TOVS OPERATIONAL SYSTEM UPGRADING AND APPLICATION ASPECTS IN NSMC OF CHINA

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1. INTRODUCTION

Since 1983, the National Satellite Meteorological Center (NSMC) of China Meteorological Administration has been receiving and processing the NOAA/HRPT AVHRR data operationally. In 1986 the Statistical Retrieval Method (SRM) had been put into operation to process the TOVS data. For over a decade, this statistical-based operational system has been used to generate meteorological parameters in NSMC.

The Simultaneous Physical Retrieval Method (abbreviated hereinafter as SPRM) developed by Smith et al (1985), is essentially different from usual single parameter retrieval methods. It has many advantages and is a more potential method. However, adapting this algorithm into operational practice for processing TOVS data over the East-Asia continent including Qinghai-Xizang Plateau, much work has to be done.

Starting from 1991, activities aiming at improving and upgrading the TOVS retrieval system, including replacing the statistical retrieval algorithm by physical-based algorithm has been initiated (Dong, et al, 1995). After several years hard working, now the system upgrading has been realized. In addition, some activities concerning TOVS data applications in regional climate research have been carried out.

2. ERROR ANALYSIS AND NUMERICAL SIMULATION

2.1 Theoretical analysis

Improving the accuracy of the retrieved meteorological parameters is the key point of extending applications of satellite sounding data. It is generally realized that the retrieval errors mainly originated from two sources, i.e. measurement errors and errors from the data processing system. The measurement errors are from the weakness of the sounding instruments, such as the poor vertical resolution and the measurement noise. Improving the measurement accuracy is limited by current technology and beyond discussion of this paper. The errors from the data processing system originated from several factors, such as the ill-posed nature of the retrieval problem, the algorithm and the numerical quadrature error, etc. Reducing the errors from the data processing system are the key points for our system upgrading.

Following J. Eyre(1987), we performed the following error analysis. For linear inversion from satellite measurements, the basic equation can be expressed as the form

$$X_r - X_0 = W \cdot [y_m - y_c(x_0)] \tag{1}$$

where X_r is the vector of the retrieved atmospheric parameters,

X_0 is the first guess vector of the atmospheric parameters,

y_m is the vector of the radiance or brightness temperature measurements,

$y_c(x_0)$ is the corresponding vector calculated from the first guess, and

W is the inverse matrix.

The measurements y_m, according to the forward problem, can be expressed as

$$y_m = F_t(X_t, a_t) \tag{2}$$

where F_t represents the true forward model, X_t stands for the true vector of atmospheric parameters and a_t the true model parameters, including the spectrum parameters, etc. Accordingly, the calculated corresponding vector based on the first guess vector X_0 and model parameters a_c can be expressed as

$$y_c = F_c(X_o, a_o) \tag{3}$$

For detailed error analysis, we differentiate the equation (2) with respect to X_t and a_t, and consider the measurement noise ε_m, we can obtain

$$y_m = F(X_0, a_0) + \frac{\partial F}{\partial X}(X_t - X_0) + \frac{\partial F}{\partial a}(a_t - a_0) + \varepsilon_m \tag{4}$$

Substitute (2)--(4) into (1) we can obtain

$$X_r - X_0 = (Q - I) \cdot (X_t - X_0) + W \cdot [F(X_0, a_0) - F_c(X_0, a_0)] + Q_a \cdot (a_t - a_0) + W \cdot \varepsilon_m \tag{5}$$

where $Q = W \cdot \frac{\partial F}{\partial X}$, $Q_a = W \cdot \frac{\partial F}{\partial a}$, I is identity matrix.

From Equation(5) one can analysis the origination of the retrieval errors. The first term of the right-hand of Equation(5) reflects the mapping of the first guess departure from the true state of the atmosphere into the retrieval errors. The second term stands for the mapping of the forward model error into retrievals. This originates from the simplification of the radiative transfer equation, such as ignore the scattering term, liberalization, numerical quadrature error, etc. The third term represents the image of the errors of model parameters, such as the spectrum errors, etc. The term (2) and (3) can be catalogued together as forward calculation bias. The last term is the mapping of the measurement noise into the retrievals.

