Water Vapor Fields Deduced from METEOSAT-1 Water Vapor Channel Data

M. M. POC AND M. ROULLEAU[1]

Laboratoire de Meteorologie Dynamique du C.N.R.S., Ecole Polytechnique, 91128 Palaiseau Cedex, France

(Manuscript received 4 May 1982, in final form 3 April 1983)

ABSTRACT

A quasi-operational process for the determination of water vapor fields from METEOSAT-1 water vapor channel data is described. Each count of the WV picture is replaced by the corresponding mean relative humidity value using both the calibration of the WV channel and the empirical relation between radiance and relative humidity. Midlatitude summer and tropical regions are examined.

1. Introduction

Remote measurements of radiation emitted by the atmosphere in the 6.3 μm absorption band of water vapor contain information on the global distribution of the atmospheric water vapor. The TIROS and Nimbus satellites were equipped with a water vapor channel and the radiometric observations have been utilized to derive global upper tropospheric relative humidity (Möller, 1961; Möller and Raschke, 1963, 1964; Raschke, 1966; Raschke and Bandeen, 1967; Fritz and Rao, 1967) and to study tropospheric dynamics (Steranka *et al.*, 1973; Rodgers *et al.*, 1976; Roulleau, 1978).

METEOSAT-1 is the first geostationary satellite having a water vapor (WV) channel, with a spectral interval (5.65–7.45 μm) centered on the 6.3 μm absorption band. It provides pictures from which we intend to derive quantitative moisture fields.

Until now, the relative humidities derived from satellite data were generally obtained using coordinated measurements within the 6.3 μm water vapor band and the 8–13 μm atmospheric window. From four model atmospheres Raschke (1966) and Raschke and Bandeen (1967) have constructed evaluation diagrams for tropospheric relative humidities. TIROS-IV radiometer data were then used to obtain a nearly global distribution pattern of water vapor mass above the 500 mb pressure level by comparing simultaneous measurements in two infrared channels with calculated diagrams. From this comparison it was possible to determine the relative humidity in the atmosphere above the emitting cloud or surface. Fritz and Rao (1967) compared the mean relative humidities deduced from the "humidity diagram" to the mean relative humidities for the layer at 400–275 mb obtained from the soundings. The results showed that the humidities deduced from the humidity diagram are considerably lower than the observed values.

In early 1980 the European Space Agency used a very similar method to draw maps of the upper tropospheric relative humidities. The procedure was also based on the interpretation of coordinated infrared radiometric measurements in the two spectral intervals of METEOSAT-1 radiometer channels. The method produced a rms difference of 31.7% when compared with radiosondes and a rms difference of 13.2% using climatological temperature profiles (Lunnon, 1980).

Because of the difficulties of this method, we developed a different procedure to map the relative humidity from the METEOSAT WV pictures. We looked for a direct relation between the water vapor amount and the WV measurements. The amount of water vapor was measured from the radiosonde data and compared with the signal received by the water vapor channel. To obtain a quantitative pattern of relative humidities, a good calibration of the METEOSAT-1 water vapor channel was necessary. In this article we first describe the method used to calibrate the 6.3 μm channel and then establish the relationship between the mean relative humidity in the troposphere and the numerical count of the digital tapes. Finally the mean relative tropospheric humidities over tropical and midlatitude areas are mapped.

2. Calibration of METEOSAT-1 water vapor channel

When we began this study, the calibration curve for the 6.3 μm channel was uncertain, so first the calibration data available at that time are reviewed.

The normal earth view of the satellite contains a large section of space which can be used as a calibration point if its temperature is known. From the

[1] Present affiliation: Laboratoire de Physique Thermique, ESPCI 10, rue Vauquelin, 75005 Paris (France).

European Space Operations Centre (ESOC), an average digital count of 2.5 corresponds to a temperature of about 2 K. Moreover the calibration slope as measured before launching was linear, and this dependence is also assumed to be true in flight. From Tables 2 and 4 of the calibration report (Morgan, 1979), the slope is 6.5×10^{-3} W m^{-2} sr^{-1}. The moon was also used for calibration; the slope derived from the moon scan was 6.7×10^{-3} W m^{-2} sr^{-1} (Lunnon, 1980).

Eyre (1979) used a procedure quite similar to ours. The brightness temperature "seen" by the WV channel was calculated from an atmospheric profile acquired by aircraft measurements and was associated with the METEOSAT digital count. The corresponding slope was 7.3×10^{-3} W m^{-2} sr^{-1}.

In our first paper (Poc *et al.,* 1980), the method used to obtain the response of METEOSAT-1 water vapor channel was described. We established a relation between the numerical values measured by the satellite radiometer in cloudless conditions and the calculated radiances obtained with an atmospheric transmission model using data from meteorological radiosondes. This preliminary study from a few radiosondes used a rather sophisticated transmission model. It showed differences with ESOC's results that were difficult to explain. This study was completed with further data from geographical areas with greater climatic variability.

