Estimation of Vertical Moisture Profiles from GMS Cloud Data

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Abstract

An algorithm for moisture estimation from GMS (Geostationary Meteorological Satellite) cloud data adopted by the JMA (Japan Meteorological Agency) is presented. The satellite-derived moisture data have been utilized in routine moisture analyses at the JMA since 1983. In the algorithm, cloud conditions are classified into 320 categories in reference to the GMS cloud data such as cloudiness and cloud-top equivalent black body temperatures (T_{BB}) together with synoptic observations, and a typical moisture profile is determined for each of the categories based on the statistical relationship. Thus, vertical moisture profiles are objectively estimated as a function of the cloud condition.

1. Introduction

Moisture is one of the most important atmospheric parameters for numerical weather prediction (NWP) models. Special emphasis is accordingly put on the moisture analysis in order to obtain more accurate initial moisture fields, which is critical, *inter alia*, for rainfall forecast. However, radiosonde observations are not abundant enough to analyze moisture fields with a sufficient resolution, being too sparsely distributed especially over the ocean. Retrieval of moisture profiles from other observations has therefore been attempted to supplement the meagerness of the moisture data.

Smith and Howell (1971), Hayden *et al.* (1981), and Lipton *et al.* (1986) developed procedures to retrieve water vapor profiles from satellite measurements. Chisholm *et al.* (1968) investigated the relationship between surface synoptic observations and the collocated TEMP data and thus developed a diagnostic approach to estimate humidities at standard pressure levels (850 hPa, 700 hPa, 500 hPa, and 400 hPa) from surface observations. Jonas (1976) demonstrated that the upper moisture data estimated from surface observations have considerable availability for the upper level humidity analysis. Thompson and West (1967), Smigielski and Mace (1970), Walcott and Warner (1981), and Mills (1983) used cloud imageries observed by meteorological satellites to estimate water vapor fields. Walcott and Warner (1981) applied satellite cloud data to moisture analysis based on the assumptions as follows: if precipitation is observed at the surface, relative humidity is 100% from the surface to the cloud top level; if not, it is 100% only at the cloud top level. They showed that these supplementary data allowed NWP models to improve the forecast of rainfall intensity.

In light of these studies as above, the JMA established a scheme to estimate vertical moisture profiles from GMS cloud data and put it into the routine moisture analysis in 1983 (revised in 1988). In this scheme, the vertical profile of relative humidity is determined as a function of the GMS cloud data based on the statistical relationships between the GMS cloud data and the actual measurements of moisture. We hereafter call the moisture profile estimated from the GMS cloud data as "GMS moisture data".

2. GMS cloud data

The GMS cloud data, which are derived from the GMS observations at 00, 06, and 12 UTC, consist of several parameters representing cloud conditions such as cloudiness and cloud–top equivalent black body temperatures (T_{BB}) in each 0.5°× 0.5° latitude/longitude within the area of 50°N–50°S, 90°E–170°W (see Table 1).

A set of these parameters allows of objective estimation of the cloud conditions at each mesh. For example, i) the cloudiness of 100% at a mesh immediately means that the grid is filled with clouds, ii) the relatively high (low) mean T_{BB} indicates predominance of low–level (high–level) clouds, and iii) the large (small) standard deviation of T_{BB} suggests cumuliform (stratiform) clouds. Also, the cloud condition inferred at a mesh gives a rough image of a vertical moisture profile at the mesh. For example, if the cloudiness is 100 %, the mean cloud–top level estimated from T_{BB} is 700 hPa and the standard deviation of the T_{BB} is 1 K, the atmosphere above 700 hPa is considered to be dry while that of below 700 hPa be wet. Thus, the GMS cloud data roughly profile the vertical distribution of moisture.

3. Classification of cloud condition and retrieval scheme

In order to apply most appropriate vertical profiles of moisture, cloud conditions are classified into numbers of categories with three parameters of the GMS cloud data; those parameters are 1) cloudiness, 2) mean cloud–top height converted from the mean T_{BB} in reference to the analyzed temperature profile or the first guess temperature, and 3) standard deviation of T_{BB}.

