A Statistical Correlation Method for the Retrieval of Atmospheric Moisture Profiles by Microwave Radiometry

RAMESH K. KAKAR

Earth and Space Sciences Division, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

BJORN H. LAMBRIGTSEN

Institute for Atmospheric Optics and Remote Sensing, Hampton, VA 23666

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ABSTRACT

A statistical correlation technique is applied to the retrieval of vertical moisture profiles under clear-sky conditions from down-looking radiometric measurements of atmospheric radiation at microwave wavelengths. For a given set of channels, the method selects the optimum radiometric channels for estimating water vapor at specific pressure levels between the surface and 300 mb. The water vapor mixing ratio at these pressure levels is then calculated from a linear combination of the selected channel brightness temperatures. To test its validity the algorithm was applied, in a numerical experiment, to fifty independent tropical radiosondes. The rms absolute deviation of the estimated moisture profiles from the actual profiles was comparable to that obtained using an iterative retrieval method reported earlier. The statistical method, however, requires several orders of magnitude less computer time than the iterative method; it is suitable for high speed processing of large amounts of data.

1. Introduction

A technique for retrieving vertical moisture profiles, using simulated satellite based observations of atmospheric radiation near the 183 GHz water line, was recently described (Kakar, 1983). The technique consists of an iterative method of inversion of the radiative transfer equation based on Chahine's general relaxation method (Chahine, 1972). In this paper we examine a different statistical estimation technique to obtain the clear-sky vertical moisture profiles over an ocean surface. Such a method for estimation of atmospheric water vapor profiles using the statistical technique and microwave radiometry has been described by Rosenkranz *et al.* (1982). In their method, 8 channels in the 60 GHz oxygen band, 3 channels near the 183 GHz water line and 2 window channels were used to retrieve the water vapor profiles. The primary difference between their method and the one described here, is that in our method, an optimum subset of the available radiometer channels is selected for each pressure level at which the water vapor mixing ratio is to be estimated. The selection of the optimum subsets is based upon the method of "regression by leaps and bounds" (Furnival and Wilson, 1974), described earlier by Pandey and Kakar (1983), who used it to estimate sea surface temperature from the SEASAT-SMMR measured data.

To test the validity of the retrieval algorithm described here, a numerical experiment was carried out by applying the algorithm to 50 independent tropical radiosondes and comparing the estimated moisture profiles with the actual profiles.

In this paper we have developed the retrieval algorithm for the nadir view from the satellite platform. The extension to other view angles is straightforward.

2. Retrieval algorithm

In the method employed by us, the amount of water vapor $q(p)$ at a pressure level p is given by

$$q(p) = a(p) + \sum_{i=1}^{N} b_i(p) T_b(\nu_i), \quad (1)$$

where N is the number of available radiometer channels, $a(p)$ and $b_i(p)$ are regression coefficients and $T_b(\nu_i)$ the measured channel brightness temperature at frequency ν_i. The regression coefficients were obtained from a data base consisting of a set of radiosonde soundings of water vapor and temperature and the corresponding simulated "measured" brightness temperatures at each channel frequency. An optimum subset of the N channels was selected for each pressure level by the "leaps and bounds" procedure. The $b_i(p)$ for channels not selected were set equal to zero.

Equation (1) represents the first two terms of a Taylor expansion of q, where q is considered as a function in N-dimensional T_b space. The question then arises whether it is justified to ignore all higher order terms and thus treat a nonlinear problem with a linear model. This is not a trivial question and a careful study would be required to answer in full. As a preliminary examination, however, we have determined the linear correlation between q and T_b for a test sample of 50 tropical moisture profiles. In this test the temperature profile of the 50 radiosondes was fixed at a constant average value. We obtained linear correlation coefficients between q and T_b for the best 1-channel subsets in the range of 0.86–0.98 between ground and 350 mb. Subsets that included more channels had even higher correlation. Thus, a cursory investigation shows that the linear approximation represented by Eq. (1) is not unreasonable.

Three hundred and fifty radiosonde soundings from 10 stations spread across the 30°S–30°N latitude band were used to derive the regression coefficients. Each radiosonde record was normalized to 1000 mb surface pressure and consisted of temperature values at 40 pressure levels between 1000 and 0.1 mb and specific humidity values at 20 pressure levels between 1000 and 115 mb. Table 1 gives the specific humidity and temperature spread of this 350 radiosonde data set.