2.2 Numerical Simulations

Considering the above analysis we performed a series of simulations using the SPRM model. A typical middle latitude standard atmospheric profile is selected as the assumed true atmospheric profiles. Here we mainly give the following examples.

(a) First guess departure systematically from the true atmospheric state.

This is the case when weather system, such as cold front, invade retrieved region. We assume the temperature first guess profile is 3k systematic departure from the truth. Table 1a gives the simulation results, where 'Ret.' and 'True' stands for retrieval and true atmospheric profiles respectively. 'δ' represent the difference between them. From the table we can see that the first guess systematic departure from the true profile can cause non-systematic errors which are significant at some levels. This reveals the necessity for considering the air mass dependent for selecting the first guess.

Table 1a. Retrieval error simulation for T first guess 3K systemic departure from the true.

Pressure(hPa)	True-T (K)	Ret.-T (K)	δT (K)	True-W(g/kg)	Ret.-W	δW
10	230.5	230.3	-0.2	0.00	0.00	0.00
20	223.2	222.5	-0.6	0.00	0.00	0.00
30	218.5	217.6	-0.9	0.00	0.00	0.00
50	213.5	212.4	-1.1	0.00	0.00	0.00
70	209.8	208.8	-1.1	0.00	0.00	0.00
100	208.5	207.8	-0.7	0.00	0.00	0.00
150	212.7	212.9	0.2	0.01	0.01	0.00
200	219.0	219.6	0.6	0.01	0.03	0.02
250	227.2	228.0	0.9	0.04	0.06	0.02
300	235.3	236.4	1.0	0.10	0.10	0.00
400	248.5	249.7	1.2	0.34	0.26	-0.08
500	259.5	260.9	1.4	1.02	0.77	-0.25
700	276.2	277.7	1.5	3.59	3.54	-0.05
850	284.3	285.8	1.5	6.15	5.89	-0.26
1000	291.7	293.4	1.7	10.42	9.25	-1.17

(b) First guess departure from the truth mainly at the low troposphere.

This indicates the situation that the diurnal variation of temperature usually reaches the largest at the surface. If the climate first guess has been used, the largest departure from the truth usually appears at the surface when we process the data from the noon and mid-night orbit satellite, such as in the case of NOAA-14 local time. The departure will diminish with height, and to some levels the departure becomes small enough. We assume here in our simulation that the largest departure is 5k at the surface, linearly diminished with height and the departure disappeared at 700 hPa. Table 1b gives the simulation results. From the table one can see that the low level first guess departure can cause significant retrieval errors, not only at low TOVS levels, but in all the TOVS retrieval levels. Therefore, reducing the low level first guess departure is a key point to improve the retrievals.

(c)Mapping of the forward calculation biases into retrieval errors.

We have used the true biases data in the simulation for estimating the mapping of the forward calculation biases into retrieval errors. First we obtained the clear radiance from 3 passes of satellite data within our acquisition zone, and then matched clear radiance with the collocated radiosondes. All the so-called clear radiance is carefully cloud screened, and all the matched radiosondes are passed the quality check and interpolating into 40 TOVS retrieval levels. Using the forward model provided by the SPRM model and the radiosonde profiles as true atmospheric state, we got the forward calculation biases statistics. By introducing these biases into the SPRM model we can estimate the mapping of these biases into retrieval errors as indicated as table 1c. From this table we can see that the errors can not be ignored at most of the retrieval levels, and that means these biases have to be removed before retrieval.

Table 1b. Retrieval error simulation for T first guess 5K departure from the true at 1000 hPa.