Among these three parameters, the cloudiness displaying the general moisture condition of a mesh is divided into five classes, i.e., 0%, 1–20%, 21–70%, 71–99%, and 100%. The mean cloud–top height which gives the height of the uppermost moist atmosphere is divided into six levels when the cloudiness is more than 20%, i.e., 300 hPa or higher, 301–400 hPa, 401–500 hPa, 501–700 hPa, 701–850 hPa, and lower than 850 hPa. Also, the standard deviation of T_{BB} indicative of the type of cloud is divided into two classes when the cloudiness is greater than 70%: less than 3K, which means that clouds are stratiform and so the moisture gradient is generally sharp between cloud and cloud–free layers; and 3K or greater, which means that clouds are cumuliform and so the moisture gradient is moderate between the layers. Consequently, as shown in Table 2, the cloud conditions are classified into the 32 categories.

However, since the GMS cloud data describes the atmospheric conditions only above the cloud–top, synoptic reports which offer weather conditions (or moisture conditions below the cloud–base) are incorporated into the classification for the more realistic moisture profile. For example, it can be estimated that the whole layer from the cloud–top down to the surface is wet when precipitation is observed at the surface, while wet is only the layer from the cloud–top to the cloud–base when no precipitation is observed. In order to affiliate with the information, weather conditions are classified into five categories, "rain"; "rain in the past 3 hours or in the vicinity"; "no rain"; "high cloud–base" (cloud–base is higher than 2000 m above the surface); and "unknown" (no synoptic report is available). In addition, because humidity in the tropics is generally higher than in the extratropics, the locations of meshes are divided into two groups according to their latitudes, i.e., those in 23.5°N–23.5°S (tropical region) and in 23.5°N–50°N/23.5°S–50°S (subtropical region). Eventually, the above 32 categories of cloud conditions are classified further into 320 sub–categories by the combination of the five weather categories and the two regional groups.

For each of these categories, vertical moisture profiles are statistically deduced from the radiosonde data observed under the corresponding cloud conditions. In the statistics, the average radiosonde–observed profiles were defined as the estimated vertical moisture profiles, and their standard deviations (σ_R) are defined as the errors of the estimation to be used as the observation errors in the objective analysis.

Examples of the derived profile of moisture and standard deviation are shown in Table 3 and Figure 1. In this case, the cloud condition is classified as the category number 12, where the cloudiness is 71–99%, the mean cloud–top height is more than 700 hPa and less than 500 hPa, the standard deviation of T_{BB} is smaller than 3K, and the weather category is "rain". These parameters indicate that the region is mostly covered with stratus with cloud–top existing between 700 hPa and 500 hPa levels and that the precipitation is observed at the surface. The moisture profile presented in Figure 1 exhibits the wetness below 700 hPa to the surface and dryness above 700 hPa, being consistent with the moisture profile presumable from this category of cloud condition.

In addition, because some of the errors in statistically derived moisture profiles as shown above could be less than the systematic error of radiosonde observation, 5%, we employed σ_G instead of σ_R expressed by

$$\sigma_G=\sqrt{(\sigma_R)^2+(5\%)^2}$$

to be used in the objective analysis.

The operational procedure to obtain GMS moisture data is briefed as follows (the schematic flow of the procedure is illustrated in Figure 2).

(1) The category number for a cloud condition at each mesh is determined from the GMS cloud data and temperature analyses are needed to convert the T_{BB} to the cloud–top height.

(2) The category number for the weather condition is determined from the synoptic report.

(3) With these category numbers, a vertical profile of moisture is given for the mesh and used in the objective analysis along with estimation errors (or observation errors) at standard pressure levels as the moisture data at the data point; the "data point" is defined as the point where the surface observation was carried out, or the center of the mesh when no observation is available.

Thus, the GMS cloud data, together with the surface observations, approximate the vertical distributions of moisture and thereby afford objective analysis realistic moisture fields, which are absolutely effective in the regions where very few radiosonde observations are available.

4. Impact of the GMS moisture data on numerical prediction

Figure 3 illustrates the moisture analysis at 700 hPa level at 12 UTC on 24 July 1989 and the GMS cloud data at the same time when a tropical cyclone is located to the south of

Japan. Shaded in the Figure 3-(a) are the areas with relative humidity of 80% or more (or T-Td of 3°C or less). Radiosonde data and GMS moisture data are indicated by "*" and "×"/"+"), respectively, where "×" indicates the data derived with surface observations and "+" without surface observations. Note that the GMS moisture data are produced only for the oceanic areas and not for the land areas where the radiosonde data are relatively abundant and GMS data are deteriorated.