The meteorological data used here came from radiosonde stations in midlatitude and tropical regions. The areas are restricted to 1000 points and 700 lines, which represent the portion of the global image visualized at one time on the interactive computer system. The midlatitude area includes the region from 25N to 55°N and from 30°W to 20°E. We studied pictures of 14 and 16 July 1978 and pictures of 3, 6 and 29 July 1979. The tropical area includes the region from 0 to 35°N and from 35°W to 15°E; we studied pictures of 3, 6 and 29 July 1979. In 1979 a number of complete soundings were available under these latitudes during the West African Monsoon Experiment (WAMEX). Figs. 1 and 2 illustrate respectively the midlatitude picture of 16 July 1978 and the tropical picture of 3 July 1979 visualized from the digital data tapes in the three METEOSAT channels.

For all cases chosen, clear sky conditions were controlled both on the simultaneous 10.5–12.5 μm picture and on the radiosonde data. Only soundings which extended to the 100 mb level for the temperature profile and the 300 mb level for the water vapor profile were kept. The data were completed in the higher layers of the atmosphere using McClatchey's (1972) midlatitude summer and tropical model atmospheres and Mastenbrook's (1968) stratospheric water vapor data. For all the images studies, 63 radiosonde stations were available. These stations were accurately localized on the images and the count values extracted from the digital tape at the point of each station. The navigation program locates a station on the pictures with an estimated accuracy of less than four pixels, which corresponds to about 32 × 32 (km) under midlatitude conditions. The variation of the count from a shift of 32 km on the picture depends, of course, on contrast of the scene, but this variation never exceeds 12 counts even in very contrasted regions.

The METEOSAT water vapor channel covers a wide range of frequencies (1342–1774 cm^{-1}), and a large number of data points must be used to obtain an accurate calibration of the water vapor channel. Therefore, we used a more approximate model than STRANSAC (Scott, 1974; Chedin *et al.,* 1978) to interpret these pictures. A test was made with LOWTRAN-3 (Selby and McClatchey, 1975; Selby *et al.,* 1976), but comparison of the results showed that the radiances calculated from LOWTRAN were about ten percent lower than those from STRANSAC. We then used Moskalenko's empirical model (MSK) for the transmission calculations (Golubitsky and Moskalenko, 1968; Moskalenko, 1969). In the spectral region of METEOSAT water vapor channel, only H_2O absorption is taken into account in this model. The computation time of a radiance on IBM 370/168 with STRANSAC is 0.7 s per 1 cm^{-1}, with Moskalenko's model 4 ms per 1 cm^{-1}.

The radiation reaching the satellite detector was evaluated for a clear atmosphere divided into 20 layers as

$$I = \Delta\omega \sum_{1}^{n} \left(\sum_{i=1}^{20} g_{\Delta\omega} B_{\Delta\omega}(T_i)(\tau_{i+1} - \tau_i)_{\Delta\omega}\right),$$

where $\Delta\omega$ is a spectral interval corresponding to the calculation step that must be adapted to the transmission calculation step, n the number of spectral intervals, $B_{\Delta\omega}(T_i)$ the mean value for each $\Delta\omega$ of the Planck radiance which is a function of the temperature T_i of the layer, and τ_i is the transmittance of the layer extending from the top of the atmosphere to the ith level. Here, $g_{\Delta\omega}$ is the mean value of the apparatus function for each spectral interval $\Delta\omega$. The METEOSAT-1 WV channel apparatus function was known with a total error of about 10% so that it introduced an uncertainty which was impossible to specify by the mean of a significant test.

Comparison of the radiance values obtained from Moskalenko's model with those obtained from the STRANSAC model showed that the first values are only 4% lower than the second. This difference appears to be very acceptable, taking into account the uncertainties of the atmospheric data and the error of 10% from the apparatus function.

The principal source of error is from the description of the atmosphere by the soundings. We have

