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Profiling Boundary Layer Temperature Using Microwave Radiometer in East Coast of China

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Abstract—The boundary layer temperature profile is very essential for modeling atmospheric processes, whose information can be obtained using radiosonde data generally. Beside this, ground-based multi-channel microwave radiometer (GMR) offers a new opportunity to automate atmospheric observations by providing temperature, humidity and liquid water content with high time resolution, such as MP-3000A ground-based multi-channel radiometer. An experiment in east coast of China for profiling boundary layer temperature was performed at Qingdao Meteorological Station from 1 March to 23 April in 2014 using an MP-3000A radiometer. Three techniques have been applied to retrieve the boundary layer temperature profile by using the experimental data, namely the linear regression method, the back propagation (BP) neural network method and the 1-D Variational (1D-VAR) method. Elevation scanning is introduced to help improve the accuracy and resolution of the retrievals for each technique. These results are compared with the radiosonde data at the same time. The preliminary results achieved by each method show that the average day root-mean-square (rms) error for temperature is within 1.0 K up to 2 km in height. The 1D-VAR technique seems to be the most effective one to improve the precision of the boundary layer temperature profile.

1. INTRODUCTION

The knowledge of atmospheric profiles, such as temperature and water vapor, is much relevant to several applications in the fields of meteorology, telecommunication, radio astronomy, air traffic safety, etc. Radiosonde observation is a fundamental method to obtain the atmospheric information, in spite of its inaccuracies, high cost, sparse temporal sampling and logistical difficulties, such as temperature, water vapor and refractivity profiles. Generally, a radiosonde is launched at 8 UTC and 20 UTC at routine meteorological stations. Typically it takes 40 minutes to ascend through the troposphere and about 2 hours to ascend to maximal height. Thus continuous measurement in real time cannot be achieved to follow the evolution state of the atmosphere only using a radiosonde.

In the last few decades, a more accurate method called continuous all-weather technology has been proposed. Passive radiometric profiling equipment, namely ground-based microwave radiometer, was applied to detect and achieve atmospheric profiles. Nowadays, ground-based microwave radiometers (GMRs) are robust instruments providing continuous unattended operations and real time accurate atmospheric observations under nearly all weather conditions [1, 2]. For typical GMRs, channels near the 60 GHz oxygen complex are used to sound temperature, and channels near the 22.235 GHz water vapor line are used for humidity [1–4]. Microwave profilers which can measure at several frequencies near the 60 GHz oxygen absorption complex are well established techniques for observing the tropospheric temperature profile. The performance of this technique at the boundary layer can be improved significantly by scanning at different elevation angles.

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The profiles of temperature and water vapor have been retrieved using the brightness temperature data measured by the six-channel microwave radiometer and the surface pressure, temperature and humidity data, by means of linear statistical inversion [5]. In the movement of the regression techniques, neural networks (NN) have also been introduced by Churnside et al. [6] to retrieve the temperature profiles. As to the boundary layer temperature and humidity profiles, 1D-VAR method has been used by Cimini et al. [2010] in Arctic regions using ground-based millimeter-wave radiometer's observations as input.

Previous works show the feasibility of retrieving the boundary layer temperature profile using brightness temperature data in zenith and scanning elevation collected by a ground-based multi-channel microwave radiometer. In this study, we present some retrieval results with related observations from a multi-channel microwave radiometer (MP-3000A) which can be applied under various climatic conditions. To obtain the boundary layer temperature profiles with a high vertical resolution (down to 50 m close to the surface), experiments are taken at four frequencies (54–59 GHz) and under several elevation angles from 90 to 30 degrees.

The basic principles, instruments and radiosonde data are introduced in Section 2, including the radiative transfer equation, atmospheric absorption spectrum, critical parameters of MP-3000A and source of basis data. In Section 3, three inversion algorithms are imported, including the linear regression method, BP-ANN technology and 1D-VAR algorithm. The iteration factor of 1D-VAR is obtained by testing the precision of historical retrieval data. In Section 4, the inversion algorithms using ground-based microwave radiometer observations are simulated and compared with the radiosonde data. In the last section, a conclusion is drawn for the preliminary study, and the future work is discussed.