Basically, GMS moisture data are produced with the density of one in every 2° latitude-longitude grid. In addition, reliability of the GMS moisture data determined with the surface observations take precedence of those without surface observations. Further, the GMS moisture data are not produced within 300 km from the radiosonde observations. It is because that the accuracy of the GMS cloud data are not satisfactory over the land. Comparing the Figure 3.(a) to 3.(b), one can find that the moisture field in Figure 3-(a) is quite reasonable with the well demonstrated moist area accompanied by the tropical cyclone.

In Figure 4, GMS cloud imagery at 00 UTC 27 July 1988 is presented. The three figures on the left of Figure 5 are the objective moisture analyses at 500 hPa, 700 hPa and 850 hPa levels at the same time. It should be noted that the three zonal cloud systems around latitudes of 40°N, 20°N and the equator shown in Figure 4 are analyzed consistently in Figure 5 even though radiosonde data are sparse or non-existent in most of these regions. The three figures on the right of Figure 5 are shown the objective moisture analyses without GMS moisture data; the results of the forecast-analysis cycle conducted for the last seven days without the GMS data. Note that the zonal cloud systems, in particular that around 20°N in latitude, and the cloud free regions are not clear in these figures.

As indicated in these cases, the GMS moisture data allow the objective analysis to analyze moisture fields fairly accurately over radiosonde-data sparse ocean areas, providing realistic moisture distributions in the synoptic-scale cloud systems such as tropical cyclones and ITCZ. More specifically, such data bring out the sharp moisture contrast between the cloud and cloud-free regions in initial fields of numerical models, and lead to the more reasonable difference of precipitation potential between those two regions, thus having a significant impact on the models' forecast performances, on the precipitation forecast in particular.

5. Summary and remarks

Vertical moisture profiles are objectively estimated from GMS cloud data with predetermined profiles typical to the cloud conditions, which were derived based on the statistical relationships. In the estimation process, moisture conditions are classified into 320 categories with synoptic reports and cloud conditions determined by the GMS cloud data such as cloudiness and T_{BB}, and a vertical moisture profile typical to each category is given by the statistics. Thus, upper moisture data are objectively estimated as a function of the cloud condition defined by the GMS cloud data.

GMS moisture data are quite useful in moisture analysis and precipitation forecast, particularly in the tropical oceans. But we should note that they are not capable of describing moisture profiles in detail since they are derived through statistical procedures. For example, when cirrostratus exist in the upper level while low level clouds exist with precipitation, the GMS moisture data will indicate that the all levels are wet even if the middle level is actually dry.

An isolated radiosonde observation may represent the moisture condition at a point. When we consider that the radiosonde data represent the moisture conditions only along their passage, a large difference in moisture observation could occur depending on the radiosonde passage in the area where there are sharp contrasts in moisture distribution, e.g., inside and outside a cumulonimbus.

It is not easy to conclude which is the fair representative of moisture distribution in that particular region. Nevertheless, the effectiveness of the data are evident especially from the standpoint of the synoptic analysis of moisture field. The GMS moisture data could represent synoptic scale moisture fields, although they are not suitable for representing such small scale moisture fields as the meso-scale moisture field. Therefore, it is concluded that the GMS data give invaluable information when they are used for the synoptic-scale analysis to compensate for the lack of radiosonde data.

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Table 1. GMS cloud data (Original)
Region : 50N–50S / 90E–170W
Resolution : 0.5 x 0.5 degree

Data No.	Item		Unit	Remarks
1	Cloudiness	-400 hPa	%	
2		400-500 hPa		
3		500-600 hPa		
4		600-700 hPa		
5		700-		
	Cloud-top temperature		K	For cloud pixel
6	Mean			
7	Minimum			
8	Standad Deviation			

Table 3. An example of GMS moisture data.