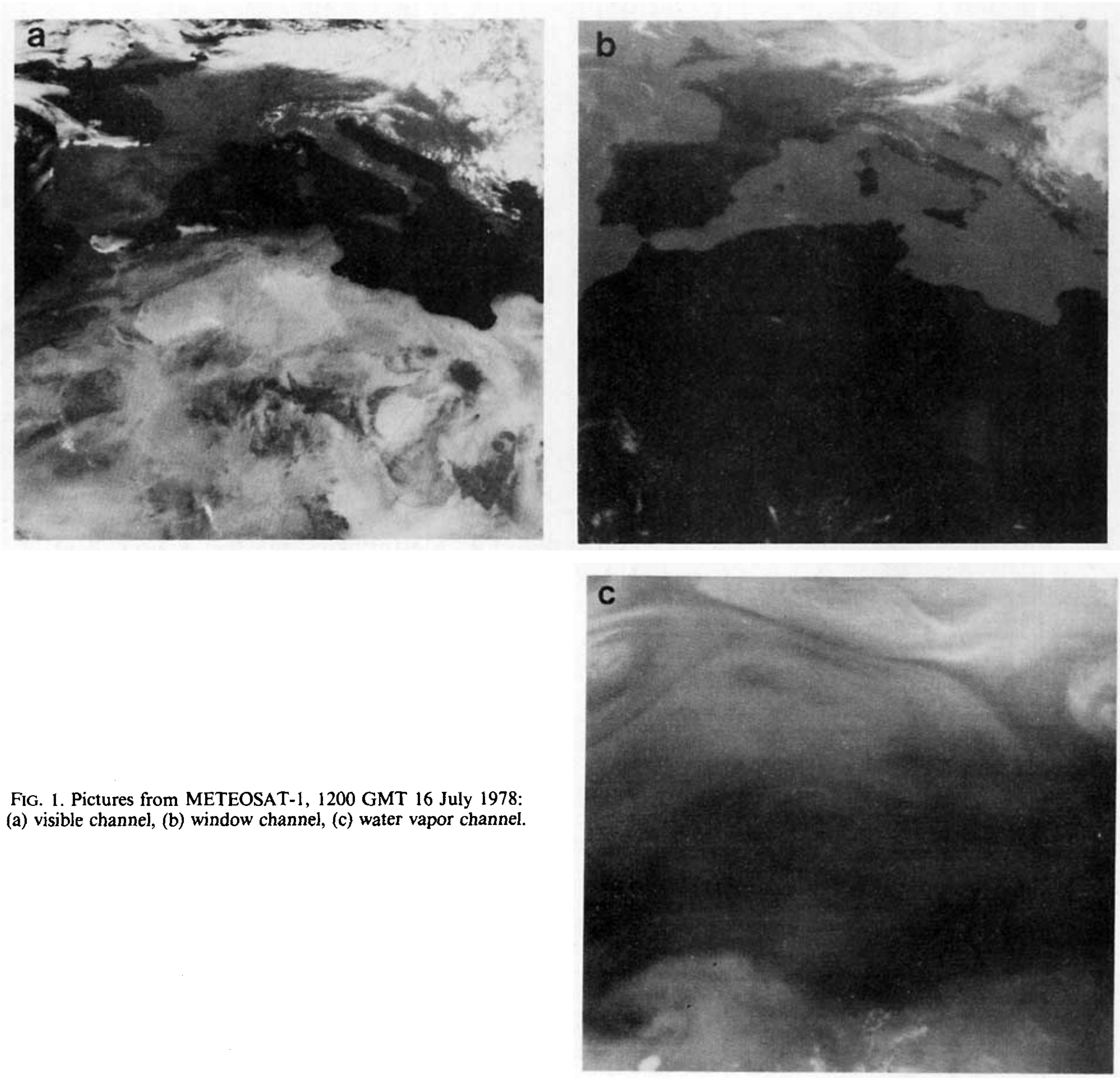

FIG. 1. Pictures from METEOSAT-1, 1200 GMT 16 July 1978: (a) visible channel, (b) window channel, (c) water vapor channel.

evaluated the effect of a constant absolute error of ±5% in the relative humidity profile on the radiance. The evaluation used the STRANSAC transmission model and led to a relative error in radiance of ±5%. Also a constant absolute error of ±1 K along the temperature profile gives a relative error for the radiance of ±3%.

To summarize, an approximate evaluation of the errors in the radiometric values extracted from the WV pictures is

$$\text{count: } \Delta C = \pm 6, \quad \text{radiance: } \frac{\Delta I}{I} = \pm 8\%.$$

The calibration line obtained for the METEOSAT-1 water vapor channel is represented in Fig. 3. Calculations have been performed with Moskalenko's model for 63 radiosondes. Space views on the pictures studied confirmed that a count of 2 corresponds to a zero radiance. The regression line passing through the origin has a slope of 6.8×10^{-3} W m^{-2} sr^{-1} with a mean square deviation of 7×10^{-4} W m^{-2} sr^{-1}. Then the different values of slopes proposed for the calibration of the METEOSAT-1 WV channel are in good agreement.

A different method was developed by Beriot *et al.*, (1982). The authors used the calibrated measurements from channel 12 of the HIRS/2 aboard TIROS-N to calibrate the water vapor channel aboard METEOSAT-1. They found a slope of 7.2×10^{-3} W m^{-2} sr^{-1}. To compare our method with theirs, we