2. BASIC PRINCIPLES, INSTRUMENTS, AND RADIOSONDE DATA

2.1. Basic Principles

The radiative transfer model forms part of the forward model, and it is used to translate the profile of state space into observation space. Other components of the forward model include the discretization of the atmospheric profile to a finite number of levels and the partitioning of the state space variables into the control variables used in the retrievals such as the averaged profiles of temperature, absolute humidity and liquid water. Forward models are needed for all physical retrieval techniques.

The brightness temperature T_B for the spherical atmosphere, observed at a height h and frequency f under the observing zenith angle, is described by the radiative transfer equation [9],

$$T_B = T_\infty \exp\left[-\tau\left(f,\infty\right)\right] + \int_0^\infty T(h)k\left(f,z\right)\sec\theta \exp\left[-\tau\left(f,\infty\right)\right]dz \tag{1}$$

where $k(f,z)$ is the absorption coefficient, T_∞ the cosmic background temperature (equal to 2.7 K approximately), and $T(h)$ the temperature profile which depends on the height above the ground, and $\tau(f,\infty)$ is the optical depth given by

$$\tau\left(f,\infty\right) = \int_0^z k\left(f,y\right)dy \tag{2}$$

In the microwave range, the atmospheric absorption is attributed to three contributions: oxygen, water vapor, and liquid cloud water, which is given by

$$k\left(f,y\right) = k_{O_2} + k_{H_2O} + k_{liquid} \tag{3}$$

The total atmospheric attenuation at a given microwave frequency, may therefore be expressed as the sum attenuation caused by oxygen, water vapor, and cloud liquid water.

As we know, the oxygen spectrum includes 33 spin-rotational lines between 51.5–67.9 GHz. In the lower troposphere, they are incorporated into a single band of strong absorption by pressure broadening mechanism, referred to as 60 GHz oxygen complex. The absorption is very strong near the centre of this band due to the strength and density of the spectral lines. Thus the channels energy of a ground-based radiometer detecting down-welling radiation encounters very strong absorption near the band centre. The differential absorption between different channels provides the principle for retrieving the temperature profiles.

Figure 1. The experimental scene.

2.2. Instruments

The observation of Radiometric MP-3000A microwave radiometer was used in this study. Thirty-five channels in total are available in the Radiometric MP-3000A microwave radiometer: twenty one in the oxygen band 51–59 GHz, which provide information for the temperature profile and fourteen between 22–30 GHz near the water vapor line, which provide humidity and cloud information. This radiometer also includes sensors to measure pressure, temperature and humidity at ∼1 m over the surface [10].

Profiles of temperature, water vapor and relative humidity are obtained at 37 levels [11]: from 0 to 500 m over the ground level with 30 m grid interval, from 500 m to 1 km with 50 m, and from 1 km to 2 km with 100 m. The profiles are derived using the measured brightness temperatures with linear regression method, neural network retrieval algorithms and 1D-VAR method, respectively. The neural network was trained for brightness temperatures which were calculated using a microwave radiation transfer model and radiosonde profiles data for years.

The experiment was performed on the coast of Qingdao metrological station in China (36.05°N, 120.43°E), from 1 March to 23 April in 2014, as shown in Fig. 1.

Traditionally, the atmosphere profiles are retrieved only using the brightness temperature in zenith, which have poor precision. The inversion capability can be improved by adding the brightness temperature in elevation in the retrieval process [4, 9]. According to the weighting function for oxygen component in the height between 0 to 10 km in Qingdao, it is adequate that using ten frequencies in zenith and four in six different degrees to retrieve the boundary layer temperature profile (as shown in Table 1).

Table 1. Multi-channel parameter.

frequency (GHz)	Elevation (degree)
51.248, 51.760, 52.280, 52.804, 53.36, 53.848, 56.020, 57.288, 57.964, 58.800	90
54.400, 54.340, 55.500, 56.660	90, 62, 45, 34, 30, 28

2.3. Radiosonde Data

Up to now, radio soundings are still used as standard atmospheric monitor and can provide the most accurate information about the vertical structure of the troposphere [12]. The radiosonde data used for analyse are collected by Qingdao Metrological Station, providing profiles of pressure, temperature, relative humidity, and dew point temperature, in which date, hour, latitude, longitude, and altitude are also included. Totally almost nine-year historical radiosonde data are used for analysis in this study. These data are used by the regressing retrieval method, neural network training and 1D-VAR method.

About 29 samples in total were selected during the observation period, except the data gap between 4 April and 8 April, whose data were affected by cloud and rain.