Pressure(hPa)	True-T (K)	Ret.-T (K)	δT (K)	True-W(g/kg)	Ret.-W	δW
10	230.5	229.8	-0.7	0.00	0.00	0.00
20	223.2	222.3	-0.9	0.00	0.00	0.00
30	218.5	217.5	-1.0	0.00	0.00	0.00
50	213.5	212.4	-1.1	0.00	0.00	0.00
70	209.8	208.7	-1.2	0.00	0.00	0.00
100	208.5	207.4	-1.1	0.00	0.00	0.00
150	212.7	211.7	-0.9	0.01	0.01	0.00
200	219.0	218.1	-0.9	0.01	0.03	0.02
250	227.2	226.2	-1.0	0.04	0.06	0.02
300	235.3	234.3	-1.0	0.10	0.11	0.01
400	248.5	247.3	-1.2	0.34	0.38	0.04
500	259.5	258.3	-1.2	1.02	1.24	0.22
700	276.2	279.9	3.7	3.59	5.27	1.68
850	284.3	288.1	3.8	6.15	9.78	3.63
1000	291.7	295.6	4.0	10.42	16.92	6.50

Table 1c. Retrieval error simulation for calculated brightness temperature biases.

Pressure(hPa)	True-T (K)	Ret.-T (K)	δT (K)	True-W(g/kg)	Ret.-W	δW
10	230.5	230.6	0.1	0.00	0.00	0.00
20	223.2	222.9	-0.3	0.00	0.00	0.00
30	218.5	218.1	-0.4	0.00	0.00	0.00
50	213.5	213.2	-0.3	0.00	0.00	0.00
70	209.8	210.3	0.4	0.00	0.00	0.00
100	208.5	209.5	1.0	0.00	0.00	0.00
150	212.7	213.5	0.9	0.01	0.01	0.00
200	219.0	219.6	0.6	0.01	0.03	0.02
250	227.2	227.3	0.1	0.04	0.05	0.01
300	235.3	235.1	-0.2	0.10	0.07	-0.03
400	248.5	247.7	-0.8	0.34	0.16	-0.18
500	259.5	258.3	-1.2	1.02	0.56	-0.46
700	276.2	274.7	-1.5	3.59	3.69	0.10
850	284.3	282.9	-1.4	6.15	6.67	0.52
1000	291.7	290.4	-1.3	10.42	11.41	0.99

3. DESCRIPTION OF THE UPGRADED TOVS RETRIEVAL SYSTEM

3.1 Construction of the first guess field

Due to the ill-posedness of retrieval problem, constructing optimum first guess field is very important as a priori restriction for obtaining stabilized and regularized solutions. Currently there are mainly two kinds of methods for finding first guess solution. One is to use pattern recognition technique, that is, to set up a data base with matchups between radiosondes and satellite observations in space and time from a large number of data, for example, TIGR (TOVS Initial Guess Retrieval) data set used in 3I method (Improved Initialization Inversion) developed by Chedin et al (1985). By using the minimum variance principle according to satellite measurements and other auxiliary data in the TIGR data set to find the corresponding first guess solution. The second one is to directly use numerical prediction fields as first guess for retrieval. This kind of first guess will be certainly closer to real atmospheric condition than climate data if the numerical prediction is positive. As the regional nature of our retrieval system and the radiosonde stations are relatively denser within our acquisition area, we decide to use objective analysis fields of radiosonde data received by China Meteorological Administration as initial guess values in the upgrading system.

3.2 Removing the forward calculation biases

All physical retrieval should start from forward calculations. As the error simulation experiments pointed out in the previous section that the forward calculation biases will cause significant retrieval errors, removing the biases within the retrieval procedure is a necessary step in the data processing system. However, due to some important physical parameters, such as surface emissivity and transmittance, etc., these biases can not be removed accurately by transmittance tuning. We believe that more reasonable method will be to estimate the biases statistically from the forward calculated radiance with the associated satellite observed radiance, and remove these biases directly from the calculated values. For our system we perform this kind of bias removing on a regular basis.