Category No. 12	
Cloudiness	71 - 99%
Mean Cloud Top Height	501 - 700 hPa
Standard Deviation of Cloud Top Temperature	0.0 - 2.9K
Weather Category	Rain
Region	Tropics (23.5N - 23.5S)

Height (hPa)	Relative Humidity (%)	σ_R (%)	σ_G (%)
300	22.2	9.5	10.7
400	19.5	12.5	13.7
500	19.4	13.8	14.7
600	28.6	15.8	16.6
700	87.5	13.3	14.2
800	89.5	7.2	8.8
850	90.1	5.9	7.7
924	92.3	4.6	6.8
1000	88.7	7.4	8.9

σ_G = Observation errors. σ_R = Standard Deviation.

Table 2. Classification of cloud conditions

No.	Cloudiness (%)	Mean Cloud Top Height (hPa)	Standard Deviation (K)
1	0	-	-
2	1-20	-	-
3	21-70	-300	-
4		301-400	
5		401-500	
6		501-700	
7		701-850	
8		851-	
9	71-99	-300	0.0-2.9
10		301-400	
11		401-500	
12		501-700	
13		701-850	
14		851-	
15		-300	3.0-
16		301-400	
17		401-500	
18		501-700	
19		701-850	
20		851-	
21	100	-300	0.0-2.9
22		301-400	
23		401-500	
24		501-700	
25		701-850	
26		851-	
27		-300	3.0-
28		301-400	
29		401-500	
30		501-700	
31		701-850	
32		851-	

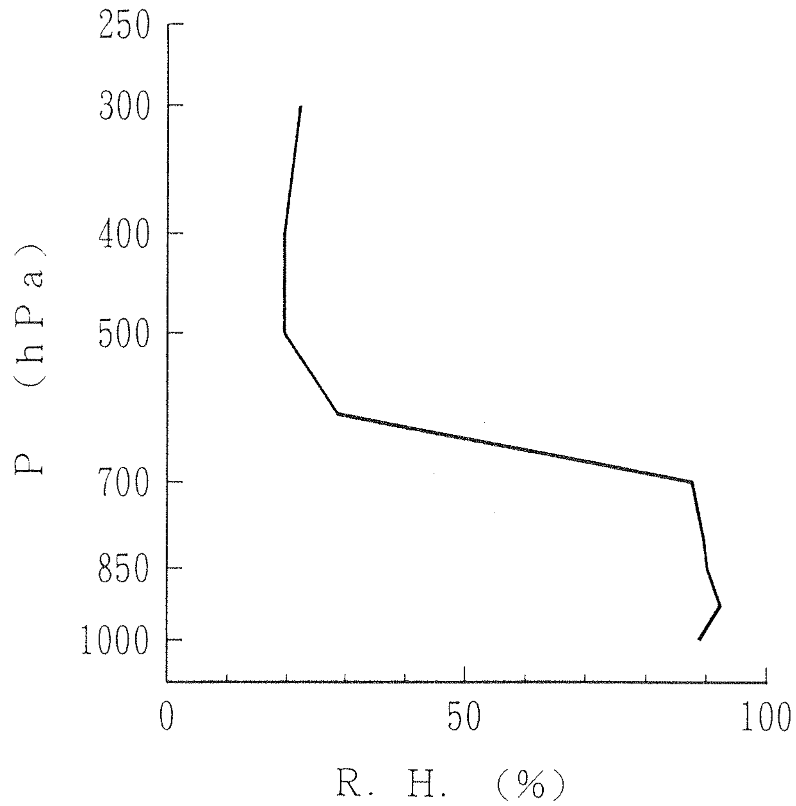

Fig. 1. An example of GMS moisture data. The vertical profile of category 12 (Graphical representation of Table 3).