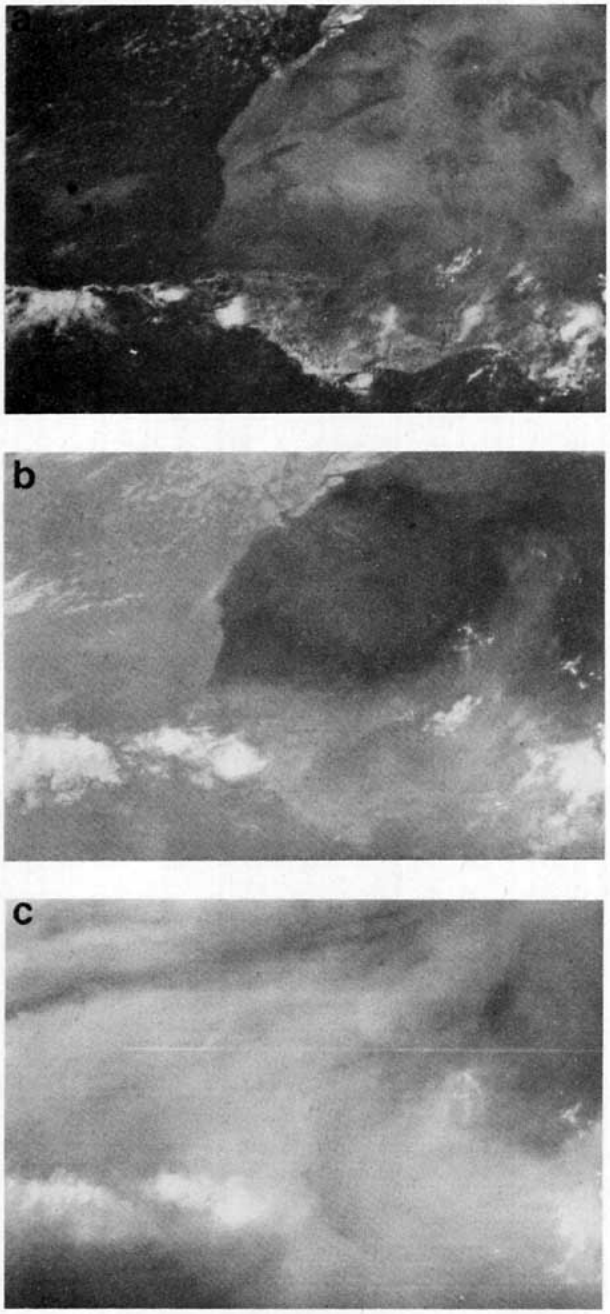

FIG. 2. As in Fig. 1, but for 1130 GMT 3 July 1979.

show in Fig. 4 their calibration line obtained from TIROS-N data and our results (points). Since they computed their transmission functions with the STRANSAC line-by-line model, the comparison shown in Fig. 4 is for radiances calculated with that model. Our points are spread around the line with the same dispersion as Beriot *et al.* found, a rms deviation of 7×10^{-4} W m^{-2} sr^{-1}. Thus, our method appears to be as good as the method based on similarities of weighting functions of channels of operational vertical sounders. From the different results for the slope of the calibration line, we think that 7×10^{-3} W m^{-2} sr^{-1} is a reliable value.

3. Mean relative humidity evaluation

The amount of water vapor is evaluated from the radiosonde measurements and associated with the radiance value calculated with Moskalenko's model. The water vapor channel measures radiation emitted from atmospheric layers situated above a given level. In order to determine that level and the thickness of the layer in which the water vapor quantity is measured, we have drawn contribution functions for the radiosounding stations corresponding to the pictures studied. As an example, Fig. 5 shows the contribution functions for three midlatitude stations: Rome, where humidity and temperature profiles are close to the climatic mean, Tunis, which is a drier and warmer case, and Belfast, which is a colder and wetter case. This figure shows that the radiance contribution is about half of its maximum value at the 600 mb pressure level, so this level is taken as the lower boundary of the layer. Since the midlatitude radiosondes give the humidity profiles to the 300 mb level, this pressure level is considered as the upper limit of the layer in which water vapor quantity is evaluated.

Figure 6 shows the contribution functions for two tropical stations, Nouadhibou and Dakar. For these curves the 500 mb level is taken as the lower limit of the layer under tropical latitudes. The soundings during the WAMEX experiment give humidity profile to the 250 mb level, which is then considered as the upper limit of the layer under these latitudes.

A suitable choice of the hygrometric parameter was necessary to evaluate the amount of water vapor. In our preliminary study (Poc *et al.*, 1980) a correlation was found between radiance and precipitable water vapor above 600 mb for two midlatitude cases. However, images corresponded to a stable meteorological case; similar evaluations for different weather situations both under midlatitude and tropical conditions demonstrated that the correlation was not significant. This result can be explained if one notices that the precipitable water was evaluated from the dew point profile, i.e., from the pressure and the dew point data, considering the humid air as an ideal gas. The radiance depends upon the two parameters of temperature and humidity. The relative humidity, which varies with the temperature and the dew point profile, is a more suitable parameter to correlate with the radiance. A mean relative humidity is then defined as the arithmetic mean of the relative humidity values in the layer. These means are calculated for all radiosounding measurements corresponding to the 1978 and 1979 pictures studied in the two selected geographical regions. Results obtained for stations under midlatitude summer conditions are plotted on