3.3. Determination of Surface Parameters

The importance of reasonably determining surface parameters has been revealed in the previous simulations section because the large low level departure from the first guess will strongly influence retrieval accuracy. The extrapolation method has been used to get the surface temperature(T_s) and surface moisture (W_s) based on the first guess field as described in section 3.1. Another important surface parameter is surface atmospheric pressure, because the surface elevation and surface thermal state is introduced into remote sensing equation through surface pressure, as well as both the forward and inversion calculation are all related to accuracy of determined P_s. Using the polytropic atmosphere pressure--height formula, P_s can be presented as

$$P_s = P_0 EXP\left(-\frac{g}{R_d}\int_{Z_0}^{Z_s}\frac{dZ}{T_0-\gamma_T(Z-Z_0)}\right) \tag{6}$$

where 'Z_s' is the averaged elevation above sea level for retrieval box, Z_0 and T_0 indicate geographical height and atmospheric temperature at a certain standard pressure P_0, respectively. 'γ_T' is the lapse rate of temperature from Z_s to Z_0, g and R_d are gravity acceleration and dry air constant, respectively.

In climate first guess, P_0 is taken to be 1000 hPa, Z_0 and T_0 are taken to be geopotential height and climate average value of atmospheric temperature at 1000 hPa, respectively. 'γ_T' is taken to be 0.65K/100m. In this case, the computed surface pressure is much different from the real surface pressure and thus will cause errors in the computed brightness temperatures, and hence introduce retrieval errors, especially over the Qinghai-Xizang Plateau with the average surface pressure around 600 hPa. In ISPRM, determination of P_s is based on the initial guess analysis fields. First, we find the surface graphical elevation Z_s from the high resolution topography data set within the location of retrieval box. Then we can determine the retrieval pressure level P_0 (TOVS level) which is the nearest one to the elevation Z_s and to get the pressure level parameters (T_0, W_0, H_0) from the analysis field profile. The 'γ_T' value is determined by interpolation of the values of two adjacent pressure levels just above the surface. Our experiment studies show that the above method for determining surface parameters can obviously improve the low level retrieval accuracy.

3.5 System integration, testing and products distribution

The new system integration include developing the interface between retrieval package with the first guess fields; integrating the surface parameter determination subroutine into the main program, as well as estimating the bias from the true satellite data and removing these bias before performing retrievals, establishing routine sequence for the operational system, etc. Figure 1 shows the flow diagram of the system.

By realizing all above upgrading considerations we call the new system the Improved SPRM (ISPRM). The ISPRM has been put into pre-operational running in parallel with the Statistical Regression Method system since January 1995. After tuning to the new system, the system validation and comparisons has been carried out for the two retrieval systems during the two successive months from September 15 to November 15, 1995, with more than two thousands of collocated radiosondes. Table 2 gives the validation and comparison results.

From the table we can draw the following conclusions:

- The Root Mean Square Differences (RMSD) between temperature retrieval and collocated radiosondes averaged from 1000 hPa to 50 hPa are 2.12K and 1.92K for SRM and ISPRM respectively, which indicate that the new system really is really an improvement on the old one, especially at low levels.

- The moisture improvement (relative humidity) is mainly at the low levels, i.e., below 700 hPa. We believe that this improvement mainly attributes to the reasonable treatment of the surface parameters for new system.
- With the same radiosonde data set, the ISPRM has gotten more samples than the SRM system, which indicates that the ISPRM system can obtain more retrievals over cloudy region.
- With this big sum of collocated samples, this validation and comparison laid solid foundation for replacing the old system with the new one.

Table 2. Two successive months' validation and comparison results of ISPRM and SRM retrievals with collocated radiosondes (September 15 to November 15, 1995)

(T: in K, H: Geopential Height in Meters, R: Relative humidity in %, Ave for average)