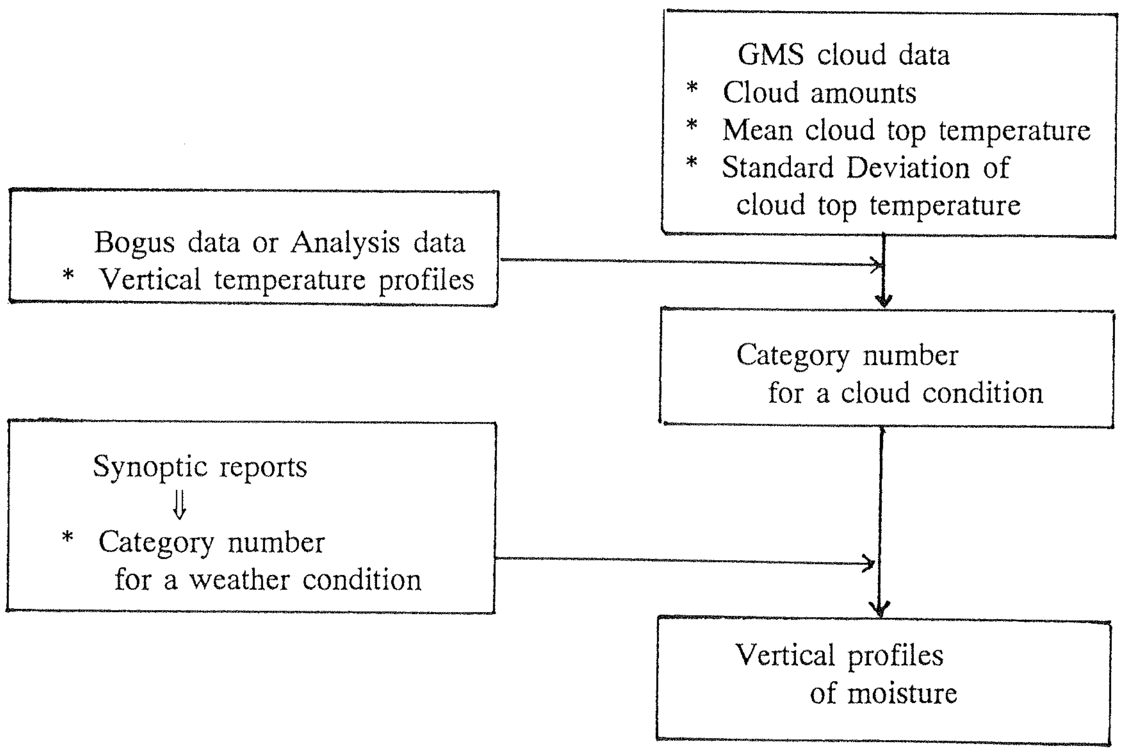

Fig. 2. The operational procedure to obtain GMS moisture data.