The radiometer channels recommended for the Advanced Microwave Sounding Unit (AMSU), the next-generation U.S. operational microwave sounder, were examined for their moisture sounding capability in our numerical experiment. The AMSU is a 20-channel microwave sounder. The brightness temperature $T_b(\nu_i)$ for each channel was calculated for the nadir view for each one of the 350 radiosondes, assuming a specular ocean surface. The radiative transfer model and computational procedure described in the earlier paper (Kakar, 1983) were used in this calculation. The oxygen absorption coefficients below 60 GHz, however, were calculated according to the Rosenkranz (1975) model.

TABLE 1. Specific humidity and temperature spread of the 350 radiosonde data base.

Pressure level (mb)	Temperature (K)		Specific humidity (g kg^{-1})	
	Minimum	Maximum	Minimum	Maximum
300	227.2	245.2	0.02	0.49
350	234.9	252.2	0.05	1.34
400	238.2	259.2	0.07	2.07
430	242.7	262.7	0.12	2.76
475	248.9	267.6	0.18	3.72
500	252.2	270.2	0.18	4.27
570	258.8	275.8	0.29	5.94
620	263.0	280.0	0.34	7.22
670	267.0	284.0	0.38	8.74
700	269.2	286.2	0.40	9.59
780	272.0	290.2	0.74	12.16
850	274.2	295.1	0.88	15.28
920	273.7	299.5	2.25	20.46
950	273.5	302.1	2.91	23.54
1000	273.2	307.2	3.50	28.46

A value between zero and 15 m s^{-1} was selected, at random, for the surface wind speed. The corresponding sea-surface emissivity was calculated, assuming that the emissivity model of Pandey and Kakar (1982) can be used at the channel frequencies being examined, with the exception that the fractional foam cover was not allowed to exceed the value calculated from an empirical expression derived by Wu (1979).

The "leaps and bounds" procedure eliminated eight of the 20 AMSU channels and selected a few from the remaining twelve for the estimation of moisture at 15 pressure levels between 1000 and 300 mb. The selected channels for the 30°N–30°S latitude band are shown in Table 2 along with the pressure level at which each was selected in the optimum channel subset. Nearly equivalent second channel subsets for the 300, 570 and 950 mb levels are also displayed. The corresponding AMSU-specified brightness temperature sensitivity ΔT is also shown for each channel in Table 2. The 150 GHz channel has now been replaced by a channel at 166 GHz in the AMSU complement because the latter frequency is protected for satellite based earth observations. The 166 GHz channel was found to be slightly inferior to the 150 GHz channel in its moisture sensing capability; i.e., if both 150 and 166 GHz channels were present in the data base, the 150 GHz channel was always preferred by the selection algorithm.

To illustrate the relationship between brightness temperatures and moisture, some of the results at 570 mb are shown in Figs. 1 and 2. At this pressure level, the subset consisting of radiometer channels at 52.8 and 183.3 ± 7 GHz was found to be optimum for retrieving moisture. As shown in Fig. 1, the individual channel brightness temperatures do not appear to be highly correlated with the specific humidity at 570 mb. On the other hand, as shown in Fig. 2, a much higher degree of correlation is indicated between this specific humidity and a linear combination of the two brightness temperatures. To understand why this higher correlation exists, we have to remember that in our example, the brightness temperature at 183.3 ± 7 GHz is approximately given by

$$T_b(183.3 \pm 7) \approx \bar{T}[1 - \exp(-\tau)],$$

where $\bar{T}$ is proportional to the brightness temperature at 52.8 GHz and is the effective temperature of the absorbing layer near 570 mb, whereas τ is the opacity of this absorbing layer. This is because the 52.8 GHz temperature weighting function and the 183.3 ± 7 GHz water vapor contribution function (Kakar, 1983) peak near the 570 mb pressure level. If $\bar{T}$ is constant,

TABLE 2. Optimum AMSU channels for retrieval of water vapor mixing ratio in the 30°S–30°N latitude band. Primary channel selections are denoted by asterisks, while nearly equivalent channel subsets for some of the pressure levels are denoted by plus signs.

Pressure level (mb)	AMSU channels (GHz)											
	18.7	23.8	31.4	50.3	52.8	53.3	54.4	89.0	150.0	183.3 ± 1	183.3 ± 3	183.3 ± 7
300							*+			*	+	
350							*				*	
400							*				*	
430							*				*	
475						*					*	
500						*					*	
570	+	+	+		*			+				*
620	*	*						*				
670		*		*					*			
700	*	*							*			
780	*	*										
850			*					*	*			
920			*					*				
950	+	+	*+					+	*+			*
1000	*	*	*					*				
ΔT(K)	0.5	0.5	0.5	0.4	0.25	0.25	0.25	1.0	1.0	1.0	1.0	1.2

a steady decrease in the value of $T_b(183.3 \pm 7)$ is expected with an increase in specific humidity. A tendency towards this relationship between $T_b(183.3 \pm 7)$ and specific humidity is evident from Fig. 1. The variability in $\bar{T}$ decreases this negative correlation. A knowledge of $\bar{T}$, on the other hand, restores it.