		P(hPa)	1000	850	700	500	400	300	250	200	150	100	70	50	Ave.
	ISPRM	Sample	14462	23014	27145	29522	29242	28845	28341	27094	27694	25042	15778	15262	24283
T(p)		RMSD	1.87	1.97	1.85	1.80	1.80	1.82	1.84	1.81	1.82	2.20	2.10	2.12	1.92
(K)	SRM	Sample	13005	18433	24886	25858	25544	25086	24110	22854	23034	21189	12572	12758	20762
		RMSD	2.47	2.51	2.18	2.03	1.99	2.10	2.23	2.32	2.23	2.35	2.13	1.99	2.21
	ISPRM	Sample		10645	26599	28446	29928	29614	29600	28888	27990	26415	16813	15992	24573
H		RMSD		14	21	25	23	21	13	17	18	29	28	23	21
(M)	SRM	Sample		12694	25284	27090	27221	26620	26752	26142	25261	23331	12983	12959	22394
		RMSD		20	22	23	18	21	16	21	24	33	28	22	23
	ISPRM	Sample	10974	20719	24353	29173	28774	25800							23299
R		RMSD	8.1	12.5	16.6	26.4	27.9	35.1							21.1
(%)	SRM	Sample	9218	11489	16037	17884	17439	14899							14494
		RMSD	10.6	14.0	16.4	26.1	27.6	35.5							21.7

3.6. TOVS products distribution

From January 1, 1996, the TOVS products distributing system has been initiated, which mainly distribute the retrieved products over China provisional meteorological stations via Local Network connected to the China Meteorological Administration. At the moment the main products include: retrieved level temperature (15 standard levels), level moisture (6 layers from 1000 hPa to 300 hPa), and geopotential heights (15 standard levels), total ozone, stability index, as well as cloud parameters. Users who can get access to this network can get these products in near real time.

4. APPLICATION ASPECTS ON TOVS DATA

4.1 Outgoing Longwave Radiation (OLR) estimation from HIRS/2

As many authors indicated (Ellingson, et al 1989, 1994) that since the radiance data measured by HIRS/2 contains more information on atmospheric variables than the AVHRR, it is a potentially better instrument for operational estimates of OLR. The OLR is estimated from NOAA-10 and NOAA-11 HIRS/2I as the weighted sum of brightness temperatures converted from HIRS/2 radiance measurements, given as

$$OLR = a_0 + \sum_{i=1}^{n} a_i T_{Bi} \tag{7}$$

where the a's are regression coefficients, which can get from the retrieval package, and T_{bi} is the observed channel brightness temperatures.

Figure 2a depicts The monthly averaged regional OLR distribution of January 1991. For estimating the time sampling accuracy we also calculated the daytime, night and day-night differences of the OLR distribution as depicted in figure 2b, 2c and 2d. This example shows that adequate data sampling frequency is needed for accurate estimation of OLR distributions.

4.2 Cloud Radiative Forcing

The differences in fluxes between averaged conditions and cloud-free conditions, often called cloud radiative forcing, has been derived from the HIRS measurements over the same region as OLR. These data products (OLR, cloud radiative forcing, etc.) has been used for regional climate studies in China.

4.3 Drought monitoring experiment using microwave emissivity

Surface microwave radiation is governed by physical temperature and surface emissivity. MSU channel 1 surface emissivity ε_{v1} can be obtained from the radiative transfer equation as follow

$$\varepsilon_{v1} = \frac{T_{B1} - \int_{p_s}^{0} B(T)\frac{\partial\tau(p)}{\partial P}dp - \int_{p_s}^{0}[\frac{\tau(p_s)}{\tau(p)}]^2 T(p)\frac{\partial\tau(p)}{\partial p}dp}{T_s\tau(p_s) - \int_{p_s}^{0}[\frac{\tau(p_s)}{\tau(p)}]^2 T(p)\frac{\partial\tau(p)}{\partial p}dp} = \frac{T_{B1} - A_{up} - A_{DN}}{T_s\tau(p_s) - A_{DN}} \tag{8}$$

where T_{B1} is the observed MSU channel 1 brightness temperature, T_s is the surface temperature, A_{up}, A_{DN} are MSU channel 1 upward and downward atmospheric contribution terms, respectively. $\tau(p_s)$ is the total atmospheric transmittance from the surface to the top of the atmosphere.

