° N, we choose 70°—50°N as zone 1.

(3) *Determine the number of samples in each zone*

After passing the quality tests and deleting the duplicate samples, it is necessary to check how many samples are available in each zone. If the number of samples in a zone is less than or equal to the number of standard samples (see Table 3), then all the samples are saved for the zone. Otherwise, we only save clear sounding[2] samples. In the latter case, if the number of the clear sounding samples is still greater than the standard, we arbitrarily select samples from the clear sounding samples for the zone. If the number of the clear sounding samples for that zone is less than the standard, then all the clear sounding samples for that zone are saved. In addition, we have to select some additional samples from the partly cloudy sounding[2] samples at random to complement that zone.

3. *Statistical Sample Sorting*

The statistical regression method for temperature retrieval is based on a large amount of statistical dependent samples. Therefore, the temperature retrieval coefficients are generated by using dependent samples. If the statistical samples in each zone have a random distribution, the samples can be separated into two parts: one is correlated, and the other is not. The correlated samples are used to generate retrieval coefficients. The non-correlated samples are used to test the accuracies of the retrieval coefficients.

2) There are three types of satellite soundings (McMillin et al.[4] 1982). (1) The clear soundings: There are no clouds in satellite observation fields of view (i. e., clear area), HIRS/2 and MSU measured radiances are used to retrieve soundings. (2) The partly cloudy soundings: Clouds cover a part of the fields of view. The technique for producing estimated clear radiances is used. The estimated clear radiances then are used to retrieve soundings. (3) The cloudy soundings: Clouds cover the whole field of view. In this case, it may not be possible to obtain clear HIRS/2 radiances. The MSU radiances which are only slightly affected by nonprecipitating clouds are used to retrieve soundings.

IV. CALCULATING COEFFICIENT MATRIX

1. *Optimal Expansion of Empirical Orthogonal Functions*

Usually, an empirical orthogonal function expansion technique is applied to the calculation of coefficient matrix. The advantage of this technique is that it is less sensitive to the assumed satellite random measurement noise level than the least-square technique (Smith et al.[5] 1976). When retrieving temperatures, it is impossible to avoid the effect of the varying degree and type of actual cloudiness. For example, if the satellite observing field of view is partly covered by clouds, we have to estimate clear radiances using the technique by McMillin et al.[4] (1982), so that a relatively large random error will exist in any set of cloud-free radiances. However, the effects of random errors on the accuracy of retrieved temperatures are greatly suppressed by using expansion of empirical orthogonal functions. Since empirical orthogonal functions are obtained by calculating eigenvectors of covariance matrices[5], that is also called the method of eigenvectors of covariance matrices.

Suppose the atmospheric temperature profile is given by

$$\mathbf{t}^{(k)}=(t_{1k},t_{2k},\cdots,t_{Nk}{}^{*}),$$

where t_{ik} are atmospheric temperature departures from its mean value, the asterisk (*) indicating matrix transposition, then, for the K sets of statistical samples, we have

$$\mathbf{T}=(t_{ik}), \tag{7}$$

where the subscripts i and k have the same meaning as in Eq. (5). The covariance matrix of matrix (7) is defined as

$$\Psi(\mathbf{T})=\begin{pmatrix} \overline{t_1t_1} & \overline{t_1t_2} & \cdots & \overline{t_1t_N} \\ \overline{t_2t_1} & \overline{t_2t_2} & \cdots & \overline{t_2t_N} \\ \cdots & & & \\ \overline{t_Nt_1} & \overline{t_Nt_2} & \cdots & \overline{t_Nt_N} \end{pmatrix},$$

where

$$\overline{t_it_j}=\frac{1}{K}\sum_{k=1}^{K}t_{ik}t_{jk}. \tag{8}$$

Since the covariance matrix Ψ(T) is a positive definite real symmetric matrix, its eigenvalues are positive and real.

Suppose that the eigenvalues of the covariance matrix Ψ(T) are λ_1, λ_2, $\cdots$, λ_N, and the eigenvectors are $\mathbf{u}^{(1)}$, $\mathbf{u}^{(2)}$, $\cdots$, $\mathbf{u}^{(N)}$, then any atmospheric temperature profile can be expanded in terms of this set of eigenvectors (empirical orthogonal functions), i. e.,

$$\mathbf{t}^{(k)}=\sum_{l=1}^{N}\mathbf{C}_l^{(k)}\mathbf{U}^{(l)},$$

where $c_l^{(k)}$ is expansion coefficients. It can be theoretically proven that this expansion is "optimal" (Zeng[6], 1974) in the sense of distance space.