Optimum channel subsets of different population, other than those given in Table 2, were also found by the "leaps and bounds" procedure. Lowest retrieval errors were obtained, however, when the subsets of Table 2 were used in the retrieval algorithm.

3. Results and conclusions

This retrieval method was tested in a numerical simulation experiment by applying it to data derived from 50 independent tropical radiosondes. The results are presented in Table 3. The second and third columns of this table give a statistical description of the 50 radiosondes we used in this experiment and which were not among the 350 used to derive the regression coefficients. Thus, the second column gives the average water vapor mixing ratio for 15 pressure levels between 300 and 1000 mb, while the third column shows the standard deviation of the mixing ratio for these pressure levels. Brightness temperatures for the 12 AMSU channels of Table 2 were calculated for each of the 50 radiosondes using the numerical

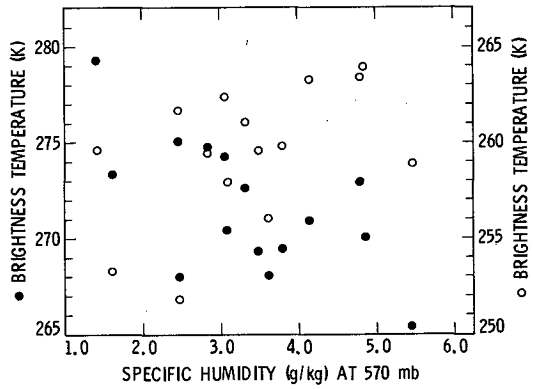

FIG. 1. Variation of brightness temperature at 52.8 GHz (open circles) and 183.3 ± 7 GHz (dots) versus specific humidity at 570 mb for a few typical examples at tropical latitudes.

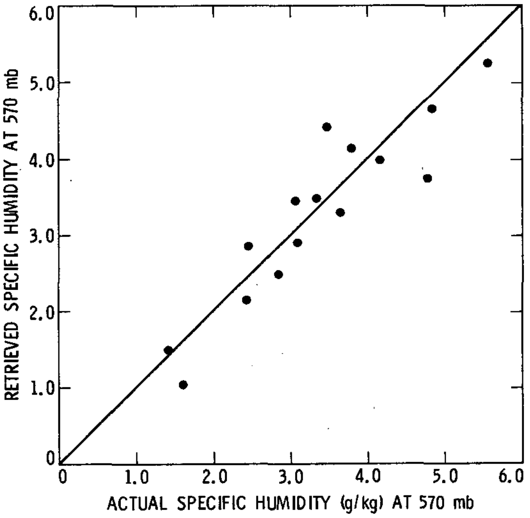

FIG. 2. Comparison of actual and retrieved specific humidity at 570 mb for a few examples at tropical latitudes.

TABLE 3. Comparison of the simulated statistical and iterative retrievals.

	50 Radiosondes		rms absolute deviation for 50 retrievals ($g\ kg^{-1}$)			
Pressure level (mb)	Average humidity ($g\ kg^{-1}$)	Standard deviation ($g\ kg^{-1}$)	Twelve channel statistical	Four channel iterative	Improved four channel iterative	Statistical over land
300	0.090	0.066	0.05	0.05	0.04	0.04
350	0.292	0.233	0.12	0.13	0.14	0.12
400	0.476	0.429	0.25	0.23	0.24	0.25
430	0.702	0.562	0.26	0.28	0.29	0.27
475	1.013	0.788	0.35	0.42	0.42	0.38
500	1.173	0.913	0.41	0.55	0.48	0.45
570	2.127	1.293	0.42	0.76	0.69	0.47
620	2.740	1.620	0.77	0.87	0.74	0.66
670	3.340	1.947	0.66	1.02	0.86	0.93
700	3.624	2.138	0.70	1.14	1.03	1.12
780	6.142	2.315	0.56	1.20	0.81	1.26
850	8.143	2.745	0.87	1.34	1.14	1.60
920	10.471	3.077	0.68	1.27	0.95	1.86
950	11.616	3.329	0.84	1.51	1.08	2.11
1000	13.447	3.859	1.40	2.33	1.56	2.54

procedure outlined earlier in this paper. To simulate "measured" brightness temperatures, a Gaussian noise term was added to each calculation. The standard deviation of this noise term was chosen equal to the ΔT values given in Table 2. Using these simulated "measured" brightness temperatures and the regression coefficients $a(p)$ and $b_i(p)$, we accomplished the retrieval of each moisture profile by the application of Eq. (1).