MSU channel 1 is only a near-window channel in which the atmospheric gases' contribution has to be take into account for accurately determining the surface emissivity. The MSU channel 2 mainly sense the low troposphere, and is almost not influenced by surface emissivity. By simulation we find the close correlation between MSU channel 2 measurements and A_{up}, A_{DN} and $\tau(p_s)$. T_s can be determined by HIRS/2 window measurements. Thus, from equation (8) we deduced the microwave surface emissivity around 50.31 GHz, as depicted in figure 3. The purposes of deriving the surface emissivity are two-fold. First we seek the possibility of establishing a surface emissivity data base, which could be used in the future data processing system, such as regional ATOVS data processing, for processing and correcting the low troposphere microwave channel measurements. Second, according to N. Grody(1988), the emissivity for wet soil can be less than 0.8, whereas the emissivities for dry soil are usually large than 0.9. We are doing an experiment trying to link the drought information with emissivity distribution. We have compared the emissivity distribution with the rainfall distribution in the same period, it does reveal some clues. However, for the very coarse resolution of MSU, it seems that further study is needed on this aspect with the advent of NOAA-K series in the near future.

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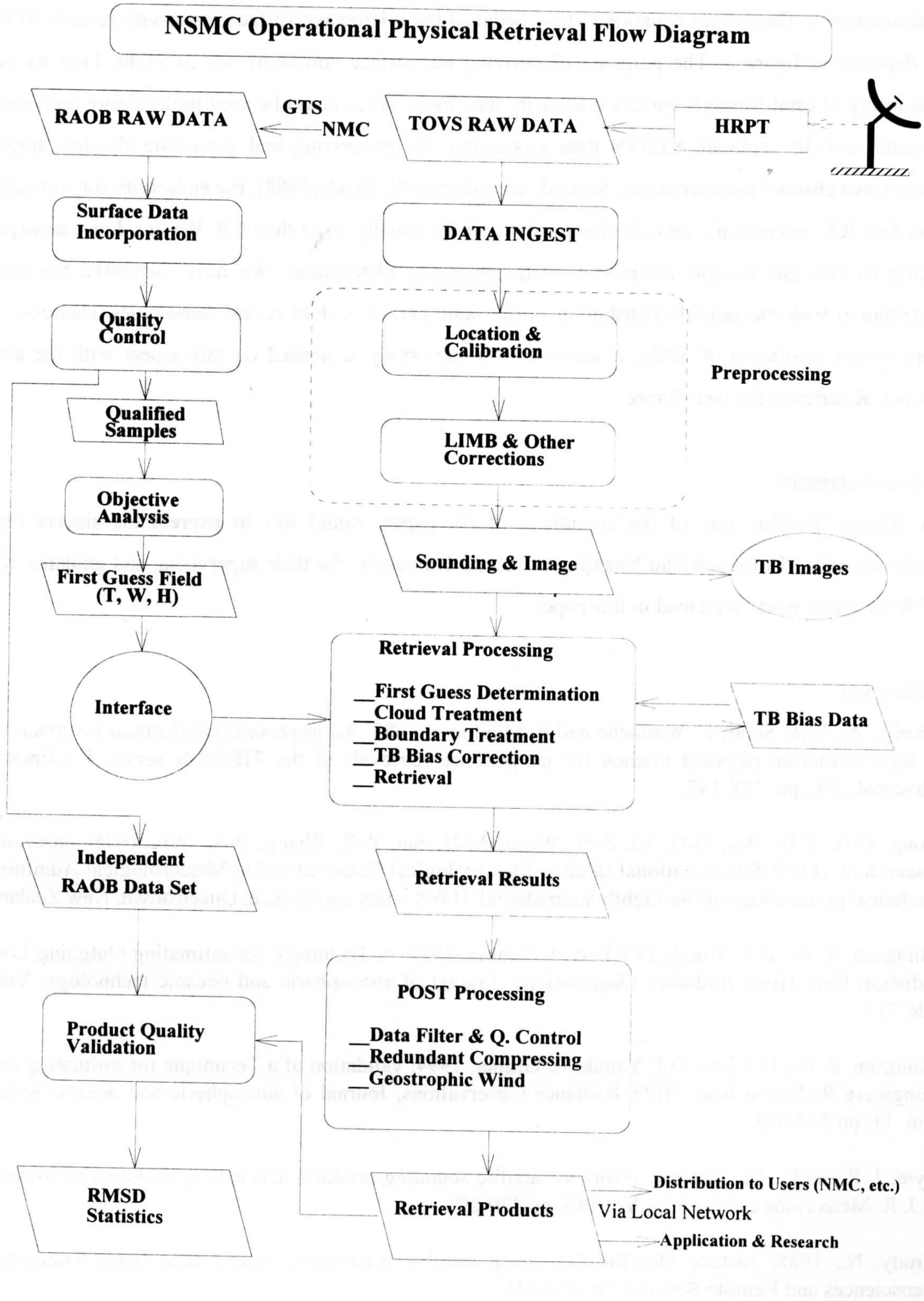