3. RETRIEVAL TECHNIQUES

A variety of techniques can be used to derive the information of the atmospheric state vector x from the observation vector y, which is regarded as radiometric in our case [13–15]. In fact, the Forward (F) problem, represented by the Radiative Transfer Equation (RTE), is not analytically solvable, whose discrete form can be expressed by:

$$y = F(x) \tag{4}$$

Conversely, the inverse problem of estimating x from accepted non-unique solutions is often ill-posed because only a finite number of highly correlated observations affected by measurement error are available. From this aspect, the observations act as constraints that need to be coupled with auxiliary information, known as a priori, to provide a meaningful solution. In the following, the main features of the three techniques applied to the radiometric observations during the experiment are illuminated.

3.1. Regression Retrieval Method

Although the retrieval of boundary layer temperature profile is nonlinear, it can also be implemented as an empirical statistical regression between sets of observations and profiles. The application of this method is limited to the site where long time-series radiosonde observations should be available.

The traditional linear statistical inversion method summarized by Westwater [3] and Rodgers [16] is used in this study. The independent vector y contains brightness temperatures in zenith T_{b_zenith} and slant path T_{b_slant}, surface pressure P, water vapor density ρ, surface temperature T, refractivity N, dry refractivity N_d, wet refractivity N_w, humidity Rh and integral water vapor content V [14]. The dependent vector x contains the boundary layer temperature profile. The dependent vector is obtained linearly using the independent vector as

$$x = f\left(T_{b\_zenith}, T_{b\_slant}, P, T, \rho, N, N_d, N_w, Rh, V\right) \tag{5}$$

The steps are given as follows:

Step 1. The ten regression coefficients are obtained using a statistical method following Formula (5) and the historical radiosonde data.

Step 2. The compound correlation coefficient for each input variable is achieved when the resultant correlation exceeds 0.998.

Step 3. Using the recollected input parameter, output the result.

3.2. BP Neural Network

Nonlinear statistical regression can also be implemented by an artificial neural network [17]. The standard forward neural network is composed by input, hidden, and output layers with full connection between adjacent layers. A standard back propagation algorithm was used for training, based on a data set of thousands of historical radiosonde profiles.

For clear RAOBs, a three-layer BP neural network is used, which has 38 input nodes (including 34 brightness temperature, surface pressure, water vapor density, surface temperature and humidity), 69 hidden nodes, and 37 output nodes representing the boundary layer temperature profile from 0 to 10 km height. The transfer function is a sigmoid one. The Levenberg-Marquardt algorithm is adopted during the train process. The total number of epochs is 10000, and train goal is 0.0001.

3.3. 1-D Variational (1D-VAR) Retrieval Technique

One Dimensional Variational Assimilation Retrieval (1D-VAR) is an estimation method which is widely used to retrieve boundary layer temperature profile consistent with a given set of observations. This is followed by a similar approach to the integrated profiling technique published by Lohnert et al. [18]. This method provides the basis of the integrated profiling system as it retrieves profiles of temperature etc. The variational methods provide a statistically optimal method of combining observation with given background, which accounts for both assumed error characteristics. For this reason they are often referred to as optimal estimation retrievals.

The 1D-VAR method used in this study is based on early work [4, 8–13]. In fact, 1D-VAR is equivalent to a Bayesian approach where the estimation is the maximum of a posteriori probability state vector. A cost function is given by:

$$J(x) = \left[x - x^b\right]^T B^{-1} \left[x - x^b\right] + \left[y^0 - H(x)\right]^T R^{-1} \left[y^0 - H(x)\right] \tag{6}$$

Its minimum value corresponds to the maximum of a posteriori probability state x^a. $H(x)$ is the forward model, $H = \partial y/\partial x$ the Jacobin matrix, y the observation vector (the brightness temperature collected by the radiometer), x^a the state vector (the boundary layer temperature profile), x^b the background data, B the background error matrix, and R the observation error matrix. The vector derivative of the cost function in the form of Equation (6) is given by:

$$\nabla_x J = -\left[\nabla_x H(x)\right]^T R^{-1} \left[y - H(x)\right] + \left[x - x^b\right]^T B^{-1} \left[x - x^b\right] \tag{7}$$

Further differentiation of $f = \nabla_x J$, rewriting $\nabla_x H(x)$ as H,

$$\nabla_x f = B^{-1} + H^T R^{-1} H - \left[\nabla_x H(x)\right]^T R^{-1} \left[y - H(x)\right] \tag{8}$$