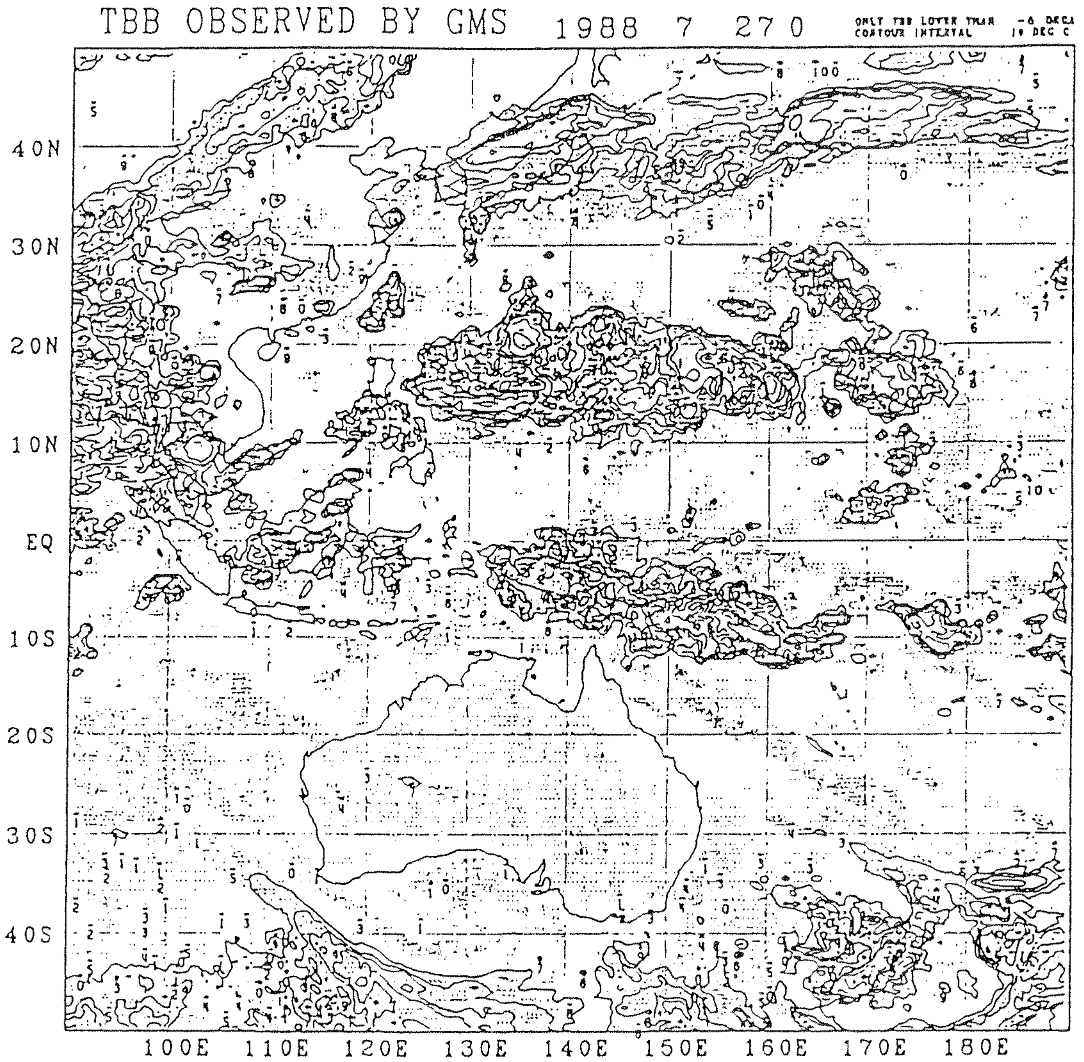

Figure 4.

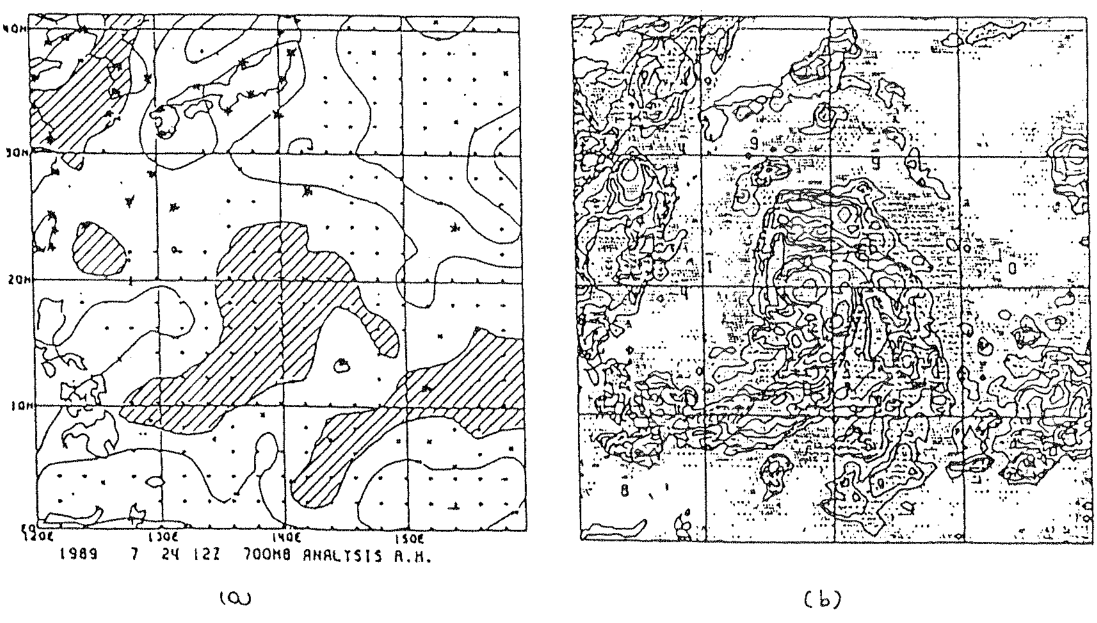

Figure 3. (a): 700 hPa moisture field analysis at 12 UTC 24 July 1989.
(b): Tbb field observed by GMS. Time/day are the same as (a).