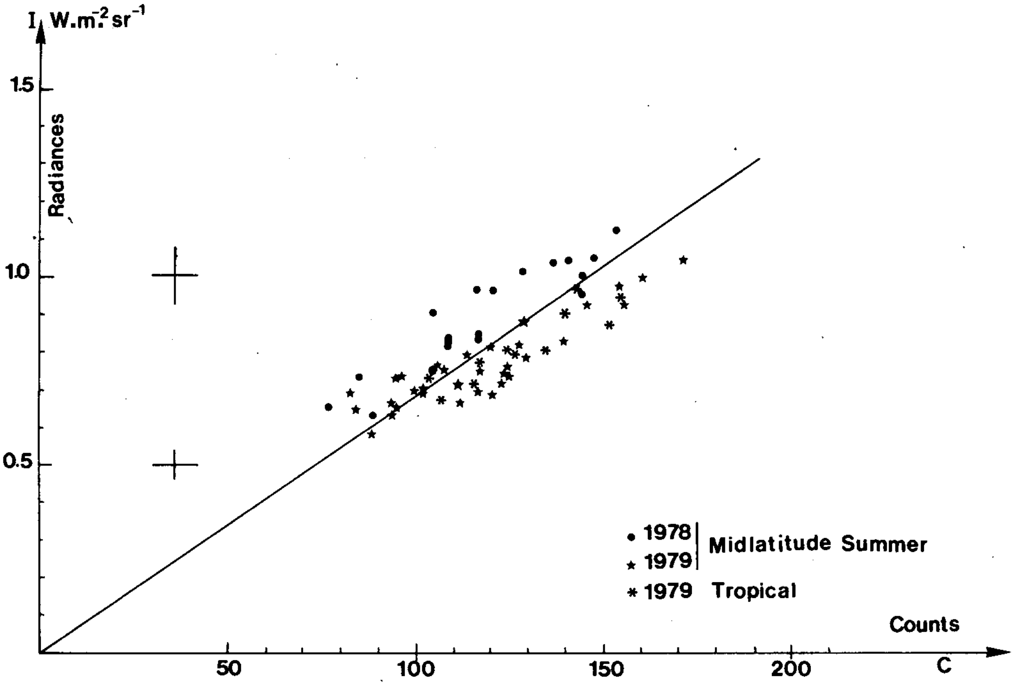

FIG. 3. Different calibration lines for the METEOSAT-1 water vapor channel.

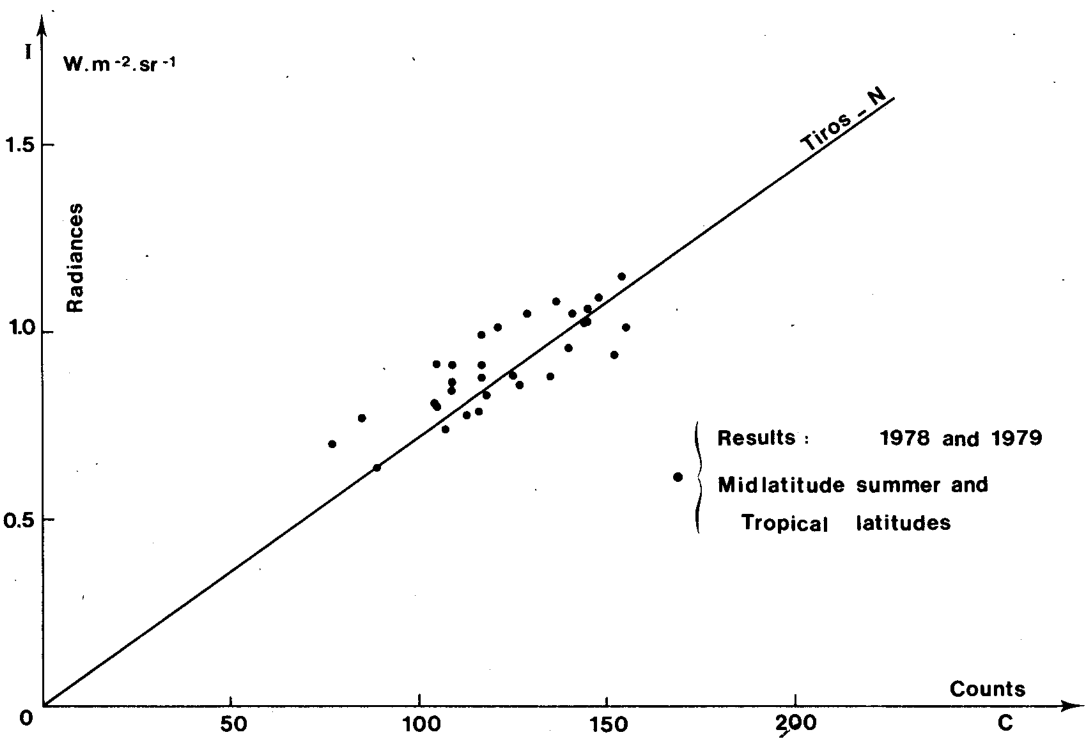

FIG. 4. Comparison between the calibration methods. Radiance values computed using the STRANSAC transmission model.

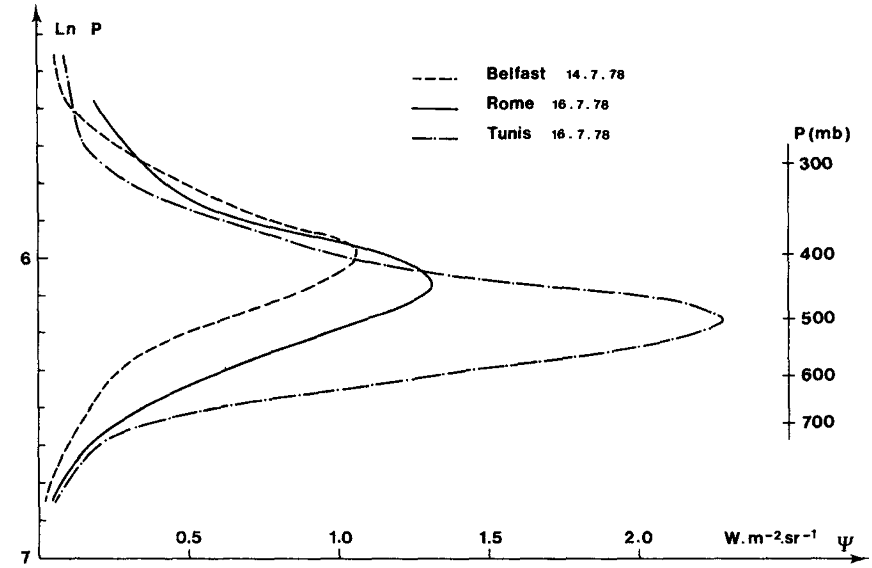

FIG. 5. Contribution functions for 3 stations under midlatitude summer conditions. Values computed using Moskalenko's transmission model.