Further, arrange the eigenvalues in the order from large to small, i. e., $\lambda_l \geqslant \lambda_{l+1}$, and define a relative variance

$$e_J=1-\sum_{l=1}^{J}\lambda_l\Big/\sum_{l=1}^{N}\lambda_l,$$

where $J\leqslant N$. For a given threshold value of the relative variance, say $e=0.001$, the J

eigenvectors can be determined, which make the following inequality hold

$$\varepsilon_J \leqslant \varepsilon.$$

In practice, J is always less than N ($J<N$). Therefore, the optimal representation of any atmospheric temperature profile by J eigenvectors is

$$\mathbf{t}^{(k)} \doteq \sum_{l=1}^{J} c_l^{(k)} \mathbf{U}^{(l)}.$$

2. *Calculation of Coefficient Matrix*

Suppose that we have two sets of statistical samples matched in time and space, they can be writtern in matrix forms

$$\tilde{\mathbf{T}} = (\tilde{t}_{ik}),$$
$$\tilde{\mathbf{T}}_B = (\tilde{b}_{ik}),$$

where i, j and k have the same meaning as in Eqs. (5) and (6). Based on Eq. (8), covariance matrices $\Psi(\tilde{\mathbf{T}})$ $(N\times N)$ and $\Psi(\tilde{\mathbf{T}}_B)$ $(M\times M)$ of $\tilde{\mathbf{T}}$ and $\tilde{\mathbf{T}}_B$ can be obtained.

Let U and V represent eigenvector matrices of covariance matrices $\Psi(\tilde{\mathbf{T}})$ and $\Psi(\tilde{\mathbf{T}}_B)$ respectively, Λ and Ω represent diagonal matrices consisting of the corresponding eigenvalues. Thus, we have

$$\Psi(\tilde{\mathbf{T}}) = \mathbf{U}\Lambda\mathbf{U}^*,$$
$$\Psi(\tilde{\mathbf{T}}_B) = \mathbf{V}\Omega\mathbf{V}^*,$$

where the asterisk (*) refers to matrix transposition.

Applying the mathematical derivation of Smith et al.[5] (1976), we obtain

$$\tilde{\mathbf{T}} = \mathbf{U}\Psi(\mathbf{CD})\Psi^{-1}(\mathbf{D})\mathbf{V}^*\tilde{\mathbf{T}}_B,$$

where **C** is the expansion coefficient matrix of temperature statistical samples $\tilde{\mathbf{T}}$ based on their empirical orthogonal functions, **D** that of the corresponding brightness temperature statistical samples $\tilde{\mathbf{T}}_B$, Ψ (**CD**) the covariance matrix of expansion coefficient matrices **C** and **D**. Let

$$\mathbf{A} = \mathbf{U}\Psi(\mathbf{CD})\Psi^{-1}(\mathbf{D})\mathbf{V}^*,$$

and use the vector notation, we have

$$\mathbf{t} = \mathbf{A}\mathbf{t}_B,$$

where matrix **A** is the coefficient matrix to be used for retrieving atmospheric temperature profiles from TOVS observed brightness temperatures.

V. RESULTS AND DISCUSSIONS

We select the brightness temperatures observed by HIRS/2 channels 1—16, MSU channels 2—4 (see Table 1) as predictors, and the temperatures of the lower 20 sounding levels (from 115 to 1000 hPa) as predictants. By means of the technique described in section III, NOAA-7 TOVS data and the corresponding radiosonde data[3] were processed for the period of 13—16 February, 1984. There are 164 correlated samples over the mid-latitude region (30°—60°N). Each one consists of radiosonde data and the brightness temperatures of HIRS/2 channels 1—16 and MSU channels 2—4 of TOVS. The coefficient matrix is calculated by using the

3) NOAA-7 data were received at Beijing Meteorologoical Satellite Ground Station. The radiosonde data came from National Meteorological Center. Before the matchups were conducted, we used the updated coefficients of NESS in February 1982 to process the TOVS data. Moreover, we only had 15 mandatory level radiosonde data at that time. There were no any surface data or significant level data available.

expansion of empirical orthogonal functions outlined in section IV, based on 164 correlated samples. And the procedure automatically determines the number of empirical orthogonal functions according to a given threshold value $\varepsilon=0.0001$. In our processing, 11 empirical orthogonal functions were selected for the observed brightness temperatures, 13 for the radiosonde temperatures. Thus, the new atmospheric temperature profiles were predicted by using the coefficient matrix and new NOAA-7 TOVS observed brightness temperatures.