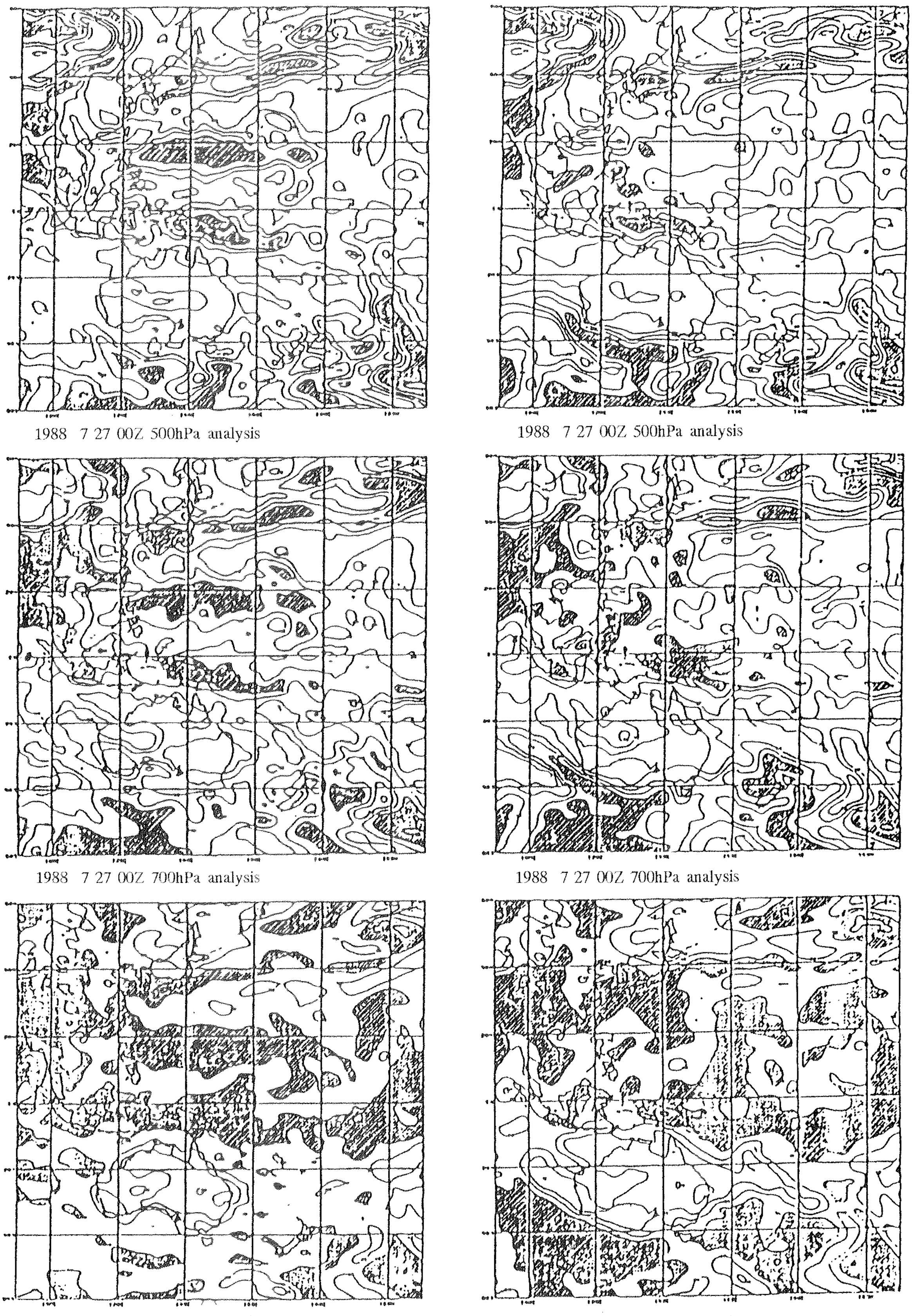

Figure 5. On the left are moisture fields that are objectively analyzed using GMS data. On the right are moisture fields, not referred to GMS data in objective analysis. Upper: 500 hPa level, middle: 700 hPa level, Bottom: 850 hPa level.