The third term on the right-hand side of Equation (8) is small in moderately nonlinear problems and can be ignored in small residual problems [19]. Substituting the remaining term into $x_{i+1} = x_i - [\nabla_x f(x_i)]^{-1} f(x)$ yields the modification Gauss-Newton method [14, 15, 22, 23]. It was suggested by Levenberg [20] and Marquardt and [21] to improve the convergence in moderately nonlinear problems, where the first guess is too far from the truth for the increment to be reliable. A parameter, γ, to modify the direction of the step is added to this method, which is adjusted after each iteration. In the form suggested by Rodgers [19], the Levenberg-Marquardt method can be written as:

$$x_{i+1} = x_i + \left((1+\gamma) B^{-1} + H_i^T R^{-1} H_i\right)^{-1} \left[H_i^T R^{-1} \left(y^0 - H(x_i)\right) - B^{-1} \left(x_i - x^b\right)\right] \tag{9}$$

where γ is a factor, which is adjusted after each iteration depending on how the cost function has changed.

- If $J(x)$ increases, reject this step, increase γ by a factor of 7 and repeat the iteration,
- If $J(x)$ decreases, accept this step, decrease γ by a factor of 4 for the next iteration.

The iteration factor γ is equal to 2 or 10 by *Rodgers* [2000]. It is an important parameter in the retrieval process. In practice, the factor γ should be computed on historical radiosonde data retrievals.

4. RESULTS, CONCLUSION AND DISCUSSION

4.1. Results

The steps of the simulation and inversion process are given as follows:

1> Calculate the brightness temperature at multi-frequency in zenith and elevation using Formula (1);

2> The coefficients of the Linear regressing method are received by analyzing the 9-year set of historical radiosonde data, testing the algorithm performance with the radiosonde launched in Qingdao Metrological Station from March to April in 2014.

3> The BP neural network was trained using the historical radiosonde data too [24–26], and the inversion profiles were retrieved using the real radiosonde data obtained in the experiment.

4> Concerning the 1D-VAR, choosing the mid-latitude reference atmosphere as the initialize state vector (according to ITU-R P835-5, 2012), the background data is the average temperature profile calculated by the radiosonde data. The background error matrix is a diagonal one with its element equal to 1 in diagonal line [27–29]. The observation vector is the actual brightness temperature measured by MP-3000A. The observation error matrix is the covariance one calculated by the brightness temperature, antenna parameter etc. This method needs more time in calculation than the former two algorithms.

5> Analyzing the results of the three methods. Besides the inversion method, there are other factors determining the retrieval accuracy, defined as the bias and root-mean-square (rms) of estimated minus true profile, given by:

$$E_{\text{bias\_day}} = \frac{1}{N}\sum_{j=1}^{N}\sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(T_{\text{Retr}}^{j,i} - T_{\text{Radio}}^{j,i}\right)} \quad E_{\text{bias\_layer}} = \frac{1}{M}\sum_{i=1}^{M}\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(T_{\text{Retr}}^{j,i} - T_{\text{Radio}}^{j,i}\right)} \tag{10}$$

$$E_{\text{RMS\_day}} = \frac{1}{N}\sum_{j=1}^{N}\sqrt{\frac{1}{M}\sum_{i=1}^{M}\left(T_{\text{Retr}}^{j,i} - T_{\text{Radio}}^{j,i}\right)^2} \quad E_{\text{RMS\_layer}} = \frac{1}{M}\sum_{i=1}^{M}\sqrt{\frac{1}{N}\sum_{j=1}^{N}\left(T_{\text{Retr}}^{j,i} - T_{\text{Radio}}^{j,i}\right)^2} \tag{11}$$

where N is the number of data (equal to 29) and M the number of layers (equal to 37). $T_{\text{Retr}}^{j,i}$ and $T_{\text{Radio}}^{j,i}$ are the retrieving and actual boundary temperature profiles in the ith layer jth day. $E_{\text{bias\_day}}$ and $E_{\text{bias\_layer}}$ are the average day bias and layer bias. $E_{\text{RMS\_day}}$ and $E_{\text{RMS\_layer}}$ are the average day rms and layer rms, respectively. The inversion results are shown in Fig. 2 and Table 2.