Figs. 3—6 show comparisons of TOVS retrieval temperature profiles with radiosonde temperature profiles. As can be seen from these figures, good agreement is found for most pressure levels. Thus the satellite retrieval temperature profiles can approximately discribe the vertical changes of the atmospheric temperatures. Fig. 7 shows comparisons of RMS temperature errors on 18 (9 samples), 20 (14 samples) and 21 (11 samples) of February 1984. Table 4 gives relative mean bias, absolute mean bias and RMS of 34 statistical samples in 3 days.

The negative values of relative mean bias in Table 4 indicate that satellite soundings are colder than radiosondes, while the positive mean, satellite soundings wormer. From Table 4, it can be seen that the absolute mean bias and RMS are about 2—3 °C at most pressure levels, but at 850 hPa level, it is greater than 3°C. Moreover, there are some radiosonde stations whose surface pressure is less than 1000 hPa in our region, so that comparison of TOVS retrieval temperature profiles with radiosonde temperature profiles can not be conducted at this pressure level.

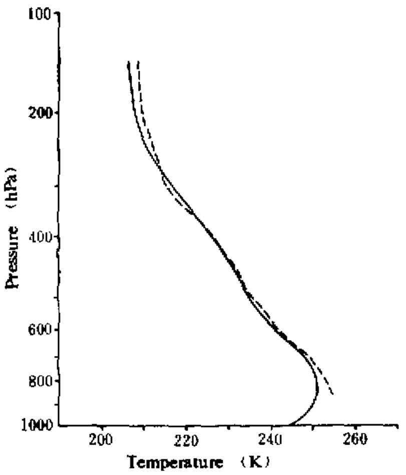

Fig. 3. Comparison of a satellite retrieval temperature profile (solid line) with a coincident radiosonde temperature profile (dashed line).
The observation time is 2240 GMT 18 February 1984 for satellite and 0000 GMT 19 February 1984 for radiosonde. And the location is 50.88°N, 94.44°E for satellite and 51.67°N, 94.39°E for radiosonde, station No. 36096.

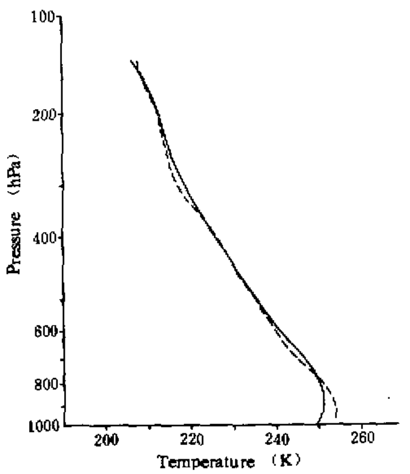

Fig. 4. As in Fig. 3, except for the different location.
51.13°N, 80.09°E is for satellite and 50.35°N, 80.25°E for radiosonde, station No. 36177.

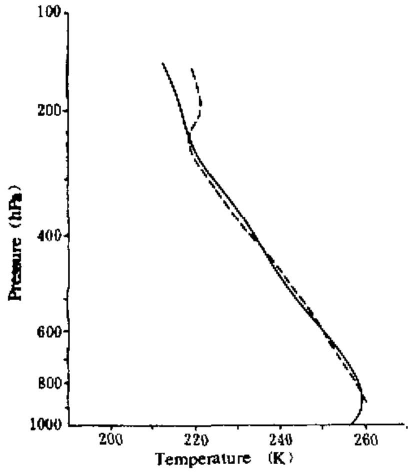

Fig. 5. As in Fig. 3, except for the different observation time and location. 2200 GMT 21 Feb. 1984 and 41.86°N, 100.51°E for satellite, and 0000 GMT 22 Feb. 1984 and 41.95°N, 101.07°E for radiosonde, station No. 52267.

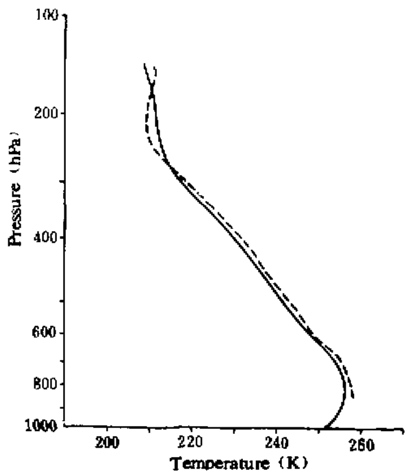

Fig. 6. As in Fig. 3, except for the different observation time and location. 2200 GMT 21 Feb. 1984 and 43.76°N, 81.31°E for satellite, and 0000 GMT 22 Feb. 1984 and 43.95°N, 81.34°E for radiosonde, station No. 51431.