Fig. 7, which gives the variation of the mean relative humidities $\bar{U}$ with the radiances I in the WV channel. A least-squares fit used to find the relationship between $\bar{U}$ and I is expressed as

$$\bar{U} = 14.6I^{-2.5}, \quad (\bar{U} \text{ in \% and } I \text{ in W m}^{-2}\text{ sr}^{-1}).$$

Fig. 8 shows similar results measured under tropical conditions. The least-squares curve is

$$\bar{U} = 18.3I^{-3.4}.$$

Unfortunately we have a smaller number of soundings in the tropical regions. Nevertheless, it appears that the same variations of the mean relative humidity give a variation of the radiance smaller under tropical than under midlatitude summer conditions.

4. Water vapor fields

The relations of Section 3 can be used for the analysis of water vapor fields in the cloudless middle tro-

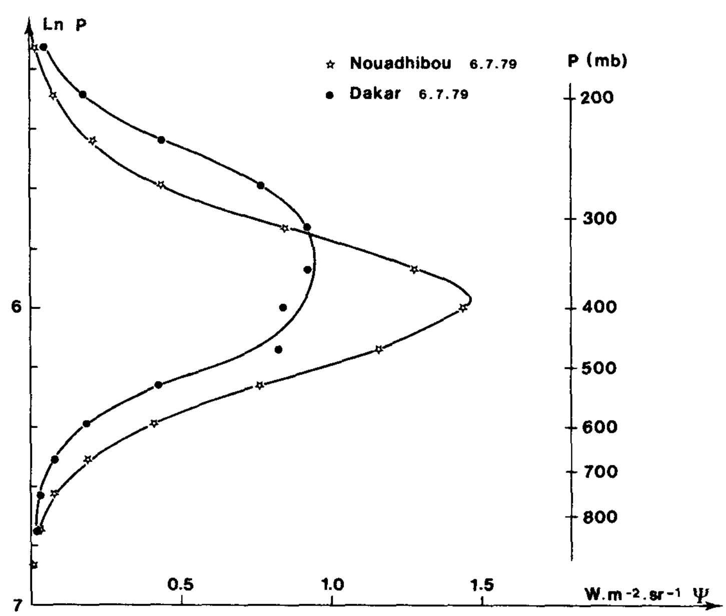

FIG. 6. As in Fig. 5 but for two stations under tropical conditions.

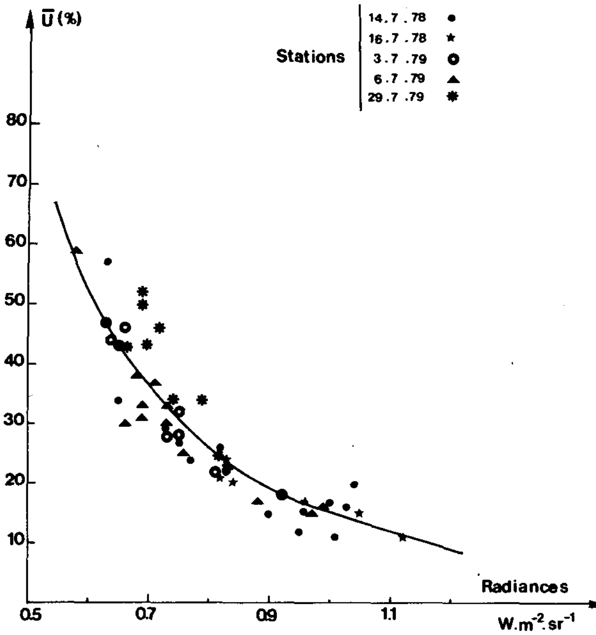

FIG. 7. Variation of radiances with mean relative humidity in the atmospheric layer, 600–300 mb. Midlatitude summer conditions.

posphere. As long as there is no cloud formation, the isolines for the count are associated with the isolines for mean relative humidity. A quantitative pattern of the humidity field can then be drawn directly with the computer, using the counts of the pictures stored on magnetic tapes. The procedure may be summarized in three steps:

1) The part of the image visualized on the interactive computer system is made of 1024 points and 700 lines. This number of data points is far too large to build the maps directly. A transformed image is recomputed, extracting the counts from the digital data tape at regular intervals of lines and points (every 14 lines and 9 points).

2) Then for both the calibration that relates counts to radiances and the relation between radiance and mean relative humidity, each count is replaced by the corresponding humidity value. Maps of these values, and also the relative humidity values at each point, are produced.