Figure 1. Upgraded TOVS Operational System Flow Diagram

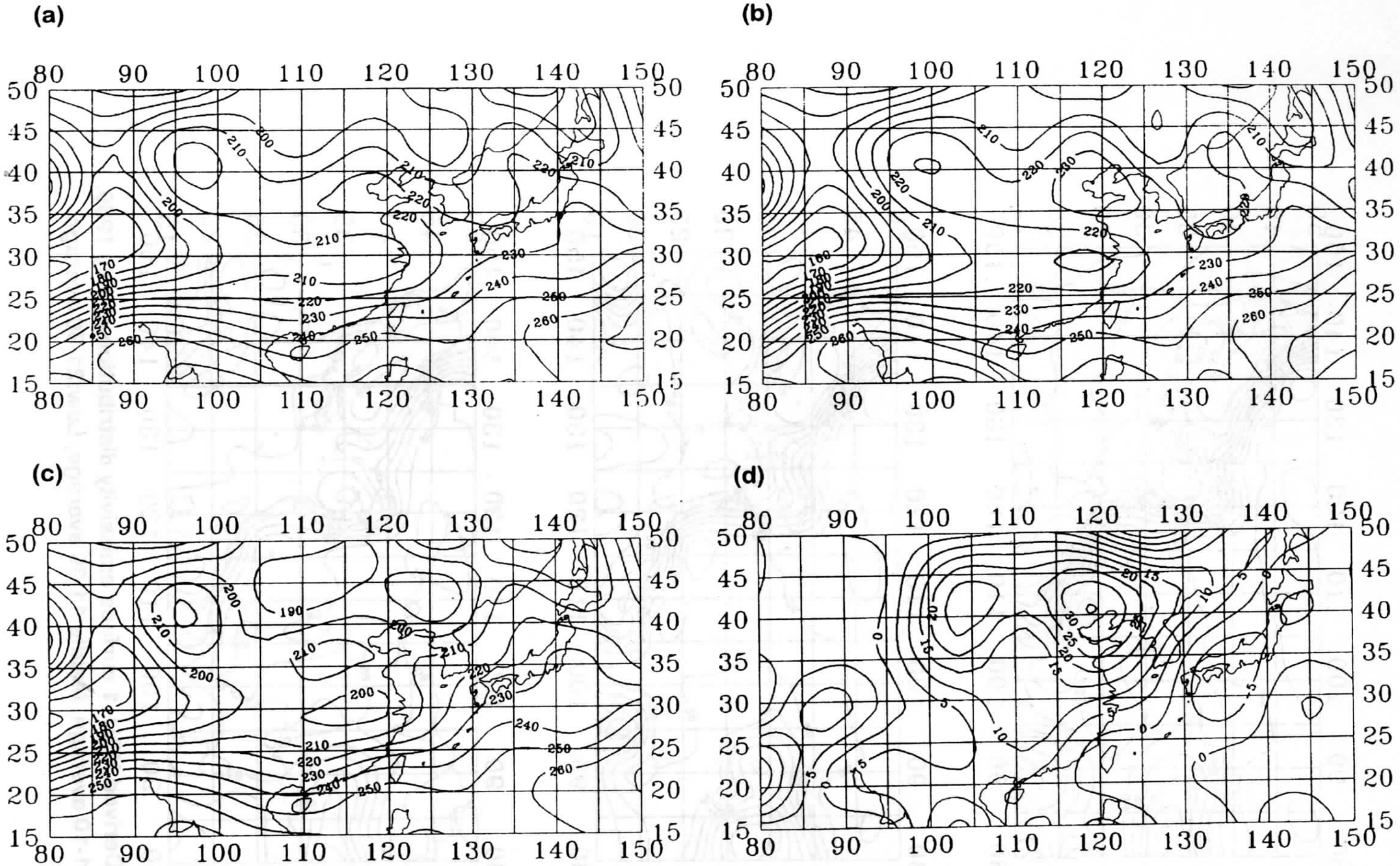

Figure 2. OLR Distribution of January 1991 Derived from HIRS Measurements.
Upleft: Monthly average, Upright:Daytime average