The rms absolute deviation of the water vapor mixing ratio for these 50 retrievals is given in the fourth column of Table 3. The ratio of the square of numbers in the fourth and the third column is a measure of the effectiveness of the retrieval algorithm. A lower ratio implies a more effective algorithm. For comparison, equivalent rms deviations obtained with the iterative method reported in an earlier paper (Kakar, 1983) are shown in the fifth column. The iterative method used one window channel at 150 GHz and the three water absorption channels at 183.3 ± 1, ±3 and ±7 GHz and the same 50 radiosonde test sample. A temperature sensitivity of 1 K for all four channels and knowledge of the atmospheric temperature profiles to within 2 K was assumed in all 50 cases. The iterative method required more than two orders of magnitude more computer time (UNIVAC 1100) than the statistical correlation algorithm and yet the iterative solutions were much worse than the statistical correlation solutions. However, this is an unfair comparison for two reasons. First, the iterative method used only four radiometeric channels compared to the twelve used in the statistical method. A second reason is that the four water absorption channels selected as the AMSU complement are not the best ones available for retrieving water vapor in tropical regions. A closer examination of Table 2 clearly shows that the 89.0, 150.0, 183.3 ± 1 and ±3 GHz channels form a better 4-channel set for retrieval of the tropical moisture profiles (the 183.3 ± 1 channel is selected for pressure levels to 115 mb). In fact, when the 50 test profiles were retrieved using the latter four-channel subset in the iterative algorithm much improved retrievals were obtained, especially for the bottom 5 pressure levels. These results are shown in the penultimate column of Table 3. The precipitable water content was retrieved to within 4.6% rms by the statistical correlation method, to within 8.5% rms using the iterative method and the original four channel set, and to within 5.5% rms using the iterative method and the improved four channel set. In general, the iterative method gave superior results when the moisture mixing ratio or the temperature in the test set of radiosondes was outside the range, shown in Table 1, for the 350 radiosonde data base. The moisture retrieval over land was much worse than that over ocean due to the low contrast between the surface and the atmosphere near the surface (i.e., an emissivity near 1 makes the surface brightness temperature nearly equal to the atmospheric temperature over land). The rms absolute deviations for retrievals over land are given in the last column of of Table 3.

The present numerical experiment was carried out for tropical latitudes, and Tables 2 and 3 strongly indicate that reasonable retrievals of water vapor mixing ratio from surface to ∼300 mb are possible without having to use the 183.3 ± 1 and ±7 GHz AMSU channels. Although these two channels do occur in the optimum channel subsets for 300, 570 and 950 mb levels, nearly equivalent channel subsets are available which do not require these two channels, as indicated in Table 2. In other words, a somewhat simpler radiometer than the AMSU system could adequately measure water vapor mixing ratio in the tropics. This is an interesting result since, in weather forecasting studies, the initial specification of humidity is much more important in the tropics and midlatitude synoptic situations because of the weak dynamical forcing there. It is relatively less important in the strongly dynamic situations at higher latitudes. The relative importance of humidity measurements at higher latitudes and altitudes above 300 mb in the tropics will determine the utility of the 183.3 ± 1 and ±7 channels; the subject needs to be investigated. A word of caution due to noninclusion of clouds in the present simulations is also in order. The presence of clouds may alter the composition of the optimal channel subsets shown in Table 2. Further study is needed before final conclusions can be drawn regarding the relative utility of the proposed AMSU channels.

The ability of the retrieval method to pick an optimum channel subset for each pressure level provides a means for optimizing channel frequencies. Thus, it is possible in principle to determine if a slightly higher or lower frequency, than that presently selected for any given channel, is more effective in retrieving the mixing ratio profiles.

The 89.0 and 150.0 GHz channels were selected in the optimum channel subsets for several pressure levels. The atmospheric absorption at these frequencies, in the simulations, is dominated by a semi-empirical term known as "anomalous" absorption (Gaut and Reifenstein, 1971). The importance of these two channels in the retrieval algorithm points to a strong need for developing a better understanding of this "anomalous" absorption, or at least experimentally refining the semi-empirical expression in the neighborhood of these two channels.

Finally, it should be noted that since, in the statistical correlation technique, the water mixing ratio is obtained from a simple linear combination of the measured brightness temperatures, the method is suitable for low cost, high speed processing of large amounts of data.

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