3) The best representation of water vapor fields from these maps would have been to draw relative humidity isolines. This involves a sophisticated computer program not available in our laboratory. We used a simpler process, shading differently the various ranges of relative humidity, each range being separated by white areas. Fig. 9 shows an example of the result obtained. On these maps, the continents have been superimposed, and a point of known latitude and longitude can easily be located by the computer. The dark areas represent cloudy regions, with relative humidity greater than 70%. This cut-off results because for all radiosondes used in clear sky conditions the mean relative humidity was less than 70%. However the white areas are confusing because they may have multiple meaning.

Nevertheless, these maps, obtained for fractional parts of the global pictures, allow one to follow the spatial and temporal variability from consecutive images. At a given point, the relative humidity varies either from the dynamic motions of the air masses or from the thermodynamical processes inside the air mass. From the temperature and the mean relative humidity, the precipitable water vapor above a certain level can be determined and, perhaps, even the fluxes.

5. Conclusion

From the radiances computed for particular geographical points corresponding to the soundings stations of the international net and from the counts of the magnetic tape, we were able to calibrate the WV channel. The linear relation for the response of the WV channel had a slope of 7×10^{-3} W m^{-2} sr^{-1}, which is in good agreement with the results obtained by other researchers.

Empirical relations between radiance and mean tropospheric relative humidity were established for drawing water vapor fields. A quasi-operational pro-

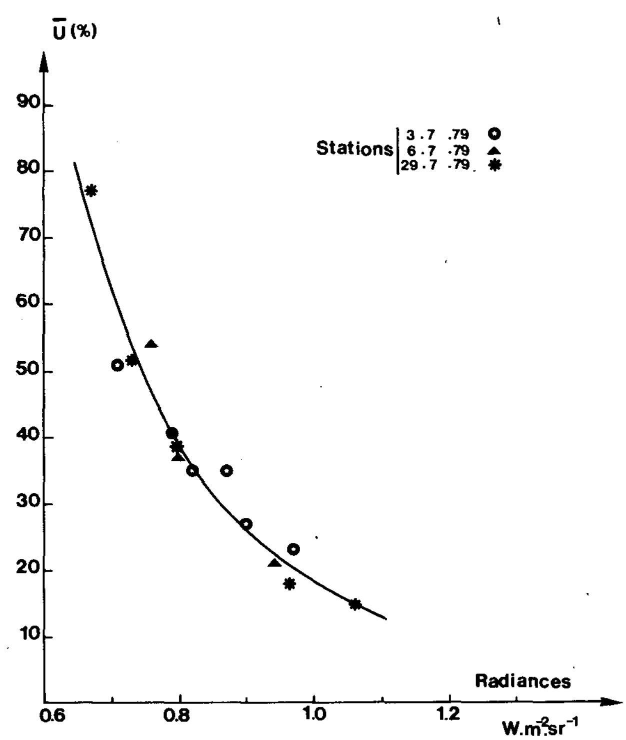

FIG. 8. As in Fig. 7 but for 500–250 mb tropical latitudes.

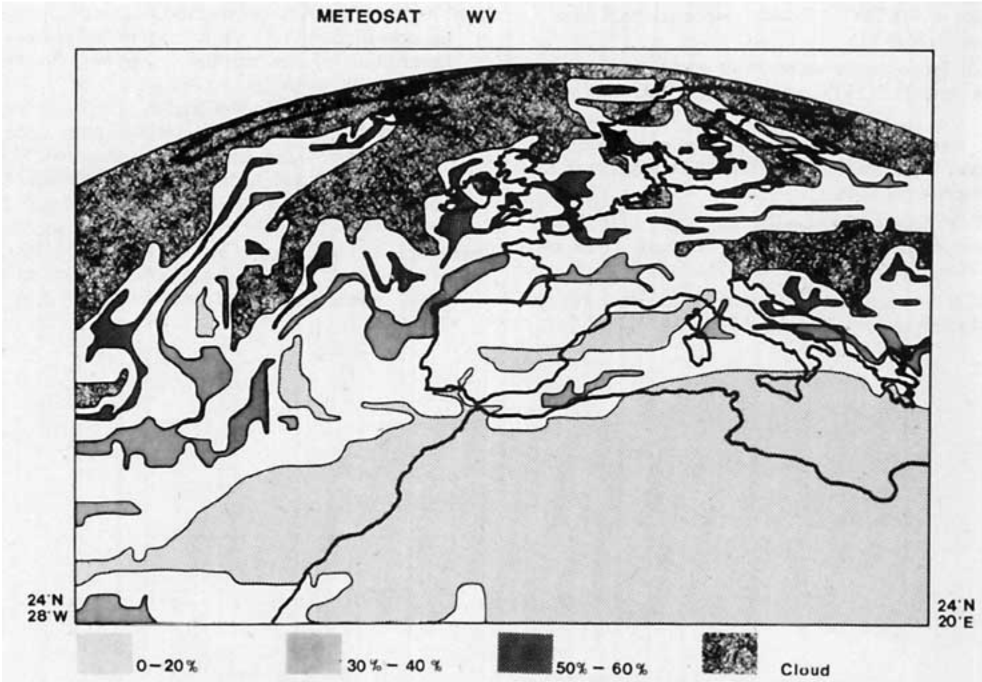

FIG. 9. The field of mean relative humidity obtained from the METEOSAT-1 WV channel digital data on 3 July 1979 under midlatitude summer conditions.

cess was used to determine areas of different values of mean relative humidity on the pictures studied. These results are valid under midlatitude summer and tropical conditions. For different air masses the method should be tested in other regions and for other months.