Lowleft: Night average, Lowright:Day-night differences

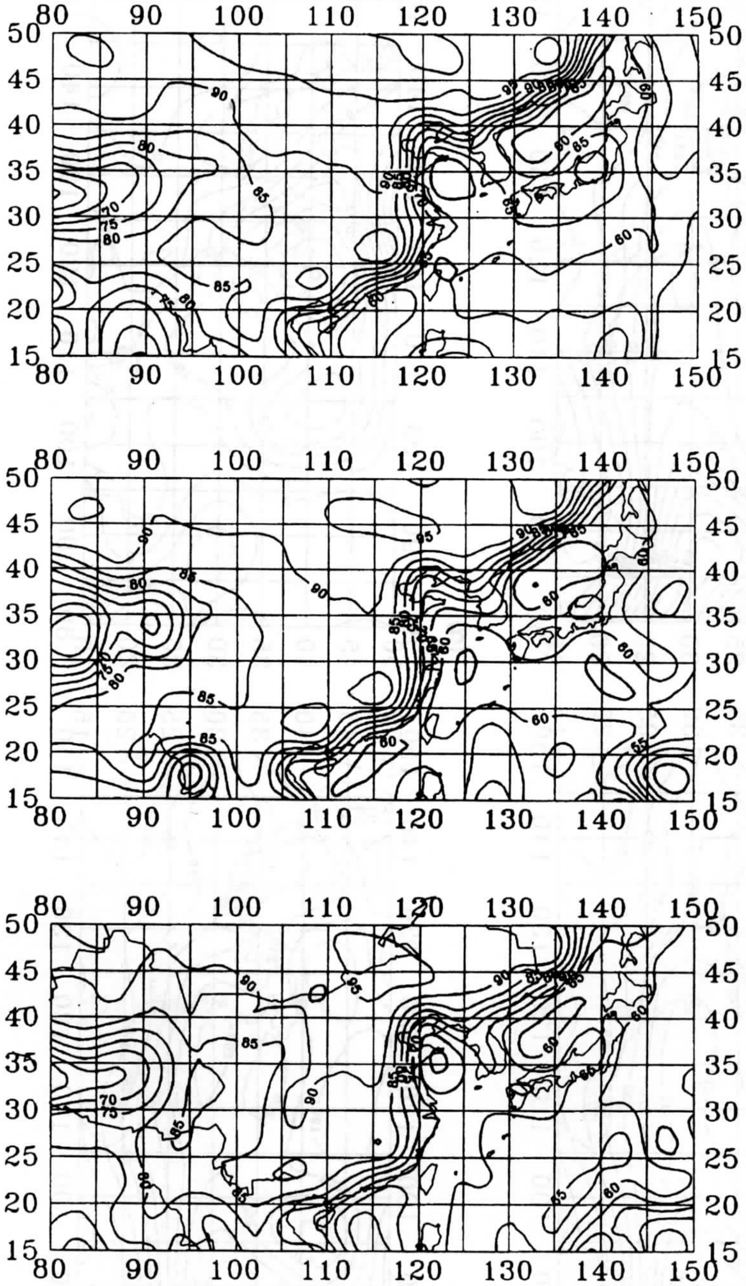

Fig.3. Derived MSU- 1 surface emissivity distribution of July 1989.
Up:1-10 average, Middle:11-20 average, Low:21-30 average

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