The above schematics indicate that the average layer bias of linear regression method is the smallest in the vertical height range 0–2 km considering brightness temperature's measurement error to be 0.3 K. The 1D-VAR algorithm has almost the same average day bias compared with the linear regression. However, we can still argue that the 1D-VAR performs better than other techniques because its average

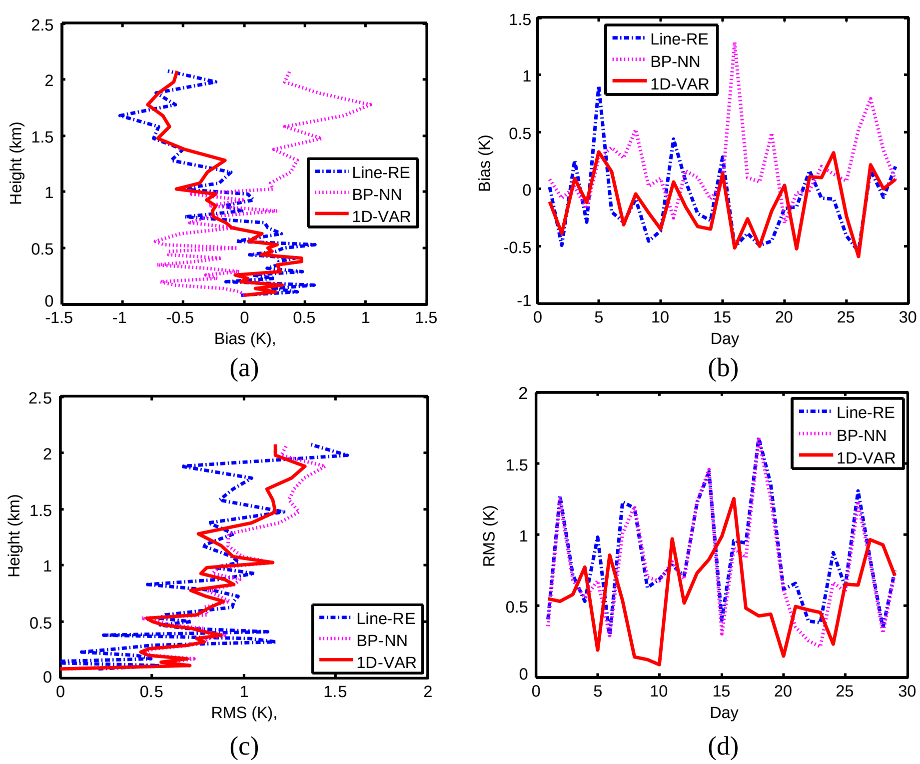

Figure 2. Retrieving profile examples.

Table 2. Average bias and rms results.

Algorithm	Bias_layer (K)	Bias_day (K)	RMS_layer (K)	RMS_day (K)
Line regression	−0.0596	−0.1224	0.7590	0.8341
BP neural network	−0.0654	0.1765	0.8607	0.7688
1D-VAR method	−0.1232	−0.1129	0.8122	0.5907

day rms is the smallest. In fact, 1D-VAR initiates the iteration with an average temperature profile, which rarely depends on the historical radiosonde data, so it has expansive foreground and application value.

4.2. Conclusion and Discussion

A different method of retrieving the boundary layer temperature profile from ground-based multi-channel microwave radiometer is presented in this paper. A microwave radiometer MP-3000A and three inversion algorithms are introduced. The retrieving accuracy of these techniques is demonstrated in terms of average bias and rms with radionsonde observations at Qingdao Metrological Station in 2014. The results are concentrated in the lowest 2 km. The retrieval rms of the boundary layer temperature profile is smaller than 1 K for all the three methods. Elevation scanning is used to improve the accuracy of retrieved profiles in the boundary layer. The results are also limited by the atmospheric absorption model, horizontal inhomogeneity, beam breadth of antenna, accuracy of brightness temperature, etc. In spite of these causes, 1D-VAR is a convenient way to combine observations using the microwave radiometers with an atmosphere background such as Numerical Weather Prediction (NWP) models MM5, and 1D-VAR has the advantage of improving short-term forecast.

Future work should include analyzing the seasons of the large rms and biases, and improving the accuracy. The MM5 data can be used as background data to retrieve boundary layer and troposphere temperature parameter. The 1D-VAR algorithms are also planned to be extended to retrieve water vapor density, humidity and refractive index profiles.

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