The association of mean relative humidity with proper altitude is a problem. The contribution functions of Figs. 5 and 6 show that the atmospheric layers of maximum contribution to the radiance are not situated at the same altitude under tropical and midlatitude summer conditions. A first approach was developed in our preliminary study (Poc *et al.*, 1980). Further work was carried on and will appear in a subsequent paper.

Acknowledgments. The authors are indebted to Professor J. Lenoble, of Laboratoire d'Optique Atmosphérique, Université de Lille, France, for her helpful suggestions and criticisms. Special thanks are extended to the staff members of the Laboratoire de Météorologie Dynamique for their contributions which have made the technical part of this study possible.

REFERENCES

Beriot, N., N. A. Scott, A. Chedin and P. Sitbon, 1982: Calibration of geostationary satellite infrared radiometers using the TIROS-N vertical sounder. Application to METEOSAT-1. *J. Appl. Meteor.* **21**, 84–89.

Chedin, A., N. Husson, N. A. Scott and D. Gautier, 1978: ν_4 band of methane ($^{12}H_4$ and $^{13}CH_4$). Line parameters and evaluation of Jovian atmospheric transmission at 7.7 μm. *J. Mol. Spectrosc.*, **71**, 343–368.

Eyre, J. R., 1979: A calibration for the water vapor channel of METEOSAT based on aircraft measurements of temperature and humidity. Meteor. O. 19 Branch Memorandum No. 53, Meteorological Office, Bracknell, 14 pp.

Fritz, S., and P. K. Rao, 1967: On the infrared transmission through cirrus clouds and the estimation of relative humidity from satellites. *J. Appl. Meteor.*, **6**, 1088–1096.

Golubitskiy, B. M. and N. I. Moskalenko, 1968: Spectral transmission functions in the H_2O and CO_2 bands. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.* **4**, 346–359.

Lunnon, R. W., 1980: Upper tropospheric humidity. METEOSAT Tech. Note ESA, Momo-MET T.N. 8.

Mastenbrook, H. J., 1968: Water vapor distribution in the stratosphere and high troposphere. *J. Atmos. Sci.*, **25**, 299–311.

McClatchey, R. A., W. R. Fenn, J. E. A. Selby, F. E. Volt and J. S. Garing, 1972: Optical properties of the atmosphere. AFCRL 72-0497, No. 411.

Möller, F., 1961: Atmospheric water vapor measurements at 6–7 μm from a satellite. *Planet. Space Sci.*, **5**, 202–206.

——, and E. Raschke, 1963, 1964: Evaluation of TIROS-III radiation data. Interim Report 1, Meteorologisches Inst., University of München. NASA Grant 305, 114 pp., Final Report, NASA Grant, 84 pp.

Morgan, J., 1979: METEOSAT-1, Calibration Report, Issue 3. ESOC., 13 pp.

Moskalenko, N. I., 1969: The spectral transmission function in the bands of the water vapor, O_3, N_2O and N_2 atmospheric components. *Izv. Acad. Sci. USSR, Atmos. Oceanic Phys.*, **5**, 1179–1190.

Poc, M. M., M. Roulleau, N. A. Scott and A. Chedin, 1980: Quantitative studies of METEOSAT water vapor channel data. *J. Appl. Meteor.*, **7**, 868–876.

Raschke, E., 1966: Tropospheric water vapor content and surface temperatures from TIROS-IV radiation data. NASA CR 595, 110 pp.

——, and W. R. Bandeen, 1967: A quasi-global analysis of tropospheric water vapor content from TIROS-IV radiation data. *J. Appl. Meteor.*, **6**, 468–481.

Rodgers, E. B., V. V. Salomonson and H. Lee Kyle, 1976: Upper tropospheric dynamics as reflected in Nimbus-4 THIR 6–7 μm data. *J. Geophys. Res.*, **81**, 5749–5758.

Roulleau, M., 1978: Inversion methods and applications. *Remote Sensing of the Atmosphere,* Elsevier, 149–159.

Scott, N. A., 1974: A direct method of computation of the transmission function of an inhomogeneous gaseous medium. I: Description of the method. *J. Quant. Spectrosc. Radiat. Transfer,* **14**, 691–704.

Selby, J. E. A., and R. A. McClatchey, 1975: Atmospheric transmittance from 0.25 to 28.5 μm: Computer code Lowtran-3". AFCRL-TR-75-0255, Environ. Res. Pap. No. 513.

——, E. P. Shettle and R. A. McClatchey, 1976: Atmospheric transmittance from 0.25 to 28.5 μm: Supplement Lowtran 3B. AFCRL-TR-76-0258. Environ. Res. Pap. No. 587.

Steranka, J., L. J. Allison and V. V. Salomonson, 1973: Application of Nimbus-4 THIR 6–7 μm. Observations to regional and global moisture and wind field analyses. *J. Appl. Meteor.*, **12**, 386–395.