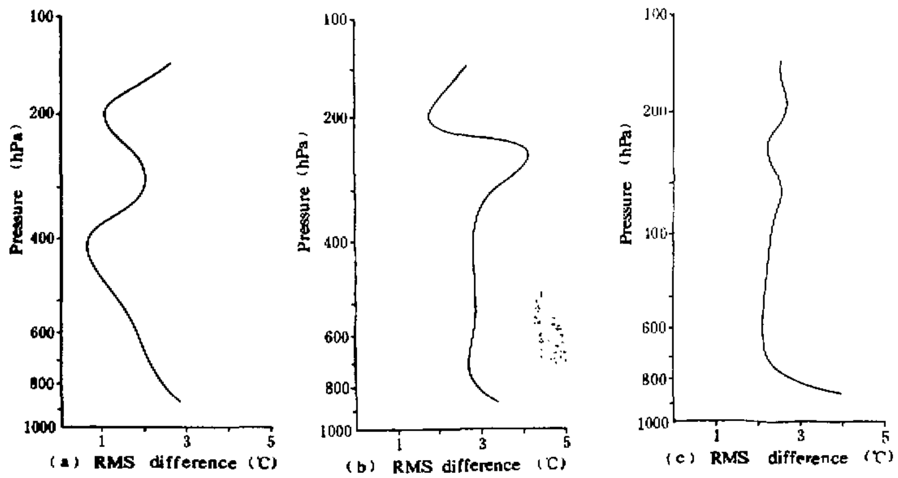

Fig. 7. The RMS difference between satellite retrieval temperatures and radiosonde temperatures.
(a) 2240 GMT 18 Feb. 1984 for satellite and 0000 GMT 19 Feb. 1984 for radiosonde, 9 matched samples;
(b) 2210 GMT 20 Feb. 1984 for satellite and 0000 GMT 21 Feb. 1984 for radiosonde, 14 matched samples;
(c) 2200 GMT 21 Feb. 1984 for satellite and 0000 GMT 22 Feb. 1984 for radiosonde, 11 matched samples.

Table 4. Comparisons of Satellite Retrieval Temperatures with Radiosonde Temperatures*

Pressure (hPa)	850	700	500	400	300	250	200	150
Relative Mean Bias	−2.1141	0.4427	−0.7298	−0.5459	1.9796	1.7895	−0.2347	−1.9171
Absolute Mean Bias (℃)	3.0559	1.9775	2.0166	1.8180	2.3167	2.6600	1.8257	2.2658
RMS (℃)	3.5429	2.4000	2.3718	2.3860	2.8010	3.1395	2.1640	2.7567

*Comparisons for 34 pairs of matchups in 3 days (i. e., 18, 20, 21 February 1984)

There are several factors causing the accuracies of TOVS retrieval temperature not to be as good as expected. The first, the accuracy of retrieval temperatures obtained by statistical regression method is mainly dependent on whether large amounts of matched good statistical samples can be selected for calculating updated coefficients matrix, and whether these statistical samples can outline features of variability of atmospheric temperatures very well. Because of the limitation of objective conditions, we have only used 164 statistical samples without the surface and significant level data to calculate updated coefficients. These statistical samples are not enough for extracting all the information for temperature retrieval. The second, many areas in China are hills and mountains, hence there are no radiosonde data at 1000 or 850 hPa (even 700 hPa) over these areas. This results in some difficulties in determining the statistical samples, and is also the main cause that a larger error of temperature retrieval occurs at 850 hPa. Finally, the observing time and space locations for radiosonde data and satellite sounding data are not coincident, which also produces errors in retrieved temperatures.

VI. SUMMARY

In summary, a procedure for satellite sounding and radiosonde data matchups has been presented. Based on the statistical samples matched in time and space, which have been selected by this procedure at mid-latitude zones, the updated coefficients of atmospheric temperature retrieval are calculated by using eigenvectors of statistical covariance matrices. Comparisons of retrieved temperature from satellite sounding data with radiosonde data show that the absolute mean bias and RMS are about 2—3°C at most pressure levels.

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